NHTSA'S ADVANCED AIR BAG TECHNOLOGY RESEARCH PROGRAM

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Paper 98-S5-W-29

ABSTRACT

This paper reports on the National Highway Traffic Safety Administration's (NHTSA's) research program on Advanced Air Bag Technology. This program was initiated to establish the technical basis for new vehicle performance requirements for improved occupant crash protection. The primary tasks include: real-world crash investigations, development and certification of test dummies and associated injury criteria, evaluation of advanced air bag technology, and development of test procedures. NHTSA also has initiated cooperative research programs with NASA/Jet Propulsion Laboratory and Transport Canada, and is gathering information and data through the Motor Vehicle Safety Research Advisory Committee (MVSRAC). Research work will be used to support rulemaking activities on advanced air bag systems. This paper presents an overview of this effort.

BACKGROUND

In recent years, a number of crashes have been reported where injuries and fatalities have been the result of aggressive air bag deployment; that is, the severity and crash environment did not warrant the severity of injury/fatality sustained by the occupant. Those most susceptible to injuries/fatalities from aggressive air bag deployments include out-of-position child passengers, out-of-position adult drivers (usually unbelted), and infants in rear-facing child safety seats. As of May 1, 1998, 99 fatalities have been attributed to the air bag deployment. These include 57 fatalities of children (13 infants in rear facing child safety seats) and 42 fatalities of adults (38 drivers, 4 passengers).

On March 19, 1997, NHTSA published a final rule that temporarily amends the agency's occupant crash protection standard to ensure that vehicle manufacturers can quickly depower air bags so that they inflate less aggressively. More specifically, the agency adopted an unbelted sled test protocol as a temporary alternative to the standard's full scale unbelted barrier crash test requirement. The agency took this action to provide an immediate, interim solution to the problem of the fatalities and injuries that current air bag systems are causing in relatively low speed crashes to a small, but growing number of children and occasionally to adults. This final rule was one that allowed modification of the air bag performance to address the identified safety problem. A number of other actions also were undertaken by the agency. These actions included the following:

• On October 27, 1995, NHTSA issued a strong warning in a press release, "SAFETY AGENCY ISSUES WARNING ON AIR BAG DANGER TO CHILDREN." The release warned that children who are not protected by a safety belt could be seriously injured or killed by an air bag, and in the strongest possible terms urged parents to insist that their children ride belted in the back seat whenever possible. Three "rules" were advocated:
- Make sure all infants and children are properly restrained in child safety seats or lap and shoulder belts for every trip,
- The back seat is the safest place for children of any age, and
- Infants riding in rear-facing child safety seats should never be placed in the front seat of a vehicle with a passenger-side air bag.

• On November 9, 1995, NHTSA published a request for comments to inform the public about the agency's efforts to reduce the adverse effects of air bags and to invite the public to share information and views with the agency.

• On May 21, 1996, Secretary Peña announced the formation of an air bag coalition. Coalition members pledged almost $10 million to pursue a three-point program:
- An extensive national effort to educate drivers, parents, and care-givers about safety belt and child safety seat use in motor vehicles, with special emphasis on those equipped with air bags.
- A campaign to assist states to pass "primary" safety belt use laws.
- Activities at the state and local level to increase enforcement of all safety belt and child seat use laws, such as increase public information and use of belt checkpoints.

• On August 1, 1996, NHTSA published a notice of proposed rulemaking, proposing amendments to FMVSS Nos. 208 and 213 to reduce the adverse effects of air bags, especially those on children. NHTSA proposed the following for passenger cars and light trucks whose passenger-side air bags lacks smart* capability:

- To require new, enhanced warning labels, and
- To permit manual cutoff switches for the passenger-side air bags (to accommodate parents who need to place rear-facing child seats in the front seat).

• On November 27, 1996, NHTSA issued the final rule on new air bag warning labels. The rule stated that:

- Vehicles with air bags are required to have three new warning labels, two of which replaced the then existing labels.
- Rear facing child safety seats are required to have a new label to replace the then existing label.

• On January 6, 1997, the agency issued three notices. The first was a final rule extending the time period for the installation of manual cutoff switches for specified passenger vehicles until September 1, 2000. The second was a notice of proposed rulemaking for allowing the vehicle manufacturers to depower air bags so that they inflate less aggressively. The third was a notice of proposed rulemaking to allow automobile dealers and repair shops to deactivate air bags at a customer's request.

• The latest regulatory action was announced on November 18, 1997. In this, the agency issued its final rule regarding air bag on-off switches. The switches would be permitted for specific circumstances. These include:

- For front seat occupants experiencing a medical condition that poses a special risk that outweighs the risk of hitting their head, neck, or chest in a crash if the air bag is turned off,
- For drivers who are not able to adjust their customary driving position to allow a minimum of 10 inches between their breastbone (sternum) and the center of the steering wheel,
- For people who must transport infants in rear-facing infant seats in the front passenger seat,
- For people who must transport children ages 1 to 12 in the front passenger seat, and
- For people who are unable to avoid situations, such as a car pool, that require a child 12 years or younger to ride in the front seat.

