ASSESSMENT OF ADVANCED AIR BAG TECHNOLOGY AND LESS AGGRESSIVE AIR BAG DESIGNS THROUGH PERFORMANCE TESTING

Glen C. Rains
Aloke Prasad
Lori Summers
National Highway Traffic Safety Administration
United States
Mark Terrell
Federal Office of Road Safety
Australia
Paper Number: 98-S5-O-06

ABSTRACT

On March 19, 1997, the National Highway Traffic Safety Administration (NHTSA) published a Final Rule amending FMVSS No. 208 to allow manufacturers to de-power air bags in their passenger vehicles. This is considered an interim solution to the problems associated with aggressive air bag deployments. Consequently, the amended rule has a sunset provision that removes the amendment, with the addition of "advanced" air bag requirements to be developed in the future.

As part of the process to develop test procedures, a study was conducted to test the capabilities of advanced air bag technologies, and evaluate less-aggressive air bags designed for a belted market in Australia. Testing consisted of static air bag deployments and dynamic HYGE sled and crash testing using Hybrid III adult and child dummies.

Advanced systems testing indicate that Multi-stage inflation can tailor bag deployments for the crash severity. However, it was still challenging for the platform tested to meet IARV's when child dummies were out-of-position (OOP) relative to the air bag. The Holden air bag used in Commodore VS and VR models in Australia passed an FMVSS No. 208 full-frontal rigid barrier crash test with unbelted dummies, although lack of knee bolsters caused the dummies to submarine somewhat on the driver-side. OOP results were moderately aggressive on the driver-side and very aggressive on the passenger-side with the 3 and 6 year old dummies.

BACKGROUND

FMVSS No. 208[1] is the frontal impact protection regulation in the United States. Until March of 1997, this standard required air bags to automatically deploy in a 30 mph frontal barrier crash test with two belted or unbelted H-III 50th percentile male dummies. After a number of cases in which the air bag deployment forces resulted in a serious to fatal injury, the National Highway Traffic Safety Administration (NHTSA) began a comprehensive investigation to understand the causes of these fatalities.

Initial studies into the crashes revealed one prevalent characteristic that was common to almost all the cases. Each occupant, driver or passenger, was in close proximity to the air bag module when it deployed. Reasons for these out-of-position (OOP) occupants were different for the driver and child passenger. Driver fatalities were predominantly of small-stature adults, who due to their stature, were seated close to the steering wheel. Child passenger fatalities were split into two groups. The first were infants in rear-facing child seats that were in the right-front passenger seat. The back of the child seat was very close to the module when it deployed. The second child passenger fatality scenario involved un- restrained children who were thrown into the instrument panel during pre-impact braking. Then, as the crash occurred the bag deployed with the child on or very close to the air bag module.

The NHTSA began to investigate the options available to quickly avert additional fatalities. A public education campaign was initiated to inform parents of the dangers to children riding in the front seat with a passenger air bag and advised them to correctly restrain their children in the back seat. To address driver fatalities, recommendations were developed for how far to sit from the air bag module. Inasmuch as education alone was not expected to eliminate the problem, a test program conducted at NHTSA's research lab, the Vehicle Research and Test Center (VRTC), was conducted to examine the effects of an air bag deployment to out-of-position (OOP) occupants. It was discovered that reducing the air bag inflator output, without any other changes, reduced the loads applied to OOP child and adult dummies. There was, however, a corresponding increase in injury measurements on full-size dummies in sled tests that simulated the FMVSS No. 208 full frontal barrier crash test. Therefore, NHTSA began investigating ways to allow air bag "de-powering".

In response to agency inquiries on de-powering, auto manufacturers claimed that to "de-power" their air bags, FMVSS No. 208 would need to be amended. The American Association of Automobile Manufacturers (AAMA) proposed a sled test that simulates a car-to-car crash in a lower severity impact than the frontal barrier test. Consequently, the reduced severity crash would require less occupant restraint and manufacturers would be able to reduce the inflator output. The requirement to change FMVSS No. 208 to allow the auto manufacturers to de-power their air bags hinged on the industry's claim that the then current barrier test required overly aggressive and large air bags, particularly on the passenger-side, where children would be seated. The agency determined that a temporary change to the standard to allow air bags to be de-powered and reduce the risk of air bag induced fatalities, outweighed the risks put upon occupants in high speed crashes. A sunset provision was added to the regulatory amendment that removes the sled test option on September 1, 2001. At that time, there would be new regulatory requirements to introduce advanced air bags that should prevent harm to OOP occupants and meet the FMVSS 208 barrier crash test with unbelted dummies.

Advanced Systems Development and Testing

Air bag suppliers and automobile manufacturers have been developing and researching a variety of technologies to improve air bag performance, and reduce the potential of inflation-induced injuries from aggressive air bag deployment. Some of the advanced technologies may provide more information about the crash and have the capability to tailor or suppress the air bag restraint response to the individual occupant. The general categories of information provided by advanced technologies include: occupant safety belt use, occupant position relative to the air bag module, occupant size/mass, and the crash severity. This information can be used to make a more informed decision on the type of air bag deployment scheme to employ. Other advanced systems make use of less technical alternatives such as compartmented air bags, advanced fold patterns, controlled venting systems, and lower inflation onset rates to reduce aggressiveness while maintaining full occupant protection.

