MEASURING AIRBAG INJURY RISK TO OUT-OF-POSITION OCCUPANTS

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ABSTRACT

Real-world crash experience has shown the need to reduce the risk of injury from inflating airbags to out-of-position occupants including small adult drivers. The small (5th percentile) female Hybrid III dummy positioned very close to the steering wheel/airbag assembly is the primary means currently available for assessing potential risk of severe chest and head/neck injury to out-of-position drivers. However, researchers have identified shortcomings with this dummy in reliably assessing potential interactions between the head/neck and the deploying airbag. Several noncrash airbag deployment tests in two late-model vehicles were conducted with a small female Hybrid III dummy. The dummy's spine had been modified to permit the upper torso to rotate forward without the buttocks leaving the driver seat in order to better simulate at-risk positions that a belted driver could achieve. Tests with the standard Hybrid III head and neck, even though supplemented with a foam neck shield as recommended by Melvin et al. (1993), confirmed non-biofidelic interaction between the dummy and deploying airbag. Several modifications to the dummy's head skin and neck shield were tested to determine whether any gave more repeatable and biofidelic results. None of the head skin/neck shield configurations tested was found to provide a reliably biofidelic indication of airbag inflation injury risk.

INTRODUCTION

More than 74 million cars and light trucks on U.S. roads are equipped with driver airbags, and all cars and most light trucks manufactured since the 1997 model year also have passenger airbags. Studies show that airbags have reduced deaths in frontal crashes by about 26 percent for belted drivers and by about 32 percent for unbelted drivers (Ferguson et al., 1995). Deaths in frontal crashes also have been reduced by about 14 percent for belted passengers and by about 23 percent for unbelted passengers (Braver et al., 1997). The National Highway Traffic Safety Administration (NHTSA) estimates that as of May 1998 airbags had saved nearly 3,000 lives in the United States (NHTSA, 1998). Thus, airbags are effective in reducing the risk of death and injury associated with many severe frontal car crashes.

Despite this overall effectiveness, real-world experience has shown that some out-of-position occupants are being injured and even killed by deploying airbags. As of May 1998, NHTSA attributed 99 deaths in low-severity crashes to airbag inflation energy. These deaths include 38 adult drivers, 4 adult passengers (a belted 98-year-old female, an unbelted 88-year-old female, an unbelted 57-year-old male, and an unbelted 66-year-old female), 44 children ages 1-11, and 13 infants (10 restrained in rear-facing infant seats and 3 seated on adult passengers' laps).

Two phases of airbag deployment have been associated with high, injury-causing forces: the punch-out phase and membrane-loading phase (Horsch et al., 1990). The punch-out phase occurs before or immediately after an airbag escapes from the module. If this escape is blocked by an unconscious driver slumped over the steering wheel, for example, the gas pressure inside the airbag becomes greater than normally required to break the module cover, and the resulting high force is concentrated on that part of the driver blocking the airbag's deployment path. Generally, the risk of injury from punch-out forces is significantly reduced with even a small separation between the occupant and airbag module. The membrane-loading phase occurs after the airbag is out of the module. The injury-causing forces result from a combination of the airbag's internal pressure and the tension forces arising from the inflating airbag wrapping around the occupant in its path. Membrane forces on an out-of-position occupant can be high even with some separation between the occupant and airbag module.

Drivers who must sit close to the steering wheel to drive, either because of short stature or medical reasons, compose one group potentially at risk of such injuries. Sixteen of the 38 adult drivers whose deaths have been attributed to airbags were 160 cm (63 inches) tall or shorter, and all but one with fatal neck injuries were women. Tests with dummies also indicate that smaller, more fragile drivers are at greater risk than larger drivers of injuries caused by the forces of deploying airbags (Melvin et al., 1993). Consequently, most current efforts to study airbag injury risk to out-of-position drivers use the small (5th percentile) female Hybrid III dummy and associated injury reference values.