As can be seen, the agency has undertaken a substantial regulatory effort to reduce the safety problem resulting from aggressive air bag deployment. However, the agency has determined that these steps fall short of solving the problem. In the final regulatory evaluation [1] published in conjunction with the issuance of the March 19, 1997, final rule, the agency estimated that if manufacturers depowered their air bag systems on average by 20 to 35 percent, 47 children's lives could be saved from the estimated 140 children who otherwise would be killed over the lifetime of one model year's fleet. Furthermore, projections were made regarding the disbenefits to adult occupants that would occur in high severity crashes as a result of depowering the air bag systems. The estimated disbenefit was that 45 to 409 driver and passenger adult fatalities would result from depowering the air bag systems by 20 to 35 percent.

In addition to the regulatory actions, NHTSA held a "Smart Air Bag Public Meeting," on February 11-12, 1997. This meeting was attended by a broad array of parties interested in air bag issues. Based on the discussions that took place at that meeting, the agency established objectives for an advanced air bag technology research program, and determined that the agency would need detailed information regarding advanced air bag technology and the ability to evaluate such technology in order to meet its objectives. The documents describing these objectives and information needs have been placed into Public Docket NHTSA-1997-2814. The agency determined that meeting its objectives would require industry cooperation, since the industry would be the source of advanced technologies and could provide detailed information regarding these technologies. The agency concluded that a cooperative research effort under the sponsorship of the Motor Vehicle Safety Research Advisory Committee (MVSRAC) would be the best means for achieving these objectives. As a result, the Advanced Air Bag Technology Working Group was established under the MVSRAC Crashworthiness Subcommittee. The purpose of this working group is to perform research and to compile information regarding advanced air bag technology. In particular, the working group is performing research activities to define safety problems that are likely to continue despite the introduction of depowered air bags, to develop advanced systems that would address the identified safety problems, and to

* In this proposal, the agency considered smart air bags to include any system that automatically prevents an air bag from injuring the two groups of children that experience has shown to be at special risk from air bags: infants in rear-facing child seats, and children who are out-of-position (because they are unbelted or improperly belted) when the air bag deploys.

develop procedures that could be used to evaluate the safety performance of advanced air bag systems. Members represent those in the best position to assist in the performance of the research and in the gathering of information regarding advanced air bag technology, and include representatives of government, domestic and foreign automobile manufacturers, restraint system suppliers, the insurance industry, academia, and the medical community.

In addition to the agency actions, the National Transportation Safety Board (NTSB) convened a Public Forum on Air Bags and Child Passenger Safety on March 17-20, 1997, in Washington, DC. As a result of reviewing the testimony from this meeting, NTSB issued 9 safety recommendations, H-97-10 through H-97-18, to the agency regarding improved adult and child occupant protection standards and evaluation procedures. These recommendations are:

- H-97-10: Develop and implement a set of crash test standards that utilize the currently available 5th percentile crash test dummy.
- H-97-11: Develop and implement a set of vehicle crash test standards using biologically representative child dummies and appropriate injury criteria.
- H-97-12: Develop and implement, in conjunction with the automobile industry, a comprehensive crash investigation program to evaluate the effectiveness of air bags. This program should provide for long-term and short-term evaluation of variations in air bag designs, advanced air bag technologies, and various methods to deactivate air bags.
- H-97-13: Develop, in conjunction with the Centers for Disease Control and Prevention, data collection procedures and establish a database for recording all air bag-induced injuries identified by the medical community.
- H-97-14: Revise the Fatality Analysis Reporting System and the National Automotive Sampling System to record specific information regarding the air bag equipment installed in the vehicle and its performance in the crash, such as the following: Did the air bag deploy, was it a depowered air bag, was there a cutoff switch, and was it on or off.
- H-97-15: Develop, in conjunction with the States, uniform measurement procedures and tools for the States to use when conducting surveys on seatbelt and child restraint use and revise the 1992 guidelines to ensure that a probability-based design is used to select a representative sample of the population. Provide this information to the States.
- H-97-16: Develop guidelines for the collection of standardized data elements, including data fields for air bags, which will provide for better comparisons and evaluation of traffic crashes. Revise and update the guidelines as necessary. Provide these guidelines to the states.
- H-97-17: Evaluate, through public comment, the New Car Assessment Program (NCAP) test procedures to determine (a) if the crash test procedures are counterproductive to development of air bag technology that is safe for all occupants, and (b) if the NCAP program provides consumers with the safety information they need to purchase a vehicle. If necessary, develop new methods for providing meaningful information to consumers on vehicle safety in high speed and other types of crashes.
- H-97-18: Develop and implement, in conjunction with the domestic and international automobile manufacturers, a plan to gather better information on crash pulses and other crash parameters in actual crashes, utilizing current or augmented crash sensing and recording devices.

While the agency already had efforts underway addressing these recommendations, the recommendations resulted in added impetus to achieve and expedite the research activities.

With the above as background, the agency has initiated an extensive research program on Advanced Air Bag Technology. This program is to establish the technical basis for new vehicle performance requirements that lead to improved occupant crash protection. The objective of this research activity is to eliminate the fatalities and reduce the severity of the injuries resulting from aggressive air bag deployment, while simultaneously providing benefits to normally seated restrained occupants and restoring full protection for unbelted large adults in high severity crashes. The requirements will be established using the state-of-the-art developments of advanced air bag technology. The program includes tasks to investigate real-world crash performance, to develop and certify test dummies and associated injury criteria, to develop test procedures, and to evaluate advanced air bag technology. In undertaking this program, the agency has joined in cooperative efforts with Transport Canada, the Australian Federal Office of Road Safety, and with the National Aeronautics and Space Administration/Jet Propulsion Laboratory. This paper presents an overview of the program.

