SHORT COMMUNICATION: STAPP CAR CRASH CONFERENCE

A study of submarining occurrence factors in reclined sitting posture

Garam Jeong, Dohyung Kim, Kyungwon Seo, Janghoon Choi and Seokhoon Ko
Hyundai Mobis

ABSTRACT – A series of crash simulations and sled tests were performed to investigate the factors causing the submarine phenomenon. A parametric study was conducted on various factors such as ATD type, seat recline angle, and restraint device, and the results were analyzed. In the study, the submarine phenomenon was shown to be highly affected by the type of ATD and seat recline angle. It was also shown that the submarining could be controlled by lower body restraint devices such as KAB or SCAB. SCAB had the effect of delaying the time of submarine occurrence, and KAB had the effect of returning the passenger's posture to the normal sitting position. On the other hand, it was found that upper body responses of ATD in the reclined position can be mitigated through the dual-depth PAB.

INTRODUCTION

The emergence of self-driving cars has affected not only the driving tasks but also the vehicle interior. In particular, the adoption of the reclined seat in the vehicle is increasing due to increased degree of freedom in the seated posture. [1]. A number of OEMs are promoting so-called “zero-gravity” sitting postures, and safety suppliers are collaborating with seat companies to develop restraint devices for the reclined sitting posture. The influence of a reclined sitting posture on passenger safety can be broadly approached from two perspectives. First, in a reclined sitting situation, the occupant sits further away from the instrument panel, which delays the loading of the airbag against the passenger. This increases passenger momentum and may increase injury values (such as HIC or Nij). [2] Second, it is known that a reclined sitting posture can result in a higher occupant risk for injury. The risk for submarining may increase because the pelvis of the occupant is rotated rearward, potentially allowing the lap belt to slip off the pelvis and transfer load to the abdomen. [5] In addition, it is known that the reclined position induces higher compression forces to the lumbar spine vertebrae compared to an upright position since the lumbar spine vertebrae are more in line with the impact direction in the reclined position. [6]

Figure 1 Reclined seat and sled test for a reclined sitting position

Garam Jeong, grjeong@mobis.com

A number of previous studies were performed to investigate the mechanism of submarine occurrence and to reduce passenger injuries caused by submarining. In 2007, Couturier et al. proposed a method to assess submarining in a frontal crash. [4] They investigated the submarining of the HIII-50% ATD in frontal crashes with a normal sitting position. Richard et al. also studied occupant restraint optimization in frontal crashes to mitigate the risk of submarining. The results of FE simulations and the PMHS sled tests were analyzed and compared [3]. In 2023, Lee et al. analyzed a series of sled tests for passengers in a reclined sitting posture. It was shown that ATD responses such as HIC and Nij increase when passengers are in the relaxed sitting position [2]. Although a number of studies have been conducted so far, data on submarine generation factors in reclined sitting posture are still insufficient. In this study, the effect of several parameters - such as interior design, seating position, ATD type and restraint criteria - on the protection level of the occupant were investigated by simulation and sled tests.

METHODS

In this study, factors affecting occupant submarining were investigated through sled tests and crash simulations. The typical passenger seat belt with retractor pre-tensioner was adopted. Frontal airbags were applied, including PAB (passenger airbag), KAB (knee airbag) and SCAB (seat cushion airbag), which are known to have submarine prevention effects. In the case of PAB, considering the increased distance between the passenger and IP due to the reclined posture, the dual-depth PAB, which has increased cushion thickness in a reclined sitting condition, was applied and compared to the conventional PAB. In the case of KAB, the enlarged KAB, whose capacity is increased by about 30% compared to the conventional KAB, was applied together with the conventional KAB to compare the effect. The crash pulse of 35 mph

US NCAP scenario was used for the simulation and the test.

First, crash simulations for male/female ATD were performed. For the simulations, crash simulation tool 'MADYMO' was used to simulate a collision accident environment in a reclined sitting posture. Both THOR-50M ATD and Hybrid III-5F in MADYMO were used, respectively, to simulate ATD kinematics and responses. A total of 9 simulations were conducted, as shown in Table 1. Through the simulations, factors that do not affect submarine occurrence were excluded, and from this an efficient sled test matrix was established. The reclined angle of the seatback was set to 47 degrees, since it is the designed seatback angle of the chosen vehicle in this study when vehicle's "Relaxed Mode" is activated. Moreover, perthe author's previous studies, it was shown that the submarine occurrence rate tends to increase at high recline angles of 40 degrees or more. Therefore, the reclined angle of 47 degrees seems to be enough to induce submarining of a small passenger (e.g., females, adolescents).

Second, a series of sled tests were conducted based on the selected factors. The reclined angle was also set to 47 degrees, as can be seen in fig. 1. The test matrix is shown in Table 3. In the tests, the vehicle interior design variables were excluded considering the results of the crash simulation. Through the tests, major environmental factors affecting the occurrence of submarining were investigated. In addition, the effect of each type of airbag on preventing/mitigating submarine occurrence was confirmed through the evaluation of each type of restraint device. For both the simulations and sled tests, H-III 5% and THOR 50% ATDs were applied to predict injury levels of female and male occupants, respectively. In the present study, the results of the sled test and crash simulation were evaluated through ATD behavior analysis and measured values such as chest deflection.

