PERFORMANCE EVALUATION OF DUAL STAGE PASSENGER AIR BAG SYSTEMS

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ABSTRACT

A research program was initiated to evaluate the performance of prototype dual stage passenger air bags in terms of both restraint system performance and deployment aggressivity for different size occupants. Variations in inflator partitions, vent hole diameter sizes, and deployment timing were examined. High speed unbelted sled tests were conducted with both 50^{th} percentile male and 5^{th} percentile female Hybrid III adult dummies at 48 kmph; and belted sled tests were conducted at 56 kmph. Low risk deployment tests with child dummies were conducted to evaluate air bag aggressivity. Overall, it was concluded that the dual stage air bag systems under evaluation had improved performance over the baseline single stage systems in terms of providing high speed protection while reducing aggressivity to out-of-position occupants; however, some dual stage systems may require additional occupant detection methodologies to suppress or control inflation.

INTRODUCTION

Since the early 1990s, the National Highway Traffic Safety Administration (agency) has undertaken many efforts to bring about changes in human behavior and restraint system technology in order to reduce the risk of death and serious injuries to out-of-position children and small adult drivers. The agency's initial actions were focused on a public education campaign to alert the public about the dangers of air bags to children in general and to infants in particular. Parents were urged to place their children in the back seat and to ensure that their children were properly restrained. In addition, the agency required that informative warning labels be placed in new passenger vehicles and on child restraints.

In November 1996, the agency announced a comprehensive plan intended to provide for the continued reduction of risks to out-of-position children and small adult drivers while also improving the overall performance of air bags installed in passenger vehicles. The plan provided for immediate, interim, and long term measures. The immediate and interim measures were focused on behavioral changes and on relatively modest technological changes. The long term measures focused on utilizing advanced air bag technologies that reduced the risk of death and serious injuries to out-of-position child and adult occupants while providing protection in high severity crashes.

One of the promising technologies identified for addressing the risk of death and injury to out-of-position children and small adult drivers while providing protection in high severity crashes was the multistage inflator-based air bag system. The agency entered into a cooperative research agreement with Takata Corporation, a major supplier of automotive restraint systems to develop and evaluate the potential of a prototype dual stage inflator passenger air bag system with respect to both in-position and out-of-position performance. This paper is written to highlight this activity.

PROJECT OVERVIEW

Prototype dual stage air bag systems were developed and evaluated in terms of restraint system performance and air bag deployment aggressivity for different size occupants. The evaluation of the restraint system performance was based on the protection afforded to both 5^{th} percentile female and 50^{th} percentile male Hybrid III adult dummies subjected to an unbelted 48 kmph (30 mph) rigid barrier crash environment (as simulated by a sled test). Additionally, the system was evaluated on the protection afforded to the 50^{th} percentile male adult dummy subjected to a belted 56 kmph (35 mph) rigid barrier crash environment (as simulated by a sled test). The evaluation of the deployment aggressivity was based on the results from conducting out-of-position static deployment tests using the 12-month-old CRABI infant dummy, the 3-year-old and 6-year-old child dummies, and the 5th percentile female adult dummy. In evaluating the systems, a number of parameters were investigated. These included the relative output partition of a two stage inflator, the ignition time delay between the two stages, and the vent hole diameter of the air bag cushion.

PROTOTYPE HARDWARE FOR DUAL STAGE PASSENGER AIR BAG MODULE

The hardware for the prototype dual stage passenger air bag module consisted of the cushion, inflator, and the molded plastic cover. See Figure 1. The following describes these components.

Figure 1. Dual Stage Module Hardware.

The selected air bag cushion had an L-shaped configuration with a volume of 106 liters. Figure 2 depicts the shape of the cushion in the fully deployed state. The folding pattern utilized a state of the art technique designed to provide a benign deployment. The cushion had two symmetrical vent holes, each with an identical diameter. The vent hole diameter was one of the parameters investigated in this study. Three vent hole diameters were investigated--55, 65, and 75 millimeters. The module cover was modified from a production system in order to work with this air bag. While tailored to this air bag, neither the module cover nor the tear seam represented particularly unique designs.

The prototype dual stage inflator utilized in this program was comprised of a pair of non-azide, pyrotechnic, single stage inflators. (It should be noted that the dual stage inflator was custom fabricated and was neither planned nor considered suitable for production.) Each of the dual stage inflators used in the program was designed to have an equivalent propellant mass and tank pressure curves if both stages are ignited simultaneously. The nominal output for the combined inflators was 525

Figure 2. Air Bag Cushion Configuration (Deployed) for Dual Stage Module.

kiloPascals in a 60 liter tank. The inflator output was another of the parameters investigated in this study. The inflator output was varied in two ways. The first technique for the variation in output of the inflator was accomplished by varying the ratio of the nominal propellant between the two single stage inflators that were combined to make the dual stage inflator. The ratios of propellant used in this study included 70/30, 60/40, and 50/50 combinations. The second technique for the variation in inflator output was accomplished by delaying the time between igniting the first and second inflators In each case, the inflator with the greater propellant allotment was ignited first, followed by the delayed ignition of the inflator with the lesser amount of propellant. Ignition delays of 10 and 20 milliseconds were investigated. Figure 3 shows the tank pressure curves for the inflators. Note that the pressure curves shown on the right side of Figure 3 represent the resultant of adding the pressure curves of the individual stages with the appropriate time delay (as shown on the left side of the Figure 3).

In December 1997, NHTSA sent an information request to nine automobile manufacturers requesting detailed technical information on the current industry practice on air bag technologies, and how air bag design and performance characteristics had evolved through the 1990s. The manufacturers provided the agency with the requested data, much of which was proprietary and confidential. The data included information on MY 1990 through MY 1998 vehicles. The agency published a report that uses those data, as well as other available information, to illustrate the general trends in air bag design and performance characteristics. Part of the information presented in

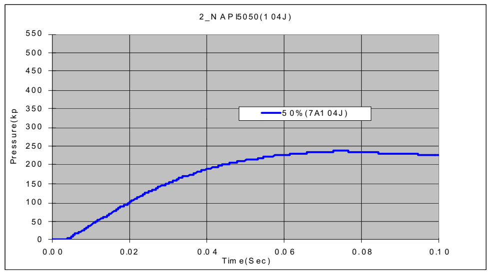
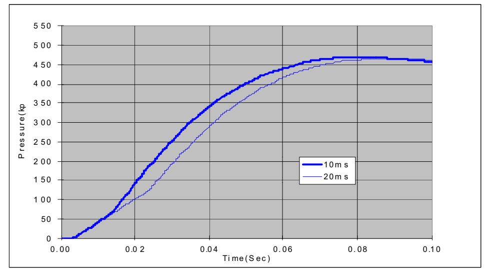
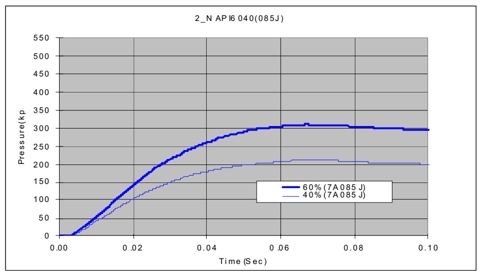
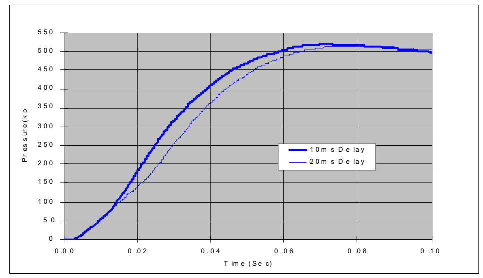
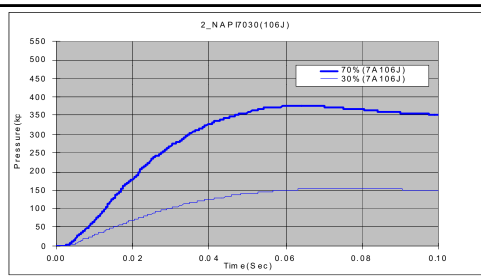
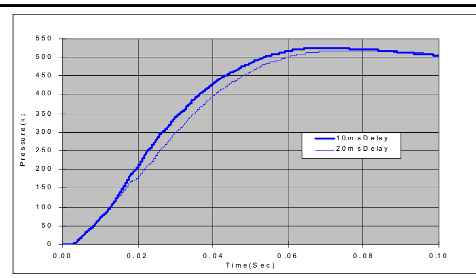
Propellant Allotment	Single Stage	Dual Stage
50 / 50		
60 / 40		
70 / 30		

Figure 3. Dual Stage Inflator Characteristics.

the report included characteristics of the inflator. The manufacturers provided in graphical form the inflator characteristics as determined using a "tank test." Using these graphs, the agency determined the average peak pressure and rise rate for each inflator. (The average rise rate was determined by fitting a best-fit line to the data in the area where the pressure was changing the fastest, and then determining the slope of the line.) Finally, in order to make comparisons of the inflators across the manufacturers, the data then were scaled to adjust for tank volume. All data were normalized to 100 liters using the PV product method [1]. Shown in Figures 4 and 5 are the scaled peak pressures and scaled rise rates for model years 1993-98 for the passenger air bag inflators. Also shown are the corresponding data for the prototype dual stage inflators used in this program. As can be seen, the characteristics of the 50/50 prototype inflators are slightly below the average characteristics of the model year 1998 inflators, and the characteristics of the 60/40 and 70/30 prototype inflators are approximately in the 50 to 60th percentile range. It is interesting to note that while the time delay had little effect on the peak pressure of the prototype inflators, the longer time delay (i.e., the 20 millisecond delay) demonstrated an observable reduction in the rise rate for the 60/40 and 70/30 prototype inflators.

