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PERFORMANCE EVALUATION OF SLIM LOW-RISK-DEPLOYMENT DUAL-TYPE PASSENGER AIRBAG SYSTEM WITH DISPERSED INFLATION PRESSURE

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ABSTRACT−Motor vehicle passenger airbags have been proven to be effective for reducing the possibility of passenger injury during a crash. However, the inflation of the airbag sometimes causes serious injury when a passenger is positioned close to the airbag. The United States Federal Motor Vehicle Safety Standard (FMVSS) 208 requires the use of a low-risk-deployment (LRD) passenger airbag system. This paper proposes a newly developed airbag system comprising two slim airbags mounted on the instrument panel. A series of tests were conducted using the FMVSS 208 test procedures to demonstrate the effectiveness of the proposed system. It was found that the system not only satisfied the injury criteria of FMVSS 208, but was also effective for protecting passengers of all sizes.

KEY WORDS : Passenger airbag, Federal motor vehicle safety, Low-risk deployment, Slim dual-type passenger airbag system

1. INTRODUCTION

The mortality rate of motor vehicle accidents has been on the increase with the greater proliferation of motor vehicles in recent times. According to reports of the National Highway Traffic Safety Association of the United States (NHTSA), approximately 370,000 people have suffered fatal injuries or death due to motor vehicle accidents since 2000 (NHTSA, 2012).

In South Korea, reports indicate that road accidents have caused more than 6,000 deaths annually since 2000, and the death toll continues to increase yearly (Hong and Park, 2011; Park and Kim, 2011). The approach towards reducing road accident fatalities in both countries has involved the strengthening of vehicle safety regulations. Consequently, automobile manufacturers have adopted the mounting of safety components such as passenger airbags in new vehicles as a standard feature rather than an optional one.

However, there have been reports of cases in which the inflation pressure of an airbag designed primarily for a generic adult physique caused serious injury or death to small-bodied adult, a child, or an infant sitting in the front passenger seat (Smith and Cummings, 2004; Kim *et al*., 2012).

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Towards solving this problem, the power of airbag systems produced since 1997 has been reduced by approximately 30 %. However, this approach has not been able to simultaneously satisfy the requirements for large passengers and infants (Duma *et al*., 2005; Kiuchi, 1998). Consequently, the newly revised Federal Motor Vehicle Safety Standard (FMVSS) 208 of the NHTSA requires the use of an advanced airbag system that protects passengers of differing body sizes as well as unusually positioned passengers (Breed, 1998).

Accordingly, all motor vehicle manufacturers have developed airbag systems that satisfy the current regulation. Among existing advanced airbag systems are occupant classification systems (OCSs), which operate by sensing the passenger or active vent system, and accordingly adjusting the size of the vent hole of the airbag cushion (Ford and Busacca, 2008; Wallace, 2003; Yoo, 2015).

The passenger-sensing system adjusts the activation and operating pressure of the airbag by determining the size of the passenger through various methods such as the load on the seat and its distribution. The disadvantage of this system is its susceptibility to malfunction with deterioration of the sensors. The vent-sensing system is also limited by the dependency of its performance on the mounting location of the airbag (Lee *et al*., 2011; Shin *et al*., 2011).

To address the above issues, this paper proposes a slim dual-type airbag system mounted on the instrument panel of a motor vehicle. The pressure of the airbag is concentrated on the sides of the passenger to prevent injury to the head, neck, or chest during the inflation of the airbag as a result of a head-on collision. The system was verified by the conduction of out-of-position (OOP) tests for 3-, 6-, and 1-year olds as suggested in FMVSS 208, as well as dynamic tests for males and females.

2. DESIGN OF THE SLIM DUAL TYPE PASSENGER AIRBAG

An airbag mounted on the instrument panel on the side of the front passenger is referred to as a passenger airbag. The distance between the passenger and the passenger airbag is longer than that between the driver and the driver airbag, and approximately 120 L ~ 150 L of cushion is required to effectively protect the passenger. A higher inflation pressure of 450 KPa ~ 540 KPa based on a volume of 60 L is required to fill this cushion (Wang *et al*., 2006).

