CRASH SLED TEST BASED EVALUATION OF A PRE-CRASH SEATBELT AND AN AIRBAG TO ENHANCE PROTECTION OF SMALL DRIVERS IN VEHICLES EQUIPPED WITH AUTONOMOUS EMERGENCY BRAKING SYSTEMS

Fumihito Komeno
Teruhiko Koide
Toshihito Miyagawa
Takuhiro Saito
Tokai Rika Co., Ltd.
Japan
Yoshihiro Sukegawa
Daisuke Ito
Japan Automobile Research Institute
Japan
Michihisa Asaoka
Hiroaki Yamada
Toyoda Gosei Co, Ltd.
Japan
Paper Number 13-0241

ABSTRACT

The Autonomous Emergency Braking (AEB) systems are rapidly spreading among current vehicles. In addition to the evident benefits associated with the reduction of impact speed, the AEB produces changes in the driver's posture due to inertia. Such changes need to be considered in the design process of restraint systems to optimize the protection of different occupants under all possible scenarios derived from the application of the AEB. The objective of this study is to quantify, in terms of potential reduction of injury indicators at frontal crash scenarios, two new techniques based features:
1) In-positioning function of a motorized pre-crash seatbelt (PSB) that pulls the webbing into the retractor during a pre-impact braking,
2) Enhanced interaction of an airbag with out-of-position occupants by means of a widely deployment airbag.

A series of crash sled tests were conducted with a sled system that produces controlled pre-impact braking and frontal crashes. Modified 50th percentile male and 5th percentile female Hybrid III dummies were used in order to reproduce more accurately human upper body's ability to flex forward under pre-impact braking conditions. The modifications were done at the abdomen-lumbar region and were validated against low speed sled tests with volunteers. The dummies were placed on the sled system and restrained with either a conventional seatbelt or a PSB, in combination with either a normal airbag or a widely deployment airbag. The pre-crash sled was accelerated to a speed of 64 km/h followed by a 0.8 g deceleration, prior to collision against a barrier at a speed of 48 km/h.

Less upper body forward motion during pre-impact braking was observed for the dummies with PSBs, compared to those with conventional seatbelts. This confirmed that the PSB was effective in restraining dummy's posture, thus leading to a proper restraint by the airbag and decreased injury values at the head-neck region. These observations were more pronounced for the 5th percentile female Hybrid III dummy. In addition, the widely deployment airbag contributed to the reduction of injury values.

INTRODUCTION

In vehicle crash safety studies, driver’s behavior and injury mechanisms at crash are often discussed. In such discussions, knowledge obtained from crash tests with standard Anthropometric Test Devices (ATD) in ideal seating postures is often assumed to be representative of the real crash situation. However, driver’s posture varies according to age, gender, and physique. In addition, in real crashes, the posture may change just before the collision due to either body inertial loading by AEB or driver's crash avoidance maneuvers. Consistent with the latter, the analysis of traffic accident data in Japan revealed that around 60% of drivers took crash avoidance maneuvers such as braking, swerving, or both of them at the pre-crash phase [1]. The same accident data source suggested that the type of pre-crash reaction might show differences in injury site and injury degree. Therefore, further examination of restraint systems that account for posture changes, their influence on the driver motion at the pre-crash phase, and their possible influence in terms of safety improvements is needed.

Commercially available vehicles have been equipped with pre-crash seatbelts, a restraint system device designed to control posture changes during the pre-crash phase. In addition, this device enhances driver's restraint after collision by automatically furling the belt with the electric motor [2]. Good et al. [3] investigated the basic features of the restraint effect of a pre-crash seatbelt based on data from tests with volunteers and ATD, and defined the appropriate posture changes for a numerical model that takes the effects of the pre-crash seatbelt into consideration. Schöeneburg et al. [4] reported that a pre-crash safety device with reversible seatbelt tensioner reduced neck extension moment in crash tests involving pre-impact braking. All these studies suggest that driver's posture change of the driver in the pre-crash phase influences the occupant injury.

