

THE EFFECTS OF ROAD CONTACT ANGLES AND PITCH/YAW ANGLES ON THE INJURIES OF DRIVERS IN CRIS TEST

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ABSTRACT

This paper shows the effect of the roof contact angle with ground and pitch/yaw angle on head and neck injuries in CRIS tests. In this study the effect of these conditions on injury in a rollover is simulated and analyzed by using a commercial multi-body software (ADAMS). The vehicle model consists of a rigid lower body and deformable upper body. Each member of the upper body is characterized to get the similar behavior to the results obtained from an equivalent finite element model. To evaluate the severity of driver's injuries in a CRIS test, a computer simulation to replicate the dynamic CRIS test is developed. The angular velocity of vehicle is set to a constant value of 270 degree/sec and the lateral velocity is varied to be 28.8kph or 35kph so that it can roll 2 or 3 turns. The roof contact angle with ground is selected to be 135, 145 and 155 degrees. The pitch and yaw angles of the vehicle is also varied to be 2 or 5 degrees and 0, 10, or 20 degrees, respectively. In addition to the peak acceleration of the dummy head, the maximum shear force, compressive force, and bending moment acting on the dummy neck are calculated to evaluate the rollover safety for various conditions. The simulation results are then compared to the KNCAP evaluation criteria. Considering the fact that the rollover accidents with less than 2 full turns account for about 90% of the entire rollover accidents, this study suggests that the 2-turn condition would be appropriate for a protocol of the dynamic rollover test.

INTRODUCTION

Rollover accident mortality, which represents the number of deaths per 100 automobile accidents, is high compared to other types of car accidents. In Fig 1. the occurrence rate and mortality rate for each type of vehicle accidents in Korea compared to the European data are shown. The two regions show the significant difference in the occurrence rate and mortality rate. In particular, the vehicle-only-accidents in Korea are significantly smaller than the corresponding data in Europe. This difference might be considered to be due to the road condition, behavioral characteristics of drivers and pedestrians, and composition of vehicles. (Korea National Police Agency 2011; European Commission, 2008; UNECE, 2007; NHTSA, 2007)

Although the occurrence rate of the rollover accidents is relatively smaller than other types of accidents, the mortality rate related to the rollover accidents is significantly high. According to the Korean data set, the rollover accidents appear to be rare with the rate of 0.5%. But, as shown in Fig. 1, when considering the vehicle-only-accidents, which also include the accidents that can secondarily cause the rollover such as falls and veering due to breakaway, the mortality rate becomes significantly high with a 13.8 person compared to other types of accidents. (Korea National Police Agency 2011)

This observation is also supported by the data set in U.S. In contrast to the fact that the incident rate of the rollover in U.S. is approximately 3% out of the entire vehicle accidents, the 35% of automobile fatalities occur due to the rollover. Similarly, this trend can be found in the Australian data set. (NHSTA Traffic Safety Facts 2009)

There have been various efforts to reduce the fatality due to rollover by improving the vehicle stability performance with the equipped ESC (Electrical Stability Controller), securing the passenger compartment or occupant survival space with the enhanced roof crush resistance, and mitigating the passenger's ejection during a rollover. To encourage these efforts, the NHTSA has implemented the FMVSS 126 (i.e., mandatory installation of ESC) since 2011 and phased in the enhanced FMVSS 216a (i.e., roof crush resistance) and FMVSS 226 (i.e., ejection mitigation) since 2012 and 2014, respectively. In addition, the IIHS has also implemented the new roof strength rating system.

The rollover tests are developed in an effort to replicate what happens in real world collisions: Dolly test (FMVSS 208), CRIS (Controlled Rollover Impact System), and JRS (Jordan Rollover System). The Dolly test is not used as a mandatory requirement because it cannot test various conditions such as the pitch and yaw angle and lacks the repeatability. For the other two testing methods, researchers in the U.S. and Australia have actively worked on the test protocol to ensure the practicality of safety related regulations.