REAL WORLD CRASH INVESTIGATIONS

Various analyses of real world crash data are being conducted in order to evaluate effectiveness of occupant protection systems. To date (and as directed by Congress in the enactment of the Intermodal Surface Transportation Efficiency Act of 1991), the agency has published a total of three reports on the effectiveness of occupant protection systems and safety belt use, the third having been published December 1996 [2]. As part of the effort undertaken for developing the report, the National Automotive Sampling System is utilized to analyze air bag-related issues such as effectiveness as a function of driver height and gender interaction, specific body region effectiveness estimates for various sub-populations, etc. Other analyses involve investigations of injuries and fatalities with air bags, analysis of fatalities to children under 15 with air bags, and analysis of injuries/fatalities to adult drivers, specifically to identify cases of air bag aggressiveness contributing to the injuries/fatalities. Specifically, NHTSA's Special Crash Investigation (SCI) program was established to collect detailed in-depth data on specific crashes of interest to the NHTSA. SCI cases are an anecdotal data set used to examine, document, and qualify the state-of-the-art safety systems. In the SCI program, professional crash investigators perform an extensive examination of the vehicles and scene from which they secure and analyze the evidence necessary to reconstruct the events before, during, and after the crash.

As noted earlier in the background section, NHTSA has identified 99 fatalities (57 children, 42 adults) that have been attributed to the air bag deployment, as of May 1, 1998. In the SCI investigations, it was found that pre-impact braking was involved in many of the crashes. Also, it was determined that many of the fatally injured children were unrestrained or improperly restrained. Table 1 provides a breakdown regarding the 57 child fatalities and Table 2 provides a breakdown of the 42 adult fatalities.

Table 1.
Confirmed Fatal Children from Air Bag Deployment

Children fatally injured by the passenger air bag (US=56; Puerto Rico=1)	57
- Rear Facing child safety seats	13
- Forward Facing child safety seats	2
- Unrestrained or improperly restrained children	
With pre-impact braking	35
Without pre-impact braking (US=3; Puerto Rico=1)	4
- Wearing lap and shoulder belt	
With pre-impact braking	3

Table 2.
Confirmed Fatal Adults from Air Bag Deployment

Drivers fatally injured by the Air Bag	38
- Drivers belted	11
- Drivers misused belt	3
- Drivers not belted	21
- Unknown if driver belted	3
Passengers fatally injured by the Air Bag	4
- Passengers belted	1
- Passengers misused belt	0
- Passengers not belted	3
- Unknown if passenger belted	0

With the introduction of vehicles equipped with air bags systems certified by the generic crash pulse specified as an option in the March 19, 1997 rulemaking, the SCI program also is investigating the field performance of production vehicles certified in this manner. The agency has implemented several early notification mechanisms to identify these crashes, including using notifications provided by State Farm Insurance Company as of April 1, 1998. (The State Farm notification was made possible through their and the Insurance Institute for Highway Safety's participation in the Advanced Air Bag Technology Working Group of the Motor Vehicle Safety Research Advisory Committee.) As of April 1, 1998, the SCI has initiated 56 cases involving such vehicles. The reader is referred to a companion ESV paper that has been written regarding the SCI investigations for further details regarding the program [3].

DEVELOPMENT AND CERTIFICATION OF TEST DUMMIES

In the advanced air bag technology research program, NHTSA has been conducting experimental testing and developing test procedures for a range of adult and child anthropomorphic test devices (ATD's) to cover a broader range of occupant sizes in the real world. Adult ATD's included the 5th percentile female, 50th percentile male, and the 95th percentile male Hybrid III dummies. Child ATD's included the 6-year-old and 3-year-old Hybrid III child dummies, and the 12-month-old CRABI dummy. Currently only the 50th percentile male Hybrid III dummy is included in the CFR Part 572, and utilized in current FMVSS No. 208 testing. However, research and testing is being conducted to finalize the certification procedures necessary for incorporating the alternative test dummy sizes into the Federal motor vehicle safety standards.

Calibration and Testing

NHTSA's Vehicle Research and Test Center (VRTC) has conducted numerous types of tests with the 5th percentile female Hybrid III adult dummy, the 6-year-old and 3-year-old Hybrid III child dummies, and the 12-month-old CRABI dummy. For each of the dummies, initial calibration tests are conducted to document baseline performance and to ensure that the test dummies meet the required biofidelity corridors, as delivered by the manufacturer. Periodic calibration tests are also conducted throughout component and sled tests to document deviations from the baseline performance, and post-test calibration tests are conducted following the completion of the sled tests to establish final dummy response. VRTC also has conducted static out-of-position tests with the 5th percentile female Hybrid III adult dummy on the driver's side, and the 6-year-old and 3-year-old Hybrid III child dummies on the passenger side to establish repeatability, and durability performance in the component level environment. Tests with the 12-month-old CRABI dummy in a rear facing child safety seat also have been conducted in static deployment tests of the passenger side air bag. Finally, VRTC is evaluating the performance of each of the test dummies in the sled environment with various restraint conditions. Again, determination of repeatability and durability of the test dummies are the primary objectives of this program.