In addition, most available studies focused mainly on average-size occupants. Small-size occupants, who are more vulnerable to the impact of a deploying airbag due to proximity to the steering wheel, would be relatively more exposed to non-optimized interaction with the airbag. Therefore, it is also important to make quantitative analysis on the relationship between accident avoidance maneuver and the amount of posture changes for small-size occupants.

In this study, a 5th percentile female Hybrid III dummy (AF05 dummy) employed as a surrogate of small-sized occupants is evaluated in addition to a 50th percentile male Hybrid III dummy (AM50 dummy). The effects of the body forward displacement during the pre-impact braking on the injury measurements at crash, and the potential improvements due to the in-positioning function of the PSB and a widely deployment airbag for out-of-position occupants, are evaluated with a pre-crash sled system [5][6], developed by Japan Automobile Research Institute (JARI), that produces controlled pre-impact braking and frontal crashes.

METHODS

The methodology of this study consists of a series of five crash tests to evaluate the potential safety improvements of a PSB in comparison to a conventional seatbelt (conventional SB) for both an AM50 and an AF05 dummies. In addition, for the AF05 dummy, a normal airbag (spec1 AB) was tested and compared with a widely deployment airbag (spec2 AB). Table 1 below shows the test matrix from this study and a description of the test apparatus, the restraint systems, the dummies and the testing conditions utilized in this study follow.

Table1.
Test Matrix

No.	Dummy	Seatbelt	Airbag
1	AM50	Conventional	Spec1
1-1		PSB	Spec1
2	AF05	Conventional	Spec1
2-1		PSB	Spec1
2-2		PSB	Spec2

Test apparatus

This study employed the pre-crash sled developed by JARI (See Figure 1). The sled reproduces controlled emergency braking prior to impact and can be customized to include different restraint systems from actual vehicles.

The crash tests with the sled are conducted on the rail of vehicle crash test facilities at JARI. The sled is accelerated on the rail by a pulling unit until it reaches a target speed. Then, the sled is released from the pulling unit, and a programmed braking pulse is applied before the sled collides against a row of shock absorbers placed in front of a fixed barrier.

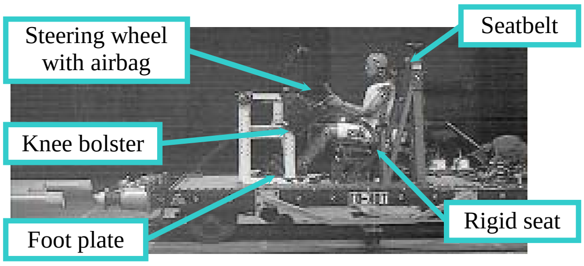


Figure1. Picture of the pre-crash sled with a dummy and the restraint systems used in this study

Restraint systems

The pre-crash sled was equipped with a three point seatbelt, a driver's airbag, a steering wheel, a steering column, a knee bolster, foot plates and a rigid seat. The rigid seat was used to eliminate the difference in seat deformation characteristics between car models. Either the conventional SB or the PSB were used for the tests. Both belt systems have an emergency lock retractor, a pre-tensioner and a force limiter. In addition, the PSB has a motorized retractor which automatically tightens the belts when the vehicle's pre-collision sensing device determines that a collision is imminent. Finally, two kinds of airbags were used: the spec1 AB or the spec2 AB.

Dummy modifications and positioning

Upper body flexion of Hybrid III dummies at braking has been shown to be lower than human volunteers under the same conditions [7]. Good et al. [8] also reported that these dummies were poor human surrogates when acted on by a motorized shoulder belt tensioner while out-of-position. To mitigate these limitations, AM50 and AF05 dummies were modified in order to match their kinematics to human volunteer data during pre-impact braking for males and females, respectively.