Some researchers have identified problems associated with the Hybrid III dummy's design that make it difficult to accurately measure injury risk in tests in which an airbag is deployed at close range to the dummy (Horsch et al., 1990). The dummy's head and neck are different from those of a human in two important ways. First, the neck is much smaller in diameter than the segment of the population it is intended to represent. Second, there is a hollow area between the chin and neck that provides an unrealistically large reaction surface for airbag membrane loading (Figure 1). An inflating airbag, even while still folded, could push into this area and, as it expands, generate higher forces than could be generated for a human of the same size. Research indicates that a realistic contact surface in this area is critical to assuring biofidelic airbag loading (Melvin et al., 1993).

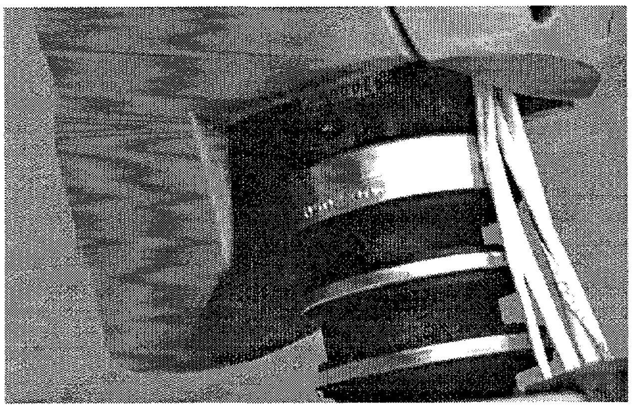

Figure 1. Standard Hybrid III Head and Neck.

The Insurance Institute for Highway Safety has completed a series of noncrash airbag deployment tests using the 5th percentile female Hybrid III dummy with various head and neck modifications to evaluate interactions between the dummy and airbag. Fourteen of the drivers killed by airbag deployments are believed to have been belted, indicating that belt use does not always protect such drivers from airbag inflation injury. Therefore, the dummy was modified to permit the upper torso to rotate forward without the buttocks leaving the driver seat to simulate positions a belted driver might achieve under some circumstances. The dummy's abdominal insert was removed, and the lumbar spine was replaced with a hinged joint with just enough friction to maintain the dummy's posture when not externally supported.

MEASUREMENT METHOD

The series of deployment tests reported in this study includes airbags from two different vehicle models: the 1996 Dodge Grand Caravan and 1996 Honda Accord. Each model was tested several times with the 5th percentile female Hybrid III dummy positioned in the driver seat with the lap/shoulder belt fastened. Vehicle adjustments were made appropriate for a small driver: steering wheel fully down, seat belt D-ring adjustment fully down, seat fully forward, etc. The dummy was leaned toward the steering wheel with the buttocks against the seat back. Two different out-of-position configurations were tested in each model: the dummy leaning forward enough to achieve a chest-to-steering wheel hub clearance of 12 cm and the dummy leaning forward as far as possible. In the latter condition, the dummy's forehead rested against the upper steering wheel rim, and the measured, horizontal clearance between the chest and steering wheel hub was 8 cm in the Honda Accord and 7 cm in the Dodge Grand Caravan.

Tests were conducted with the unmodified dummy and with the dummy modified using three different approaches to improving the biofidelity of head/neck and airbag interaction: standard head skin with a separate, molded foam neck shield; modified head skin and neck wrap; and modified head skin with integrated neck shield. Two different foam neck shields were used, and both wrapped around the neck and extended into the hollow area between the chin and neck. The first design, Molded Foam I (Figure 2), was a modified 50th percentile male Hybrid III dummy neck shield devised early in the Institute's testing because a shield for the 5th percentile female