In real-world rollovers, the driver's injury is affected by not only the strength of vehicle's body structure (or chassis strength?), but also the posture of drivers. (Ridella et al. 2009; Cooper et al. 2001; Moffatt et al. 2003; Friedman et al. 2003) Seat belts prevent a driver to be ejected, thereby contributing to reducing fatal injuries. In the analyses of the CFIR data set, Huelke et al. have reported that seat belts reduce the severe injuries and fatalities by 91% under the roof crush of less than 6 inches (152mm). Evans et al. have reported that according to the FARS data, lap/shoulder belts can be effective to reduce fatalities by 82% and thus significantly contribute to the ejection prevention. (Huelke et al. 1973; Huelke et al. 1977; Evans, L. 1988)

Therefore, this study replicates the CRIS test using a dummy seated with a seat belt in order to prevent it from being ejected. As measured in the KNCAP (Korean New Car Assessment Programme) crash-test, the HIC15 induced to the dummy head and shear force, compressive force, and bending moment acting on the dummy neck are calculated and used to evaluate the safety under a rollover scenario.

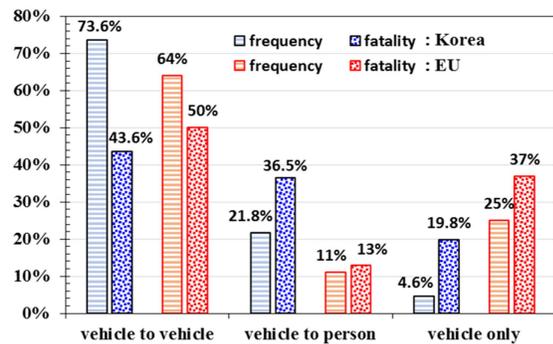


Fig. 1 Vehicle Crash Occurrence and Fatalities in South Korea and EU (Source: Korea National Police Agency 2011 and UNECE 2007)

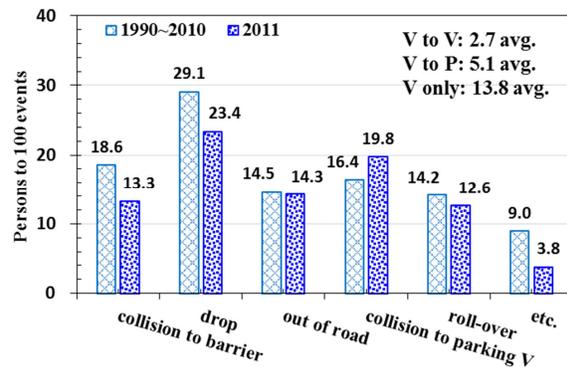


Fig. 2 Fatality of vehicle only accidents in Korea (Source: Korea National Police Agency 2011)

CRIS TEST

It is required to maintain the ceiling strength at a certain level in order to ensure the survival space for passengers during a rollover. However, according to SNPRM (Supplemental Notice of Proposed Rulemaking), most of vehicle produced prior to the year 2008 have failed to satisfy the regulation of $SWR \geq 3.0$ and resulted in serious casualties. Hence, the NHTSA has enhanced the regulations related to the ceiling strength.

It is, however, questionable if the static test would be appropriate for evaluating the ceiling strength. Currently, many researchers investigate how to better simulate a dynamic rollover accident, rather than replicating the Dolly rollover test (FMVSS 208). (Friedman, D., et al. 2009; Chirwa, E.C., et al., 2010; B. K. Han, et al. 2013)

Although the CRIS test is problematic in terms of the repeatability, it allows one to investigate the effect of the pitch and yaw angle for various road conditions and the behavior of the dummy as the roll progresses. (Linstromberf et al. 2005) The JRS test is actively used by the researchers in the CFIR(Center for Injury Research), University of Virginia, and University of New South Wales because it shows a high level of repeatability. (Grzebieta, R., et al. 2007; Kerrigan, J.R., et al. 2011; Mattos G.A., et al. 2013) This study constructs a simulation model to replicate the CRIS test and thus investigates the effect of the initial contact angle with ground, pitch/yaw angle on the safety during a rollover.

Table 1. Estimated Fleet Failure Rates Based on GVWR reported (SNPRM in January 2008).

Two-Sided Testing			
GVWR :	2.5 SWR	3.0 SWR	3.5 SWR
<2,722 kg	67.2%	78.6%	85.0%
>2,722 kg	100.0%	100.0%	100.0%
Total	75.1%	83.7%	88.6%
Single-Sided Testing			
GVWR :	2.5 SWR	3.0 SWR	3.5 SWR
<2,722 kg	44.5%	76.9%	80.9%
>2,722 kg	98.9%	100.0%	100.0%
Total	57.6%	82.5%	85.5%

METHODS

Protocol and Analysis Conditions for Simulated CRIS Test

As shown in Fig.5, in CRIS test device a vehicle is fixed to a trailer with the selected pitch and yaw angles. While the trailer moves forward at a constant speed, the vehicle falls apart from the trailer when the vehicle rotates at a desired angular velocity. As shown in Fig.6, the initial contact angles between the vehicle and the ground are varied to be 135, 135, and 155 degrees. The pitch and yaw angles are set to be 2 or 5 degrees and 0, 10, or 20 degrees, respectively.