Modified AM50 dummy In a previous study [7] the lumbar section of the AM50 dummy (Figure 2) was modified and validated against emergency braking sled test data with male volunteers [9]. These modifications were further analyzed to confirm that upper body motion, chest acceleration and chest deflection of the modified dummy was comparable to those of the original dummy in 55 km/h crash tests without pre-impact braking [10]. The modified and validated dummy was used for the tests conducted in this study.

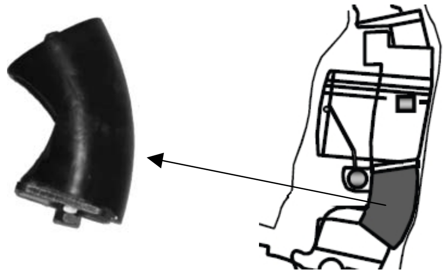


Figure2. Scheme of modified lumbar section for the AM50 dummy

Modified AF05 dummy The abdominal insert of the AF05 dummy affects upper body flexion due to interaction with the ribcage. Therefore, instead of modifying the lumbar section as in the AM50 dummy, the upper part of the abdominal insert, was partially removed in order to facilitate upper body flexion during braking. Figure 3 shows a scheme of the modified part in the AF05 dummy.

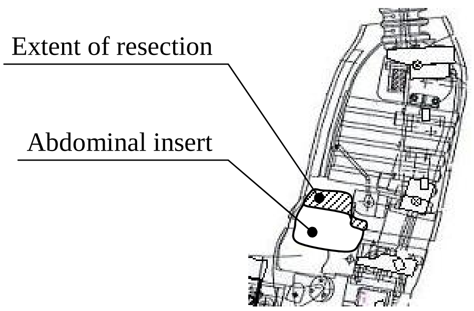


Figure3. Scheme of modified abdominal insert for the AF05 dummy

To confirm the validity of the modification, a braking test was conducted with the dummy under the same testing conditions as available female volunteer tests [11]. Although the modified dummy still presents some limitations in terms of head motion due to the rigid neck of the dummy, comparison of results (Figure 4) indicate that the shoulder motion of the modified dummy became close to that of the volunteers.

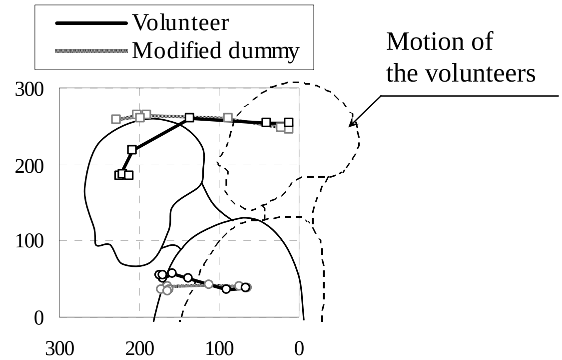
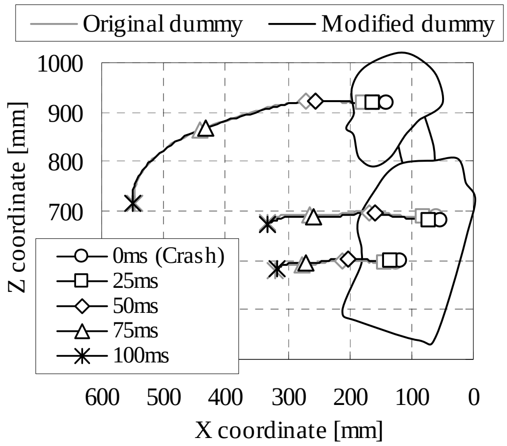
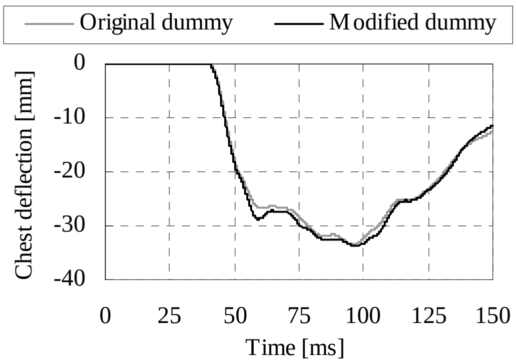