One of the emerging near-term technologies that could be ready for production in 1998[2] is multi-stage air bag inflators. Multi-stage air bag inflators have the potential of providing a low level, a high level, and a range of mid-level inflations. These levels are achieved by either firing only the primary stage of deployment, firing the primary and secondary stages simultaneously, or by firing the secondary stage at a specified time after the firing of the primary stage. Different multi stage air bag inflator technologies are under development by the industry. Some design strategies utilize a compressed gas inflator with two separate initiators; other designs consist of packaging two separate pyrotechnic charges a single inflator. In conjunction with the multi stage air bag inflator technology, a sensor mechanism and the associated control logic are required to make effective use of the different inflation levels.

A test series was conducted to examine an advanced air bag system utilizing a multi-stage inflator and advanced single-point sensor. The advanced system was provided through cooperation with TRW Inc. Dynamic sled and crash tests were conducted to examine the performance characteristics of the system in a moderate to high crash severity environment. An additional set of tests were performed on the driver and passenger air bag to test the aggressiveness of the air bag system with OOP occupants. The objectives of the tests were:

1. Assess the potential to meet Injury Assessment Reference Values (IARV's) when an occupant is OOP as well as protect occupants in high speed crashes.

2. Examine test procedures for testing OOP dummies for repeatability.

Australian Air Bag Development

The wearing rate for seatbelts in Australia is currently greater than 95% for front seat occupants and greater than 80% for rear seats. This is a result of legislation introduced in Australian states in 1970/71 which produced a rapid reduction in road deaths. The high seatbelt wearing rate allowed Australia to implement a frontal crash test standard using restrained dummies. The technical requirements of Australian Design Rule 69 (Frontal Crash Protection) are the same as those of US FMVSS No. 208, except the dummies are restrained with the vehicle's seatbelts. This has allowed manufacturers to optimize restraint systems for the restrained occupants, resulting in less aggressive air bags, with a higher deployment threshold.

One such vehicle, whose air bags are designed for the restrained occupant is the Holden Commodore. The Commodore is one of Australia's two best selling cars, with its market rival the Ford Falcon being of similar size and mass. Approximately 50% of VR and VS model Commodores were sold with the optional air bag. Initially the air bag rate was much higher for private vehicles than for fleet cars (which make up about 70% of sales in this vehicle category), however the acceptance of the value of air bags in the fleet market has increased over time to the point that air bags are now standard across the current Commodore model range.

A test series was conducted with the VS Holden Commodore Vehicle. The testing was conducted in conjunction with the Australian Federal Office of Road Safety (FORS) at the Autoliv test facility outside of Melbourne, Australia. One crash test and a series of static OOP tests were conducted with the child and small female dummies. The objectives were:

1. Assess the performance of the Holden Commodore air bag in a frontal barrier crash test with two unbelted 50[th] percentile adult male H-III dummies.

2. Determine the aggressiveness of the Holden air bag to OOP occupants.

TEST METHODOLOGY

Characteristics of Air Bag Systems Tested

Platform 1 Multi-stage air bag inflator - A multi-stage inflator was tested on a vehicle platform (referred to as Platform 1) to experimentally evaluate the performance of such devices. The advanced air bag system comprised of a compressed gas container with dual-squibs. By varying the firing time of the squibs, the inflation gas rise rate and peak pressure, when measured in a tank test, could be varied. Firing of only one squib was referred to as a first-stage air bag deployment. Firing of the second squib, a pre-determined time after the first was referred to as a multi-stage deployment. Multi-stage deployment increased the inflator output for more severe crash conditions. The closer the second firing to the first, the higher the inflator output. In the tests reported here, there were three firing sequences: First stage only deployment (low-level inflation), multi stage deployment with a 5 ms delay between squib firings (high-level inflation), and multi-stage deployment with a 20 ms delay between squib firings (mid-level inflation). Table 1 illustrates the tank test output for the driver and passenger air bag with the 3 firing sequences. A single point advanced air bag sensor with the multi-stage driver and passenger inflators was also evaluated in a crash test to examine the complete advanced air bag system. For this particular vehicle platform, a distributed sensor system was more desirable, but time limitations restricted testing to off-the-shelf equipment that was modified through adjustments of the signal processing software (crash sensor algorithm).

Table 1.
Multi-stage Inflator 60 l Tank Curve Characteristics

Deployment Stage	Driver Side (kpa x kpa/ms)	Passenger Side (kpa x kpa/ms)
Primary	100 x 5	320 x 8
Primary + 20 ms Delay	130x5	500 x 9
Primary + 5 ms Delay	160 x 8	560 x 17

Out-of-position aggressiveness from the lowest level of deployment, and moderate and high speed performance with adult dummies as the inflation rise rate and peak pressure were increased, were evaluated with a combination of static OOP tests, sled tests, and crash tests.

Holden Commodore VR vehicle - The Holden Commodore is produced by General Motors' Holden Australia. While it was developed as a European vehicle, the Commodore has been extensively modified for Australian manufacture and possesses a unique floorpan, drivetrain configuration, suspension design and therefore crash pulse. The Commodore's air bag systems are optimized for restrained occupants.

A driver's side air bag was available as an option on Commodores from the VR model (1993), with a passenger side air bag being made available on the VS series (1995). Apart from the passenger air bag, crash performance of VR and VS models would be very similar. VR and VS Commodores are also fitted with ELR seatbelts with webbing grabbers.

The Driver's side air bag in the Commodore is a full sized (65 liter) bag, however the inflator is designed to be as non-aggressive as possible. The bag produces a peak inflation pressure of 300 kPa in a 1 cubic foot tank test. The air bag has two 45 mm vents and 275 mm tethers to prevent "bag slap" for the restrained occupant. The passenger air bag is 120 liters in size and is also tuned for restrained occupants. The bag produces 240 kPa in a 100 liter tank test. There are two 30 mm vents and tethers to control the deployment pattern.