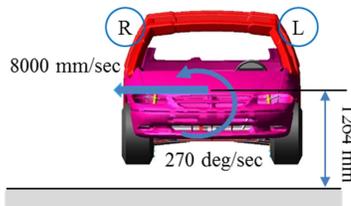


Fig.5 Layout of CRIS test protocol

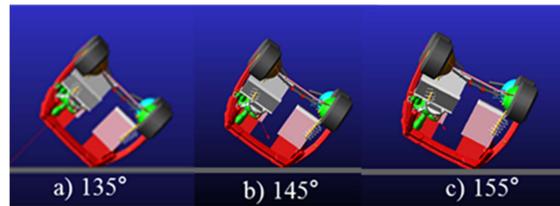


Fig.6 Seat belted Hybrid 3 dummy model

The analysis conditions for the simulated CRIS test are selected as in Table 2 so that the 2 turns and 3 turns of the rollover can be simulated. The drop height of the vehicle was set to be 0.3 m.

To assess the severity of injury for driver, a 50th percentile Hybrid III anthropomorphic test dummy (ATD) is seated in the driver's seat. The ATD is modeled to calculate the 3-dimensional forces and moments induced to its neck during the impact.

Table 2 Analysis Conditions for the Simulated CRIS Test

	2-turn condition	3-turn condition
Roll rate (deg./sec)	270	270

Velocity (kph)	28(8 m/s)	35(9.7 m/s)
Pitch angle (deg.)	2, 5	2, 5
Yaw angle (deg.)	0, 10, 20	0, 10, 20

Multibody Model for Base Vehicle

A medium-sized passenger vehicle is used for the base vehicle of this study as shown in Fig. 6. The specifications for the base vehicle used are as follows: 2,000cc for the total engine displacement, 2,700 mm for the wheelbase, 4,400 mm for the overall length, 1,861 mm for the tread distance, 1,901 mm for the overall width, 1,610 mm for the overall height, 2,000 kg for the curb weight. The roof strength of the vehicle is modeled to have a strength-to-vehicle weight ratio (SWR) of 4.5, which exceeds the IIHS requirement for the static roof strength test (i.e., a SWR of 4.0).

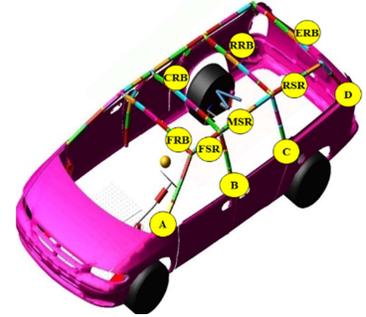


Fig.6 Full Car model for multi-dynamics analysis

The multibody vehicle model consists of the rigid lower body and the deformable upper body as shown in Fig. 5. The lower body is modeled to be rigid. The pillars, side rails, and roof bow members of the upper body are divided in 3~5 mass elements each. And the two adjacent elements are connected using the torsional and the bending spring. The characteristics of these springs are obtained using a finite element analysis (FEA), thereby mimicking the deformation of the upper body. (B. K. Han, et al. 2015)

RESULTS

Using the analysis conditions described in the Table 2, the model simulations are performed. In Fig. 7 to Fig. 12, the results for the 2-turn and 3-turn conditions are plotted. The p2 and p5 represent the pitch angles of 2 and 5 degrees and the y0, y10, and y20 represent the yaw angles of 0, 10, and 20 degrees, respectively. The effect of the initial contact angle (β) between the vehicle and ground is compared for the 2-turn and 3-turn conditions.