PROTOTYPE HARDWARE FOR SINGLE STAGE PASSENGER AIR BAG MODULE

While the focus of this cooperative research program was to develop and evaluate prototype dual stage air bag systems, a single stage passenger air bag module was needed for the purpose of comparison. Hence, a single stage air bag module was fabricated. The design selected for the single stage air bag module was selected to produce acceptable restraint performance for an unbelted 50th percentile Hybrid III male dummy in a 48 kmph barrier crash environment (as simulated by a sled test). Like the prototype dual

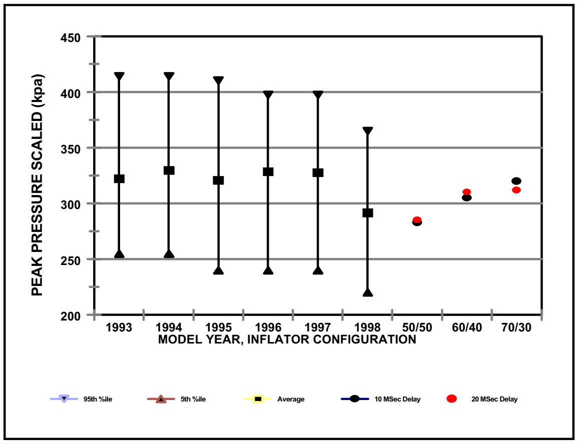


Figure 4. Scaled Inflator Peak Pressure for MY 1993-98 and for Prototype Inflators.

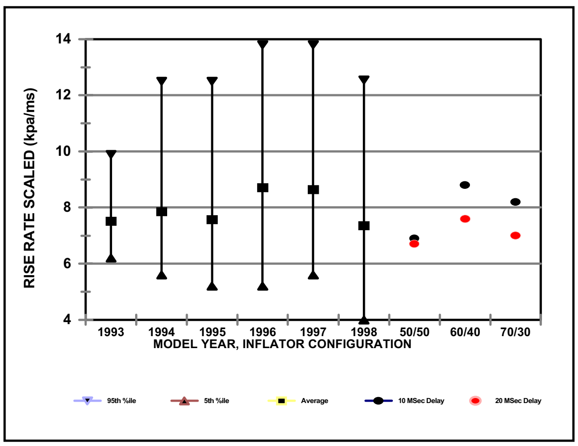


Figure 5. Scaled Inflator Rise Rate for MY 1993-98 and for Prototype Inflators.

stage passenger air bag module, the hardware for the single stage air bag module consisted of the cushion, inflator, and the molded plastic cover. See Figure 6.

The selected air bag cushion had an L-shaped configuration with a volume of 130 Liters. Figure 7 depicts the shape of the cushion in the fully deployed state. The folding pattern utilized a production-like accordion folding. The cushion had two symmetrical vent holes, each with an identical diameter. The vent hole diameter was 70 millimeters.

The single stage inflator used in this program was a solid pyrotechnic inflator. The nominal output for the inflator was 500 kiloPascals in a 60 liter tank. Figure 8 shows the pressure curve for the inflator.

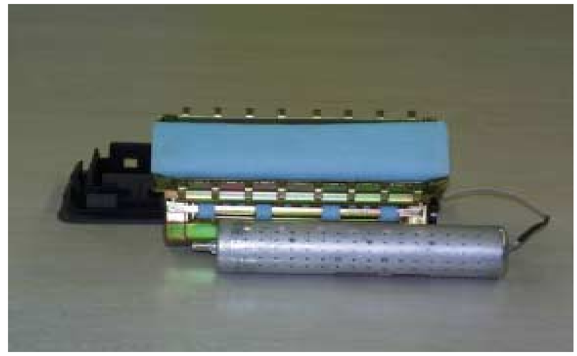


Figure 6. Single Stage Module Hardware.

Figure 7. Air Bag Cushion Configuration for Single Stage Module.

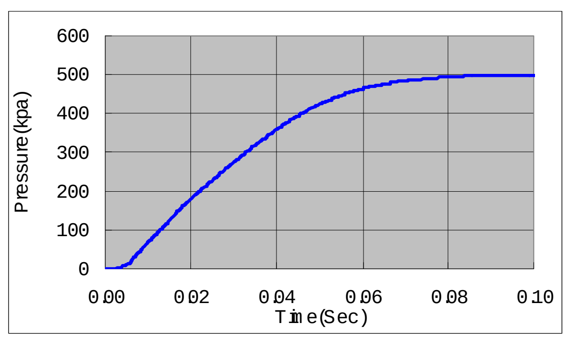


Figure 8. Single Stage Inflator Characteristics.

SIMULATED CRASH ENVIRONMENT

As mentioned, the evaluation of the restraint system performance was based on the protection afforded to the 5th percentile female and 50th percentile male adult dummies subjected to an unbelted 48 kmph rigid barrier crash environment (as simulated by a sled test) and the 50th percentile male adult dummy subjected to a belted 56 kmph rigid barrier crash environment (also as simulated by a sled test). The sled tests were conducted using a Hyge sled.

The sled tests utilized a developmental test buck representing a compact passenger vehicle. The knee bolster and seat properties were similar to those in the original vehicle. The prototype air bag modules were top mounted in a rigid instrumentation panel.

For the testing, the 50th percentile male adult dummy was the Hybrid III 50th percentile anthropomorphic test device as specified in the CFR 49 Part 572 Subpart E. The 5th percentile female dummy was the Hybrid III 5th percentile anthropomorphic test device that conformed to the specifications of the Notice of Proposed Rulemaking for Part 572 [2].

The 48 kmph sled test was conducted using a crash pulse representative of the aforementioned compact car subjected to a 48 kmph full frontal barrier crash test. As shown in Figure 9, the duration of the pulse was approximately 100 milliseconds, typical of a car in this vehicle category. The change in velocity was approximately 55 kmph (48 kmph initial velocity and 7 kmph rebound velocity).

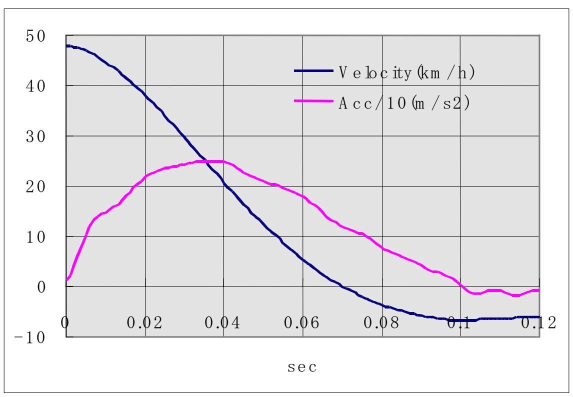


Figure 9. 48 kmph Crash Pulse Characteristics.

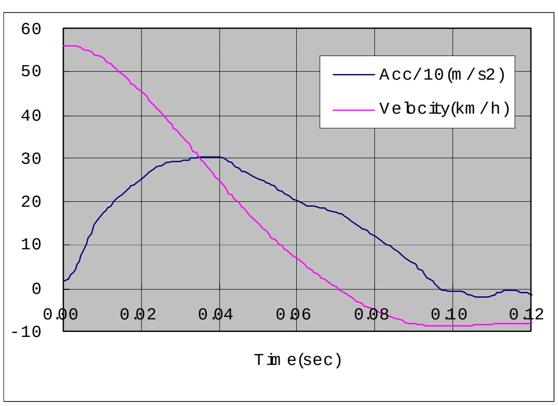


Figure 10. 56 kmph Crash Pulse Characteristics.