The Commodore has also been the subject of a real-world crash study with a collection of VS and VR models with air bags, and a number of earlier VN and VP models (no air bags) as a control group. The initial study, reported at the 1996 ESV conference [3], covered a total of 178 crashed vehicles, with 64 fitted with air bags and the remaining vehicles consisting of 54 baseline (VN & VP models) and 60 non-air bag (VR & VS without the optional air bag/s).

The driver data showed a significant decrease in head injuries, particularly of AIS 2 and above, as well as a decrease in face and neck injuries. Chest injuries were almost halved, with very significant reductions at AIS 2+ and AIS 3+. There was a slight increase in AIS 1 injuries to the upper extremities, with lower extremity injury rates being fairly similar between the air bag and non-air bag vehicles. There was however an apparent increase in the number of spinal injuries in air bag cars at AIS 1 and 2, though the number of injuries were fairly small in both vehicle types.

Overall the study reported a significant reduction in the Probability of injury and mean harm for Holden Commodores fitted with air bags.

Test Matrix

To fully test the ability of an advanced air bag system to prevent harm to OOP occupants while continuing to protect adults in higher speed impacts, a large matrix of tests would be necessary. Figure 1 illustrates a matrix of conditions that could be used to determine the conditions necessary to evaluate air bag and sensor performance when designing to protect a variety of crash and occupant conditions. Generally, a large number of these conditions would be evaluated through crash testing, sled testing, static air bag deployments, and computer simulations to prove the reliability of the system. Sensors that measure the crash severity, occupant size, occupant position, and belt use, can determine the appropriate inflation level.

Testing all the conditions in the matrix was not practicable in this test program. However, a subset of conditions were addressed to determine the general benefits and drawbacks of this particular system. Figure 2 shows the subset of tests conducted with the advanced air bag system for Platform 1. This matrix shows the static OOP tests and sled tests simulating the conditions in the matrix. Vehicle pulses at those conditions shown were provided from actual crash tests or computer simulations with Platform 1. Air bag firing times for sled tests represent the desired firing time of the sensor for that particular crash scenario using the "5 inch/30 ms" rule-of-thumb. The firing times of the first and second stage are listed in pairs. The first is the time into the crash where the first squib fires, the second is the time into the crash where the second squib fires. Consequently a 12,32 represents a 20ms delay between firing the two squibs. All static tests were conducted with the deployment of only the first stage (Firing of the primary squib). Several repeat tests were also conducted to evaluate the repeatability of the positioning procedure.

The testing with the Australian system was limited to static OOP testing and to a 30 mph full-frontal barrier crash test to examine the characteristics of an air bag system designed for a belted population when tested to the full-frontal barrier crash test in FMVSS No. 208 with unbelted 50th percentile male dummies.

Out-of-position Static Tests - The same OOP test procedures were used for Platform 1 and the Holden air bag.

The 3 and 6 year old H-III dummies were positioned to measure the aggressiveness of the air bag. Two dummy positions were developed based on the ISO 10982[4] procedures for OOP testing. Figure 3 illustrates a 3 year old dummy seated in position 1 and position 2. Position 1 sets the dummy's chest against the air bag module with a vertical spine. The dummy is then raised until the dummy's head is within 10 mm of the w/s, or the mid-sternum of the chest is in the same horizontal plane as the geometric centerline of the air bag module cover. Position 2 puts the dummy on the edge of the seat and bends the torso forward at the hip until contact with the forward structure of the vehicle. The procedure for the six-year old is the same. Figure 4 shows the six year old seated in position 2 on Platform 1.

The 5th percentile female was used to test the aggressiveness of the driver-side air bag. The dummy was placed in two positions in close proximity to the air bag. Position 1 and position 2 were based on ISO DTR 10982 test procedures for testing OOP occupants. Position 1 places the head and neck of the dummy in close proximity of the air bag module. Position 2 places the chest against the air bag module. In each

Belt-Use	Crash Mode	Delta V (mph)	3 YO OOP		6 YO OOP		5^{th} Driver OOP		5^{th} Driver	50^{th} Driver	5^{th} Pass.	50^{th} Pass.
			OOP 1	OOP 2	OOP 1	OOP 2	OOP 1	OOP 2				
Properly Belted*	Full Front	20										
		30										
	Pole	20										
		30										
Unbelted	Static	0										
	Full Front	20										
		30										
	Pole	20										
		30										

Figure 1. Matrix of Conditions to fully evaluate air bag performance.

Belt-Use	Crash Mode	Delta V (mph)	3 YO OOP		6 YO OOP		3YO Prox.		5^{th} Driver OOP		5^{th} D	50^{th} D	5^{th} P	50^{th} P
			OOP 1	OOP 2	OOP 1	OOP 2	8" Back	4" Back	OOP 1	OOP 2				
Proper Belted*	Full Front	20												
		30									×		×	×
	Pole	20												
		30												
Un-belted	Static	0	Static	Static	Static	Static	Static	Static	Static	Static				
	Full Front	20												
		30									✓×	×	✓	✓×
	Pole	20									☆◇			☆N
		30												

Figure 2 - Testing conducted with Platform 1 air bag system.