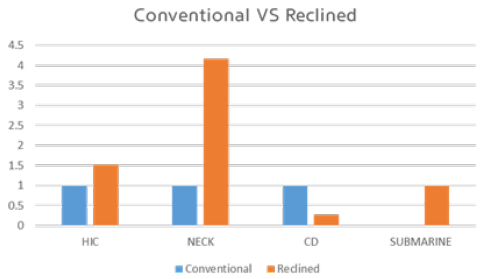
RESULTS

Crash Simulations

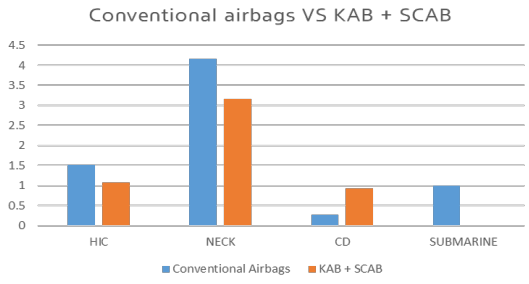
Crash simulations were performed from the perspective of system design to study submarine occurrence factors. Figure 2 shows the injuries of H-3 5% ATD according to sitting postures. In the figure, the ATD responses such as HIC (Head Injury Criteria), Neck (Nij) and CD (chest deflections) were normalized by that of the baseline result (the result of upright sitting posture) in order to directly compare the dummy responses in the reclined sitting posture with the responses in the upright sitting posture. In the current study, a value of 1 means submarine occurrence and a value of 0 means non-occurrence in in the case of submarines. As can be seen in Fig.2 (a), the upper body ATD response such as Nij increases significantly in the reclined sitting posture. The response seems to be originating from the delay of ATD restraint due to increased distance between the dummy and the IP. Moreover, the chest deflection value was decreased, which means that the seat belt does not properly restrain the passenger. It was observed that the submarine phenomenon occurred clearly in the reclined posture.

ATD	Test No.	Interior	Sitting posture	Restraint system			
				Seat Belt	PAB	KAB	SCAB
THOR 50% (#1 ~ #8) / H3-5% (#9 ~ #16)	#1 / #9	Conv.	Upright	Conv.	Conv.	No	No
	#2 / #10		Reclined	Conv.		No	No
	#3 / #11	Slim Cockpit	Reclined	Conv.		No	No
	#4 / #12		Reclined	BIS		No	No
	#5 / #13	Conv.	Upright	Conv.	Dual Depth	Conv.	Yes
	#6 / #14		Reclined	Conv.		Conv.	Yes
	#7 / #15	Slim Cockpit	Reclined	Conv.		Enlarged	Yes
	#8 / #16		Reclined	BIS		Enlarged	Yes

Table 1: Simulation Matrix *Conv. : Conventional



(a) Comparison: Sitting Postures (HIII-5%, #9 Upright vs #10 Reclined)



(b) Comparison: Restraint System (HIII-5%, #10 Conventional vs #14 w/ KAB + SCAB)

Figure 2: Simulation Results

Fig. 2(b) shows simulation results illustrating the influence of new restraint devices in reclined postures. It was shown that the increase in ATD upper body

responses due to the reclined posture could be mitigated by applying large-capacity dual-depth PAB. On the other hand, the simulation results showed that submarining could be mitigated or prevented by applying lower body restraint devices such as SCAB or KAB. In particular, it was observed that SCAB deployment had the effect of returning the passenger to an upright seated posture, with the torso and pelvis angle rotating forward. Although the application of KAB increased chest deflection, the value was low and considered insignificant.

FACTORS		Influence to Submarining
ATD	H3-5%	YES
	THOR-50%	
SAFETY DEVICE :AIRBAG	SCAB	YES
	Enlarged KAB	
	DUAL DEPTH PAB	No
SAFETY DEVICE :SEAT BELT	BIS	No
VEHICLE INTERIOR	COCKPIT	No

Table 2: Simulation Result

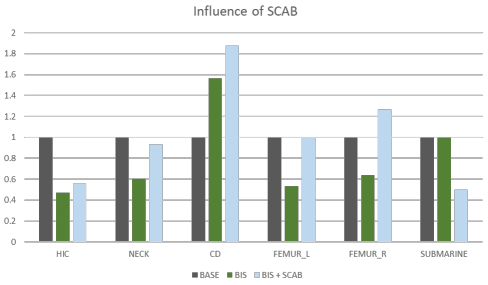
The crash simulations of THOR 50% male ATD were also performed. Compared to the female ATD cases, upper body responses such as HIC increased due to the increased momentum. On the other hand, the submarine phenomenon was less severe in the male ATD cases than the female. In both scenarios, the seat recline-angle had the greatest effect on the submarine phenomenon. The influence of vehicle interior design (slim cockpit) was limited. The submarine phenomenon occurred within 60ms, which was before the influence of interior design appeared.