Likewise, the 56 kmph sled test was conducted using a crash pulse representative of the aforementioned compact car subjected to a 56 kmph full frontal barrier crash test. As shown in Figure 10, the duration of the pulse was approximately 95 milliseconds. As shown in Figure 10, the change in velocity was approximately 65 kmph (56 kmph initial velocity and 9 kmph rebound velocity).

STATIC DEPLOYMENT TESTING

In addition to conducting tests for evaluating the performance of the prototype air bag systems in protecting 5th and 50th percentile adult dummies in a simulated crash environment, static deployment tests were conducted with selected prototype systems to evaluate the deployment aggressivity toward the Hybrid III 3-year-old and 6-year-old child dummies. Also, static deployment tests were conducted to evaluate the aggressivity toward the CRABI 12-month-old infant dummy in a rear facing child safety seat.

The dummy and child seat positioning were done using the low risk deployment procedures specified in the advanced air bag NPRM [3]. These procedures specified two positions for the 3- and 6-year-old dummies and one position for the 12-month-old infant dummy. See Figures 11 through 15. Note, however, that the setup for the 6-year-old dummy maintained the legs (as shown in Figure 13) because the proposed positioning of the dummy upper torso to the air bag module could be achieved without removing the legs.

The rear facing child safety seat used with the 12-month-old infant dummy was a convertible child safety seat manufactured by Takata. The seat was installed using the instructions specified in the owner's manual for the compact car. After

Figure 11. Three-Year-Old Child Dummy in Position 1.

Figure 12. Three-Year-Old Child Dummy in Position 2.

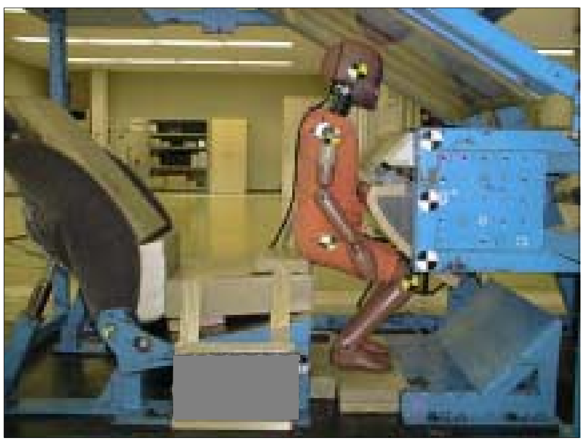


Figure 13. Six-Year-Old Child Dummy in Position 1.

installation, the infant dummy then was placed and belted in the seat.

INSTRUMENTATION

The dummies were instrumented so as to allow the computation of the injury measures proposed in the advanced air bag NPRM [3]. For the 5th percentile female and 50th percentile male adult dummies, the instrumentation provided for the measurement of head and chest acceleration, chest deflection, neck forces and moments, and femur forces. For the 3- and 6-year-old child dummies, the instrumentation provided for the same measurements as collected on the adult dummies with the exception that the femur forces were not measured. For the 12-month-old infant dummy, the instrumentation provided for the same measurements as collected on the adult dummies with the exception that the chest deflection and the femur forces were not measured.

Figure 14. Six-Year-Old Dummy in Position 2.

Figure 15. Test Position for CRABI Infant Dummy In Rear Facing Child Safety Seat.

Table 1 summarizes the dummy instrumentation. The kinematics of the dummies were documented with high speed film (1,000 frames per second) and video (500 frames per second).

INJURY ASSESSMENT CRITERIA

In assessing the performance of the prototype air bag modules, the injury criteria proposed in the advanced air bag NPRM were used [3]. An additional criterion was applied for the chest acceleration of the 50th percentile male dummy in the 48 kmph testing. For this, the chest acceleration was not to exceed 80 percent of the 60 G limit (i.e., not to exceed 48 G). This is referred as the “Target Chest G.” Table 2 summarizes the assessment criteria.

Table 1.
Dummy Instrumentation

	HIII 50% Male	HIII 5% Female	3-Year-Old Child	6-Year-Old Child	12-Month-Old Infant
Head Acceleration	3-axis	3-axis	3-axis	3-axis	3-axis
Chest Acceleration	3-axis	3-axis	3-axis	3-axis	3-axis
Chest Deflection	1-axis	1-axis	1-axis	1-axis	N/A
Neck Force	6-axis	3-axis	6-axis	6-axis	6-axis
Femur Force	2-axis	2-axis	N/A	N/A	N/A

Table 2.
NPRM Assessment Criteria

	Head	Chest			Femur	Neck						Nij Critical Values			
ATD	HIC36	Accel (G)	Comp (mm)	CTI	Load (N)	Tens (N)	Comp (N)	Shear (N)	Flex (Nm)	Ext (Nm)	Nij	Tens (N)	Comp (N)	Flex (Nm)	Ext (Nm)
50th	1,000	60	76	1	10,008	3,300	4,000	3,100	190	57	1	3,600	3,600	410	125
5th	1,000	60	62	1	6,805	2,080	2,520	1,950	95	28	1	3,200	3,200	210	60
3YO	1,000	60	47	1	-	1,490	1,800	1,400	57	17	1	2,900	2,900	125	40
6YO	900	50	42	1	-	1,270	1,540	1,200	46	14	1	2,500	2,500	100	30
12Mo	660	40	-	-	-	1,150	1,390	1,080	39	12	1	2,200	2,200	85	25

TEST RESULTS

The test program was conducted in two phases. The first phase involved the conducting tests for the evaluation of the prototype dual stage air bag systems. The second stage involved the evaluation of the prototype single stage air bag systems in order to provide comparative data for evaluation of the dual stage inflators.

Evaluation of Dual Stage Air Bag Systems: 50th Percentile Male

The most extensive testing was conducted with the 50th percentile male dummy for evaluating the influence of the different dual-stage inflators in a 48 kmph (30 mph) simulated crash environment. These tests were used to select the better performing systems for use in further evaluation with the 5th percentile female dummy, the 3- and 6-year-old child dummies, and the 12-month-old infant dummy. This testing involved the evaluation of each of the air bag system parameters being investigated. These included the relative output partition of a two stage inflator, the ignition time delay between the two stages, and the vent hole diameter of the air bag cushion. Table 3 provides a summary of this test matrix. Note that for each of the test conditions, three tests were conducted in order to provide a qualitative look at the level of repeatability. The results are presented in two parts. The first is a presentation of the data for a given inflator and a given time delay between igniting the first stage and second stage of the module. The data of the 3 tests for each configuration are provided. The second is a presentation that summarizes the results of all of the inflators on HIC, chest acceleration, and the neck extension moment.

Individual Inflator Results The results for the modules with the 50/50 inflator and a 10 millisecond ignition time delay between the two stages are shown in Figure 16 for each of the three vent hole diameters investigated. The chest acceleration criterion (60 Gs) was exceeded by the modules with the 55 millimeter diameter vent holes. Also, for this criterion, the modules with the 65 millimeter diameter vent holes

Table 3
Test Configuration for 50th Percentile Male Dummy Subject to 48 kmph Crash Environment (n=3)

Inflator Combination		**50/50**		**60/40**		**70/30**	
Delay time (msec)		**10**	**20**	**10**	**20**	**10**	**20**
Air Bag Vent Hole Diameter	**55 mm**	✔	✔	✔	✔	✔	✔
	65 mm	✔	✔	✔	✔	✔	✔
	75 mm	✔	✔	✔	✔	✔	✔

produced marginal results, i.e., each of the test results were above 90 percent of the criterion. It should be noted that none of the modules satisfied the additional more restrictive target chest acceleration requirement of 48 Gs. Based on the chest acceleration results, it has been determined that the 50/50 inflator does not provide adequate restraint. One final observation is that the modules with the 75 millimeter diameter vent holes (when compared to the other vent hole sizes) reduced both HIC and chest acceleration, but increased the neck extension moment.

The results for the modules with the 50/50 inflator and a 20 millisecond time delay are shown in Figure 17 for each of the three vent hole diameters investigated. The modules with this inflator were found to provide unsatisfactory performance as each of the modules produced chest acceleration levels above 60 Gs. Also, each of the modules provided increased dummy responses overall when compared to the corresponding 50/50 inflator modules with the 10 millisecond delay.

The results for the modules with the 60/40 inflator and a 10 millisecond time delay are shown in Figure 18 for each of the three vent hole diameters investigated. All of the modules satisfied the chest acceleration criterion of 60 Gs. Furthermore, the modules with the 65 millimeter diameter vent holes not only satisfied the 60 G chest acceleration requirement, but also 2 out of 3 modules satisfied the additional more restrictive target requirement that the acceleration level be limited to below 48 Gs. The modules with the 75 millimeter diameter vent holes exceeded the assessment criteria for CTI, Nij, and neck extension moment.