The agency has been working in conjunction with the dummy manufacturers and the SAE committees to develop and assemble the required documentation for each of the test dummies. Tasks have included finalizing a set of drawings for each dummy, reviewing, updating, and revising user manuals, and collecting applicable literature and test data documenting the development and performance of the dummies relative to biofidelity characteristics and injury assessment reference values. The agency, in cooperation with vehicle manufacturers, has been working closely to rapidly evaluate new modifications to the dummies as they become available, as well as respond to concerns raised by the various dummy users. NHTSA plans to complete testing and publish rulemaking proposals for most of the alternative test dummy sizes tested in the summer of 1998. Research on the 95th percentile male dummy may require additional time.

Advanced Dummy Modifications

Longer term research programs will focus on improving the biofidelity of current test dummies so that advanced air bag systems utilizing technologies, such as infrared or capacitive sensing, will be able to detect their presence. A project has been established (under the NHTSA-GM C-K settlement agreement) at the Johns Hopkins University Applied Physics Laboratory to develop technology that will enhance the biofidelity of the test dummies. Comparisons will be made of the characteristic output signals generated by both human subjects and test dummies. Specialized dummy treatments then will be investigated, as they may be required to enable the test dummy to be properly sensed by the full range of future advanced sensor systems. However, some sensor technologies, such as ultrasonic and active infrared, may only require a relatively straightforward surface treatment or clothing selection.

In the interim, NHTSA has observed that many manufacturers currently use human volunteers to conduct static tests of occupant presence detection systems that utilize infrared or capacitive sensing. Others have made use of fluid-filled dummies to emulate the capacitance level of the human body. Alternatively, suppression systems which dynamically track the motion of the occupant entering a designated "keep-out zone" may only require a component test fixture to be heated or fluid filled for performance evaluation, rather than a full dummy modification.

INJURY CRITERIA DEVELOPMENT

For each test dummy size utilized in the advanced air bag technology research program, NHTSA is undertaking research to establish appropriate injury criteria that correlate dummy measurements to human injury tolerance. Two body regions of particular importance in the advanced air bag research program are the head/neck complex and the thoracic region. In the majority of reported child injury/fatality cases, the right front passenger air bag has deployed into the area of the upper chest, neck, and face of the child. The rapid translation and rotation of the skull caused a number of cervical spine and closed head injuries. Thoracic injuries such as lung contusions and atrial hemorrhages also have been reported in the child cases. The air bag related injuries/fatalities in adults (mostly drivers) have been associated with three primary injury patterns. The first pattern involves multiple rib fractures, usually bilateral, with additional associated lacerations of the underlying thoracic and abdominal organs (i.e., injuries where AIS $\geq$ 4). The second pattern results from air bag contact with the face or chin causing basilar skull fracture with associated brainstem lacerations and/or subdural and subarachnoid hemorrhages. The thira pattern is not as common as the first two, but involves cardiac and pulmonary contusions and hemorrhages without any accompanying rib fractures [4].

For the neck region, developing injury criteria for children is particularly challenging due to the limited amount of biomechanical information and test data [5]. Therefore, NHTSA is conducting research to provide experimental data on the scaling between adult and child injury tolerances and to investigate the age-dependent properties of the cervical spine, with focus on the head-neck junction. Data from these tests and other published research will result in establishing a consistent set of injury criteria for adults and children. NHTSA also is investigating upper cervical spine trauma resulting from air bag loading. Dynamic tests of head/neck specimens are being conducted to determine the injury tolerance of the adult cervical spine.

For the thoracic region, NHTSA is conducting research to analyze the human thoracic response resulting from rapid impulsive loading of the anterior chest wall (as for occupants who are out-of-position), and to develop an improved thoracic injury criterion for use in air bag testing. Existing cadaver tests, dummy tests, and published data have been re-analyzed; and correlations between newly-proposed thoracic injury criteria and real world incidences of thoracic trauma are being evaluated and compared to correlations from previously published criterion. NHTSA also has conducted out-of-position testing with the 5th percentile female Hybrid III dummy and small stature female cadaveric subjects to better assess the relationship between air bag aggressivity and occupant injury response.

NHTSA is preparing to publish a document on injury criteria (for the various test dummy sizes) in conjunction with upcoming rulemaking on advanced air bags.

EVALUATION OF ADVANCED TECHNOLOGIES

Advanced Air Bag Technology Assessment

A number of advancements in air bag technology have been under development in the industry over the past few years to address the adverse effects air bags have found to have on out-of-position occupants. To evaluate the current state-of-the-art in advanced air bag technology and its future potential to improving occupant crash protection, NHTSA signed a memorandum of understanding (MOU) with the National Aeronautics and Space Administration (NASA) in December of 1996. The MOU stated that NASA was to "evaluate air bag performance, establish the technological potential for improved (smart) air bag systems, and identify key expertise and technology within the agency (NASA) that can potentially contribute significantly to the improved effectiveness of air bags"[6]. NASA selected the Jet Propulsion Laboratory (JPL) to conduct this assessment. During the course of the program, JPL visited and surveyed automobile manufacturers and restraint system and component suppliers to gather data and conduct their analysis.

In their final report, JPL made projections on the types of technologies that are being developed and may be available for model years 2001 and 2003 to provide improved information and improved response to occupant protection systems.