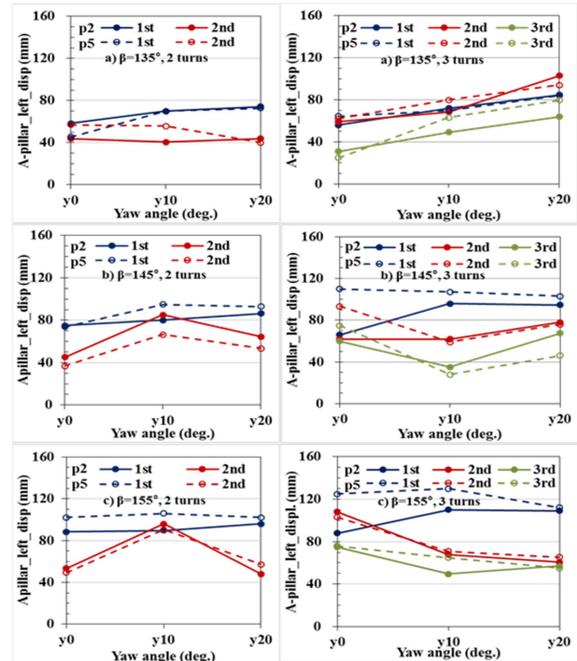


Fig.7 Maximum displacement of left A-pillar top side; Left side for the 2 turns condition and right side

for the 3 turns condition. And β is the first contact angle of vehicle with ground.

Displacement of Far-Side A-Pillar

In Fig. 5, the maximum displacement of the left A-pillar for each roll is shown. Overall, as the pitch angle increases, the displacement of the left A-pillar increases, while it is not significantly affected by the changes in the yaw angle. In addition, as the initial contact angle (β) between the vehicle and ground increased, the maximum displacement of the left A-pillar increases.

As expected, the displacement for the 3-turn condition is greater than the one for the 2-turn condition. Under the 3-turn condition, the displacement for the second turn is dramatically decreased because the collision between the ground and the side of the vehicle, not the roof of the vehicle, is made. Instead, the large displacement consequently occurs in the third turn.

The maximum displacement of the left A-pillar of the vehicle indicates how much the roof penetrated the cabin, which is closely related to the passengers' survival. In other words, when the value gets large, a driver's head can get injured due to the contact with the roof. The overall resultant maximum displacement is smaller than 5 inches (127mm). This is because the roof strength of the vehicle has a SWR of 4.5.

Variation in Head Acceleration

The driver's head acceleration when the far-side of the vehicle collides with the ground is greater than the corresponding value when the far-side of the vehicle collides with the ground. When the roof is collapsed and thus the head contacted with the roof or front side rail, the acceleration reaches its maximum. In Fig. 8, the head accelerations are shown for the 2-turn and 3-turn conditions. The maximum head acceleration occurs during the first turn and it tends to decrease as the yaw angle increases. As the initial contact angle (β) increases, the peak head acceleration for each turn increases. Under the 3-turn condition, the peak head acceleration are greater than the one under the 2-turn condition. In addition, as the yaw angle increases, the peak head acceleration decreases. The peak head acceleration is not significantly affected by the pitch angle.

In Fig. 9 the values for HIC36 and HIC15, which are calculated from the line diagram of the head acceleration, are plotted. When the initial contact angle (β) between the vehicle and ground is 135 degrees, the values for HIC36 and HIC15 are significantly small. However, when either the contact angle (β) or the number of turns increase, the values significantly increase. The difference between the HIC15 and HIC 36 decreases as the yaw angle increases. The results suggest that it would be appropriate to use the HIC15 for a rollover evaluation criterion because the duration when the peak acceleration is maintained is short during a rollover in contrast to a frontal impact. Considering that the head acceleration is significantly high compared to the value of HIC15, it is recommended that the head acceleration would be included in the evaluation criteria for the vehicle's safety performance. Currently, the KNCAP adopts only the HIC36 to assess the risk for head injury during the frontal impact testing. For example, according to KNCAP, the HIC36 value exceeding 1000 indicates a higher probability of the head injury, while the HIC36 value below 650 represents less likelihood of the head injury.

Shear/normal force of neck

Compared to frontal impact tests, a rollover test induces greater values for the frontal shear force (i.e., F_x) and lateral shear force (i.e., F_y) in the dummy neck. The values for the frontal shear force are calculated to be less than or equal to 800 N under the loading conditions used in this study, except for when the initial contact angle (β) is equal to 135° and the yaw

angle is equal to 10° . As shown in Fig. 10, the frontal shear force (F_x) is not significantly affected by the pitch angle (α), initial contact angle with ground (β), and turn condition.