✓ - multi-stage deployment; 12 ms and 17 ms
× - multi-stage deployment; 12 ms and 32 ms
◇ - multi-stage deployment; 57 ms and 77 ms
☆ - single stage deployment; 57 ms
N - no deployment

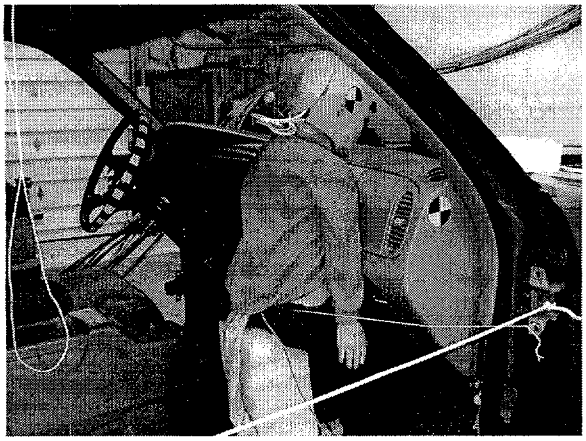

Figure 3a. Three year old, Position 1

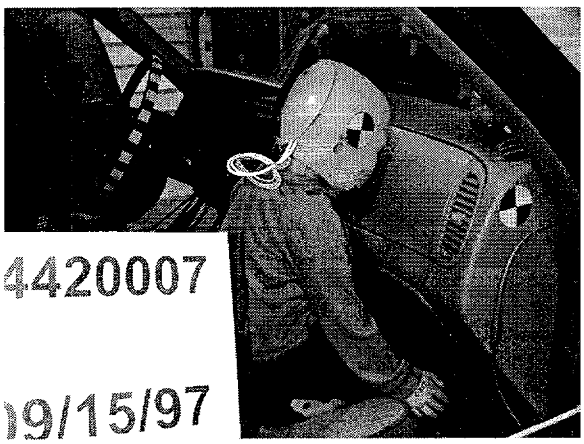

Figure 3b. Three year old, Position 2

Figure 4. Six year old - Position 2

case, the dummy spine was maintained at the same angle as the steering wheel.

Sled Tests - Sled tests were not conducted with the Holden air bag. A series of sled tests were conducted with the platform 1 air bag in a test buck at the Transportation Research Center (TRC) sled facility. Dummy size and simulated crash conditions are shown in Figure 2. A combination of firing sequences with the multi-stage inflator were also examined. The testing consisted of a sled simulation of a 48 k/hr (30 mph) crash pulse into a rigid barrier and a 32 k/hr (20 mph) center-pole crash. Each condition was tested with the 5^{th} female and 50^{th} male H-III dummies, belted and unbelted, with three combinations of the multi-stage squib firing.

Crash Tests - Platform 1 was tested at 40 km/h (25 mph) into an 305 mm (12") pole, offset 234 mm (9.2") to the left of the vehicle centerline. The offset position was chosen as the softest spot into the front of the vehicle (between the rail and the engine block) to test the sensor's ability to fire the air bag on-time and at the appropriate inflation level. A single-point sensor was used to detect the impact severity and fire the air bags. A 5^{th} percentile female dummy was placed in the driver seat and a 6 year old H-III was placed in the passenger seat. The test was recorded by 12 cameras, each at 1000 frames per second.

In order to determine the effectiveness of the Commodore's de-powered air bags in protecting un-belted occupants a vehicle was tested to the US FMVSS 208 standard. The vehicle selected was a 1993 VS Commodore with driver and passenger air bag. The Commodore's restraint system was not designed to cope with unrestrained occupants and therefore no knee bolsters are fitted on the vehicle. The test was conducted at the Autoliv Australia crash test facility. The test was at 48.7 km/h (30.2 mph) into a rigid concrete barrier (with a plywood face). 50^{th} percentile Hybrid III dummies were positioned in both driver and passenger seats. The test was recorded by 7 film cameras, including overall and close-up views on both sides, plus frontal, overhead and underside views. The camera frame rate was 1000 frames per second (3000 frames for side close-ups).

Injury Assessment Reference Values (IARV's)

Head Injury Criteria (HIC), resultant chest g's, neck criteria (Nij), chest deflection, and chest viscous criterion (V*C) were recorded and/or calculated for each test. The following table lists the injury thresholds associated with each measure. All threshold values have been developed to represent a similar risk of AIS 3+ injury.

Table 2.
Injury Threshold and Critical Values.

Injury Criteria	Threshold Measurement			
	3 year old	6 year old	5[th] female	50[th] male
HIC	900	1000	1000	1000
Chest g's	51	65	60	60
Chest Compress (mm)	28	31	41	50
V*C (m/s)	1	1	1	1
Max Nij	1	1	1	1
Fzn	2500	3000	3200	3600
Myn*	90/30	140/40	210/60	410/125

* - Flexion/Extension

Nij is a relatively new measure that is a normalized resultant of neck forces and moments. Neck axial forces are combined with the neck moment calculated about the occipital condyle using the following equation:

$$N_{ij} = \frac{F_z}{F_{zn}} + \frac{M_y}{M_{yn}}$$

where,
Fz = Upper Neck Axial Force (N),
My = Moment about Occipital Condyle (N-m),
Fzn = Axial Force Critical Value (N), and
Myn = Moment Critical Value (N).

Critical values are not compared with the individual neck injury measures, they are only used in calculating Nij.

V*C is the chest compression velocity times the chest compression divided by the chest depth. The V*C is calculated by taking the chest potentiometer and differentiating to get the chest velocity. The measured compression is then divided by the chest depth and multiplied by the calculated chest compression velocity. The result is multiplied by 1.3 to make the measurement relative to external chest compression.

Each injury measure was taken during interaction with the air bag deployment. Impacts after the dummy moves away from the air bag and strikes the seat back were not considered in any of the injury measures recorded.

PERFORMANCE TEST RESULTS

Platform 1 (Advanced Air Bag)

Static tests were conducted on a 5[th] female driver, and 3 year old and 6 year old Hybrid III passenger dummies. The test setups were described in the Test Methodology. The test results are summarized below.