Figure4. Comparison of head and shoulder motion between the modified AF05 dummy and female volunteers under braking condition

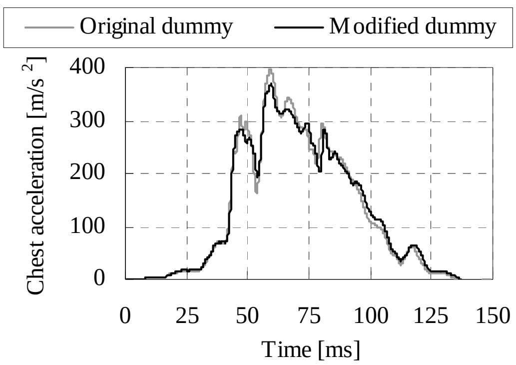
In order to verify that the reliability of the dummy at crash conditions was not affected by the modifications, additional front impact tests were conducted with the modified dummy and the original dummy. Upper body motion, chest acceleration and chest deflection for both dummies were equivalent for the original and the modified dummies, as shown in figure 5. Therefore the usability of the modified dummy for the purpose of this study was confirmed.



(a) Head, shoulder and chest motions



(b) Chest deflection



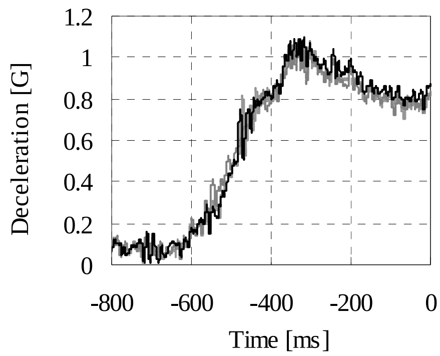
(c) Resultant chest acceleration

Figure5. Comparison between modified AF05 Hybrid III dummy and the original dummy during a 48km/h collision

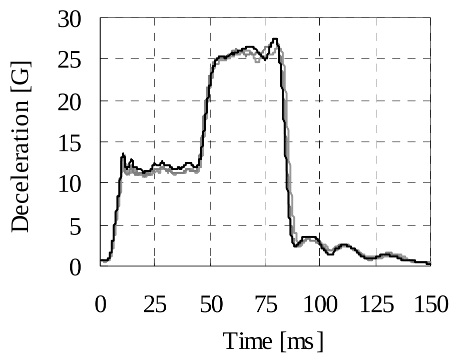
Dummies positioning Both modified and validated dummies were placed on the sled seat according to FMVSS208 standard definitions, respectively.

Braking and crash test conditions

All the five tests were performed under equivalent braking and crash conditions shown in figure 6. The sled system was programmed to reach a steady speed of 64 km/h, followed by 0.8G (Figure 6(a)), just before colliding against the barrier at a speed of 48 km/h. The crash pulse (Figure 6(b)) was similar to the longitudinal component of deceleration pulse used for offset deformable barrier crash test typically employed for passenger vehicles.



(a) Braking pulse



(b) Crash pulse

Figure6. Braking and crash pulses of the pre-crash sled tests in this study

RESULTS

Baseline injury values from tests with the conventional seatbelt and the normal airbag

Table 2 and figure 7 show the result of the sled tests of the conventional system using modified AM50 and AF05 dummies. Head injury values were at levels far from risk of injury. Hence, no further consideration on potential head injuries is done in this study. In contrast, chest deflection and neck injury values were relatively high as compared to the injury criteria established by the FMVSS208 standard; especially the neck injury value of AF05 dummy was close to the criterion.

