**Development of a Driver-side Airbag Considering Autonomous Emergency Braking**

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## ABSTRACT

Recently, in addition to conventional passive safety systems, active safety systems play an important role in the vehicle's overall safety performance. Autonomous Emergency Braking (hereinafter, AEB) system is one of the main devices among the active safety systems as it can mitigate or avoid collision events of vehicles.
In previous researches, occupant's forward behavior was observed during the pre-crash phase of the vehicle when AEB is activated. It is obvious that the behavior is not intended and can affect the injury value of the occupant. In several studies, it was reported that the neck injury value of the occupant is increased although the vehicle's impact speed decreased.
In the Present study, as a preliminary step for the "Integrated Safety", a driver-side airbag is newly developed considering driver's forward behavior induced by autonomous emergency braking system.
First, driver's forward displacement during the autonomous emergency braking condition is measured based on Euro-NCAP AEB test scenarios in order to establish the database for bag-shape design. It was shown that the forward displacement of the H-III female dummy is approximately 1.3 times larger compared to H-III male dummy. The maximum displacement of the H-III female dummy was 162 mm.
Second, a driver-side airbag is designed to mitigate the neck injury induced by the forward motion of the driver's head. The concept of the airbag is to limit the x-directional deployment length in the primary stage (~15ms) by adopting three panels.
Third, the performance evaluation of the developed driver-side airbag is performed by a series of crash simulations and SLED tests. In the simulations and the tests, the driver's forward behavior was considered in order to reflect the AEB activated condition. In the present study, it is assumed that the vehicle's speed reduces from 64 to 40 kph by the AEB activation. The injury value of the 64 kph sled test (without forward motion) and the 40 kph sled test (with forward motion) are compared with each other. As a result, it is shown that the developed driver-side airbag decreases both HIC and Nij values compared to conventional driver-side airbag when AEB is activated. The neck tension and moment values are decreased 26 and 45%, respectively when developed driver-side airbag is used.

## INTRODUCTION

Together with EURO-NCAP, NHTSA decided to evaluate the ‘active safety’ performance in their New Car Assessment Program (NCAP). That is, the importance of the active safety system including Autonomous Emergency Braking (AEB) is increasing rapidly in the field of the vehicle safety. The active safety system protects the occupants in the vehicle together with the conventional safety system and nowadays, the concept ‘Integrated-Safety’ is on the rise.

Among the active safety systems, AEB is one of the main components that detects obstacles around the vehicle and start braking autonomously. However, in the present state, it is impossible to avoid the collision entirely for all road situations even with state-of-the art AEB system since there are a number of different driving conditions such as vehicle’s velocity and weather conditions. Therefore, in the case of vehicle collisions, the conventional passive safety systems (airbag and seatbelt) still play a important role to protect occupants inside the vehicle. On the other hands, although AEB could not avoid vehicle collision entirely, it is obvious that AEB reduces collision velocity and energy when it is activated.