The results for the modules with the 60/40 inflator and a 20 millisecond time delay are shown in Figure 19 for each of the three vent hole diameters investigated. In general, the results for this inflator configuration are similar to those of the 60/40 inflator with a 10 millisecond delay. The modules with the 55 millimeter diameter vent holes produced slightly higher HIC, chest accelerations, and CTI values. Also, all of the modules exceeded the more restrictive target 48 G chest acceleration and the modules with the 55 and 75 millimeter diameter vent holes exceeded the 60 G chest acceleration criterion in one of the three tests run for each.

The results for the modules with the 70/30 inflator and a 10 millisecond time delay are shown in

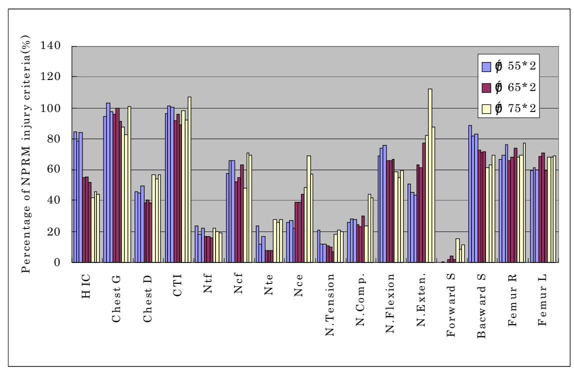


Figure 16. Test Results for Dual Stage Module with 50/50 Inflator and 10 Millisecond Time Delay between Stages (50th Percentile Male).

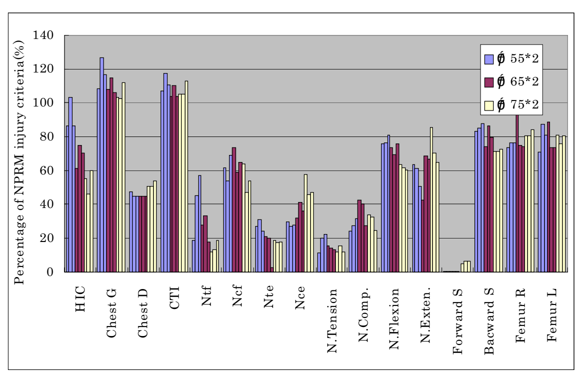


Figure 17. Test Results for Dual Stage Module with 50/50 Inflator and 20 Millisecond Time Delay between Stages (50th Percentile Male).

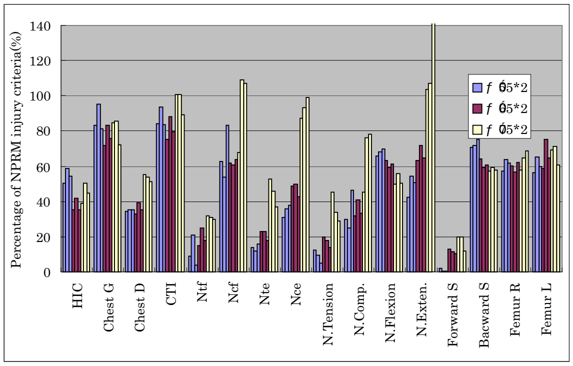


Figure 18. Test Results for Dual Stage Module with 60/40 Inflator and 10 Millisecond Time Delay between Stages (50th Percentile Male).

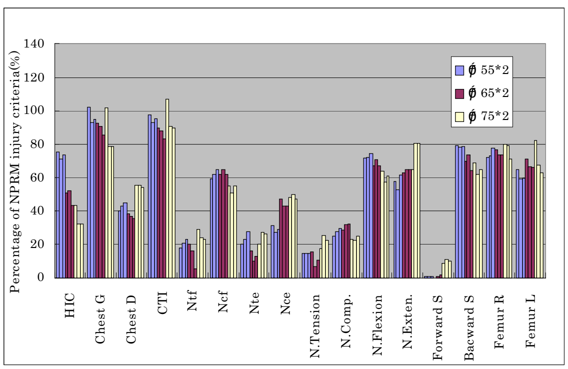


Figure 19. Test Results for Dual Stage Module with 60/40 Inflator and 20 Millisecond Time Delay between Stages (50th Percentile Male).

Figure 20 for each of the three vent hole diameters investigated. In these tests, the dummy kinematics were very similar to those observed in the test series with the 60/40 inflators. The modules with the 65 millimeter diameter vent holes satisfied all criteria and the more restrictive target 48 G chest acceleration. The modules with the 75 millimeter diameter vent holes exceeded the assessment criteria for the neck extension moment and produced marginal CTI results. The modules with the 55 millimeter diameter vent holes produced higher HIC and chest acceleration values than the modules with 65 and 55 millimeter diameter vent holes.

The results for the modules with the 70/30 inflator and a 20 millisecond time delay are shown in Figure 21 for each of the three vent hole diameters investigated. In general, the test results are similar to the 70/30 inflator modules with the 10 millisecond delay. All of the results met the assessment criteria with the exception of the modules with the 75 millimeter diameter vent holes. For these, the neck extension moment criterion was exceeded in one of the three tests. However, the modules with

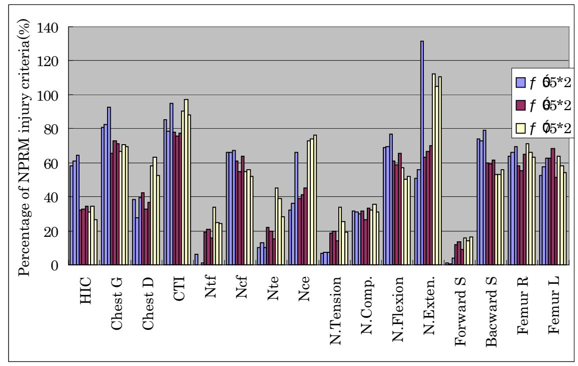


Figure 20. Test Results for Dual Stage Module with 70/30 Inflator and 10 Millisecond Time Delay between Stages (50th Percentile Male).

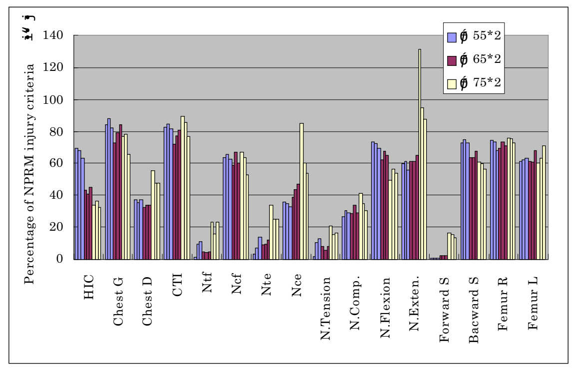


Figure 21. Test Results for Dual Stage Module with 70/30 Inflator and 20 Millisecond Time Delay between Stages (50th Percentile Male).

the 75 millimeter diameter vent holes met the more restrictive target 48 G chest acceleration requirement. Overall, the chest accelerations were higher than those measured with the 10 millisecond delay.

__Parameter Studies__ This section examines the effects of the various modules on HIC, chest acceleration, and neck extension moment. For these comparisons, the median values of the three test results for each test configuration are used.

The first comparison examines the effects of the various modules on the HIC and chest acceleration values. In these tests, it was observed that the shorter time delay between stages produced lower results regardless of the inflator combination or the vent hole diameter. Figure 22 provides the results of the median HICs for the 50/50, 60/40, and 70/30 inflators and the 55, 65, and 75 millimeter vent hole diameters for the modules utilizing the 10 millisecond time delay between the two stages. Likewise, Figure 23 provides the results of the median chest accelerations for the corresponding modules. In reviewing the data presented in these figures, a number of observations can be made.

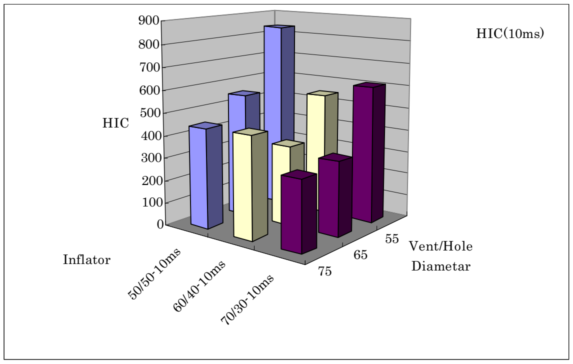


Figure 22. Comparison of Median HIC Values for Dual Stage Inflators with 10 Millisecond Delay (50th Percentile Male).