As shown in Figure 1, passenger airbags are generally classified as top-mounted, when mounted on the upper surface of the instrument panel; or middle-mounted, when mounted perpendicular to the front of the instrument panel (i.e., on the vertical surface above the glove box).

In either case of mounting a single passenger airbag, its inflation towards the passenger during a collision increases the likelihood of injury to the neck if the passenger is small (including children and infants) through the strong impact pressure on the head.

During the expansion of the cushion of a top-mounted airbag, the action of the force of the inflating cushion in a top-to-bottom direction is illustrated by the dotted line in Figure 1 (a). This force may cause serious neck injury when its strikes the passenger's head downwards. Figure 1 (b) illustrates the case of a middle-mounted airbag, wherein serious neck injury may result from the bottom-to-top cushion inflating force striking the passenger's chin in the upward direction (Kwon *et al*., 2003).

To solve the above problems, this paper proposes a slim dual-type passenger airbag system comprising two small pressure airbags with pressures of approximately 120 KPa ~ 150 KPa at a volume of 60 L mounted on the front and upper surface of the instrument panel as shown in Figure 1 (c).

The top-mounted airbag is placed in the upper part of the instrument panel while the middle-mounted airbag is placed in the front part. The two airbags do not bounce off each other during inflation but expand horizontally towards the passenger's head and lower chest, respectively. By this means, neck injury to the passenger can be reduced.

Figure 2 illustrates the mounting concepts of the top-mounted and middle-mounted airbags of the proposed system on the instrument panel. The top-mounted airbag is installed in the upper part of the panel while the middle-

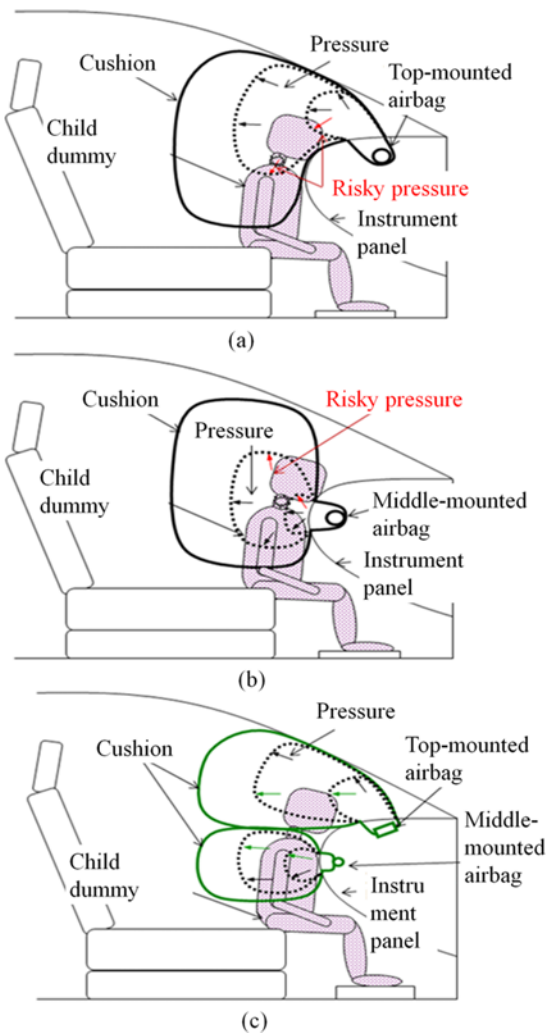


Figure 1. Comparison of concept of proposed slim dual-type passenger airbag system with those of conventional airbag systems: (a) Conventional top-mounted airbag system; (b) Conventional middle-mounted airbag system; (c) Proposed slim dual-passenger airbag system.