<u>**Model Year 2001**</u> - For model year 2001, JPL identified five technologies that could provide improved information to an advanced safety restraint system. First, crash sensors/control systems with improved algorithms could make a number of improvements. They could better discriminate crashes when air bag deployment is beneficial for occupant crash protection, they could regulate better control of the deployment threshold, and they could make determinations on the appropriate inflation level for dual-stage inflators. Second, belt use status sensors can provide information on whether an occupant is belted or not. This could enable the air bag system to be designed to deploy at a higher threshold speed for belted occupants. This deployment strategy is currently in use in some production vehicles. Third, seat position sensors can be used to approximate an occupant's initial seating distance from the air bag module, and also can be used in combination with the seat belt status sensor. A restraint system could be designed to deploy with a less aggressive inflation level for a belted occupant in the full forward seating position, and to deploy with the full inflation level for an unbelted occupant sitting in the full rearward seating position. Fourth, JPL reported that seat belt spool-out sensors could also provide additional information about an occupant's size and proximity to the air bag module. A large amount of spool-out could indicate the presence of a larger occupant, likewise a small amount of spool-out could indicate the presence of a smaller occupant. However, an extremely small amount of belt spool-out could potentially flag other scenarios, such as the occupant has placed the torso portion of the safety belt behind his/her back (as small children often do). However, JPL noted in their final report that belt spool-out sensors were not a part of any industry strategy at the time of their survey. Lastly, JPL noted that static proximity sensors could provide occupant position information by identifying occupants in a designated "keep-out zone." By identifying an occupant in a designated "keep-out zone," the restraint system could be designed to deploy only a benign level of inflation or to suppress air bag deployment entirely. While JPL reported that ultrasonic/IR sensing systems held the greatest promise at the time of their survey, they noted that they will only be available if an

aggressive development plan was undertaken. JPL further noted that these systems would not reduce injuries to all out-of-position occupants, and they could be fooled some of the time (i.e. register "deploy" in a "no deploy" scenario, and vice versa).

JPL also identified four ways that the response of an advanced safety restraint system can be improved for model year 2001. First, given the information that an occupant is located in the "keep-out zone", an automatic suppression feature can prevent the air bag from inflating. This could potentially prevent inflation induced injuries to out-of-position occupants. Second, JPL noted that dual stage inflators can provide relatively soft inflation levels for crashes of lower threshold velocity and higher inflation levels for crashes of higher severity. Third, JPL reported that advancements in air bag materials, and construction, such as compartmented air bags, radial deployments, and air bags with lighter weight fabrics, could improve the response of an advanced air bag system. These air bag improvements would not rely upon sensing schemes for additional information, rather they would deploy the same for all crash scenarios, and occupant sizes/positions. JPL reported that air bags with multiple compartments are beneficial to reducing the forces on out-of-position occupants since the chambers can be pressurized sequentially. Tear strips or perforated ports allow the gas to fill secondary chambers at a specific pressure level. Similarly air bags that deploy radially are also designed to reduce the amount of force on an out-of-position occupant by controlling the deployment direction away from the occupant. JPL reported that the lower mass attributes of lighter weight fabrics used in conjunction with lower-output inflators may have the potential for reducing the magnitude of punch-out forces on out-of-position occupants. JPL finally noted that advanced safety belt systems can greatly improve the response of an advanced restraint system. Pretensioners can initiate the coupling of the occupant to the seat earlier in the crash, and force limiters can limit the maximum belt loads exerted on the occupant. Both of these safety belt enhancements are installed in some current production vehicles.

Model Year 2003 - For model year 2003, JPL reported that there could be evolutionary changes in advanced restraint systems including the potential introduction of occupant and proximity sensors. JPL identified four technologies that could provide improved information to an advanced safety restraint system for model year 2003. First, vehicle crash sensors and control algorithms will continue to be enhanced and improved. Second, seat belt status sensors will be in wide use by model year 2003. Third, integrated occupant and proximity sensors could be available that would identify occupants in a defined "keep-out zone." Finally, precrash sensors may be available for use, but it is anticipated that their application may require further research and investigation.

JPL also identified four ways that the response of an advanced safety restraint system can be improved for model year 2003. First, automatic suppression technology to prevent air bag inflation will be available for use with occupant proximity sensors. Second, multistage inflators which may provide tailored responses for different occupant sizes and crash severities could be available. Third, advancements in air bag design will continue to evolve. Fourth, advanced safety belt features, such as pretensioners and load limiters, will be placed in an increasing number of vehicles, and inflatable safety belts will be available for use to improve safety belt effectiveness.

JPL cautioned in their final report that the expected improvements in safety and protectiveness of air bags, as described above, must be tempered by the understanding that there are key technology advances to be made.

(1) Air bag deployment time variability must be reduced by improvements in the vehicle crush/crash sensor system.
(2) Inflator variability must be reduced so that dual-stage inflators can be applied effectively.
(3) System and component reliability must receive diligent attention to achieve the high levels required under field conditions.
(4) Occupant sensors must be developed that can distinguish between small, medium, and large adults, children and infant seats with high accuracy.
(5) Position sensors to measure occupant proximity to the air bag module with the required response time and accuracy must be demonstrated.

JPL finally noted that all of the above are the subject of current development; but development, test, and integration of the advanced technologies needs to be accelerated to enable its incorporation into production vehicles [6].