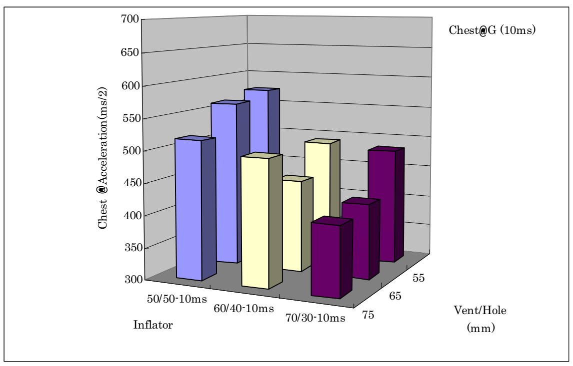


Figure 23. Comparison of Median Chest Acceleration Values for Dual Stage Inflators with 10 Millisecond Delay (50th Percentile Male).

The first is that the larger primary inflator output generally produced lower HICs and chest accelerations for a given vent hole diameter and stage delay time. Secondly, with the exception of the 60/40 inflator combination, the larger vent hole diameters produced lower HICs and chest accelerations regardless of inflator output.

The second comparison examines the effects of the various modules on the neck extension moments. Figure 24 provides the results of the median values for the 50/50, 60/40, and 70/30 inflators and the 55, 65, and 75 millimeter vent hole diameters for the modules utilizing the 10 millisecond time delay between ignition of the two stages. In contrast to the findings for the HIC and chest accelerations, the larger vent hole diameters produced higher neck extension moments. Also, the modules with the 75 millimeter vent hole diameter produced higher neck moments than any other combination of inflator and vent hole diameter.

NCAP Evaluation In addition to conducting the unbelted tests of the 50th percentile male dummy in the 48 kmph (30 mph) simulated crash environment,

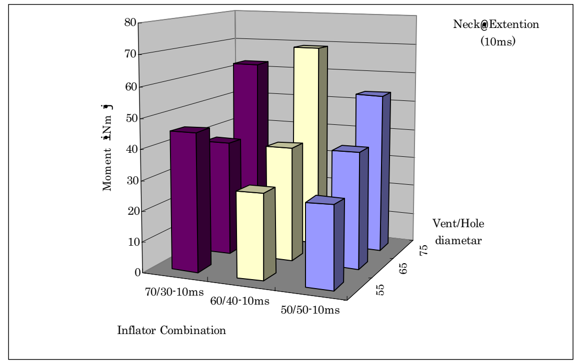


Figure 24. Comparison of Median Neck Extension Moments for Dual Stage Inflators with 10 Millisecond Delay (50th Percentile Male).

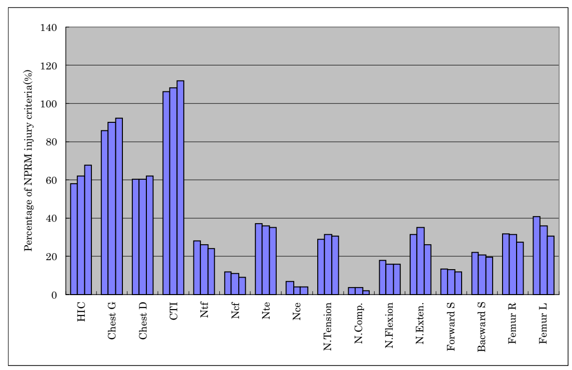


Figure 25. Test Results for 56 kmph Restraint Performance (NCAP, 50th Percentile Male).

tests were conducted to evaluate the performance that would be achieved in the U.S. New Car Assessment Program test, i.e., belted front seat occupant in a 56 kmph (35 mph) simulated crash environment. For these tests, the modules with the 60/40 inflator, 10 millisecond time delay between stages, and the 65 millimeter vent hole diameter were used. The results are shown in Figure 25. As seen here, all the measured injury criteria satisfied the injury reference levels except CTI. With respect to the NCAP evaluation, 2 of the 3 tests were rated as 4 star and the third was rated as 3 star.

Summary In this section, the results were presented for the extensive testing conducted with the 50th percentile male dummy for evaluating the influence of the different dual-stage inflators in a 48 kmph crash environment. This testing involved the evaluation of each of the air bag system parameters being investigated–the relative output partition of a two stage inflator, the ignition time delay between the two stages, and the vent hole diameter of the air bag cushion. For each of the test conditions, three tests were conducted in order to provide a qualitative look at the level of repeatability. The median values of the three tests were used to make further comparisons of the measured HICs, chest accelerations, and neck extension moments. The chest acceleration requirement was not exceeded in the test series using the 60/40 inflator with a 10 millisecond time delay, the 70/30 inflator with a 10 millisecond delay, and the 70/30 inflator with a 20 millisecond delay. Of these, five specific module configurations satisfied the more restrictive target 48 G chest acceleration requirement. These included the 60/40 inflator with a 10 millisecond time delay and 65 millimeter vent hole diameter; the 70/30 inflator with a 10 millisecond time delay and 55 millimeter vent hole diameter; the 70/30 inflator with a 10 millisecond time delay and 65 millimeter vent hole diameter; the 70/30 inflator with a 20 millisecond time delay and 55 millimeter vent hole diameter; and the 70/30 inflator with a 20 millisecond time delay and 65 millimeter vent hole diameter. Note that the modules with the 50/50 inflators exceeded the 60 G chest acceleration criterion in at least one of the three tests conducted for each configuration. Finally, while increasing the vent hole diameters generally resulted in decreasing HIC and chest acceleration values, it also resulted in increasing neck extension moments.

Evaluation of Dual Stage Air Bag Systems: 5th Percentile Female

After conducting the extensive testing with the 50th percentile male dummy, tests were then run for evaluating the influence of the dual-stage inflator on the 5th percentile female dummy in a 48 kmph (30 mph) simulated crash environment. For this evaluation, the module with the 60/40 inflator, 10 millisecond ignition time delay between stages, and 65 millimeter vent hole diameter was utilized. This module was selected since it was the lowest first stage inflator level of those modules that satisfied all injury criteria requirements for the 50th percentile male in the same crash environment. These tests were run using the seating position specified in the agency's NPRM, i.e., the full forward position. As in the testing with the 50th percentile male dummy, three tests were conducted in order to provide a qualitative look at the level of repeatability. In addition to this testing, other tests were conducted with the seat located in the mid-travel position in order to examine the effects of seat location. For these tests, the 50/50, 60/40, and 70/30 inflators were used. However, the ignition delay time and the vent hole diameter were identical (i.e., 10 milliseconds and 65 millimeters) to those used for testing in the full forward seating position. The matrix for these tests is shown in Table 4.

48 KMPH Performance in Full Forward Seating Position: This section provides the results for the dual-stage inflator with the 5th percentile female dummy in a 48 kmph (30 mph) simulated crash environment while seated in the full forward seating position. As stated above, the module with the 60/40 inflator, 10 millisecond ignition time delay between stages, and 65 millimeter vent hole diameter was utilized. The results are provided in Figure 26. As can be seen in Figure 26, the injury measures met the reference criteria with the exception of those for the neck. That is, the neck compression, flexion moment, extension moment, aft shear, and Nij exceeded the reference values tabulated in Table 2. In viewing the test films, it appeared that the high neck loads resulted from the air bag being deployed over the dummy's head.

48 KMPH Performance in the Mid-Travel Seating Position: This section provides the results for the dual-stage inflator with the 5th percentile female dummy in a 48 kmph (30 mph) simulated crash environment while seated in the mid-travel seating position. As stated above, the modules with the 50/50, 60/40, and 70/30 inflators with the 10 millisecond ignition time delay between stages and 65 millimeter vent hole diameter were utilized.

Figure 27 provides the results for tests of the module with the 60/40 inflator, 10 millisecond ignition time delay between stages, and 65 millimeter vent hole diameter in which the 5th percentile dummy is seated in the mid-travel seating location among those presented above for the full forward seating position. As reported in the previous section, high neck loads were produced when the dummy is seated in the full forward position. When the dummy is seated in the mid-travel position, the results of the neck loads were reduced such that only the neck flexion moment exceeded the reference injury criteria.

Figure 28 provides the results for tests of the modules with the 50/50, 60/40, and 70/30 inflators with a 10 millisecond ignition time delay between stages and 65 millimeter vent hole diameter in which the 5th percentile dummies are seated in the mid-travel seating position. Here it is seen that the neck flexion moments exceeded the reference injury levels for each of the inflators. The 70/30 inflator produced the lower HIC and neck load values. Each of the inflators produced marginal results or slightly exceeded the limits for the chest acceleration, neck extension moment, neck shear load (aft), and Nij (particularly, $N_{Compression\text{-}Flexion}$).