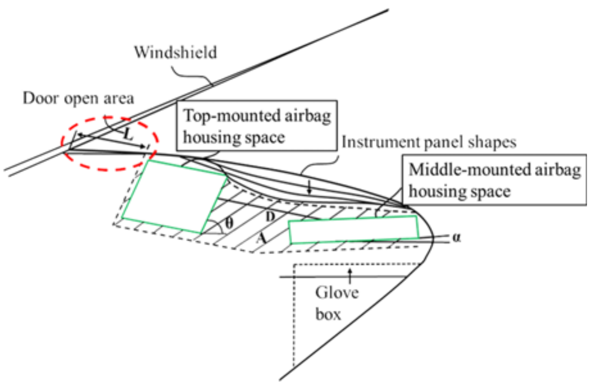


Figure 2. Perspective view of slim dual-type passenger airbag.

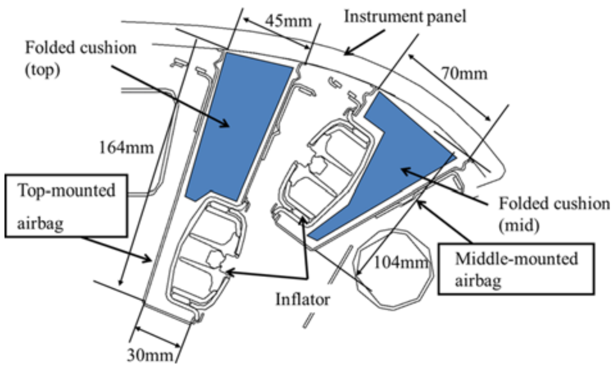


Figure 3. Packaging of slim dual-type passenger airbag system designed using CATIA program (Ver. 5.0).

mounted one is installed in the front part of the panel. Considering the proximity of the top-mounted airbag to the windshield, a space of length L = 150 mm ~ 200 mm is allowed between the two to enable the airbag door to open during inflation. This limited space also prevents the expansion of the airbag in the windshield direction. In addition, the glove box restricts the positioning of the middle-mounted airbag.

The area A where the two airbags can be mounted is indicated by the grey dotted lines. Furthermore, recent designs of the upper skin of the instrument panel favor a concave surface and this further reduces the installation area in the upper part of the panel.

It is also necessary for the two airbag cushions to be separated by a certain minimum distance so that they slide rather than bounce off one another during inflation. Specifically, a distance D = 100 mm ~ 250 mm is required between the top-mounted and middle-mounted airbag. In addition, the middle-mounted airbag should also be installed within an angle a of 0° ~ 15° to the horizontal, and the top-mounted one at about 60° ~ 75° to the horizontal to maintain an angle f of approximately 60° between the two. By satisfying the above two conditions, the proposed slim dual-type airbag system enables the installation of two airbags within the available space in the instrument panel.

Figure 3 shows the package design of the proposed slim dual-type passenger airbag system. The top-mounted airbag is 30 mm ~ 45 mm wide and 164 mm long, while the middle-mounted airbag is 28 mm ~ 70 mm wide and 104 mm long. The system was suitably designed for

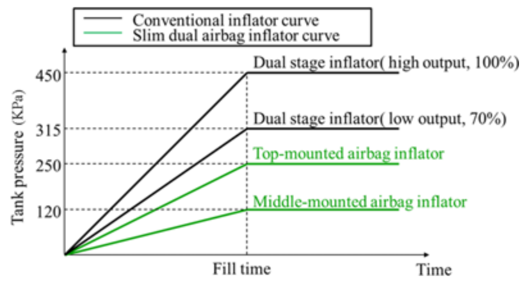


Figure 4. Comparison of inflator outputs of current dual-stage inflation airbag system and proposed slim dual-type airbag system.

installation beneath the concave surface of the instrument panel.

Figure 4 compares the inflation pressures of the proposed slim dual-type passenger airbag system with that of the dual-stage inflation airbag system, which uses a smart passenger airbag. The dual-stage inflation system differs from conventional airbag systems, which uniformly inflate. In the low-output implementation of the dual-stage inflation system, the airbag is inflated to 7/10 of the conventional airbag pressure when the vehicle speed is less than 30 km/h ~ 35 km/h and the passenger seatbelt is fastened.