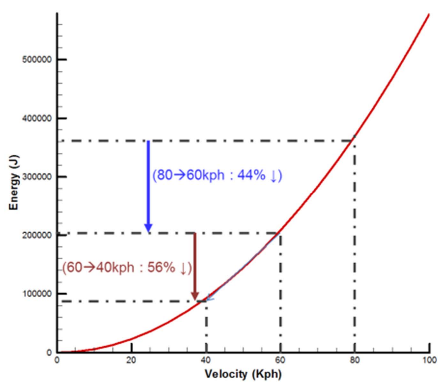



***Figure 1. Collision energy (MASS = 1,500kg)***

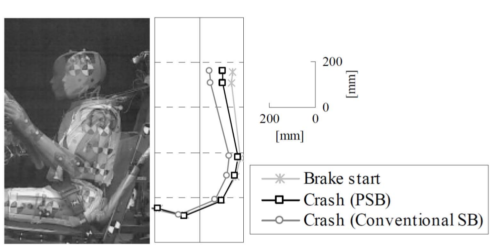



***Figure 2. Dummy Behavior (Komeno et al, 2013)***

Figure 1 represents the collision energy for various collision speed levels. As can be seen in the figure, collision energy decreases 44 and 56 % when collision velocity decreases from 60 to 40 kph and 40 to 20 kph, respectively. However, in the previous researches, it was observed that some injury values (especially a neck injury) of the occupants are increased despite the speed reduction benefit[1)-3)]. It is expected that the increased injury values are originated from the increased forward behavior of the occupants due to AEB activation. Generally, the forward movement of the occupants can be increased since the deceleration level of the vehicle is very high (above 1.0g) when AEB is activated. In addition, unawareness of the AEB activations would increases the occupant’s forward movement even more.

In general, the increase of the forward movement may leads to high neck injury value because of high inner pressure of the airbag especially at its initial stage (0-15ms after deployment). That is, the forward behavior of the occupant decreases the distance between the occupant’s head and the steering wheel (or airbag) which means the quasi out-of-position condition.

Actually, until now, the active and the passive safety system have been developed individually to each other. Therefore, the good aspects of the active safety devices are not integrated efficiently with the conventional passive safety system. It is obvious that the optimization of the active and passive safety systems should be studied and applied.

***Figure 3. Integrated Safety (Infantes et al, 2013)***

A number of efforts were made by previous researchers in order to integrate active and passive safety systems. In 2013, Komeno et al. investigated the influence of the AEB system to occupant injury. In the paper, it was shown that the neck injury value was pretty high even with the low collision velocity (48 kph). In addition, the high neck injury value was modified when adopting new passive safety systems[1)]. Infantes et al. also studied the crash safety performance considering the AEB system in 2013. The forward displacement and the occupant’s injury values were measured and analyzed for the AEB activated condition. In the manuscript, most of the injury values were reduced when AEB is activated since the collision velocity of the vehicle is decreased. However, the neck injury of the driver-side occupant was increased due to the driver's forward behavior[2)]. The paper also suggests the test method that can reflect the safety performance of the integrated active/passive safety system. The studies for occupant's posture were also performed. In 2011, Schöeneburg et al. studied the relation between active seat belt system and a AEB system. The paper shows that reversible seatbelt tensioner reduced neck extension moment when AEB is activated.

As mentioned above, a number of studies have been performed related to integrated active/passive safety system. However, most of the past studies were concentrated in modifying active seat belt systems and AEB's logic. An effort to modify the airbag module for integrated safety is not performed in earnest. That is, there are still many rooms to do in the field of integrated safety systems.

In the present study, as a preliminary step of the developing integrated active/passive safety system, a driver-side airbag is newly developed which can reduces the neck injury of the occupants in the AEB activated situation.

The content of the paper is as follows. First, the forward displacement of the H-III dummy is measured at the various AEB activated conditions. Second, the design of the driver-side airbag is performed considering the measured forward displacement value. Finally, the performance of the suggested airbag is evaluated using series of the crash simulations and the SLED tests.

## Measurements of Dummy Behavior

The forward displacement of the H3 50% dummy is measured at various AEB-activated conditions. The test is performed using mid-size sedan vehicle which is under mass production. For low speed conditions, the test scenario is chosen based on Euro-NCAP Car to Car Rear stationary (CCR's) test scenario. For high speed conditions, initial speed of 56 and 64 kph cases are added since the speed values are the highest speed for the present crash test mode for both Europe and United-States. The test matrix and the schematic are presented in Table. 1 and Figure. 4, respectively.

In the test, the vehicle starts to move at defined initial speed in Table.1. After that, the vehicle detects the obstacle and is decelerated by AEB systems. On behalf of the volunteer test, 5 and 50 percentile H-III dummies were used considering the SLED test validations.

Figure 5 shows the dummy behavior for the initial vehicle speed of the 30 kph. As can be seen in the figure, the head of dummy moves to forward direction after AEB is activated even in the lowest initial speed. The detailed results of the tests are summarized in Table. 2.