NHTSA notes that in the advanced air bag research program, testing was conducted of both driver and passenger dual stage air bag inflators with multi-stage inflation capabilities [7]. The air bag inflators were able to generate a third, mid-level of inflation by staging the firing of the primary and secondary stages by a small period of time (approximately 20 msec). This mid-level of inflation was designed to be approximately equivalent to a "depowered" level of inflation (i.e., having a lower pressure onset rate and peak pressure). Assuming sufficient technological advances are made, as listed by JPL above, this could allow a belted occupant of small stature (sensed by a belt spool-out sensor), or a belted occupant sitting in the full forward seating position (sensed by a seat position sensor), or any belted occupant, regardless of size and position, the opportunity for a "depowered" inflation level to minimize the risk of inflation induced injuries. (The full power inflation could then be utilized for an unbelted occupant.) The mid-level of inflation could also be used in moderate severity crashes based on input from the crash sensor signal.

MVSRAC Participation

At the third meeting of the Advanced Air Bag Technology Working Group, NHTSA presented a formal plan and test matrix for evaluating advanced air bag inflators and crash sensors at NHTSA's Vehicle Research and Test Center (VRTC). The objective of the program was to assess the potential for advanced air bag systems to reduce injury to out-of-position occupants and maintain protection for adults in higher speed collisions. NHTSA sought to test three vehicle platforms: a small car, a minivan, and a sport utility vehicle. It was agreed upon among the working group members that two platforms would be provided by members of the AAMA, and one platform would be provided by the members of the Association of International Automobile Manufacturers (AIAM).

The first platform (referred to as Platform 1) was provided to NHTSA by the AAMA, and included advanced driver and passenger multi-stage air bag inflators and an advanced single-point crash sensor. VRTC conducted three phases of testing on this platform: static out-of-position tests, moderate and high speed sled tests, and a full scale crash test.

The static out-of-position tests were conducted with a 5th percentile female Hybrid III dummy on the driver's side in two test positions. On the right front passenger side, tests were conducted with both the 6-year-old and 3-year-old Hybrid III children in two positions. Using the first position as a baseline, two additional tests were conducted with the 3-year-old Hybrid III dummy by translating the dummy 100 mm and 200 mm back from the instrument panel. Two additional tests were conducted in the second position to test repeatability with both the 6-year-old and 3-year-old Hybrid III dummies. In all the static out-of-position tests only the primary stage of the multistage inflator was used.

Results from the out-of-position tests suggested that the 5th percentile female could potentially meet the injury assessment reference values in the out-of-position tests with small improvements in the advanced air bag. However, the 6-year-old and 3-year-old Hybrid III children could not meet the injury assessment reference values on the passenger side. The proximity tests using the 3-year-old Hybrid III suggested injury measures decreased as the dummy was moved further away from the air bag and larger distances were required for the 3-year-old dummy. The repeat tests suggested that the test procedure was repeatable for HIC, chest G's and neck measurements [7].

The second phase of testing on Platform 1 consisted of conducting sled tests with the normally seated adult 5th female and 50th male Hybrid III dummies, belted and unbelted. The sled tests simulated two conditions: a 48 kmph rigid barrier crash and a 32 kmph center-pole crash. Three different inflation levels were used: primary only, primary + 20 msec delay (mid-level), and primary + 5 msec delay (full-power). Results from the sled test indicate that the advanced multi-stage inflator successfully restrained the 5th percentile female and 50th percentile male dummies in a 48 kmph sled test using variable outputs of the inflator [7].

The final phase of testing on Platform 1 consisted of a full scale 40 kmph offset pole test to the left of the vehicle centerline. The advanced single point sensor was used to detect the crash severity and deploy the appropriate level of inflation. An unbelted 5th percentile female Hybrid III dummy was positioned in the driver's seat, and a unbelted 6-year-old Hybrid III was positioned in the passenger's seat. The advanced sensing system was able to detect the crash and fire only the primary stage of deployment; however the sensor fired late in the crash event resulting in the 6-year-old being severely out-of-position [7]. Therefore, the advanced system tested for Platform 1 was not able to meet the out-of-position testing requirements on the passenger side for the child dummies; however, the system was able to meet the high speed requirements for the 5th percentile female and 50th percentile male adult dummies. Further development is needed to improve sensor timing and aggressivity to out-of-position occupants. (The reader is referred to a companion ESV paper for detailed information about the testing [7].)

Cooperative Research Programs

NHTSA conducted a test series with the VS Holden Commodore Vehicle in conjunction with the Australian Federal Office of Road Safety (FORS). The Holden Commodore vehicle contains air bags designed for the Australian environment which has a very high safety belt usage rate. Frontal barrier crash tests with unbelted adult occupants and out-of-position tests were conducted to assess the performance and aggressivity of the air bag system. The driver air bag system marginally passed the high speed requirements, and resembled a next generation air bag system in the out-of-position tests. However, the passenger air bag system did not perform well in the out-of-position tests, but passed all the high speed test requirements. The reader is referred to a companion ESV paper for further details regarding this testing [7].

NHTSA has also evaluated advanced driver air bag modifications through a cooperative research program with Automotive Systems Laboratory, Inc. (ASL)/Takata Corporation. The objective of the program was to identify critical parameters that could reduce the risk of injury to out of position drivers yet still satisfy the crash test requirements of FMVSS No. 208 in a 48 kmph barrier crash using unbelted dummies. Prototype driver air bag inflators and modified air bag folds and cover designs were considered both in isolation and in combination. The results demonstrated that modifications to the inflator module (through air bag folding and cover design) produced substantial reductions in the risk of air bag-induced injury to the out of position driver while still matching the FMVSS No. 208 performance of the production system. Recently a new cooperative research program was initiated between NHTSA and ASL/Takata to evaluate dual stage passenger side air bags in terms of both restraint performance and aggressivity for different size occupants. The project will examine the influence that variations in inflator rise rate, peak pressure and deployment timing can have on both restraint performance and aggressivity.