Table2.
Test results

No.	Dummy	HIC_{15}	Nij	Chest Def. [mm]
1	AM50	196	0.56	34.0
2	AF05	194	0.85	26.0

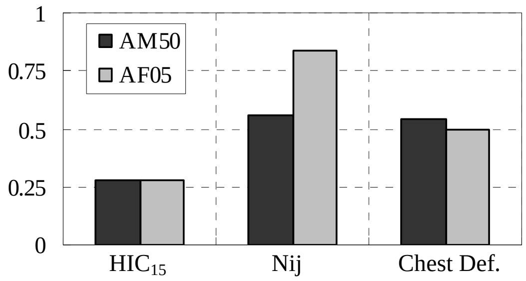
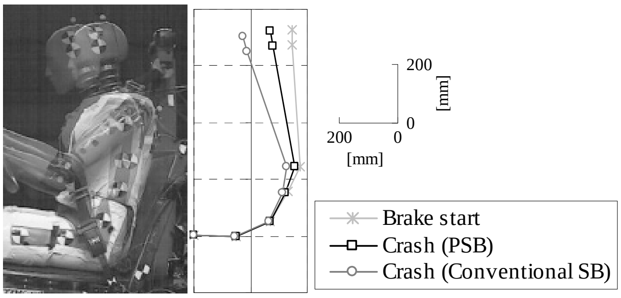


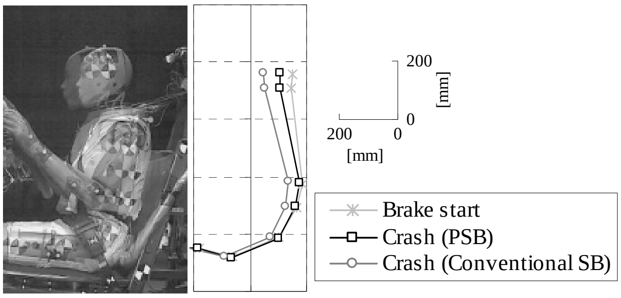
Figure7. Injury measures relative to injury criteria established by FMVSS208 (injury criteria = 1)

Average and small size occupant kinematics during pre-impact braking: effectiveness of the PSB's in-positioning function

Figure 8 shows a comparison of dummy body kinematics during braking for the PSB and the conventional SB for the AM50 dummy ((a) above) and the AF05 dummy ((b) below), respectively. The figure shows superimposed captures of the dummy at the end of the braking phase for the PSB and the conventional SB tests, respectively and a comparative schematic representation of the dummy posture at the beginning of the brake (light gray line with asterisks), in comparison to the posture at the beginning of the crash for the PSB test (black line with squares) and the conventional SB test (gray line with circles).



(a) AM50 dummy



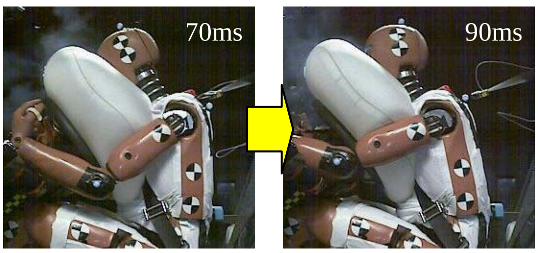
(b) AF05 dummy

Figure8. Comparison of pre-impact motion of the dummies with the PSB and the conventional SB

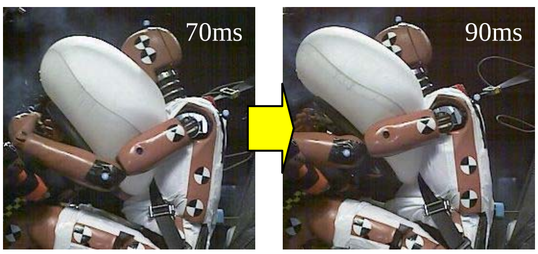
For both occupant sizes less body forward displacement and flexion were measured for the tests with the PSB, which confirms the correct functionality of the safety device.