According to KNCAP criteria for frontal impact tests, the results of shear forces are included in the safe region for all testing conditions as shown in Fig. 10: the F_x values below 1.9kN and exceeding 3.1 kN indicate a higher probability or less likelihood to be safe, respectively. In Fig. 11, it is shown that the lateral shear force (F_y) is greater than the frontal shear force (F_x). In addition, it is the lateral shear force (F_y) that is significantly affected by the turn condition, rather than the frontal shear force (F_x). When compared to the KNCAP shear force criteria for frontal impact testing, the lateral shear force, F_y is also included in the safe region. However, the resultant force of the frontal and lateral shear forces may exceed the KNCAP shear force criteria. In case of the 3-turn condition, in order to satisfy the KNCAP criteria, additional constraining devices such as a curtain airbag would be required to reduce the impact with the front side rail.

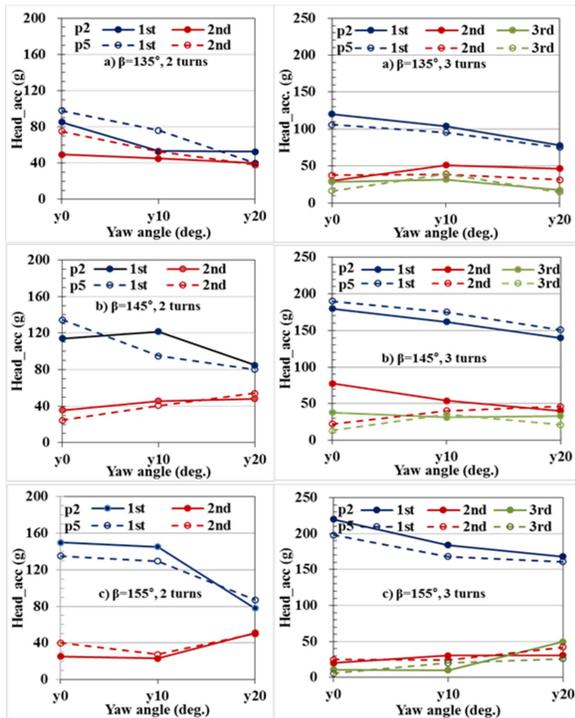


Fig.8 Maximum value of head acceleration at each roll; Left side for 2 rolls condition and right side for 3 rolls condition.

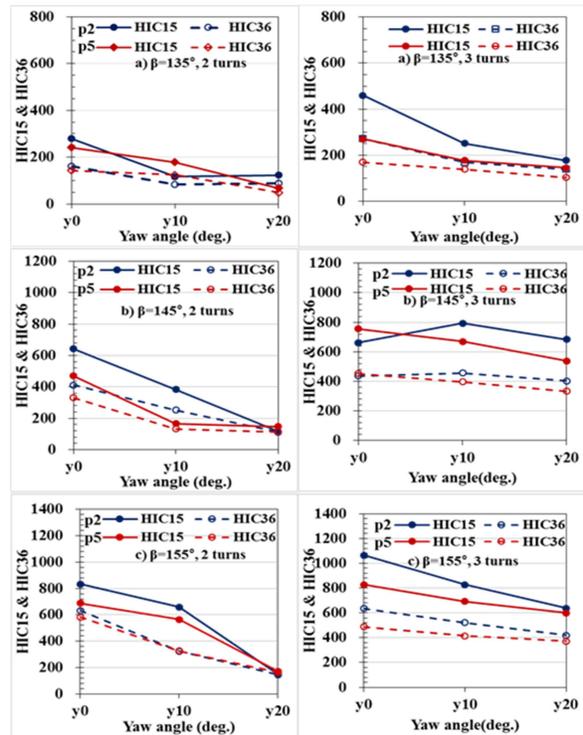


Fig.9 Maximum HIC value of head; Left side for 2 rolls condition and right side for 3 rolls condition.

The compressive force (i.e., F_z) on the neck will occur when the vehicle's chassis is collapsed and the dummy dives toward the roof, thereby impacting the roof or front side rail. The compressive forces on the neck (F_z) for each test conditions are shown in Fig.12. In the current model, the distance between the dummy head and roof ceiling is set to $\delta=80$ mm. When the initial contact angle with ground (β) increases, a large displacement at the A-pillar is induced and thus the contact between the dummy head and the roof ceiling occurs thereby producing the compressive force on the dummy's neck. In real situation, the dummy also dives toward the roof ceiling augmenting the compressive force on the neck. The effect of the constraining devices such as a seat belt cannot be excluded. However, instead of considering the complicated dynamics of a seat belt, in this simulation the seat belt is simplified by maintaining the tension on it at a constant level. In the 2-turn condition, the largest compressive force acting on the neck occurs when the far side of vehicle contacts with the ground during the first roll.