Sled Tests

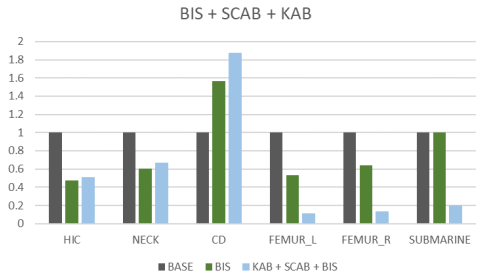
A series of sled tests were conducted considering the crash simulation results. Figure 3 shows the influence of the restraint systems on the ATD responses in reclined sitting positions. Similar to crash simulation results, the ATD responses - such as HIC (Head Injury Criteria), Neck (Nij) and CD (chest deflections) - were normalized using the result of upright sitting posture as baseline. BIS (belt-in-seat) was found to have no significant effect on the submarine occurrence of ATD. However, as the upper body restraint force increased, it had the effect of reducing the ATD's upper body response, specifically HIC and Nij, as shown in Fig. 3(a). On the other hand, it was shown that SCAB was effective in delaying the occurrence of submarining, as shown in Fig. 4. SCAB returned passengers to normal postures and induced the belt to restrain the passenger properly. The large capacity KAB was also found to be effective in mitigating the submarine phenomenon. It seems that the enlarged KAB restrained the passenger's lower body and prevented the ATD's body from slipping under the lap belt. The lab belt load was shown to be reduced with a gentle slope.

ATD	Num	Sitting Position	Restraint System			
			Seat Belt	PAB	KAB	SCAB
H-III 5% (#1~#6) THOR 50 (#7~#12)	#1 / #7	Reclined	Conv.	Conv.	-	-
	#2 / #8		BIS		-	SCAB
	#3 / #9				Enlarged	-
	#4 / #10				Enlarged	SCAB
	#5 / #11			Dual Depth	-	-
	#6 / #12				Enlarged	SCAB

Table 3: Sled Test Matrix (US NCAP 35 mph)



(a) Comparison: Influence of SCAB (w/o SCAB + conventional seatbelt, #1; w/o SCAB + BIS, #5; w/ SCAB + BIS, #2)



(b) Comparison: Influence of KAB (w/o KAB + conventional seatbelt, #1; w/o KAB + BIS, #5; w/ KAB + BIS, #6)

Figure 3: Sled test

In the case of THOR-50% ATD, different trends were observed. The submarine was not observed in the case of THOR-50% male dummy for either the reclined or upright test condition. On the other hand, in the reclined condition, upper body responses of THOR-50% such as HIC increased due to delayed ATD restraint. The increased upper body responses

were mitigated by applying the dual-depth PAB, as seen in Fig. 5.

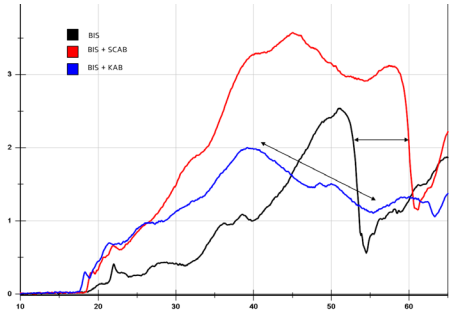


Figure 4: Lab-belt force

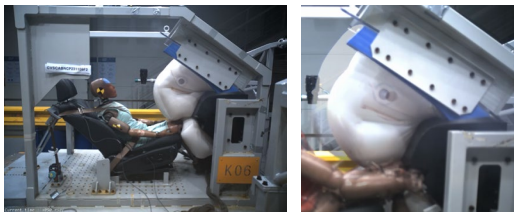


Figure 5: Restraint Systems (enlarged KAB, #4 (left); dual depth PAB, #12 (right))

DISCUSSION

It was shown that, as the recline angle of the seat increases, the probability of submarine occurrence increases. Moreover, female ATDs were found to have a higher probability of submarine occurrence than male ATDs. Passenger restraint devices, especially airbags, have shown the potential to mitigate submarining. Airbag devices that restrain the lower body, such as SCAB and KAB, have shown the effect of delaying or mitigating submarine occurrences. Independent of the submarine phenomenon, upper body responses of the ATD have increased due to delayed passenger restraint by the safety device in the reclined sitting posture. The ATD responses can be mitigated by appropriate airbag device such as dual-depth passenger airbag. In this study, the effect of several parameters on ATD submarining and passenger protection level was investigated based on ATD-based simulation and sled test results. Such ATD-based analysis has limitations in simulating the exact behavior of human occupants in a reclined seat and should be supplemented through follow-up studies on human body simulation or advanced ATD.

CONCLUSION

In this study, crash analysis and sled test were performed to investigate the main factors causing submarine occurrence. The main factors were the recline angle of the seat and the type of ATD. It was observed that lower extremity restraint airbags such as KAB and SCAB mitigate submarining of ATD. SCAB had the effect of delaying the onset of submarine occurrence, and KAB had the effect of returning the passenger's posture to the upright sitting position. It was also shown that dual-depth PAB reduces ATD's upper-body responses in relaxed sitting positions.

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