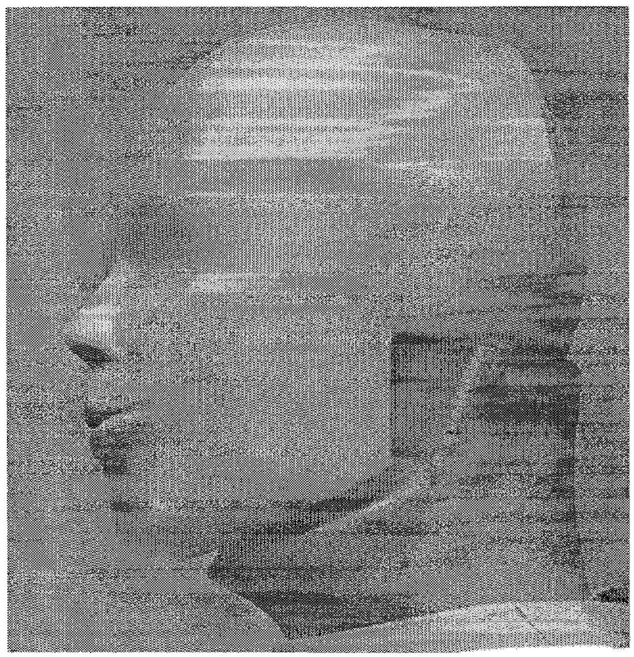

Figure 2. Standard Head Skin and Molded Foam I.

dummy was not commercially available. The 50th percentile neck shield had been developed originally in response to the Horsch et al. (1990) research on out-of-position airbag risk. The Institute's modification trimmed this larger shield to fit the small female dummy. Subsequent to the Institute's initial tests, a version of this foam neck shield, Molded Foam II (Figure 3), specifically designed to fit the geometry of the small female dummy, became available from Applied Safety Technologies Corporation (part no. V00279).

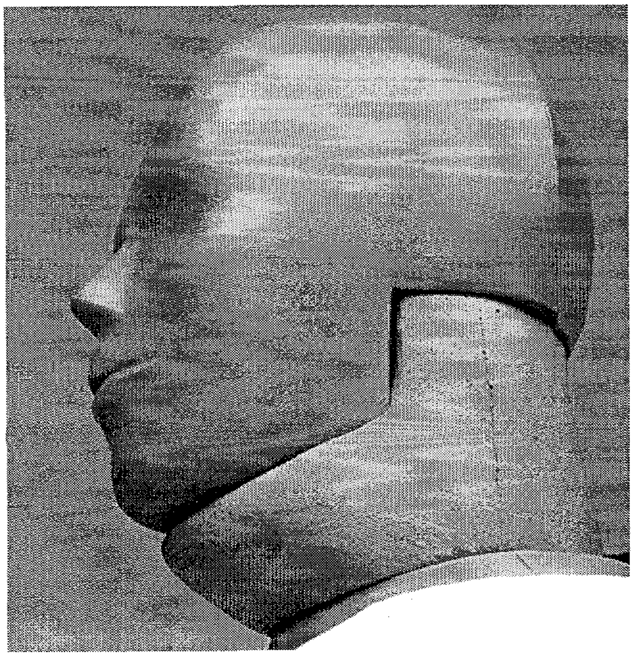

Figure 3. Standard Head Skin and Molded Foam II.

The other tested designs included modifications of the vinyl covering (skin) of the dummy's head and chin. Both were developed by the Society of Automotive Engineers Hybrid III Dummy Family Task Group and built by First Technology Safety Systems. The Modified Head Skin and Neck Wrap (Figure 4) added vinyl skin under the chin to partially cover the hollow area (chin strap) and extended the vinyl skin in the area of the tempero-mandibular joint rearward to cover the right-angle-shaped

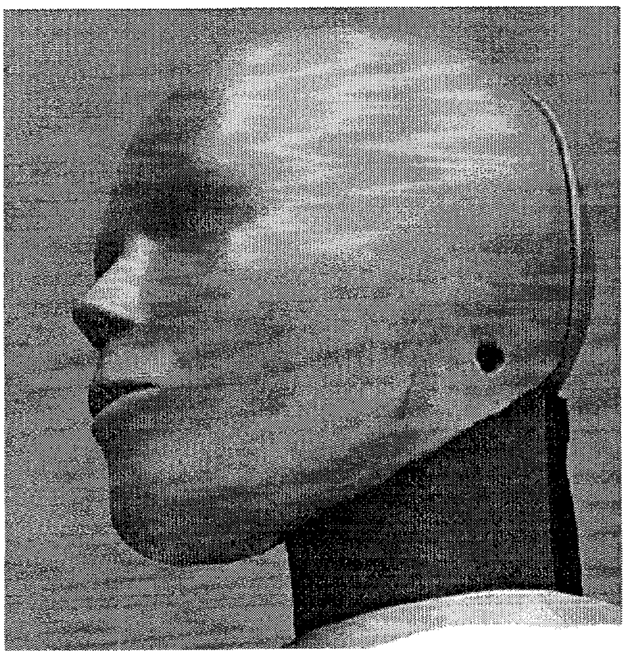

Figure 4. Modified Head Skin and Neck Wrap.

notch visible in the dummy's profile. This design also included a rectangular piece of 7-mm thick rubber foam wrapped around the neck and fixed with Velcro along the back of the neck.