Table 4
Test Configuration for 5th Percentile Female Dummy Subject to 48 kmph Crash Environment (n=3)
65 Millimeter Vent Hole Diameter

Inflator Combination		50/50		60/40		70/30	
Delay time (msec)		10	20	10	20	10	20
Seat Position	Full Forward			✔			
	Mid-Travel	✔		✔		✔	

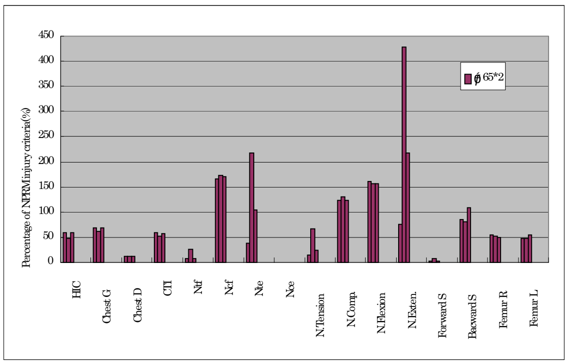


Figure 26. Test Results for Dual Stage Module with 60/40 Inflator and 10 Millisecond Time Delay between Stages (5th Percentile Female).

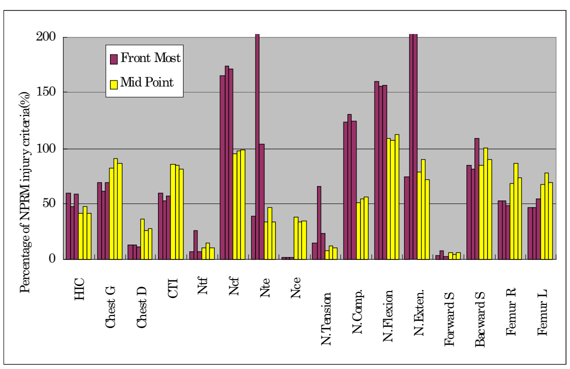


Figure 27. Front vs Mid-Travel Seat Position Test Results for Dual Stage Module with 60/40 Inflator and 10 Millisecond Time Delay between Stages (5th Percentile Female).

In addition to conducting tests for evaluating the performance of the prototype air bags systems in protecting 5th and 50th percentile adult dummies in a simulated crash environment, static deployment tests were conducted with selected prototype systems to evaluate the deployment aggressivity toward the Hybrid III 6-year-old and 3-year-old child dummies. Also, static deployment tests were conducted to evaluate the aggressivity toward the CRABI 12-

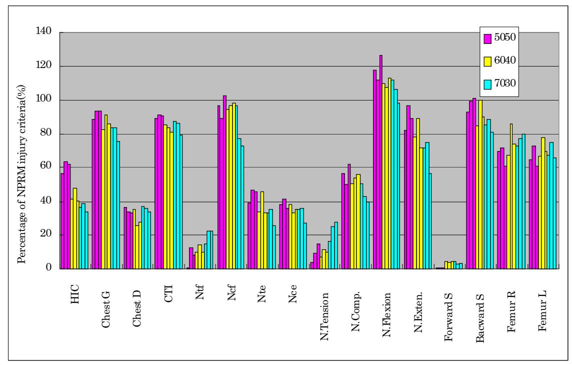


Figure 28. Mid-Travel Seat Position Test Results for Dual Stage Modules with 10 Millisecond Time Delay between Stages (5th Percentile Female).

Evaluation of Dual Stage Air Bag Systems: Aggressivity to Out-of-Position Children

month-old infant dummy in a rear facing child safety seat. This section presents the results of these tests.

__Static Deployment Tests: 6-Year-Old and 3-Year-Old Child Dummies__ The dummy positioning was done using the low risk deployment procedures specified in the advanced air bag NPRM [3]. These procedures specified two positions for the 3-year-old and 6-year-old dummies. As previously noted, however, the setup for the 6-year-old dummy maintained the legs because the proposed positioning of the dummy upper torso to the air bag module could be achieved without removing the legs. The tests for both dummies were conducted using the modules with the 60/40 inflator and 65 millimeter vent hole diameter. For the first set of tests, the second stage was ignited 100 milliseconds after the first stage. Figures 29 and 30 provide the results of the testing with the 6-year-old dummy. Figures 31 and 32 provide the results of the testing with the 3-year-old dummy. As seen in Figures 29 and 31, the test results for the 6-year-old and 3-year-old dummies in Position 1 configuration are well below the injury reference values. For the tests using the Position 2

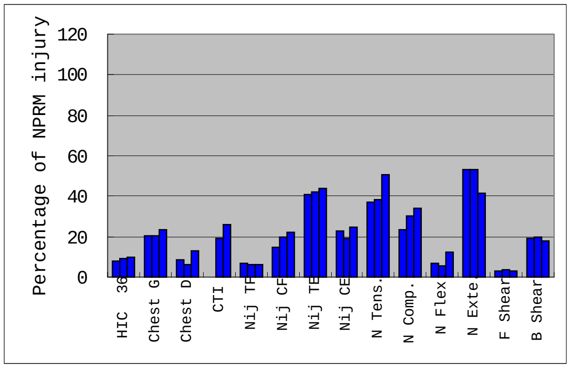


Figure 29. Results for 6-Year-Old Static Out-of-Position Tests (Position 1) using Module with 60/40 Inflator, 100 Millisecond Time Delay, and 65 Millimeter Diameter Vent Holes.

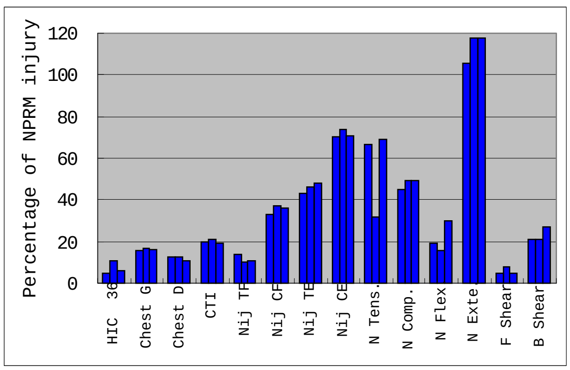


Figure 30. Results for 6-Year-Old Static Out-of-Position Tests (Position 2) using Module with 60/40 Inflator, 100 Millisecond Time Delay, and 65 Millimeter Diameter Vent Holes.

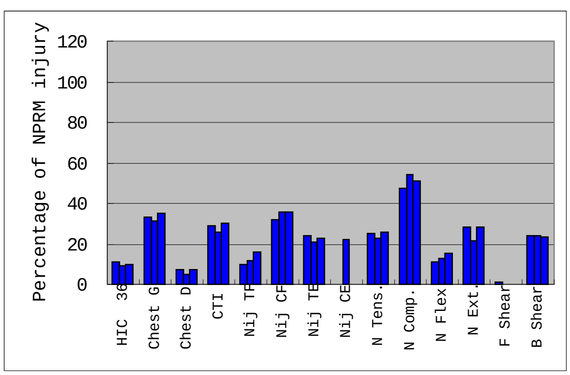


Figure 31. Results for 3-Year-Old Static Out-of-Position Tests (Position 1) using Module with 60/40 Inflator, 100 Millisecond Time Delay, and 65 Millimeter Diameter Vent Holes.

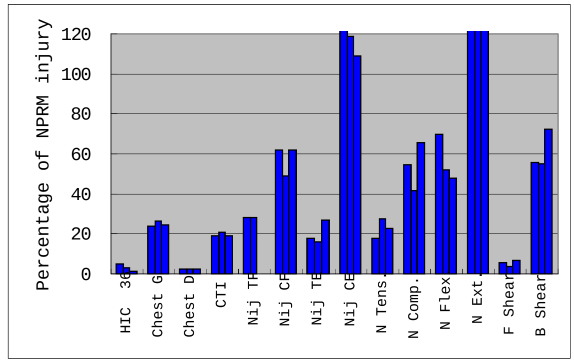


Figure 32. Results for 3-Year-Old Static Out-of-Position Tests (Position 2) using Module with 60/40 Inflator, 100 Millisecond Time Delay, and 65 Millimeter Diameter Vent Holes.

configuration, the neck extension moment exceeds the reference value by a substantial margin for both child dummy sizes. Furthermore, the results for the 3-year-old dummy in Position 2 indicate the Nij (specifically, $N_{Compression\text{-}Extension}$) exceeds the reference value by a large margin. Overall, Position 2 is observed to be more severe than Position 1 for this module configuration.