Under other conditions, the high-output implementation is activated, wherein the airbag is fully inflated for passenger protection (Cox and Jordon, 2011). As shown in Figure 4, 1/2 of the pressure of a conventional inflator is used in the proposed slim dual-type passenger airbag because the system distributes the cushion volume in two parts. Accordingly, the highest pressure of the top-mounted airbag is only 250 KPa at 60 L, which reduces the possibility of neck injury to the passenger.

3. TEST SETUP

The instrument panel of currently mass-produced compact vehicles with engine capacities of less than 2,000 cc was used for the testing of the proposed airbag system in this study.

Table 1 gives the design parameters of the slim dual-type airbag that were used for the testing. The factors that determine the occurrence of injury during the deployment of an airbag were specified as the cushion volume, size of the vent hole, inflator output and housing size (Jeon *et al.*,

Table 1. Design parameters used for testing.

Top-mounted airbag	Middle-mounted airbag	
Cushion volume	78 L	38 L
Output	230 KPa at 60 L Disk inflator	110 KPa at 60 L Disk inflator
Vent hole	2 × ϕ35 mm	No vent
Housing	Width 70 mm	Width 40 mm

2003; Marklund and Nilsson, 2003).

The design of the proposed system assigned the distribution of approximately 130 L of cushion to each of the top- and middle-mounted airbags. This was based on the cushion volume of existing airbags that was observed to effectively protect the passenger during static and dynamic tests (Ko *et al*., 2007).

The disk-type inflator was selected among available cylindrical inflators for reasons of space. The vent holes consisted of two pairs of holes on either side of the cushion, and served the purpose of exhaling the inflation gas. A larger vent hole is positively correlated to a lower likelihood of injury.

Vent holes of ϕ35 mm were used in the top-mounted airbag, which was set to exhale the gas at an appropriate pressure level to reduce the possibility of injury when the cushion contacts the passenger. The absence of vent holes in the middle-mounted airbag also enabled its cushion to properly support that of the top-mounted airbag from below during deployment.

Figure 5 shows the inflator output curves of the top- and middle-mounted airbags. As can be observed from the curves, the inflation time limit for reducing the occurrence of injury during dynamic testing is approximately 60 ms (Wang *et al*., 2006). The initial inflation curve is important for static testing because the performance of the airbag is determined by the inflation over the first 20 ms. As can be observed from the curve for the top-mounted airbag over this period, there is an offset in the downward direction relative to the curve for the generic inflator. This indicates that the possibility of injury to the passenger is reduced by the use of a low initial pressure. Although the inflation output of the middle-mounted airbag is higher than that of the top-mounted airbag, the possibility of injury remains low because the pressures after the first 20 ms are lower.

Figure 6 shows the set-up used to conduct an out-of-position (OOP) test for a 12 months old (CRBIN) dummy. Regulations require the conduction of tests using a 12 months (CRBIN) dummy in a child restraint system (CRS). There are 16 methods for conducting crash tests using a CRS, comprising the use of seven types of rear-facing

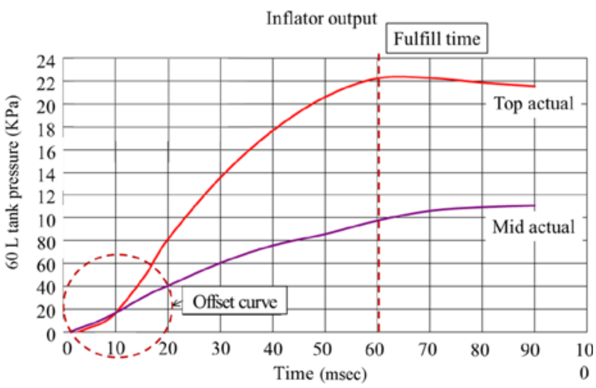
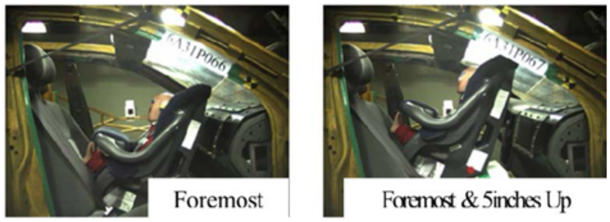


Figure 5. Actual inflator output curves.