Average-size occupant kinematics during crash: effectiveness of the PSB on optimized dummy-airbag interaction

Figure 9 shows images at 70 and 90 ms of the tests with the AM50 dummy. In the test with the conventional SB ((a) above), the head suffered from retro-flexion around 70 ms. The PSB alleviated the head retro-flexion ((b) below).



(a) Conventional SB



(b) PSB

Figure9. AM50 dummy motion during crash

Small-size occupant kinematics during crash: effectiveness of the PSB in combination with the widely deployment airbag on optimized dummy-airbag interaction

Figure 10 shows images from an anterior view of the AF05 dummy during crash for the baseline test with the conventional SB and the spec1 AB ((a) left) in comparison to the test with the PSB and the spec2 AB ((b) right). For the baseline test, the dummy head initiated contact with the airbag before full deployment. For the test with the PSB and the spec2 AB, the combined effect of the PSB delaying the approximation of the occupant to the steering wheel and the airbag widely deployed along the steering rim led to an optimized interaction between the dummy and the fully deployed airbag.

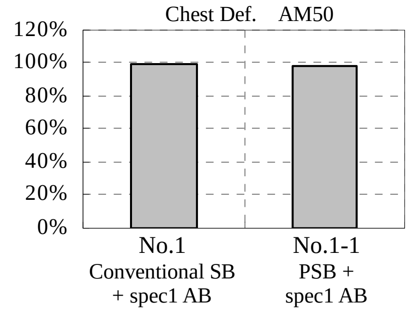
(a) Conventional SB & spec1 AB (b) PSB & spec2 AB

Figure10. AF05 dummy motion during crash

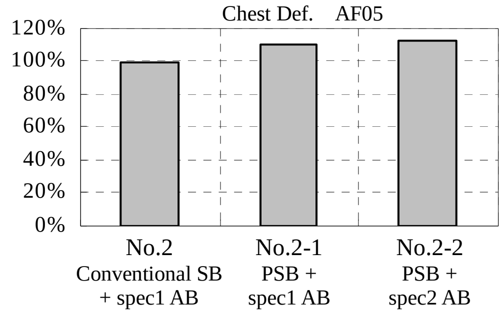
Potential safety improvements in terms of reduction of chest and neck injury values

Figure 11 shows chest deflection measurements normalized with respect to the baseline tests for the AM50 dummy ((a) above) and the AF05 dummy ((b) below). No significant differences were found concerning to chest deflections for neither the AM50 dummy nor the AF05 dummy.

In contrast, the Nij values normalized to the baseline values obtained with the conventional SB and the spec1 AB for each dummy were substantially reduced as shown in figure 12. In comparison to the baseline tests, the tests with the PSB alone resulted in a reduction of the Nij of an 18% for the AM50 dummy, and a 27% for the AF05 dummy. Moreover, for the AF05 dummy, a further reduction effect of 42% resulted from the test combining the PSB and the spec2 AB.

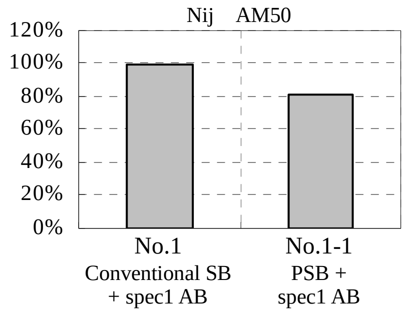


(a) AM50 dummy

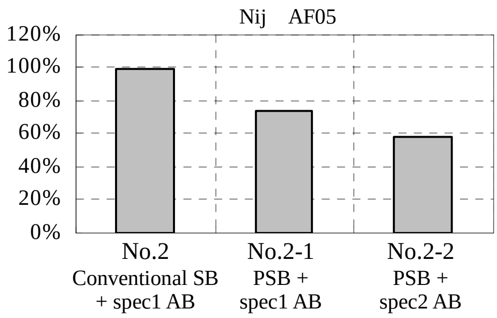


(b) AF05 dummy

Figure11 Chest deflection normalized to baseline values (100% corresponds with the value obtained at the tests with the conventional SB and the spec1 AB)