Static OOP Test Results - HIC and chest g's were very low in the OOP tests with the 5[th] female H-III driver (Table 3). Chest compression was 34 mm in position 2 (chest on the air bag module). V*C marginally failed. Nij, the neck injury criteria were well below the threshold value of 1.0 in both positions.

Based on these results, it appeared that with a first-stage deployment of the multi-stage air bag, the 5[th] female could meet injury threshold values with only small improvements in the advanced air bag to reduce the V*C measurement.

A test series on the passenger-side was also conducted using the 3 year old H-III dummy. Table 4 shows the results of a proximity study when the 3 year old dummy was moved back along the longitudinal axis of the vehicle. Position 1 was used as the baseline test and two additional tests were performed with the dummy in the same geometric orientation, but backed off the instrument panel by 100 mm (4 inches) and 200 mm (8 inches). As expected, injury measures declined as the dummy was moved away from the air bag as it deployed.

V*C calculations were questionable because of anomalous readings in the chest pot for the first two positions. However in the 200 mm back position, V*C was still over 1 m/s. Nij was reduced from 4.38 to 1.65, to 0.23, at position 1, position 1-100 mm back, and position 1-200 mm back, respectively. Figure 5 shows the reduction in Nij as the dummy was moved back. It appears that at approximately 150 mm (6 inches), the Nij goes below 1.0. This type of information is useful for air bag system designers who may set up "risk zones" that would suppress the air bag once an occupant entered. In this case to prevent Nij from exceeding 1.0, the risk zone could not be any closer than 150 mm to the instrument panel. Therefore,

Table 3
5Th Female Static OOP Driver Tests.

Injury values	Units	Test condition			
		Pos. 2	Pos. 2	Average Pos. 2*	Pos. 1
HIC 36		13	13	13	11
Head Resultant	g	17	17	17	46
Chest resultant	g	25	24	25	15
Chest compression	mm	34	31	32	13
V*C	m/s	1.21	0.86	1.04	0.19
Neck shear	N	277	267	272	390
Neck tension	N	539	418	479	1163
Neck compression	N	32	73	53	57
Flexion Moment about Occipital Condoyle	N-m	20	23	22	2
Extension Moment about Occipital Condoyle	N-m	25	25	25	33
Max N_{ij}		0.55	0.52	0.53	0.68

* The Average column has the average of the results of the two ISO 2 tests.

Table 4
3 Year Old Proximity Tests.

Injury values	Units	Test condition		
		Pos. 1	Pos. 1 (4"back)	Pos. 1 (8"back)
HIC 36		273	91	13
Head Resultant	g	140	77	40
Chest resultant	g	103	89	43
Chest compression	mm	"questionable data"		23
V*C	m/s	"questionable data"		1.20
Neck shear	N	2432	397	336
Neck tension	N	3415	2435	586
Neck compression	N	1	1	85
Flexion Moment about Occipital Condoyle	N-m	10	6	9
Extension Moment about Occipital Condoyle	N-m	92	24	5
Max N_{ij}		4.38	1.65	0.23

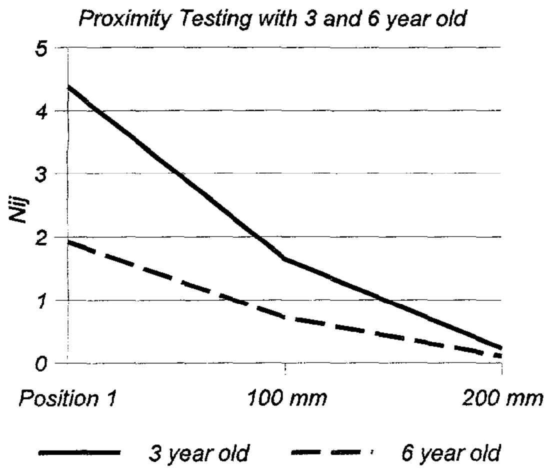

Figure 5. Proximity results for 3 and 6 year old. Six year old 100 and 200 mm results are extrapolated.

a suppression system, working in conjunction with the multi-stage inflator here, may still suppress the air bag deployment when the occupant enters within 150 mm (6 inches) of the instrument panel. These risk zones would be dependent on the aggressiveness of individual air bag systems in vehicles.

Position 2 was tested three times to examine the repeatability of the test procedures (Table 5). It appeared that HIC, chest g's and neck measurements were repeatable. Some discrepancies were found, again, in the chest potentiometer readings which affected the V*C calculation. Only one of the three test gave reliable V*C results.

When looking at the 3 year old tests as a whole, it is apparent that the first-stage deployment of the multi-stage inflator was not low enough to pass IARV's when the dummy was on the instrument panel. Clearance of at least 150 mm (6 inches) appeared to be necessary in position 1 while less clearance may be possible for position 2.

A similar test matrix was used when testing the OOP 6 year old, except no proximity study was done (Table 6). The Nij calculated for the 6 year old tests was less than half that of the 3 year old. Consequently, if the relative difference between the 6 year old and 3 year old Nij is the same at 100 mm and 200 mm, the point where Nij crosses over the 1.0 level is approximately 80 mm (Figure 5).

In the repeatability tests for position 2, Nij, HIC, and chest g's were in close agreement. However, as was seen in the 3 year old, chest V*C and compression were not very repeatable. The combination method of calculating V*C eliminates differentiation of the chest pot and makes the V*C calculation more stable.