The modified vinyl head skin in the fourth design tested, Modified Head Skin and Integrated Neck Shield (Figure 5), was similar to the Modified Head Skin and Neck Wrap, but instead of wrapping the neck with foam, the vinyl skin was extended down from the posterior edge of the chin strap to provide a continuous surface from the top of the head to the top of the dummy's torso jacket.

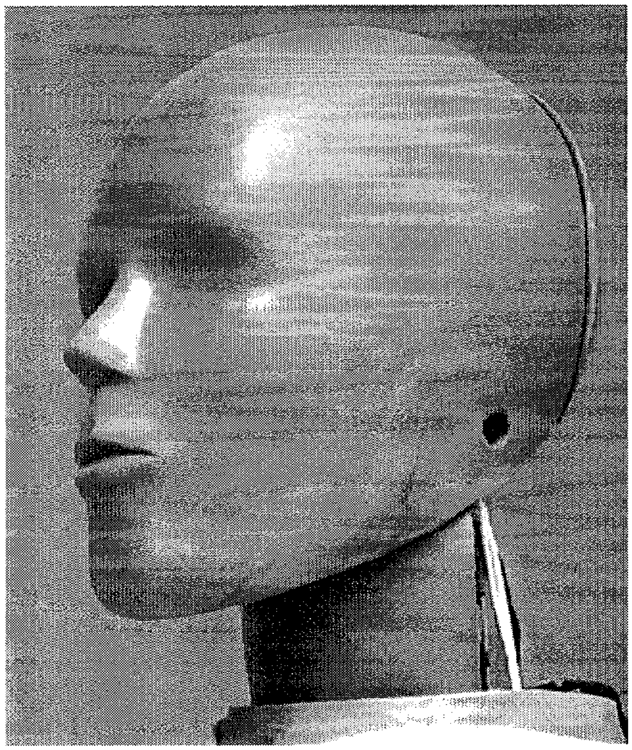

Figure 5. Modified Head Skin and Integrated Neck Shield.

Instrumentation for the airbag deployment tests measured three head accelerations, six upper neck loads, three chest accelerations, and chest compression. Compression of the neck produced positive axial forces; bending the neck to tip the head forward produced positive anterior-posterior (A-P) moments; and pushing the head forward while restraining the torso produced positive A-P shear forces. Neck flexion/extension bending moments were measured by the six-channel, through-the-head load cell at a point 17.78 mm above the dummy's occipital condyle. For comparison with injury reference values, the measured moments were translated to the occipital condyle (OC) location by adding the moment (in Nm) associated with the measured A-P shear force (in N) as follows:

$$\text{Occipital } M_{A\text{-}P} = M_{A\text{-}P} + [0.01778(F_{A\text{-}P})] \qquad (1.)$$

High-speed and still photography were used to record airbag deployments. The vinyl skin in the area behind the chin on the standard head skin and on the upper surface of the chin strap on the modified head skin were colored with grease paint. If the airbag entered the hollow area between the chin and neck, the paint would transfer to the airbag fabric to indicate whether the airbag circumvented the neck and chin shields.

Dummy Neck Calibration

In addition to the airbag deployment tests, neck-pendulum calibration tests were conducted to determine whether the various head/neck modifications prevented the neck from meeting specified flexion and extension response characteristics (Society of Automotive Engineers Dummy Testing Equipment Subcommittee, 1994). These tests consisted of attaching the head and neck upside down to the end of a rigid-arm pendulum, swinging the assembly at a specified speed and stopping the pendulum arm, allowing the neck to bend under the force of the head's momentum. The calibrated response was defined by the measured neck bending moments and head rotation.