Comparing to the criteria for the compressive force in a frontal impact, when the space between the roof ceiling and head is enough and seat belt works properly thereby minimizing the diving effect, the compressive force acting on the neck, F_z is included in the safe region.

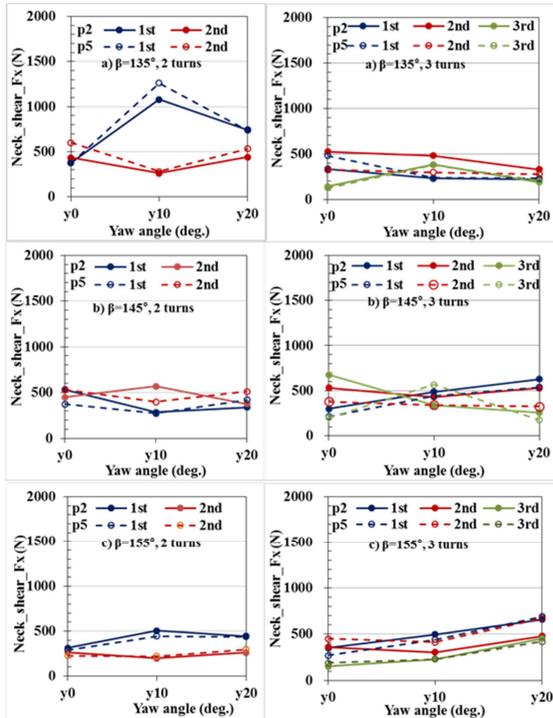


Fig. 10 Max. frontal shear-force acting on the neck (F_x) at each roll; Left side for 2 rolls condition and right side for 3 rolls condition.

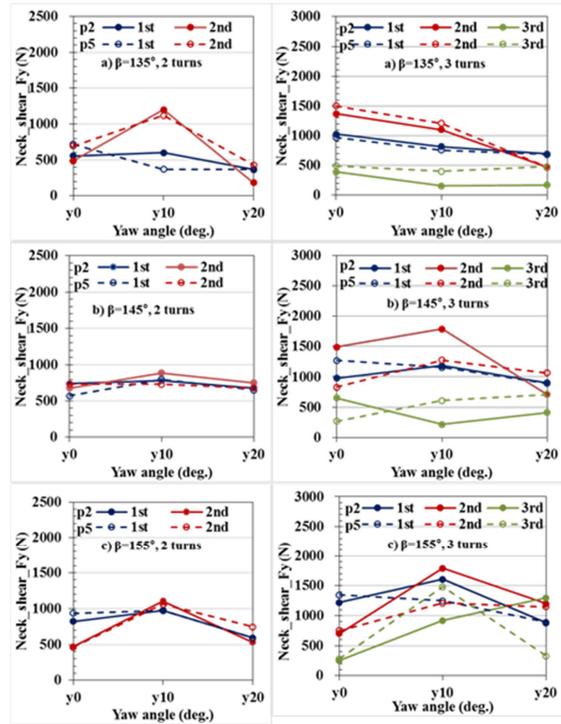


Fig. 11 Max. lateral shear-force acting on the neck (F_y) at each roll; Left side for 2 turns condition and right side for 3 turns condition

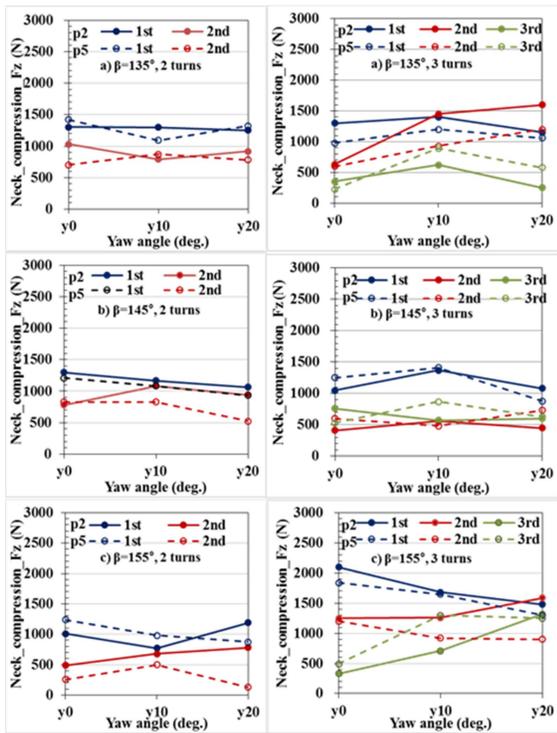


Fig. 12 Axial force acting on the neck (F_z) at each roll; Left side for 2 roll condition and right side for 3 roll condition.