**Table 1. Test matrix (Dummy Behavior)**

| # | TEST MODE | Initial Speed | Dummy |
|---|---|---|---|
| 1 | Low - Speed | 30 | 5/50 % |
| 2 | | 40 | 5/50 % |
| 3 | | 50 | 5/50 % |
| 4 | High - Speed | 56 | 5/50 % |
| 5 | | 64 | 5/50 % |


*Figure 4. Measurements of Dummy Behavior*

***(a)Before AEB*** ***(b)After AEB***

***Figure 5. Dummy Behavior (30 kph)***

**Table 2. Test results**

**(a) Forward Displacement, 5% Dummy**

| # | TEST MODE | Initial Speed | Displacement (mm) |
|---|---|---|---|
| 1 | Low Speed | 30 | 120 |
| 2 | | 40 | 127 |
| 3 | | 50 | 131 |
| 4 | High Speed | 56 | 152 |
| 5 | | 64 | 162 |

**(b) Forward Displacement, 50% Dummy**

| # | TEST MODE | Initial Speed | Displacement (mm) |
|---|---|---|---|
| 1 | Low Speed | 30 | 95 |
| 2 | | 40 | 103 |
| 3 | | 50 | 101 |
| 4 | High Speed | 56 | 123 |
| 5 | | 64 | 128 |

In Table.2 it is shown that the maximum dummy behavior was observed at the highest initial speed case with 5 percentile H-III dummy. The measured maximum value was 162 mm. For all the test cases, the forward displacement of the 5 percentile dummy was approximately 1.3 times greater than 50 percentile dummy in average. In general, the distance between the head and the steering wheel is about 310 to 320 mm when forward seat track is adopted to H-

III 5 percentile dummy. In the case, it is obvious that the distance between the head and the steering wheel reaches within 150 mm which may lead to quasi out-of-position situation as shown in Figure. 6.

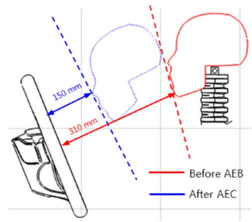
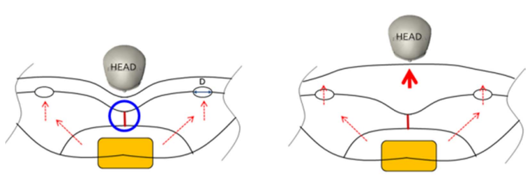



***Figure 6. Head-Wheel Distance***

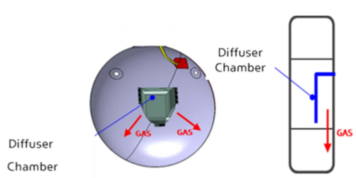
It is known that the forward behvior of the H-III dummy is relatively smaller than that of the human body or THOR dummy. In 2013, Shaw et al. dicussed that the behavior of the human body is 1.54 times greater than the H-III dummy. That is, in the real accident situation, the distance between the head and the wheel could become more closer.

**Driver-Side airbag : Design Concept**

The design of the driver-side airbag is performed considering the measured dummy's forward displacement as a preliminary step to approaching integrated safety. In the present study, the basic design concept is to limit the x-directional length and the inner pressure of the airbag cushion in the initial stage (10-15ms). It is expected that the neck injury value would decrease if the x-directional length and the inner-pressure of the airbag decreased at initial bag contact stage. On the other hands, after the initial stage, the airbag should maintain the conventional x-direction length and the inner pressure to guarantee the safety performance of the occupant whed AEB is not activated (conventional collision situation).




***(a)TYPE A : Seperated Chamber Concept***



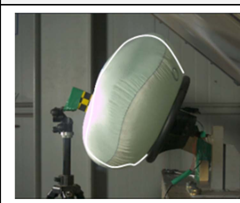

***(b)TYPE B : Diffuser Chamber Concept***

***Figure 7. Design Concept***

Figure. 7 illustrates design concepts of the proposed driver-side airbag in the present study. Two different concept is prposed. The first concept (TYPE A) is designed to be composed of separated chambers. That is, at initial stage, a first chamber is deploying prior to a second chamber and limit the x-directional length of the airbag. After that, the gas at the first chamber flows to second chamber so as to deploy the second chamber (15ms~). In addition, the TYPE A concept is designed to reduce the inner-pressure of second chamber at initial stage since the second chamber could directly contact the head of the occupants or dummies. In case of TYPE B concept, the airbag is designed relatively simply by using small inflator pocket. The overall shape of the airbag is similar to the conventional driver-side airbag. The only difference is that the direction of the inflated gas flow is controlled to flow to lower part of the airbag. That is, the deployment of the airbag is started from the lower part of the airbag which may lead to relatively slow deployment and low inner-pressure at the upper part.