(a)



(b)

Figure 6. Out-of-position (OOP) test conditions using (a) 12-month-old rear-facing Evenflo Discovery child restraint system (CRS) with handle up (left) and handle down (right), and; (b) 12-month-old convertible Cosco Touriva CRS seat.

CRSs and nine types of convertible CRSs (Kapoor *et al*., 2006; Yoo, 2015; Park and Yoo, 2009). In a rear-facing CRS crash test, the CRS is mounted with the 12 months dummy facing the back of the vehicle. Conversely, a convertible CRS test may use a 12 months or 3 years dummy, which may face either the front or rear of the vehicle. Current FMVSS 208 regulations stipulate the use of only a rear-facing 12 months dummy for an OOP test.

Figure 6 (a) shows the setup of the crash test conducted using an Evenflo Discovery CRS, which has a low back compared to other rear-facing CRS seats. The test considered both handle up and handle down cases. The results showed that the CRS moved closer to the airbag in the handle up case, whereas it moved away from the airbag in the handle down case. The possibilities of the airbag causing injury under the two conditions were compared. Figure 6 (b) shows the setup for a crash test using a convertible CRS, namely, a Cosco Touriva CRS, which has a high seatback. The height of the seatback made it difficult to conduct the test and the positioning of the CRS had to be raised by 5" (approximately 127 mm), which constituted a harsh test condition (Yoo, 2015).

Figures 7 (a) and (b) show the setups of the OOP tests conducted on the slim dual-type passenger airbag with the dummy baby in Position 1, wherein it was placed upright and aligned with the airbag system. The vehicle seat was pushed forward as much as possible so that the chest of the dummy nearly touched the instrument panel. Because the proposed system consists of top- and middle-mounted airbags, two variations of Position 1 were considered, namely, with the chest of the dummy aligned with the top- and middle-mounted airbags, respectively.

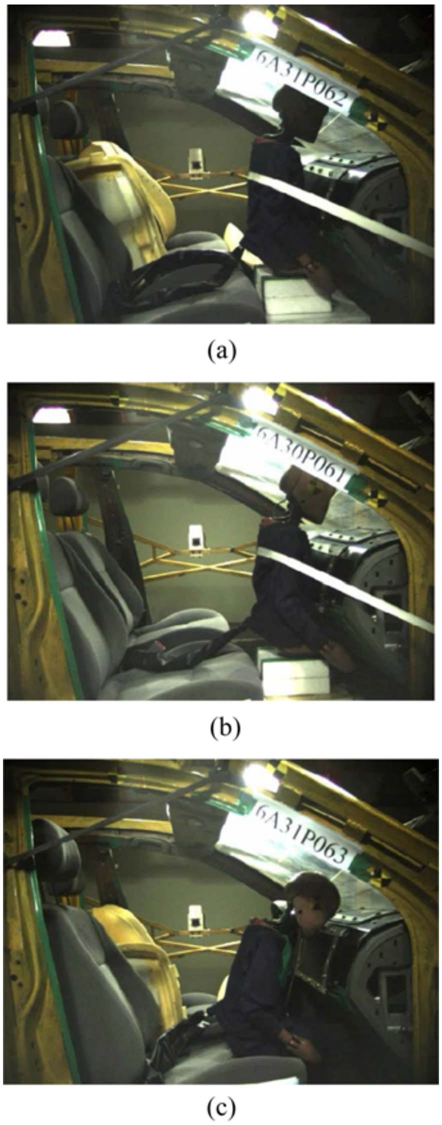


Figure 7. Out-of-position (OOP) test conditions: (a) Position 1 with chest aligned with top-mounted airbag; (b) Position 1 with chest aligned with middle-mounted airbag; (c) Position 2.

Figure 7 (c) shows the setup of the test with the dummy in Position 2, wherein it was aligned with the center of the airbag system with its upper body bent forward and the vehicle seat pushed forward as much as possible so that the chest of the dummy nearly touched the vehicle instrument panel. For dynamic testing of the proposed system, a collision simulation tester (sled test) was employed.