NHTSA also has a cooperative research agreement with Automotive Technologies International (ATI) to adapt their ultrasonic pattern recognition system for sensing occupant position to the passenger compartment of a prototype vehicle. The passenger acoustic detection device was installed and trained to identify the presence of a rear facing child safety seat, and further trained to recognize that a person is out-of-position. The system utilizes a set of ultrasonic transducers and a neural network decision algorithm which is programmed or trained to recognized conditions for air bag suppression and non-suppression.

DEVELOPMENT OF TEST PROCEDURES

In the advanced air bag technology research program, NHTSA has been developing and evaluating test procedures for advanced air bag systems. To evaluate air bag aggressiveness to out-of-position occupants, NHTSA has developed driver and passenger static air bag deployment test procedures. On the driver's side, the 5th percentile female Hybrid III dummy is used in two positions. The first positions the dummy head/neck in close proximity to the air bag module (Figure 1) and the second elevates the dummy such that the chest is against the module (Figure 2). These positions were based on ISO DTR 10982 test procedures for testing out-of-position occupants.

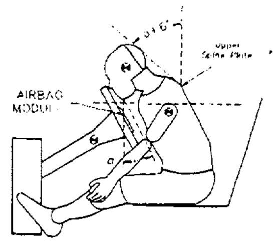

Figure 1. 5th Female, Position 1.

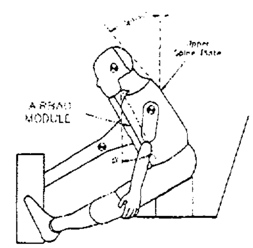

Figure 2. 5th Female, Position 2.

For the right front passenger, NHTSA has developed test procedures for the 6-year-old and 3-year-old Hybrid III child dummies. Again, two positions are used: one positions the dummy's chest in close proximity to the air bag module with its spine vertical, while the other positions the dummy on the seat edge and rotates the upper torso toward the air bag module. The two dummy positions were developed based on the ISO 10982 [8] procedures for out-of-position testing. Figures 3 and 4 illustrate the positioning of the 6-year-old Hybrid III dummy and Figures 5 and 6 illustrate the positioning of the 3-year-old Hybrid III dummy.

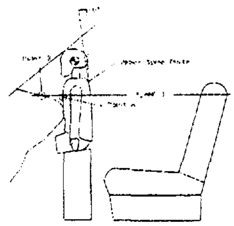

Figure 3. 6YO, Position 1.

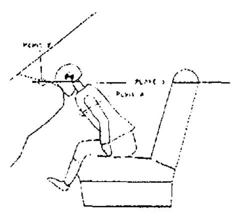

Figure 4. 6YO, Position 2.

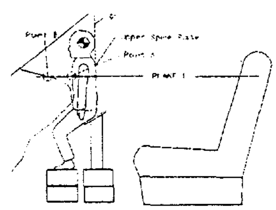

Figure 5. 3YO, Position 1.

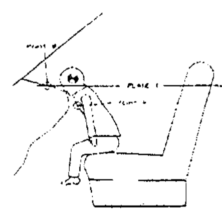

Figure 6. 3YO, Position 2.

These out-of-position test procedures were developed by, and tested extensively by VRTC over the past two years of air bag and dummy certification programs. Repeat tests were also conducted to confirm repeatability and reproducibility of test results.

NHTSA has also been working with Transport Canada in a joint research program to develop a low speed deformable offset barrier test procedure using belted 5th percentile female Hybrid III driver and passenger dummies. Figure 7 illustrates the crash test configuration, and Figure 8 illustrates the driver seating position for the 5th percentile female Hybrid III dummy. The combination of low speed

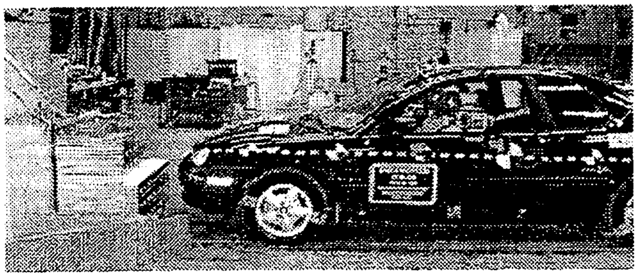

Figure 7. 40 kmph, 40% Offset Test Procedure.