The second set of out-of-position tests that were conducted using the 3-year-old and 6-year-old dummies utilized modules with the 50/50, 60/40, and 70/30 inflators. Again, the vent hole diameter was 65 millimeters. For these tests, the second stage was not ignited. Figures 33 and 34 provide the results of the testing with the 6-year-old dummy. Figures 35 and 36 provide the results of the testing with the 3-year-old dummy. It should be noted that a testing malfunction occurred in one of the Position 2 tests of the 6-year-old dummy. That test is excluded from the results. As seen in Figures 33 and 35, the Position 1 test results for the 6-year-old and 3-year-old dummies are well below the injury reference values for each of the inflator configurations. In the Position 2 tests for the 6-year-old dummy, the neck extension moments exceeded the reference value with the 60/40 and 70/30 inflators. In the Position 2 tests for the 3-year-old dummy, the neck extension moments and Nij exceeded the reference values with the 60/40 and the 70/30 inflators. (The 60/40 inflator exceeded the reference value for $N_{Compression\text{-}Extension}$, and the 70/30 inflator exceeded the reference value for $N_{Tension\text{-}Extension}$.) In general, as the first stage power increased, the dummy injury measures increased. Overall, Position 2 is observed to be more severe than Position 1 for each of the inflators in this module configuration.

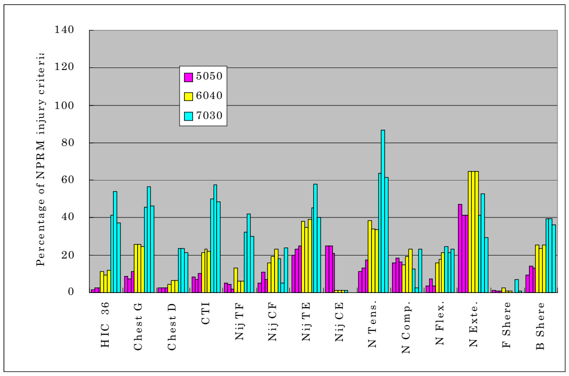


Figure 33. **Results for 6-Year-Old Static Out-of-Position Tests (Position 1) using Modules with 65 Millimeter Diameter Vent Holes.**

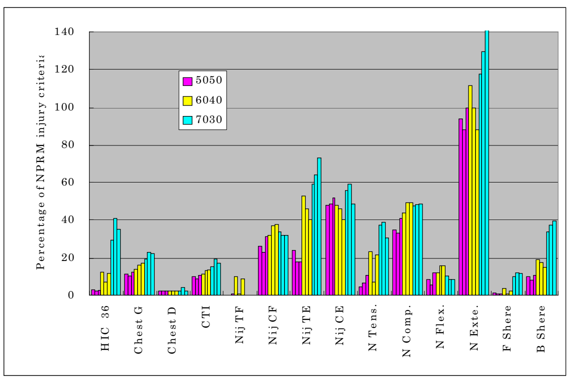


Figure 34. **Results for 6-Year-Old Static Out-of-Position Tests (Position 2) using Modules with 65 Millimeter Diameter Vent Holes.**

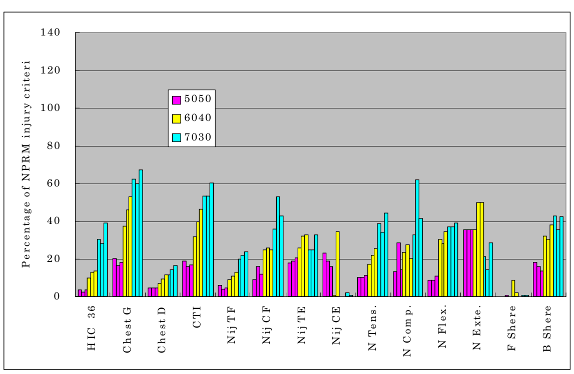


Figure 35. **Results for 3-Year-Old Static Out-of-Position Tests (Position 1) using Modules with 65 Millimeter Diameter Vent Holes.**

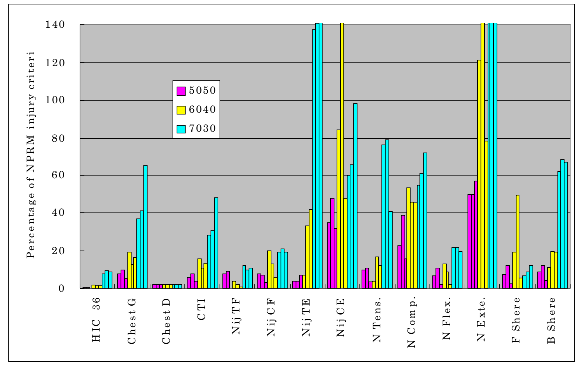


Figure 36. **Results for 3-Year-Old Static Out-of-Position Tests (Position 2) using Modules with 65 Millimeter Diameter Vent Holes.**

Static Deployment Tests: CRABI 12-Month-Old Infant Dummy in Rear Facing Infant Seat

The rear facing child safety seat used with the 12-month-old infant dummy was a convertible child safety seat manufactured by Takata. The seat was installed using the instructions specified in the owner's manual for the compact car. After installation, the infant dummy then was placed and belted in the seat. The tests were conducted using the modules with the 60/40 inflator and 65 millimeter vent hole diameter. The second stage was ignited 100 milliseconds after the first stage. Figure 37 provides the results of the testing with the 12-month-old infant dummy. As seen here, all of the test results were substantially below the injury reference values.

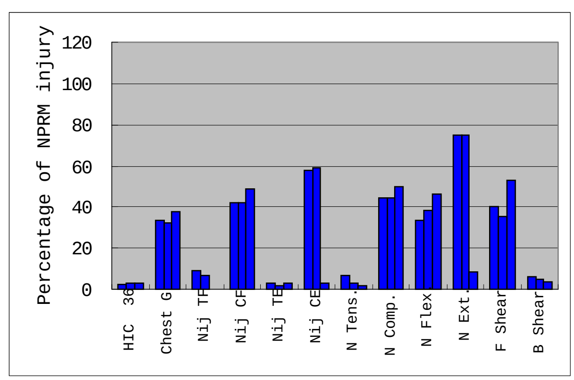


Figure 37. **Results for CRABI 12-Month-Old Infant Dummy Static Tests In Rear Facing Infant Seat using Module with 60/40 Inflator, 100 Millisecond Time Delay, and 65 Millimeter Diameter Vent Holes.**

Comparison of Single Stage versus Dual Stage Inflators

The single stage inflator test series was conducted to evaluate the performance of the dual stage inflator versus that of the single stage inflator. As mentioned, the single stage inflator used in this program was a solid pyrotechnic inflator. The nominal output for the inflator was 520 kiloPascals in a 60 liter tank. The dual stage inflator utilized the 60/40 inflator, 10 millisecond time delay between stages, and the 65 millimeter vent hole diameter. The nominal output for the combined inflators was 525 kiloPascals in a 60 liter tank. Comparison tests were conducted using the 48 kmph (30 mph) simulated crash environment for the 50th percentile male and 5th percentile female dummies in the mid-travel seating position and using the out-of-position aggressivity evaluation for the 3-year-old and 6-year-old child dummies.

Single Stage vs Dual Stage Inflators: 50th Percentile Male Dummy Figure 38 provides the results using the single and dual stage inflators in the testing of the 50th percentile male dummy in a 48 kmph (30 mph) simulated crash environment. As can be determined in examining the data, the results show virtually equivalent performance between the dual stage inflator and the single stage inflator. Both inflators met all injury criteria reference levels.

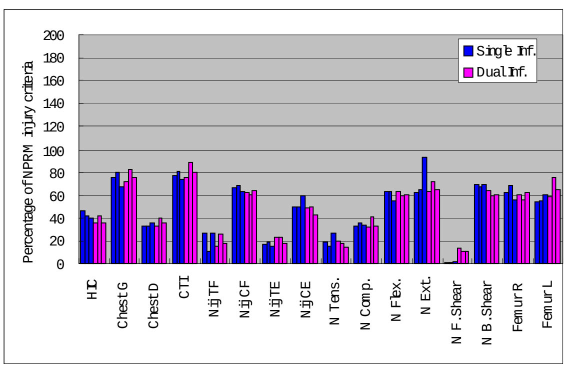


Figure 38. **Single Stage vs. Dual Stage Inflator (60/40 Inflator, 10 Millisecond Time Delay, 65 Millimeter Diameter Vent Holes) for 50th Percentile Male.**

Single Stage vs Dual Stage Inflators: 5th Percentile Female Dummy Figure 39 provides the results using the single and dual stage inflator in the testing of the 5th percentile female dummy in a 48 kmph (30 mph) simulated crash environment. While the dual stage inflator exceeded the injury reference values for neck flexion moment, the single stage inflator exceeded the injury reference values for Nij ($N_{Tension-Extension}$ and $N_{Compression-Extension}$), neck tension, neck flexion, and the neck extension moment. As can be determined in examining the data, the results show lower chest measures for the single stage inflator, but substantially higher Nij ($N_{Tension-Extension}$), neck tension, and neck extension moments.