A collision simulation tester is a machine that simulates vehicle collision using air or hydraulic pressure controlled according to collision signals obtained from actual vehicle crash tests (Kim *et al*., 1998). The dynamic testing considered the 5th%ile female 25-mph unbelted and 5th%ile female 30-mph belted conditions, which are prescribed by FMVSS 208 for the 5th%ile smallest-bodied females under belted and unbelted conditions. In addition, 5th%ile male 25-mph unbelted tests were also conducted (Short and Kozak, 2000) to consider the lower 50 % of all males by height and weight. Here the %ile means percentile.

4. RESULTS AND DISCUSSION

The static and dynamic tests were conducted under the conditions presented in Table 1 to evaluate the performance

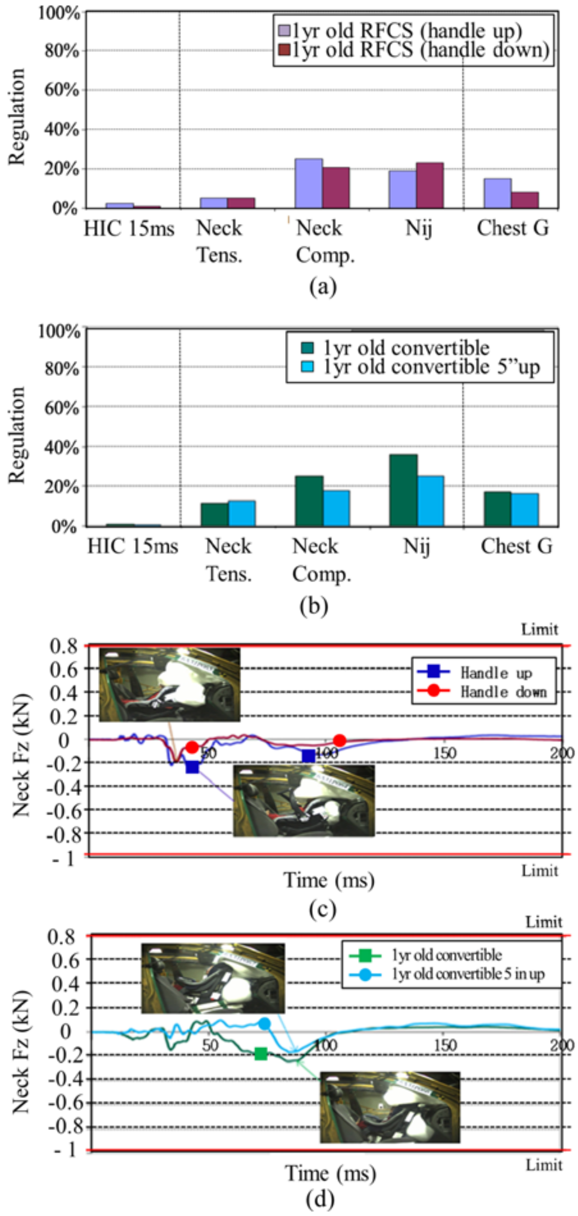
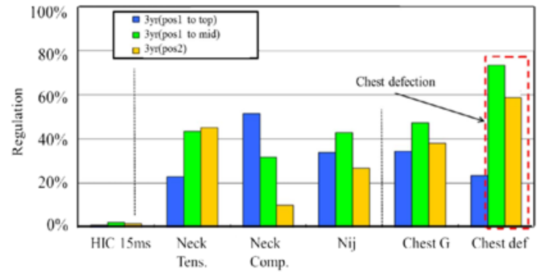


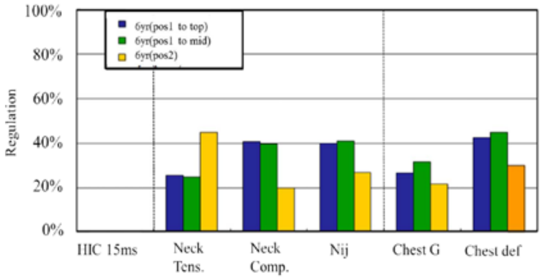
Figure 8. OOP test results: (a) 12-month-old rear-facing CRS with handle-up/handle-down; (b) 12-month-old convertible CRS/convertible CRS 5" up; (c) Neck F_z acceleration curve for 12-month-old rear-facing CRS; (d) Neck F_z acceleration curve for 12-month-old convertible C.

of the proposed slim low-risk dual-airbag system.