| TYPE A | TYPE B |
|---|---|
|  |  |

***(a)10 ms***

| TYPE A | TYPE B |
|---|---|
|  |  |

***(b)35 ms***

***Figure 8. Airbag Deployment Test***

Figure. 8 (a) shows the deployment characteristics of proposed two different concept. In the figure, the white line indicates a conventional driver side airbag shape at 10 ms time region. As can be seen in the figure, both the two proposed concept limit the x-directional length effectively. The reduced lengths of the TYPE A and TYPE B concepts compared to conventional driver-side airbag are 94 and 155 mm, respectively. On the other hand, as mentioned above, the airbag should maintain the shape of the conventional airbag at final stage considering normal positioning of the occupants when AEB is not activated. Figure. 8 (b) shows the airbag shape after full deployment. In the figure, it is shown that the proposed concepts have almost equal shape compared with conventional driver-side airbag.

In general, an inner pressure is also known as an important factor that influences head and neck injury. That is, at initial deploymen stage (10-15ms), the inner pressure should be lower to reduce injury induced by out-of-position occupants. On the other hand, the pressure should be high enough to constraint the occupant behvior after airbag loading begins. Therefore, the inner pressure values of the proposed airbag concepts are measured together with the deployment test. Figure. 9 illustrate the measured inner pressure value for the proposed concepts and the conventional airbag. It is shown that the inner pressure of both the proposed concepts are lower than that of the conventional airbag at initial stage. Both the peak and the averaged pressure values of the proposed concepts are lower than that of the conventional airbag.

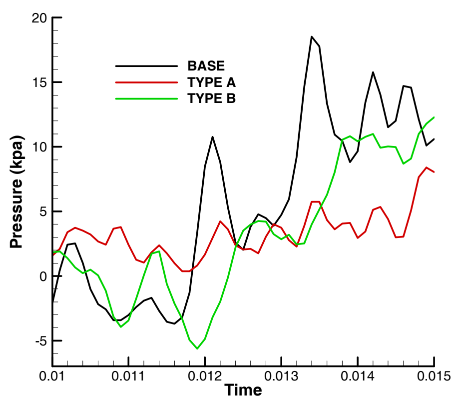



***Figure 9. Inner Pressure***

**Crash Simulation**

The crash simulations for the proposed airbag concepts are performed before the sled tests to predict the performance of the airbags to main injury values such as HIC (Head Injury Criteria) and neck injury. Actually, until now, there aren't any suggested crash test protocols for the integrated active/passive safety evaluation. Therefore, only a few numbers of OEMs and institutes established their own protocol to perform their preliminary study related to integrated safety. In the previous researches, offset collision mode is usually chosen for the crash test mode. The offset mode for integrated safety evaluation is quite meaningful. It is expected that the collision may occur by unsuspected cut in of the surrounding vehicles when AEB is activated. Similar to the previous researches, the crash simulation mode is chosen as the offset mode in the present study. It is assumed that the initial velocity and the collision velocity of the vehicle are 64 and 40 kph, respectively. Moreover, H-3 5 percentile dummy is used for crash analysis since it shows large forward displacement compared with 50 percentile dummy. In the analysis, the measured maximum forward displacement of 162 mm is adopted to reflect the AEB activated conditions as shown in Fugure. 10.