Sled Test Results - A series of sled tests as outlined in Figure 2 was conducted with the advanced air bag system on a Platform 1 sled-test buck. Table 7 summarizes the test results for the severe impact test simulation with a 5 ms delay in firing the second squib. The sled test simulated a full frontal rigid barrier impact at 30 mph. The unbelted 5th female driver and passenger passed all the IARV's except the driver chest compression and driver and passenger Nij. The 50th male driver and passenger met all the IARV's in Table 2.

Another test series was conducted using a softer air bag (20 ms delay in firing second squib) with the belted and unbelted 5th female and 50th male (Table 8). For the 5th female driver, the belted occupant failed Nij, chest g's, chest compression, and chest V*C. The unbelted only failed chest compression by a marginal level. The 5th female, belted passenger passed all injury criteria. The 50th male unbelted driver failed chest g's. Both 50th male unbelted passengers also failed chest g's. The belted male passenger passed all the injury criteria. Consequently, it appears that along with crash severity, belt-use would also be a good discriminator on what inflator level to fire.

It can be surmised from Figure 6 that occupant size is also an important factor in discriminating the inflator level needed. Figure 6 is a bar chart comparing the injury response on unrestrained 5th and 50th male dummies with the high and mid-level inflation. The IARV's were normalized by their threshold value. For the 5th driver and 50th passenger, HIC and chest g's increased as the delay in firing the second squib increased from 5 to 20 ms. V*C for the 5th driver also increased, but the V*C on the 50th male was very low in both firing sequences. The Nij, however, decreased as the delay in the second squib firing increased. Subsequently, the unrestrained 5th female did not require the high-level needed by the 50th male in this simulated crash condition.

One final sled test series was conducted in a simulated 32 km/h (20 mph) center-pole impact. Here the time-to-fire was 57 ms into the crash. The sled series tested conditions with a 20 ms delay in firing the squib and a primary deployment only. The 5th female was tested on the driver side with the primary only and unbelted (Table 9). In this case the restraint was sufficient to pass the injury reference values. The 5th female driver was also tested with the second squib firing 20 ms after the first. In this case the air bag provided more restraint than was necessary and

Table 5
3 Year Old Repeatability Tests.

Injury values	Units	Test condition		
		ISO 2	ISO 2	ISO 2
HIC 36		555	516	468
Head Resultant	g	161	186	137
Chest resultant	g	128	125	127
Chest compression	mm	**	**	49
V*C	m/s	**	**	5.80
Neck shear	N	962	955	948
Neck tension	N	3736	4097	3838
Neck compression	N	1	1	1
Flexion Moment about Occipital Condoyle	N-m	39	39	38
Extension Moment about Occipital Condoyle	N-m	21	32	36
Max N_{ij}		1.50	2.20	2.17

Table 6
6 Year Old Tests.

Injury values	Units	Test condition			
		ISO 2	ISO 2	ISO 2	ISO 1
HIC 36		276	245	268	86
Head Resultant	g	126	119	112	91
Chest resultant	g	47	45	50	114
Chest compression	mm	32	42	46	51
V*C	m/s	2.02	3.96	6.00	5.46
Neck shear	N	1540	1505	1557	1463
Neck tension	N	3566	3479	3646	3462
Neck compression	N	186	165	194	48
Flexion Moment about Occipital Condoyle	N-m	55	58	58	3
Extension Moment about Occipital Condoyle	N-m	21	13	12	56
Max N_{ij}		1.55	1.53	1.59	1.92

Table 7
30 mph Bag fire times 12, 17.

Injury values	Units	Dummies				
		5th Female Driver Unbelted	5th Female Passenger Unbelted	50th Male Driver Unbelted**	50th Male Passenger Unbelted	50th Male Passenger Unbelted (R)
HIC 36		218	514	191	304	295
Head Resultant	g	52	77	ND	55	52
Chest resultant	g	52	53	45	48	44
Chest compression	mm	43	13	41	15	13
V*C	m/s	0.23	0.03	ND	0.03	0.04
Neck shear	N	-651	-482	383	1972	1745
Neck tension	N	1555	1977	2184	398	460
Neck compression	N	38	37	71	925	717
Flexion Moment Occipital Condoyle	N-m	7	5	23	ND	95
Extension Moment Occipital Condoyle	N-m	38	56	42	ND	20
Max Nij		1.10	1.27	ND	ND	0.43

NA - Sternal Instrumentation not available in 50th male
** - TRW Data, 0 ms delay
ND - No Data

Table 8
Full Frontal, 30 mph Bag fire times 12, 32.

Injury values	Units	Dummies						
		5th Female Driver Unbelted	5th Female Driver Belted	5th Female Passenger Belted	50th Male Driver Unbelted	50th Male Passenger Unbelted	50th Male Passenger Unbelted (R)	50th Male Passenger Belted
HIC 36		495	640	1135	524	668	654	828
Head Resultant	g	55	69	101	60	72	81	83
Chest resultant	g	57	67	55	69	63	62	51
Chest compression	mm	43	46	24	43	15	13	29
V*C	m/s	0.30	0.32	0.30	0.17	0.04	0.03	0.06
Neck shear	N	-289	-777	451	1260	2334	1910	-308
Neck tension	N	1544	1700	1597	1876	523	850	1548
Neck compression	N	71	31	34	172	571	1520	67
Flexion Moment Occipital Condoyle	N-m	4	6	8	29	121	83	8
Extension Moment Occipital Condoyle	N-m	20	36	19	6	9	45	26
Max Nij		0.75	1.08	0.78	0.58	0.30	0.45	0.61

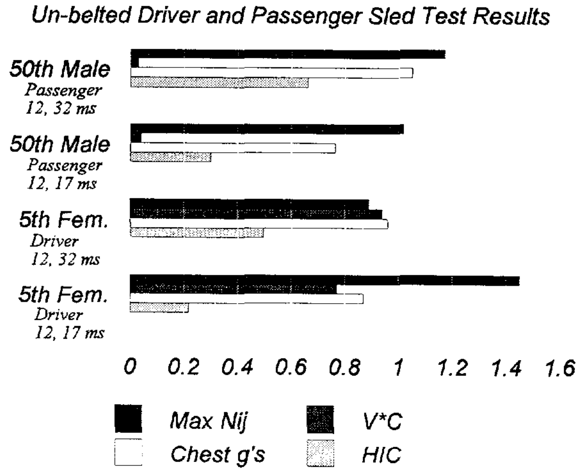

Figure 6. 48 km/h Sled Test Results.