Figures 8 (a) and (b) show the results of the OOP tests conducted using 12-months-old (CRBIN) dummies. The



(a)



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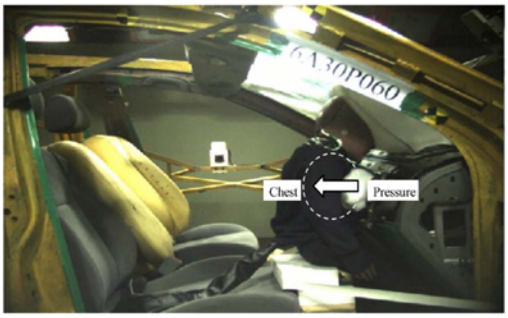

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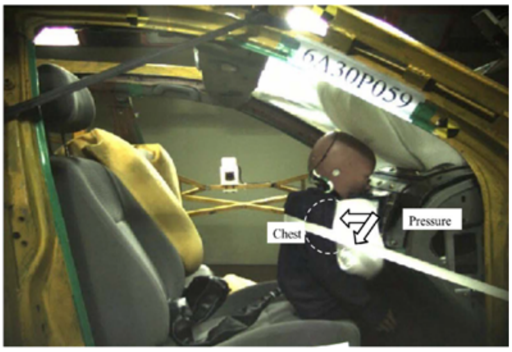
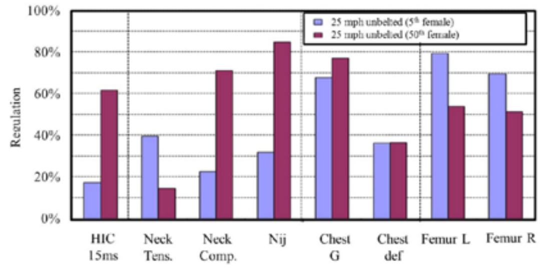


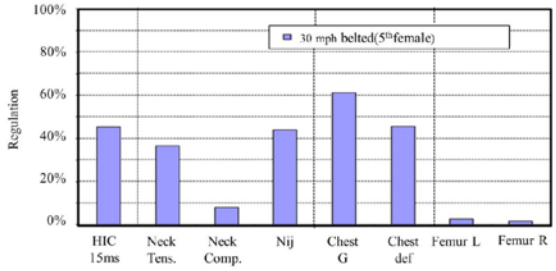
(d)

Figure 9. OOP test results: (a) 3-year old in Position 1 (chest aligned with top-mounted airbag/chest aligned with middle-mounted airbag) and Position 2; (b) 6-year old in Position 1 (chest aligned with top-mounted airbag/chest aligned with middle-mounted airbag) and Position 2; (c) Side view of 3-year old position 1 test; (d) Side view of 3-year old position 2 test.

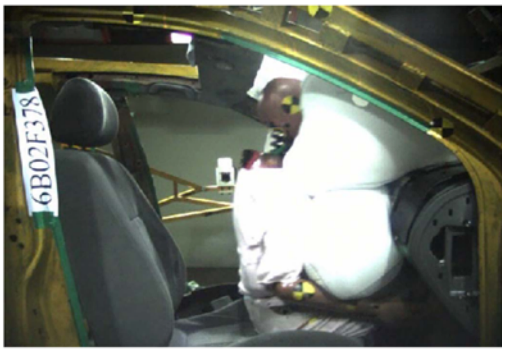
results indicate satisfactory values of below approximately 40 % for all categories of injuries regulated by FMVSS 208. Figures 8 (c) and (d) show the acceleration curves of the tensile (+) and compressive (–) forces (F_z values) applied to the neck during the inflation of the cushion, as



(a)



(b)



(c)

(d)

Figure 10. Dynamic test results: (a) 5th%ile and 50th%ile 25-mph unbelted; (b) 5th%ile 30-mph belted; (c) Deployment view for 5th%ile 25-mph unbelted; (d) Deployment view for 50th%ile 25-mph unbelted.

selected among the neck injury (Nij) factors.