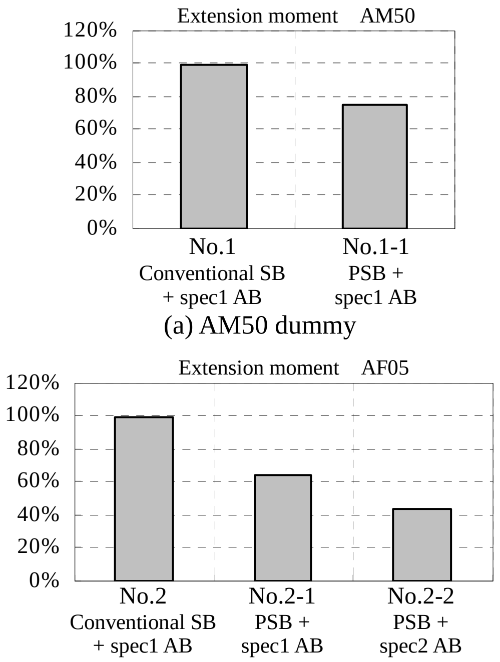
(a) AM50 dummy



(b) AF05 dummy

Figure12. Nij normalized to baseline values (100% corresponds with the value obtained at the tests with the conventional SB and the spec1 AB)

The Nij reductions were due to a reduction of neck extension moments. Figure 13 shows the extension moments normalized to baseline values. For the PSB alone, the moment was reduced by 25% for the AM50 dummy and by 36% for the AF05 dummy. Similarly to the Nij values, for the AF05 dummy, the PSB combined with the spec2 AB led to reduction of neck extension moment of 56%.



(b) AF05 dummy

Figure13. Neck extension moment normalized to baseline values (100% corresponds with the value obtained at the tests with the conventional SB and the spec1 AB)

DISCUSSION

The negative effects of posture change due to pre-impact braking in chest and neck injury outcome at crashes have been largely studied and demonstrated by means of experimental studies with out-of-position post mortem human subjects (PMHS) [12][13], ATDs [10] and computational models [14]. Our study stands on these observations, complements them with the confirmation of the correct functionality of the PSB for both average and small size occupants, and provides a quantified evaluation of potential safety improvements for the neck region as measured by the dummies at crashes.

The potential benefits of the PSB in terms of safety improvement have been shown for the AM50 and the AF05 dummies: figure 8 shows reduced dummy forward motion by the PSB during braking in comparison to the conventional SB. This additional retention of the upper body contributes to maintain the head of the occupant far from the steering wheel until the time of collision. This improvement achieved during the pre-crash phase will provide extra space and time so the airbag can completely deploy and work effectively in interacting with the dummy's head as shown in figure 9. These improvements were quantified in terms of the Nij reduction of 18% for the AM50 dummy and 27% for the AF05 dummy. In addition, this effect was more pronounced for the small-size occupant when the PSB was used together with the spec2 AB, as seen in figure 10. In this case, a further reduction effect of 42% was measured.

By modifying the abdomen-lumbar region of the dummies, improved biofidelity in terms of upper body motion was achieved. However, current studies with volunteers show that the neck region of existing dummies has different joint features and is stiffer than one of human. For further examination of detailed head-neck interaction with the airbag in general, and how it is affected by different pre-impact braking conditions in particular, it is necessary to further improve the dummies and to employ them in combination with biofidelic human computer models.

Tasks that remain to be addressed in future studies have been identified and include improvement of the biofidelity of current dummies in terms of head and neck kinematics to match human's, consideration of elderly and other vulnerable occupants, consideration of possible influence of occupant's muscle conditions at pre-impact and extension of our studies to other passenger-seat occupants.