Bending moment of neck

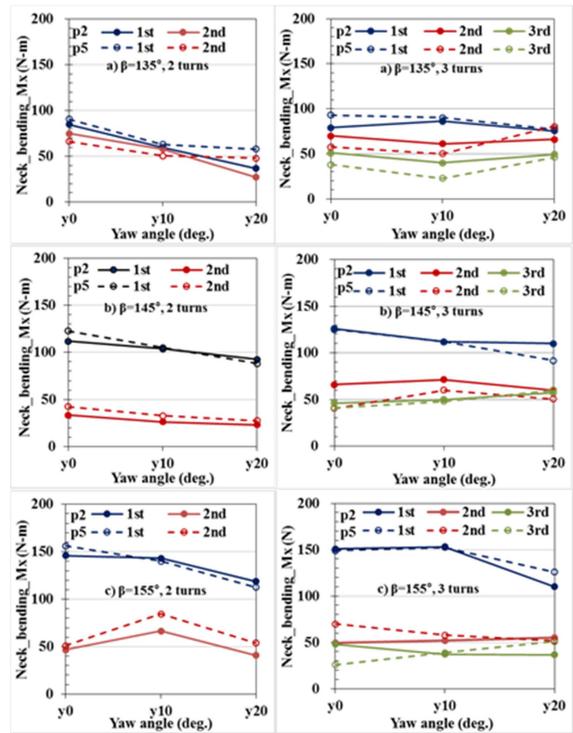


Fig. 13 Lateral bending moment (M_x) at each roll; Left side for 2 roll condition and right side for 3 roll condition

The moment induced to the dummy neck can be decomposed into the lateral bending moment (M_x) and the extension/flexion moment (M_y). The lateral bending moment (M_x) under the 3-turn condition is significantly greater than the one under the 2-turn condition as shown in Fig. 13. It also increases as the initial contact angle (β) increases while it decreases as the yaw angle (θ) increases.

Fig. 14. Criteria for the neck injury suggested by Kleinberger et al.

It is difficult to evaluate the safety of the obtained results because the injury criteria related to the lateral bending moment (M_x) has not been in agreement. Thus, referring to the injury criteria of neck shown in Fig. 14, which has been proposed by Kleinberger et al., the lateral moment (M_x) should be evaluated based on the flexion moment rather than the extension moment. (Kleinberger et al. 1998)

Similarly to the injury criteria suggested by Kleinberger et al., the safety in the lateral direction is evaluated within the range between a third and half of the safety threshold for the flexion moment (i.e., 310 N·m): the lateral bending moment below 100 N·m is higher likelihood to be safe while the corresponding value above 150 N·m indicates a higher probability to be unsafe. Based on this injury criteria, the lateral bending moment calculated from the simulation is shown to be safe when the initial contact angle with the ground (β) is equal to 135°, but as the initial contact angle (β) increases, the level of safety decreases approaching the upper limit for the injury threshold.

Lastly, the bending moment (M_y) acting in the sagittal plane can be divided in two parts: the flexion moment ($+M_y$) to bend the neck forward and the extension moment ($-M_y$) to bend the neck backward. In general, the flexion moment is slightly greater than the extension moment, but, as shown in Fig. 14, in terms of the injury threshold, the flexion moment is approximately 2.5 times greater than the extension moment. Thus, the extension moment ($-M_y$) is used to define the injury criteria.

The extension moment ($-M_y$) is induced more frequently during either the 2nd or 3rd roll than the 1st roll. This suggests that as the roll of the vehicle progresses, how the constraining devices can exhibit the significant effects on the magnitude of the extension moment.

The results show that the extension moment obtained from the simulation is approximately within the KNCAP criteria (for the frontal impact testing where the extension moment below 42 N·m is considered to be highly safe and the value exceeding 57 N·m indicates high likelihood of the injury). In addition, the range for the KNCAP injury criteria corresponds to a third to half of the injury threshold (i.e., 125 N·m) that Kleinberger et al. have suggested.

DISCUSSION

This study investigates the relationship between the risk for driver's injury and the conditions for a vehicle's rollover. In addition, to establish the appropriate criteria for vehicle's safety, the conditions for the 2-turn and 3-turn rollover are compared.