RESULTS

Neck Calibration Tests

Calibration tests were not performed with Molded Foam I. The head and neck equipped with Molded Foam II met the requirements for extension response for the 5th percentile female Hybrid III dummy, but the flexion response of this configuration (68.3 Nm) did not meet the maximum flexion bending moment requirements (69-84 Nm). The Modified Head Skin and Neck Wrap met all extension and flexion response requirements. The effects of the Modified Head Skin and Integrated Neck Shield on the specified head/neck response could not be determined with the pendulum tests because the interaction between the extended vinyl neck flap and the dummy's torso jacket could not be simulated.

Airbag Deployment Tests

In all tests, recorded head and chest accelerations as well as chest compressions were very low in comparison with reference values indicating injury risk. Therefore, these data are not presented further, and the comparison of dummy head/neck configurations focuses solely on neck injury measures. The injury assessment reference values (IARV) shown in the tables are based on General Motors' recommendation to NHTSA for use with the 50th percentile male Hybrid III dummy and were subsequently scaled to represent injury risk for small females (Backaitis and Mertz, 1994).

<u>Unmodified Dummy</u> Two 8-cm tests in the Honda Accord were conducted using the unmodified dummy (Table 1). Both tests produced maximum extension bending moments about twice the IARVs, and one test produced neck tension forces that exceeded the IARVs. In both tests, paint from behind the chin was transferred to both the front (away from the dummy) and rear (facing the dummy) panels of the airbag fabric, indicating the airbag entered the hollow space between the dummy's neck and chin. Clean sections of fabric between the colored areas indicated the deploying airbag still was folded when it contacted the painted surfaces.

Table 1
Tests with Unmodified Dummy

	Tension Force (kN)	A-P Shear Force (kN)	OC Extension Bending Moment (Nm)
IARV	2.2	±2.1	31
Honda Accord			
8 cm (KA98010)	2.3	2.0	66
8 cm (KA98011)	1.6	1.4	53

Data for the first Accord test (KA98010) is characteristic of dummy neck responses in all of this model's 8-cm tests (Figure 6). Analysis of the high-speed film showed the initial rapid tension pulse corresponded to the airbag cover flap slapping the dummy's chin as the airbag escaped the module. The longer duration tension pulse, shear force pulse, and neck extension bending moment pulse occurred as the inflating airbag wrapped around the dummy's head and neck. The neck loads peaked after the dummy began to move away from the steering wheel and then diminished to nearly zero while the dummy still was contacting the airbag. As the dummy moved away from the airbag, the film

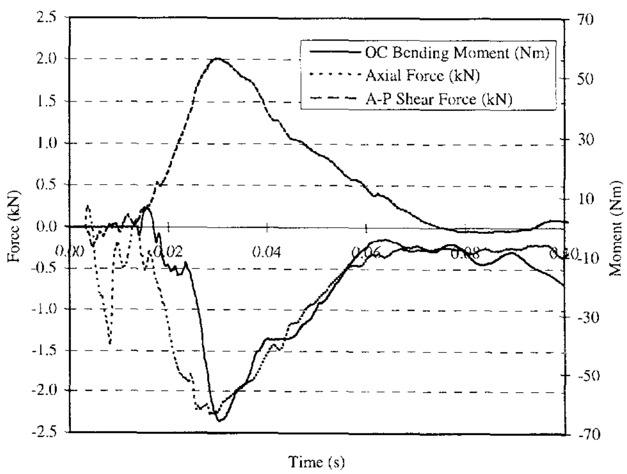

Figure 6. Standard Hybrid III head and neck response to noncrash airbag deployment in Honda Accord 8-cm test.

showed part of the airbag fabric pulled away from the tempero-mandibular notch behind the dummy's jaw.