CONCLUSION

In response to the demand of increased performance of restraint systems, pre-crash sled tests with modified dummies were carried out to evaluate potential driver protection enhancement with a PSB and a widely deployment airbag. The findings of this study show that:

1) The PSB effectively restrained the occupants, preventing them from forward traveling during pre-impact braking. This led to a reduction of neck injury values due to improved interaction with the airbag. This improvement was more pronounced for small-size occupants.

2) Additional neck injury values reductions were achieved when the widely deployment airbag was applied in combination with the PSB for small-size occupants.

REFERENCES

[1] Institute for Traffic Accident Research and Data Analysis. 2007. "Accident Analysis Report (JAPAN)"
[2] Tobata, H., Pal, C., Takagi, H., Fukuda, S., Iiyama, H. and Yakushi, R. 2004. "Development of a Brake-Operated Pre-Crash Seatbelt System and Performance Evaluation." SAE World Congress & Exhibition, SAE Paper number 2004-01-0851
[3] Good, C., Viano, D., Mcphee, J., Ronsky, J. and Pieper, J. 2008. "Motorized Shoulder Belt Tensioning: Modeling and Performance for a Diverse Occupant Population." SAE World Congress & Exhibition, SAE Paper number 2008-01-0515
[4] Schöeneburg, R., Baumann, K. and Fehring, M. 2011. "The Efficiency of PRE-SAFE Systems in Pre-braked Frontal Collision Situations." 22nd ESV 2011, No.11-0207
[5] Ito, H., Tanaka, K., Ochiai, H., Ogma, K., Watanabe, N., Maeda, A., Sukegawa, Y. and Ejima, S. 2010. "Development of Pre-Crash Sled to Evaluate Pre-Crash Safety Device." JARI Research Journal, Vol.32 No.9
[6] Sukegawa, Y., Ito, H., Tanaka, K., Ito, D. and Ejima, S. 2011. "Development of Pre-Crash Sled to Evaluate Pre-Crash Safety Device (Second Report) －Pre-Crash Sled Improvement and Validation Tests －." JARI Research Journal, Vol.33 No.9
[7] Zama, Y., Ito, D., Antona, J., Sukegawa, Y., Ito, H. and Ejima, S. 2010. "Study on Occupant Protection with Seatbelt during Pre-crash Phase." JSAE Annual Congress, 99-20105191 No.19-10
[8] Good, C., Viano, D. and Ronsky, J. 2008. "The Hybrid III Dummy Family Subject to Loading by a Motorized Shoulder Belt Tensioner." SAE World Congress & Exhibition, SAE Paper Number 2008-01-0516
[9] Ejima, S., Zama, Y., Sato, F., Holcombe, A., Ono, K., Kaneoka, K. and Shiina, I. 2008. "Prediction of the Physical Motion of the Human Body based on Muscle Activity during Pre-Impact Braking." 2008 International IRCOBI conference
[10] Ito, D., Ejima, S., Sukegawa, Y., Ito, H. and Kato, R. 2011. "Applicability of a crash dummy in sled test with pre-impact braking on the dummy responses." JSAE Annual Congress, 203-20115698 No.19-10
[11] Ejima, S., Sato, F., Ono, K., Kaneoka, K. and Shiina, I. 2013. "Prediction of pre-crash occupant kinematic behavior of small female driver under a low-speed frontal impact." JARI Research Journal, 20130501 (In press)
[12] Horsch, J., Lau, I., Andrzejak, D., Viano, D.C. and Melvin, J.W. 1990. "Assessment of Airbag Deployment Loads." 34th Stapp Car Crash Conference
[13] Lebarbé, M., Potier, P., Baudrit, P., Petit, P., Trosseille, X. and Vallancien, G. 2005. "Thoracic Injury Investigation using PMHS in Frontal Airbag Out-of-Position Situations." Stapp Car Crash Journal, Nov;49
[14] Antona, J., Ejima, S. and Zama, Y. 2011. "Influence of the Driver Conditions on the Injury Outcome in Front Impact Collisions." International Journal of Automotive Engineering, Vol.2, No.2