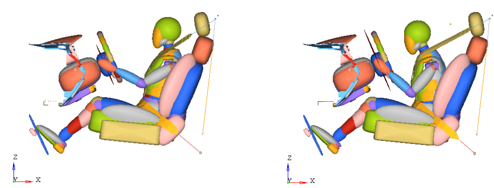
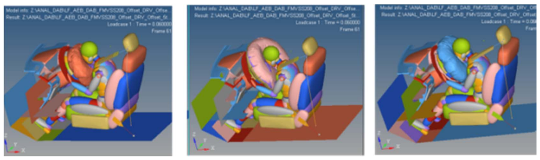


***Figure 10. Dummy seat position (0ms)***
***(Left : without AEB, Right : with AEB)***

**Table 3. Crash Analysis Matrix**

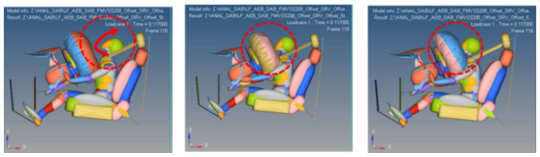
| # | Mode | Collision Velocity | Dummy | Airbag |
|---|---|---|---|---|
| 1 | w/o AEB | 64 kph (OFFSET) | 5% | BASE |
| 2 | | | | TYPE A |
| 3 | | | | TYPE B |
| 4 | w/ AEB | 40 kph (OFFSET) | | BASE |
| 5 | | | | TYPE A |
| 6 | | | | TYPE B |

Figure. 11 and 12 shows crash anlaysis results for AEB activated states at 60 and 120 ms after the collision, respectivley. In Figure. 11, it is shown that both the proposed airbag types have the concaved shape due to the limitation of the x-directional length and therefore the contact between the dummy head and the airbag cushion is weakend compare to conventional airbag (base) case. This weak contact results in the rebound motion of the dummy. In figure. 12, the dummy head rebound strongly when the conventional airbag is used. However, the rebound motion of the dummy is limited in the cases of using proposed airbag concepts. It is expected that the neck extension of the dummy is reduced due to the limitation of the x-directional length of airbag cushion at initial stage.



*(a)BASE* *(b)TYPE A* *(c)TYPE B*

***Figure 11. Crash Analysis (60ms)***



*(a)BASE* *(b)TYPE A* *(c)TYPE B*

***Figure 12. Crash Analysis (120ms)***

**Table 4. Crash Analysis Results**

| | Injury | BASE | TYPE A | TYPE B |
|---|---|---|---|---|
| w/o AEB | HIC | 1 | 0.72 | 0.68 |
| | Nij | 1 | 0.88 | 0.84 |
| | Cd | 1 | 0.82 | 0.83 |
| w/ AEB | HIC | 1.54 | 0.56 | 0.42 |
| | Nij | 1.26 | 0.78 | 0.6 |
| | Cd | 0.41 | 0.38 | 0.35 |

Table. 4 shows the calculated main injury values by the crash analysis. The results are normalized based on the result of AEB non-activated case with conventional airbag system. In the table, the injury value for HIC and Nij increases although the collision velocity decreases from 64 to 40 kph when adopting conventional airbag system. Actually, the collision energy would be reduced about 60% when collision velocity decreases from 64 to 40 kph. It seems that the effect of speed reduction by AEB system is not reflected or optimized in the conventional airbag system. The value of HIC and Nij increases approximately 54 and 26 %, respectively when AEB is activated with the conventional airbag system. The increase of the injury value should be originated from the dummy's forward displacement induced by AEB system. That is, the strong contact between the conventional airbag system and the duumy result in the increase of the main injury values. On the other hand, the effect of speed reduction seems to be reflected properly in the cases of adopting the proposed newly designed airbags. In case of TYPE A airbag system, the HIC and Nij values decreases 16 and 10 % when AEB is activated. The proposed types also shows enhanced safety performance even in the cases where AEB is not activated.