Dummy with Molded Foam I Seven tests were conducted using the modified 50th percentile Hybrid III molded foam neck shield, five in the Honda Accord and two in the Dodge Grand Caravan (Table 2). The Accord's second and third 8-cm tests (KA98004 and KA98005) produced upper neck loads similar to those in the unmodified dummy tests, and the first 8-cm test (KA98002) exhibited even higher tension loading and exceptionally high positive shear loading. Consequently, the calculated extension bending moment for the occipital condyle was lower in the first test than in the second and third tests despite similar bending moments. In these three tests, paint from behind the dummy's chin was transferred to the airbag fabric, confirming the deploying airbag circumvented the foam neck shield. Paint patterns in these tests also were similar to those in the unmodified dummy tests, and high-speed film showed the airbag fabric pulled away from the tempero-mandibular notch behind the dummy's jaw as the dummy moved away from the airbag.

Table 2
Tests with Molded Foam I Neck Shield

	Tension Force (kN)	A-P Shear Force (kN)	OC Extension Bending Moment (Nm)
IARV	2.2	±2.1	31
Honda Accord			
8 cm (KA98002)	2.4	9.2	40
8 cm (KA98004)	1.9	1.8	64
8 cm (KA98005)	1.8	1.6	57
12 cm (KA97021)	1.1	6.3	37
12 cm (KA98003)	1.0	0.2	18
Dodge Grand Caravan			
7 cm (KA97004)	2.1	1.2	48
12 cm (KA97002)	1.3	0.8	49

Because the shear force in the Accord's first 8-cm test (KA98002) was exceptionally high, it was examined further. Only one difference between this test and the other two 8-cm tests was noted. The paint pattern in the first test was located farther to the right of the airbag's center than in the other two tests. Paint in the first test was located on both sides of the first crease to the right of the airbag's center, whereas paint in the other two tests was located between the centermost creases of the airbag folding pattern. This observation offers a possible explanation for the exceptionally high shear force recorded in the first test. The location of the paint pattern in the first test suggests the airbag was folded over on itself while behind the dummy's chin. The membrane tension forces generated as the fabric suddenly unfolded can be greater than would be predicted from airbag pressure multiplied by contact area (Patrick and Nyquist, 1972). Thus, the possibility that the fabric was folded more tightly in the chin cavity in the first test than in the other two tests may account for the high shear force recorded.

The Honda Accord's two 12-cm tests generally produced lower neck forces than this model's 8-cm tests. However, the first 12-cm test (KA97021) produced a peak extension bending moment slightly higher than the IARV and the second highest A-P shear force of any test using Molded Foam I. In the first test, paint was transferred to the center of the rear airbag panel, and the high-speed film showed the airbag fabric pulled away from between the dummy's chin and neck shield as the dummy moved away from the airbag. These observations indicate the airbag circumvented the neck shield. In doing so, the airbag probably folded back on itself as it pushed past the neck shield and into the space behind the jaw. When the internal airbag pressure increased, the fabric suddenly unfolded and membrane tension forces were generated, as was hypothesized to have happened in the Accord's first 8-cm test (KA98002).

Grease paint was not used in either of the Dodge Grand Caravan tests, so it is unknown whether the airbag circumvented the neck shield. In both tests, high-speed film showed the airbag contacted the dummy below the inferior edge of the neck shield and may have pushed the neck shield into the hollow area behind the chin. As the dummy moved away from the inflated airbag, the airbag fabric pulled away from the tempero-mandibular notch behind the dummy's jaw. Neck loads in the Grand Caravan's 7-cm test were similar to those in two of the Honda Accord's 8-cm tests (KA98004 and KA98005). Although most maximum neck loads were measured during the airbag's membrane-loading phase, the maximum tension force in the Grand Caravan's 7-cm test was recorded early when the airbag cover slapped the dummy's chin. The peak tension load measured during the membrane-loading phase in this test was 2.0 kN. In the Grand Caravan's 12-cm test, the maximum extension bending moment was higher than in both the Accord's 12-cm tests, and tension and A-P shear forces were about the same as those in one of the Accord's 12-cm test (KA98003).

Dummy with Molded Foam II Only two tests were conducted using the molded foam neck shield designed specifically for the 5th percentile female Hybrid III dummy (Table 3). The Honda Accord's 8-cm test produced peak neck loads similar to those in the unmodified dummy tests and to two of the Accord's 8-cm tests using Molded Foam I (KA98004 and KA98005). Although the maximum A-P shear force and extension bending moment were measured during the airbag's membrane-loading phase, the maximum tension force was recorded early in this test when the airbag cover slapped the dummy's chin. The peak tension load measured during the membrane-loading phase in this test was 1.6 kN. The high-speed film showed the airbag pulled against the dummy's vinyl skin at the posterior of the tempero-mandibular notch, but no paint was transferred to the airbag fabric. The absence of paint on the fabric indicated the airbag did not push between the foam and the dummy's chin.