Table 9
20 mph Delayed bag deployment, (Simulated center-pole impact).

Injury values	Dummies	5th Female Driver Unbelted	50th Male Passenger Unbelted	5th Female Driver Unbelted	50th Male Passenger Unbelted
	Bag fire times Primary, Secondary (ms)	57, none	57, none	57, 77	none, none (i.e. No Bag)
	Units				
HIC 36		189	164	288	486
Head Resultant	g	53	37	61	78
Chest resultant	g	27	39	33	37
Chest compression	mm	22	7	24	32
V*C	m/s	0.27	0.00	0.10	0.10
Neck shear	N	-303	937	-545	-776
Neck tension	N	1370	963	1788	1312
Neck compression	N	62	1226	59	1817
Flexion Moment Occipital Condoyle	N-m	1	20	0	2
Extension Moment Occipital Condoyle	N-m	30	15	40	152
Max Nij		0.74	0.29	0.93	1.21

increased HIC, chest g's, chest compression, and Nij. Nij was .93 in this case. Testing on the passenger side was conducted with the 50th male dummy. The unbelted male was first tested with the first-stage deployment only. All the injury criteria were met. The air bag was then cut-off and the test re-run. For this scenario, the 50th male passed the injury criteria again, except for Nij. Consequently, an unbelted 50th percentile male still needs an air bag to meet the IARV's at this crash condition. It is important to understand the effect of inflation levels at this speed range, since it is the range of transition from no deployment, low-level deployment and mid-level deployment.

Crash Test Results - A systems test was conducted with the multi-stage inflator and a single-point advanced sensor used to determine the time-to-fire (TTF) and the firing sequence. The test was a 40 km/h (25 mph) test into a 205 mm (12 inch) pole. The pole impact was situated such that it hit the softest part of the vehicle front-end. This was a very stringent test of the sensor's capability to fire on-time, and with the correct inflation level. The vehicle peak g's at the rear deck was 29.6 and occurred 86.80 milliseconds into the crash. The sensors fired the air bag 74 milliseconds after impact, and fired the first stage of the inflator only. The results from the dummy readings are shown in Table 10. The 5th female driver failed chest compression and V*C, but passed all the other criteria. Compression was high from the chest impact with the lower portion of the steering wheel rim before the air bag deployed.

The 6 year old failed chest g's, chest compression, and V*C. The bag trajectory carried the bag around the back of the dummy. The air bag then forced the dummy into the I/P, causing high chest loads. The load cell data from the neck shear force and neck moment went open during the test. The data collected before the channels went open indicate that the Nij would have been well over 1.0. An earlier deployment of the bag would have helped reduce these loads.

Holden Commodore (De-powered air bag)

OOP Test Results - The 5th female H-III dummy was utilized and tested in Position #1 (chin on module) and Position #2 (Chest on module). The steering column was adjusted to its lowest position and retracted fully forward towards the front of the vehicle. The steering column was replaced after each test. In position 2, the windshield prevented the head from being placed on top of the steering wheel. In that case, the dummy was placed as high as possible until there was approximately 10 mm between the top of the dummy's head and windshield.

Results are summarized in Table 11. A repeat of position one was performed due to data and film collection difficulties. The driver-side air bag was not aggressive to the OOP 5th female driver. Head and chest responses were well below the IARV's. Neck response was also well below the Nij threshold.

The results of the OOP testing of the 3 year old were very typical of U.S. air bags tested for aggressiveness (Table 12). Every critical value was exceeded in position 1. Nij was over 500 percent of the IARV. HIC was over 150 percent of its threshold value.

While most results were lower in position 2 than in position 1, the neck extension in position 2 was 113 N-m, compared to 48 N-m in position 1. Six year old test results are also summarized in Table 12. As was seen in the 3 year old responses, most the injury criteria and critical values for the head and neck were exceeded in either position 1 or position 2. Chest compression and V*C IARV's were not exceeded in either case. The combo method for calculating V*C was not available because the 6 year old dummy was not fitted with sternal accelerometers. In position 1, Nij was over 300 percent of the IARV. HIC in position 2 was exceeded due to the head impact from the air bag module cover.

Crash Test Results

Test results of the FMVSS No. 208 test are shown in Table 13. The injury criteria were met on the driver and passenger test, although there was significant submarining of the dummy on the driver-side due to lack of knee bolsters in the Commodore. The omission of knee bolsters is a result of the Commodore design optimizing restraints for belted occupants.

Driver-side HIC was well within the 80% safety margin usually used by the auto industry. Chest g's were at 54 g's which would pass FMVSS No. 208, but may not be an accepted margin of safety for some vehicle manufacturers. Chest deflection was very high at 72.5 mm, with a 76.2 mm limit in FMVSS No. 208. Femur loads were also quite high at nearly 90% of the threshold value. Although V*C was not a requirement, it was recorded and reported as 1.7 m/s. This is a V*C measure failure when compared to the 1 m/s threshold.