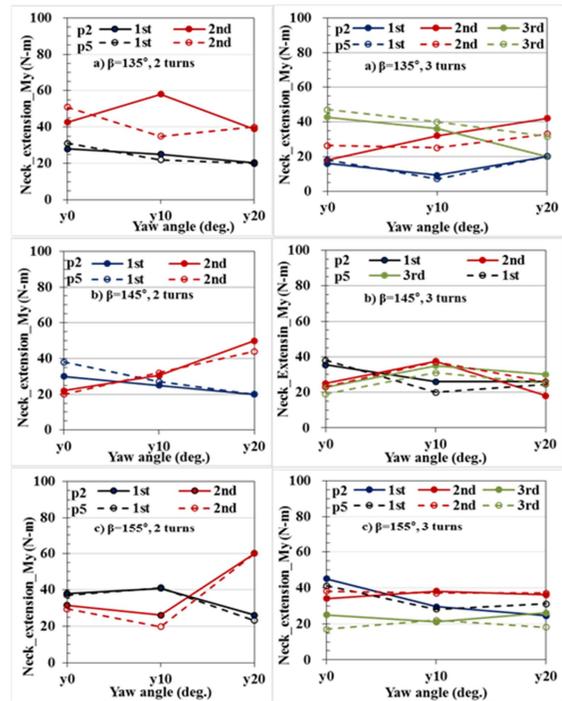


Fig. 15 Extension/flexion moment (M_y) at each roll; Left side for 3 roll condition and right side for 2 roll condition

The contact angle with ground, not the pitch and yaw angle, is the dominant factor that causes the increase in the magnitude of the A-pillar displacement. In addition, the head acceleration of the dummy seating on the driver's seat and the HIC value increase as the initial contact angle with the ground and the number of the turn increase. On the other hand, the corresponding values decrease as the yaw angle increases.

Considering the shear force induced on the neck, the shear force component in the lateral direction (F_y) is greater than the longitudinal shear force, F_x . Each shear force component independently satisfy the KNCAP criteria. However, the vector sum of the shear force components in both directions (can fail, may fail, or fails) to satisfy the KNCAP criteria. The results estimate that the compressive force (F_z) is significantly affected by not only the initial contact angle with the ground and the turn condition, but also the stiffness of roof interior and the constraining device, which is related to the diving effect.

The lateral bending moment induced on the neck (M_x) increases as the initial contact angle with the ground or the number of the turn increase. As the yaw angle increases, the corresponding value decreases. In contrast, the extension bending moment (M_y) is more affected by the yaw angle than either the initial contact angle with the ground or the number of turn.

Combining with the analysis that the rollovers with less than 2 turns account for 90% of the entire rollover accidents (Digges K and Eigen A. 2003), this study suggests that the 2-turn condition with the initial contact angle with the ground of either 145° or 155° would be appropriate for the evaluation criteria to assess the vehicle's safety performance.

CONCLUSIONS

This study investigates the relationship between the risk for driver's injury and the conditions for a vehicle's rollover. For this purpose, the multi-body model for the vehicle's chassis is constructed using ADAMS multi-body dynamics software. The injury severity for the 2-turn and 3-turn conditions is investigated in order to propose pertinent criteria for assessing the vehicle's safety performance. To systematically simulate the various vehicle conditions, a three-level L27 orthogonal array for the 5 members of the upper body, which significantly affect the deformation at the top portion of the A-pillar, is used. Through the DOE analysis, the following conclusions are obtained.

- 1) In a rollover accident, it would be appropriate to use the HIC15 for the evaluation criterion of head injury, rather than the HIC36.
- 2) In contrast to a frontal impact testing where only F_x component acting on the neck is considered, when assessing a rollover safety, both F_x and F_y components should be considered. In general, the F_y component is greater than F_x component in a rollover.
- 3) In terms of the moment acting on the neck, the extension moment ($-M_y$) should be considered as an evaluation criterion in conjunction with the lateral bending moment.
- 4) The compressive force (F_z) is significantly affected by the chassis strength and the effect of constraining devices. Therefore, pertinent regulations related to the ceiling strength (SWR), which represents the chassis strength, would be warranted. To minimize the diving effect during a rollover, the constraining devices should be improved.

The contact angle with ground, not the pitch and yaw angle, is the dominant factor for the increase in the A-pillar displacement.

ACKNOWLEDGMENTS

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