The Dodge Grand Caravan's 7-cm test also produced neck loads similar to this model's 7-cm test using Molded Foam I. However, paint transferred to the airbag fabric in this test indicated the airbag circumvented the neck shield.

Table 3
Tests with Molded Foam II Neck Shield

	Tension Force (kN)	A-P Shear Force (kN)	OC Extension Bending Moment (Nm)
IARV	2.2	±2.1	31
Honda Accord 8 cm (KA98017)	1.8	1.4	56
Dodge Grand Caravan 7 cm (KA98018)	2.0	1.5	53

<u>**Dummy with Modified Head Skin and Neck Wrap**</u> Five tests were conducted using this modification, three in the Honda Accord and two in the Dodge Grand Caravan (Table 4). The two Accord 8-cm tests produced neck tension and extension bending moment responses similar to those in this model's 8-cm tests using the foam neck shields. However, the high neck shear force in the first Accord 8-cm test using Molded Foam I (KA98002) was absent. In these two tests, some paint was transferred from the upper surface of the chin strap to the center of the rear airbag panel, and high-speed film showed the airbag pulled on the posterior edge of the chin strap as the dummy moved away from the airbag. The absence of paint on any other part of the airbag fabric could indicate that the transferred paint was from incidental contact rather than from the airbag inserting itself into the space behind the chin. No paint was transferred in the Accord's 12-cm test, and neck loads were well below IARVs.

Table 4
Tests with Modified Head Skin and Neck Wrap

	Tension Force (kN)	A-P Shear Force (kN)	OC Extension Bending Moment (Nm)
IARV	2.2	±2.1	31
Honda Accord 8 cm (KA98006) 8 cm (KA98007) 12 cm (KA98012)	 1.9 2.2 1.2	 1.4 1.4 -0.3	 52 53 17
Dodge Grand Caravan 7 cm (KA98016) 12 cm (KA98013)	 2.4 1.4	 2.6 1.7	 67 87

Although in the Accord's 8-cm tests the modified head skin and neck wrap seemed to resist airbag penetration into the hollow area between the dummy's chin and neck, this modification still allowed paint to be transferred to the airbag in both Dodge Grand Caravan tests. In the Grand Caravan's 7-cm test, paint was transferred to the front panel of the airbag, suggesting the airbag penetrated the hollow area early during deployment. Neck loads in both Grand Caravan tests were higher than in this model's 7-cm and 12-cm tests using the foam neck shields.

<u>**Modified Head Skin and Integrated Neck Shield**</u> Only two 8-cm tests were conducted in the Honda Accord using this modification (Table 5). Maximum extension bending moments and A-P shear forces were considerably lower in these tests than in this model's 8-cm tests using any other dummy head/neck modification. The continuous surface presented by the head skin's integrated neck shield assured that the airbag could not insert itself into the hollow area between the dummy's chin and neck. However, high-speed film showed that the airbag pushed the integrated neck shield against the neck and may have restricted the rearward rotation of the head. If this restriction occurred, it suggests the possibility that some airbag deployment forces were carried by the neck shield and not registered by the neck load cell. Thus, the true airbag injury risk may have been masked. The lower A-P shear and tension forces recorded in these tests might be explained by this alternative loading mechanism rather than by the absence of airbag penetration into the hollow area behind the chin.