Passenger results were typical of FMVSS No. 208 results for US vehicles. HIC was 571, chest g's were 46.6, and chest deflection was 13.2 mm.

In conclusion, while the driver-side results for OOP testing were very benign, the FMVSS No. 208 results were marginal, although it passed the criteria. Conversely, the OOP results on the passenger-side were

Table 10
Frontal Impact 40 km/h (25 mph) into 305 mm (12 inch) Pole.

Injury values	Units	5th Female Driver	6 YO seated forward
HIC 36		35	665
Head Resultant	g	51	195
Chest resultant	g	53	105
Chest compression	mm	46	35
V*C	m/s	1.33	1.45
Neck shear	N	-611	**
Neck tension	N	315	4964
Neck compression	N	1576	4262
Flexion Moment about Occipital Condoyle	N-m	7	190**
Extension Moment about Occipital Condoyle	N-m	5	7
Max Nij		0.58	**

** - Data channel went open during test

Table 11
5th female driver OOP test results.

Dummy Position		Position 1	Position 1	Position 2
HIC (36ms)		14	20	28
Head Res.	g	51	39	19
Chest Res.	g	39	13	26
Chest (3ms)	g	20	11	20
Chest Comp.	mm	6.3	9.2	21
V*C	m/s	.02	.03	.37
Neck Shear	N	460	220	230
Neck Tension	N	**	1010	830
Neck Compression	N	**	10	10
Ext.Moment about occipital condyle	N-m	14	12	14
Flxn. Moment about occipital condyle	N-m	2	3	16
Max Nij		**	.41	.38

** - Fz channel went open during test

Table 12
H-III 3YO and 6YO passenger OOP test results.

		3 YO		6 YO	
Dummy Position	**Units**	**Position 1**	**Position 2**	**Position 1**	**Position 2**
HIC (36ms)		1464	1428	766	1444
Head Res.	g	265	188	204	195
Chest Res.	g	101	44	64	58
Chest Comp.	mm	44.0	5.9	24.7	2.8
V*C	m/s	1.43	.08	.36	.01
Shear	N	2840	990	2000	1600
Tension	N	6310	3280	7110	3270
Compression	N	0	0	0	0
Ext. Moment about occipital condyle	N-m	48	113	83	75
Flxn.. Moment about occipital condyle	N-m	8	0	19	2
Max Nij		5.55	2.53	2.91	2.66

Table 13
208 Crash Test Results with Holden Commodore.

Injury Measures	US FMVSS No 208 Injury Thresholds	Driver Results	Passenger Results
HIC	1000	609	571
Chest G's	60 g's	53.8	46.6
Chest Deflection	76.2 mm	72.5	13.2
Max. Femur Load	10 kN	8.97	7.76
V*C	no requirement	1.7	0.0

SUMMARY AND CONCLUSIONS

This paper examined an advanced air bag system with multi-stage air bags and single-point sensor. The performance was tested using child dummies in OOP conditions and sled and crash tests in high speed belted and unbelted conditions using the 5th and 50th Hybrid III Dummies. In another test series, an air bag system designed for the Australian market was tested to determine how well a de-powered air bag performed with occupants OOP and in the FMVSS No. 208 full frontal barrier crash test with unbelted 50th percentile male dummies. The following conclusions were derived from these tests.

Conclusions of Testing with Advanced Air Bag

- The lowest level inflation of the multi-stage inflator could not meet IARV's for the OOP 3 and 6 year old dummies.
- 3 year old dummy readings passed the neck Nij criteria at 150 mm from the I/P. Interpolation of the 6 year old test results suggest Nij could be passed at approximately 80 mm from the I/P
- The advanced multi-stage inflator successfully restrained 5th and 50th dummies in a 30 mph sled test using variable outputs of the inflator. Sensors to determine occupant size and belt-use would work well with a multi-stage inflator system that tailors the output for a particular situation.
- Output of both stages met all injury criteria for the 50th male in 20, and 30 mph crash simulations.
- Output of both stages met all injury criteria except chest g's and chest compression for the 5th female in 20, and 30 mph crash simulations.
- A crash sensor successfully detected a soft-pulse crash and deployed only the first stage of the air bag.
- Bag fire time was late and contributed to deploying the air bag after the 6 year old was severely OOP. Further development is necessary to improve sensor timing, although the sensor in this program was not the optimal one of choice.

Conclusions of Testing with Holden air bag

- Driver 50th percentile male dummy marginally passed 208 crash test requirements.
- Driver air bag performed well in static OOP tests. Results were similar to OOP testing with U.S. de-powered driver air bags.
- Passenger air bag performed well in the crash test and 50th percentile male dummy passed all FMVSS No. 208 requirements by a comfortable margin of safety.
- Passenger air bag did not perform well in static OOP tests. Bag performance was similar to full-powered bag in US. Consequently, it appears that the passenger air bag is similar to bags designed in US for unbelted 208 barrier crash test.

REFERENCES

1. Federal Register, 49 CFR parts 571 and 572 Federal Motor Vehicle Safety Standards: Frontal Crash Protection Rules: Vol. 62, No 208, October 1997.

2. Phen, R.L., et. al., "Advanced Air Bag Technology Assessment Final Report", prepared for the National Highway Traffic Safety Administration and National Aeronautics and Space Administration, May 1998.

3. Fildes, Brian, et al., "Effectiveness of Air Bags in Australia," 1996 15th ESV Conference, Melbourne Australia.

4. ISO Draft Technical Report 10982, "Road Vehicles - Test Procedures for Evaluating Out-of-Position Vehicle Occupant Interactions with Deploying Air Bags, November 21, 1995.