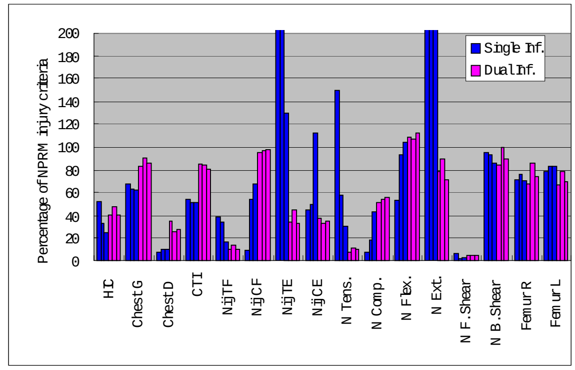


Figure 39. **Single Stage vs. Dual Stage Inflator (60/40 Inflator, 10 Millisecond Time Delay, 65 Millimeter Diameter Vent Holes) for 5th Percentile Female.**

Single Stage vs Dual Stage Inflators: 3-Year-Old and 6-Year-Old Child Dummy Out-of-Positions Tests Figures 40 through 43 provide the results for the single and dual stage inflator (60/40, 100 millisecond delay, and 65 millimeter diameter vent hole) out-of-position testing of the 3-year-old and 6-year-old child dummies. As can be seen, the dual stage inflator produced overall lower results for both dummies. In particular, for Position 1, the dual stage inflator met all injury criteria reference values while the single stage inflator exceeded the reference values for chest acceleration and the neck injury measures for both dummies. In Position 2, while the dual stage inflator exceeded the injury reference values of the Nij ($N_{Compression-Extension}$) for the 3-year-old dummy and the neck extension moment for both dummies, the other results are substantially lower than those of the single stage inflator.

Recent Activity

The aforementioned test results were obtained by Takata Corporation using its test facilities, equipment, and dummies. More recently, NHTSA's Vehicle Research and Test Center (VRTC) conducted additional testing using prototype hardware provided by Takata. While the overall objectives of the program remained the same, the recent VRTC testing also allowed for evaluating reproducibility of the Takata test results as well as allowed for evaluation of the test results using the

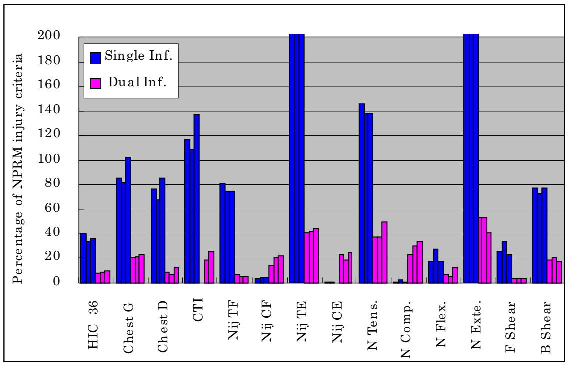


Figure 40. **Single Stage vs. Dual Stage Inflator (60/40 Inflator, 100 Millisecond Time Delay, 65 Millimeter Diameter Vent Holes) for 6-Year-Old Child Dummy in Position 1.**

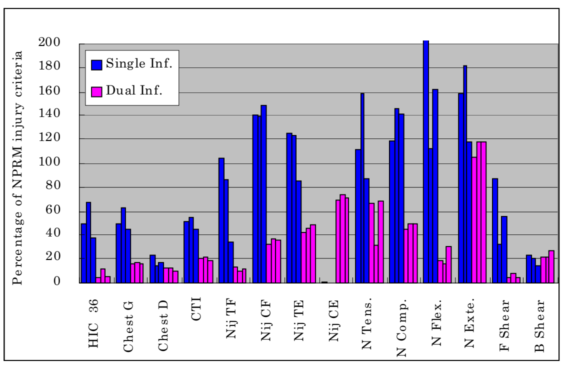


Figure 41. **Single Stage vs. Dual Stage Inflator (60/40 Inflator, 100 Millisecond Time Delay, 65 Millimeter Diameter Vent Holes) for 6-Year-Old Child Dummy in Position 2.**

injury criteria specified in the FMVSS No. 208 Interim Final Rule [4]. The effort is still underway and will be reported upon completion.

SUMMARY

A research program was initiated to evaluate the performance of prototype dual stage passenger air bags in terms of both restraint system performance and deployment aggressivity for different size occupants. Variations included 50/50, 60/40, and 70/30 partitioning of the inflator propellant, vent hole diameters of 55, 65, and 75 millimeters, and time delays between first and second stage ignition of 10 and 20 milliseconds. Unbelted sled tests were conducted with both 50th percentile male and 5th percentile female Hybrid III adult dummies at 48 kmph (30 mph); and belted sled tests were conducted at 56 kmph (35 mph). Out-of position deployment tests with child dummies were conducted to evaluate air bag aggressivity.

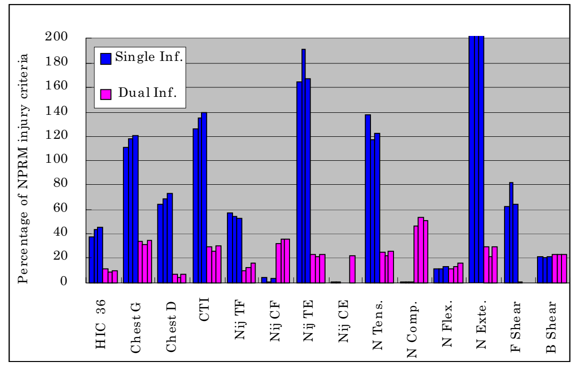


Figure 42. **Single Stage vs. Dual Stage Inflator (60/40 Inflator, 100 Millisecond Time Delay, 65 Millimeter Diameter Vent Holes) for 3-Year-Old Child Dummy in Position 1.**

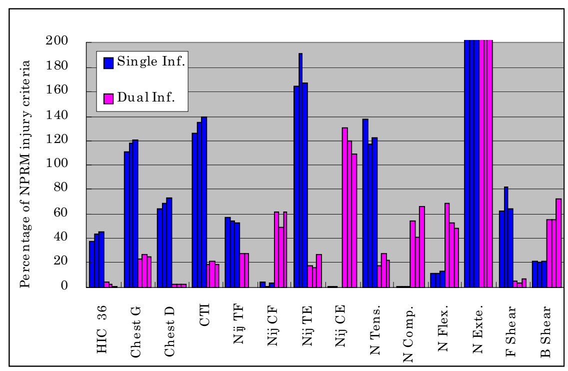


Figure 43. **Single Stage vs. Dual Stage Inflator (60/40 Inflator, 100 Millisecond Time Delay, 65 Millimeter Diameter Vent Holes) for 3-Year-Old Child Dummy in Position 2.**

For high speed restraint performance, inflator combinations with a 60/40 or 70/30 inflator partitioning and a 10 millisecond delay resulted in meeting injury criteria reference values for the unbelted 50th percentile male in a 48 kmph sled test; however, a less aggressive 50/50 inflator partitioning resulted in insufficient restraint.

In the out-of-position aggressivity tests, the 60/40 inflator combination with 65 millimeter vent hole diameter and 100 millisecond time delay met the injury criteria reference values for the 6-year-old child and the 3-year-old child dummy in Position 1, and for the 12-month-old CRABI infant dummy in the rear facing infant seat. However, this inflator was not able to satisfy the neck criteria for either the 3-year-old child dummy in Position 2 or the unbelted 5th percentile adult female dummy in the original unbelted 48 kmph sled test. The 50/50 inflator was able to meet all the low risk deployment requirements for both the 3-year-old and 6-year-old child dummies; however, it only marginally passed the chest acceleration criterion in the unbelted 50th percentile male 48 kmph sled tests.

Overall, it was concluded that the dual stage air bag systems under evaluation had improved performance over the baseline single stage systems in terms of providing high speed protection while reducing aggressivity to out-of-position occupants. It also was demonstrated that some combinations of the 60/40 and 70/30 dual stage inflators may provide sufficient unbelted occupant crash protection for 5th percentile female and 50th percentile male adult passengers in high severity crashes. However, additional occupant detection methodologies may be required to suppress or control inflation for children.

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2. National Highway Traffic Safety Administration, Notice of Proposed Rulemaking, Federal Register, Volume 63, No. 171, page 46981, September 3, 1998, NHTSA Docket No. NHTSA-1998-4283.

3. National Highway Traffic Safety Administration, Notice of Proposed Rulemaking, Federal Register, Volume 63, No. 181, page 49958, September 18, 1998, NHTSA Docket No. NHTSA-1998-4405.

4. National Highway Traffic Safety Administration, Interim Final Rule, Federal Register, Volume 65, No. 93, page 30680, May 12, 2000, NHTSA Docket No. NHTSA-2000-7013.