The test observations indicated that the time to the peak acceleration for the rear-facing CRS was approximately 30 ms ~ 40 ms, while that for the convertible CRS was approximately 80 ms ~ 90 ms. This time difference is due to the differences between the sizes and weights of the CRSs as explained in Section 3.

Although the observed injury rates in Figures 8 (a) and (b) are significantly lower than the regulation limits, they are comparable to those of NHSTA (2008). This is because the inflation force of the top-mounted airbag cushion was inclined upwards over the back of the CRS and there was no direct contact with the infant's head.

Moreover, the impact of the cushion pressure of the middle-mounted airbag on the back of the CRS was very low, as shown in Figure 5, and this resulted in the cushion inflating directly downwards.

Figures 9 (a) and (b) show the results of the OOP tests for 3- and 6-year olds. As shown in Figure 9 (a), satisfactory rates of below approximately 50 % based on FMVSS 208 were observed for all injury categories, excluding chest defection, for Positions 1 and 2 for settings relative to the middle-mounted airbag.

The observed higher rates of chest defection are due to the shorter distance between the middle-mounted airbag and the dummy's chest. This resulted in stronger impact by the pressure of the inflating cushion, as shown in Figures 9 (c) and (d). To solve this issue, further development of the middle-mounted airbag inflators is required. This may involve the implementation of an offset similar to that of the initial pressure curve of the top-mounted airbag inflator in Figure 5.

Figures 10 (a) and (b) show the results of the dynamic tests, namely, the 5th%ile female 25-mph unbelted test, 5th%ile female 30-mph belted test, and 50th%ile male 25-mph test. The injury rates satisfy the requirements of FMVSS 208, indicating that the two airbag cushions sufficiently supported the head and chest and protected the passenger by rapidly setting into place without bumping against each other as do single cushions (see Figures 10 (c) and (d).

Furthermore, although the pressures during the 5th%ile and 50th%ile unbelted tests were lower than those for conventional dual inflators, the inflation pressures of the slim dual airbags protected the dummy's femur by preventing the dummy from hitting the instrument panel (Padmanabon and Okabe, 2008).

5. CONCLUSION

In this study, we developed a slim motor vehicle dual-airbag system with a dispersive effect of the inflation pressure. Static and dynamic tests as specified in FMVSS 208 were conducted on the system. Following is a summary of the study:

(1) To solve the problem of high pressures on the order of 540 KPa being delivered to the passenger by the cushions of conventional passenger airbags during a collision, as well as reduce the injury rates, we developed a slim dual-type passenger airbag system in which the pressure was divided between two airbag cushions.

(2) The developed airbag system housing is 40 mm ~ 70 mm wide and the top- and middle-mounted airbags are respectively installed in the upper and front part of the vehicle instrument panel without interfering with the windshield or glove box. It was determined that a deployment angle of 60° and distance of 100 mm ~ 250 mm were required between the two airbags for their cushions to effectively protect the passenger by sliding into place rather than bouncing off each other.

(3) The results of OOP tests using 12 months, 3- years, and 6-years-old dummies produced satisfactory injury rates of below approximately 60 % based on FMVSS 208. In particular, the 12-months-old OOP tests using CRSs produced rates of less than 40 %, indicating superior performance compared to current commercial airbags.

(4) The results of dynamic tests using 5th%ile and 50th%ile dummies revealed that, despite the proposed system producing airbag pressures lower than the 540 KPa of conventional airbags, it effectively protected the passenger, and its two airbags did not bounce off each other during inflation. The performance of the proposed system exceeded regulation requirements by about 80 %.

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