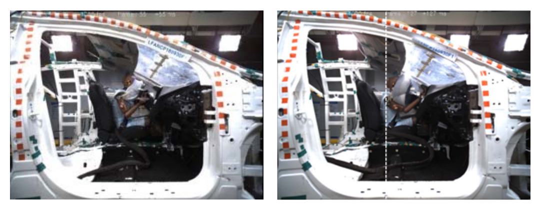
**Sled Tests**

The safety performance of the proposed driver-side airbag is validated by a series of sled tests. Similar to crash analysis scenario, the offset crash mode is chosen as a main test scenario. In addition, the full frontal mode test is also ferformed for the rigorous validation of the developed driver-side airbag. The test matrix is summarized in Table. 5.

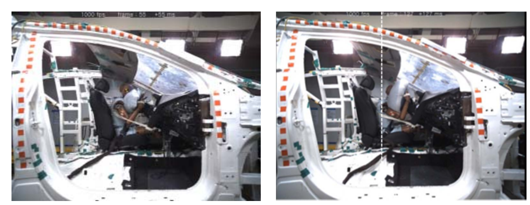
**Table 5. Test Matrix : Sled Tests**

| # | Mode | Collision Velocity | Airbag |
|---|---|---|---|
| 1 | w/ AEB | 40 kph(OFFSET) | BASE |
| 2 | | | TYPE A |
| 3 | | | TYPE B |
| 4 | | 64 kph (OFFSET) | BASE |
| 5 | | | TYPE A |
| 6 | w/o AEB | 64 kph (OFFSET) | TYPE A |
| 7 | | 56 kph (Full) | TYPE A |

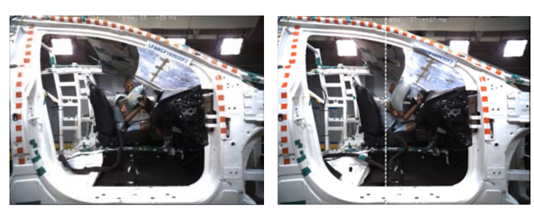
As mentioned, the measured maximum forward displacement of the dummy's head was 162 mm. The maximum forward displacement value is adopted to the present tests for when simulate AEB activated conditions (#1 to #5 of Table.5).



***(a)BASE (Conventional DAB)***



***(b)TYPE A***



***(c)TYPE B***

***Figure 13. SLED TEST (W/AEB, 40kph)***

Figure 13-(a), (b), (c) show the results of sled tests for baseline, TYPE A, TYPE B driver-side airbags respectively. Compared with the conventional airbag

system, both the propsed airbags have the reduced x-directional displacement at earlier stage (see left figures). It is also shown that the reduced x-directional displacement result in the reduced rebound motion of the dummy's head at later stage (127ms after coiilision). The limitation of the x-directional displacement also result in the main injury value of the dummy as shown in Table. 6. HIC and Nij values of both the TYPE A and TYPE B airbags are 60 and 80% compare to conventional airbag system, respectively.

**Table 6. Injury Values: Sled Tests (40 kph)**

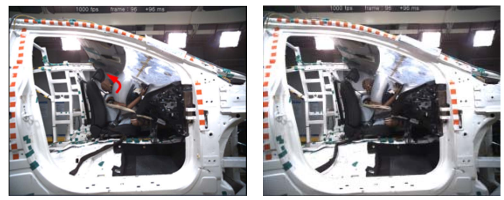
| | | BASE | TYPE A | TYPE B |
|---|---|---|---|---|
| NECK | Nij | 1 | 0.6 | 0.81 |
| | Extension | 1 | 0.45 | 0.77 |
| HEAD | HIC | 1 | 0.71 | 0.80 |

An additional series of sled tests is performed for the high-speed collision cases (#4 and #5 of Table.5). In the tests, the collision speed is assumed to be 64 kph since it is the highest speed mode in the current global OFFSET test mode. It is assumend that the velocity of the vehicle is decreased from 80 to 64 kph. The TYPE A cushion is chosed for the present test considering the results of 40 kph collision test. Figure. 14 shows the test results at 96 ms after the collision. In the figure, it is shown that the rebound motion of the dummy's head becomes larger than the previous 40 kph cases when conventional airbag system is used. The neck of the dummy is observed to be folded backward due to the strong interaction between the airbag and the dummy's head. On the other hand, the rebound motion of the dummy's head is limited when proposed TYPE A airbag is used. This behavioral characteristics are also reflected in measured injury values as shown in Fig. 15-(a). In AEB activated cases, the neck Fz value is decreased about 30 % when TYPE A airbag is adopted. It is also shown that the neck injury increases when dummy forward displacement occurs.That is, for same collision speed, the neck Fz increases aprroximately 20 % when AEB is activated. Similar trends are also observed for neck moment as shown in Figure.15-(b).