Table 5
Tests with Modified Head Skin and Integrated Neck Shield

	Tension Force (kN)	A-P Shear Force (kN)	OC Extension Bending Moment (Nm)
IARV	2.2	±2.1	31
Honda Accord 8 cm (KA98008) 8 cm (KA98009)	 1.5 1.4	 0.8 0.7	 33 33

DISCUSSION

Among the tested configurations of the 5th percentile female Hybrid III dummy's head and neck, only the continuous surface of the Modified Head Skin and Integrated Neck Shield assured that the airbag would not insert itself into the hollow area between the dummy's chin and neck. However, observation from high-speed film indicated that the airbag, pushing against the integrated shield, might itself produce erroneous neck load measurements to the extent that it hinders neck motion. Consequently, this modification did not meet one of the design criteria for an effective neck shield identified by Melvin et al. (1993). Based in part on film analysis and injury measures recorded in these tests, the Society of Automotive Engineers Hybrid III Dummy Family Task Group decided at its March 19, 1998 meeting not to recommend the integrated neck shield design for use in out-of-position airbag testing.

None of the other dummy modifications prevented the airbag from inserting itself into the hollow area between the dummy's chin and neck in either vehicle model. The Modified Head Skin and Neck Wrap seemed to fend off the Honda Accord's airbag, as did the Molded Foam II neck shield, but neither prevented the Dodge Grand Caravan's airbag from pushing into the space behind the dummy's chin. In fact, the Modified Head Skin and Neck Wrap produced the highest neck loads measured among all Dodge Grand Caravan tests. Thus, these Hybrid III head/neck configurations cannot be expected to provide reliable measures of airbag injury risk. It also is likely that airbags with different folding patterns and deployment paths will interact differently with various head/neck configurations, just as the Accord and Grand Caravan airbags interacted very differently with the Modified Head Skin and Neck Wrap.

Another difficulty revealed by these tests is that the neck extension bending moment is the measure most sensitive to airbag interaction. Neck extension bending moments exceeded published IARVs (Backaitis and Mertz, 1994) in all but three tests. However, the extension bending moment IARV describes the injury risk for a human neck extended rearward, as in a rear-end collision (Mertz and Patrick, 1971). None of the maximum extension bending moments in this series was measured at a time when the dummy's neck was extended rearward. Consequently, the meaning of neck bending moments is unclear because the heads/necks were not in position to suffer the injury on which the IARV is based. The fatal head/neck injuries to out-of-position drivers often involved basilar skull fractures, which typically are more associated with tension forces (Hopper et al., 1994). The implications of a high bending moment without neck extension are particularly obscure when the neck tension loads, which may provide a more direct indication of this kind of injury, are relatively low in comparison to the IARV.

Other interpretations of neck force measurements yield somewhat different implications. According to Mertz et al. (1997), the 2.2 kN tension force IARV may understate neck injury risk. The injury risk relationships developed by the authors, which were based on airbag tests with pigs and 3-year-old child dummies, indicate that the 2.2 kN tension force represents a 50 percent risk of a neck injury rated 3 or greater on the Abbreviated Injury Scale (AIS). A 10 percent risk of an AIS ≥ 3 injury would be associated with tension forces of about 1.9 kN or neck bending moments of 50 Nm. Thus, according to this alternate analysis of neck forces, the neck tension and bending moments recorded in this series indicate more similar risks of serious head/neck injury, and the greater sensitivity of the neck tension force seems more relevant to real-world head/neck injury experience. Nevertheless, this discussion indicates the need to further consider the issue of injury thresholds in out-of-position tests.

CONCLUSIONS

None of the dummy head/neck configurations, except the Modified Head Skin with Integrated Neck Shield, was completely effective at preventing the airbag from inserting itself into the space behind the dummy's neck, and the integrated neck shield currently is unacceptable because it cannot be determined whether the shield itself provides an alternative load path that is unmeasured. Consideration of test results from both vehicle models suggests that a well fitting, foam neck shield might have the best potential to meet the needs of out-of-position airbag testing. Molded Foam II in the Honda Accord tests prevented the airbag from entering the hollow area between the dummy's chin and neck, and in the Molded Foam I tests with the Dodge Grand Caravan the airbag pushed into the space under the neck shield instead of penetrating the space behind the dummy's neck. The Institute is investigating a subsequent configuration that combines the modified head skin with the molded foam neck shield, bonding the neck shield to the top of the chin strap of the modified head skin. However, at this time there does not appear to be a head/neck configuration of the 5th percentile female Hybrid III dummy that can reliably provide a biofidelic indication of airbag inflation injury risk to out-of-position drivers.

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