A validation for conventional test modes were also performed for both the offset mode and the full frontal mode. For the conventional mode, normal seating position is adopted following NCAP protocols. As a result, all the injury value was lower than LLV (lower limit value) of NCAP protocols.

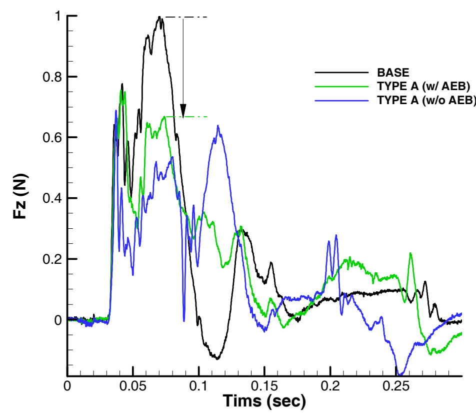
**Table 7. Injury Values: Sled Tests (64 kph)**

| | | BASE | TYPE A |
|---|---|---|---|
| NECK | Nij | 1 | 0.67 |
| | Extension | 1 | 0.55 |
| HEAD | HIC | 1 | 0.48 |

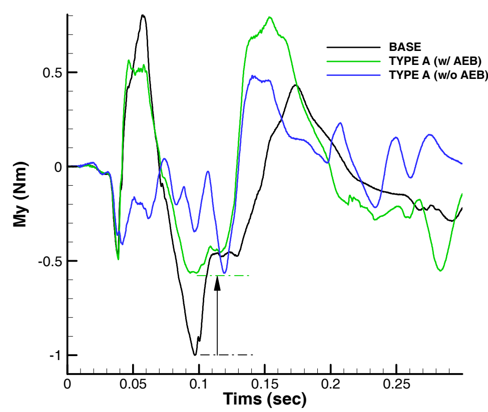


***(a)BASE*** ***(b)TYPE A***

***Figure 14. SLED TEST (W/AEB, 64 kph)***




***(a)Neck Fz (Normalized)***




***(b)Neck My (Normalized)***

***Figure 15. Neck Injury (w/AEB, 64 kph)***

## CONCLUSION

In the present study, a driver-side airbag is newly developed considering the driver's forward displacement induced by autonomous emergency braking (AEB) system. The performance of the developed airbag is compared with the conventional driver-side airbag which is under mass production and the resulting conclusions are as follows.

1) The forward displacement during the autonomous emergency braking was measured under the Euro-NCAP CCR's conditions and the maximum displacement was 162 mm. The distance between the head and the steering wheel reaches within 150 mm which means quasi out-of-position situation.
2) A driver-side airbag is newly designed to mitigate the neck injury induced by the forward motion of the driver's head. The design concept of the airbag is to limit the x-directional deployment length in the earlier stage by adopting three panel cushion.
3) The crash simulations using the two proposed airbag concepts are performed. The main injury value such as HIC and Nij increases although the collision velocity decreases from 64 to 40 kph in the case of adopting conventional airbag system. On the other hand, the effect of speed reduction seems to be reflected properly in the cases of adopting the proposed newly designed airbags. In case of TYPE A airbag system, the HIC and Nij values decreases 16 and 10 % when AEB is activated.
4) The performance of the proposed driver-side airbag is validated by a series of sled tests for both the low and the high speed conditions. As a result, the rebound motion of the dummy's head is limited when proposed new airbag is used. In AEB activated cases, the neck Fz value is decreased about 30 % when TYPE A airbag is adopted. Similar trends are also observed for neck moment. The moment value was decreased approximately 45% when TYPE A airbag is used.

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