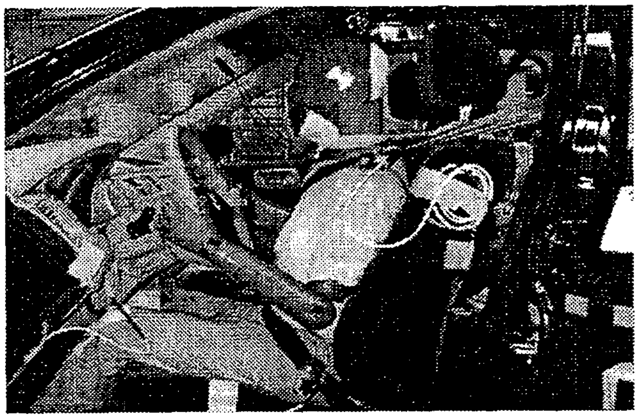

Figure 8. 5th Percentile Female Hybrid III Driver Seat Position.

and a deformable barrier result in generating a soft crash pulse just above the threshold for air bag deployment. This has the potential for presenting crash sensing challenges to some vehicle air bag systems. Vehicles that have difficulties discriminating between a "fire" and "no fire" condition in this crash mode tend to deploy the air bags late in the crash event. This results in positioning the belted 5th female Hybrid III dummies' head/neck very close to the air bag module (due to the crash forces already rotating the dummy torso forward). This test procedure has illuminated a need for reducing aggressivity to out-of-position occupants, and a need for improved low speed crash sensing to provide a more timely air bag deployment. It also aims at providing protection to small drivers, who conscientiously wear their safety belts and, by necessity, must position themselves close to the steering wheel to drive.

Associated research has also been conducted on establishing a uniform test procedure for seating the 5th percentile female Hybrid III driver and passenger dummies. The test procedure would ideally be repeatable in a single seat, reproducible amongst technicians, and be a realistic representation of the 5th percentile female seating position. NHTSA has been participating in the SAE Hybrid III 5th Percentile Dummy Seating Procedure Task Group meetings to help accomplish these goals.

Other test procedures that are in development in the advanced air bag technology research program include: static tests for air bag suppression, and dynamic tests for either air bag deployment or suppression. Static tests for air bag suppression test the advanced restraint systems ability to automatically turn the air bag off when an out-of-position adult driver or child passenger is pre-positioned close to the air bag module. For weight based sensing systems, it tests the ability of the sensor to discriminate between a child and a small adult passenger, and it tests the sensor functionality in a rough road environment (where seat loading forces can oscillate). For presence detection sensor systems, component test procedures are being developed to test the sensors ability to suppress air bag deployment based on an occupant dynamically entering a designated "keep-out zone." Dynamic test procedures are being developed that emulate crash conditions of the fatal crashes that have occurred in the real world. The test procedure involves a full scale crash test of low to moderate severity with pre-impact braking, and either benign air bag deployment or air bag suppression can be used to pass the injury criteria specified in this test. Initial research has involved hard braking tests in different vehicles and different initial seating procedures with the Hybrid III 6-year-old and 3-year-old dummies.

CRASH RECONSTRUCTIONS

NHTSA conducted crash reconstructions of real world injury and fatality cases involving children and air bag deployments from the National Automotive Sampling System (NASS). The main objective of the program was to compare the injury measures which resulted from the real world crashes to the injury measures recorded from the dummy instrumentation in the crash reconstructions. A secondary objective was to evaluate injury measures on the 5th percentile Hybrid III driver occupant. Six NASS cases were reconstructed in this program (three involved fatally injured children, one involved a seriously injured child, and two involved children with minor injuries.) Preliminary results indicate that neck injury measures recorded from the 6-year-old Hybrid III dummies were not always consistent with injuries to children of similar age and size in the selected NASS cases simulated by these tests. The reader is referred to a companion ESV paper for the specific details on the six reconstruction cases in the program [9].

EVALUATION OF NEXT GENERATION AIR BAG PERFORMANCE

Performance Testing

As a part of the advanced air bag research program, NHTSA is evaluating the performance of next generation air bag equipped vehicles. Since the introduction of 1998 model year vehicles, NHTSA's Office of Research and Development, Office of Vehicle Safety Compliance, and Office of Vehicle Safety Standards have conducted tests of 1998 model year vehicles that were certified using the unbelted sled test option of FMVSS No. 208.

NHTSA's Office of Research and Development conducted six 48 kmph rigid barrier crash tests with unbelted 50^{th} percentile male driver and passenger dummies in 1998 model year vehicles. Preliminary results indicated that all injury measures were below all current FMVSS No. 208 criteria with the exception of one test (the passenger chest Gs were slightly above 60 Gs). For these same six vehicle models, static out-of-position tests were also conducted with the 5^{th} percentile female Hybrid III adult dummy in two driver positions (Figures 1 and 2), and with the 6-year-old Hybrid III child dummy in Position 1 (Figure 3). Two additional static air bag deployment tests were conducted with the 6-year-old Hybrid III child dummy translated 100 mm and 200 mm away from the instrument panel. Preliminary out-of-position results indicate that, on average, chest and neck injury measures were slightly reduced from previous model year tests; however they still exceeded the injury assessment reference values.

In a joint research program with Transport Canada, ten 48 kmph rigid barrier crash tests and ten 40 kmph, 40% offset deformable barrier crash tests were conducted with belted 5^{th} percentile female driver and passenger dummies in 1998 model year vehicles [10]. Preliminary results from this program indicate that neck injury measures on the belted 5^{th} percentile female dummies continued to exceed NHTSA's injury assessment reference values in some of the 1998 vehicles. The problem of vehicle crash sensors firing late in the low speed offset deformable crash tests in some pre-1998 model year vehicles also continued to result in some of the 1998 vehicles. Therefore, improvements to reduce aggressivity to small belted females, and enhanced sensor performance in low speed crashes needs to further be achieved.

NHTSA's Office of Vehicle and Safety Compliance has also conducted unbelted sled tests and a small number of full scale vehicle crash tests (for vehicles that did not certify, or not fully certify, under the FMVSS No. 208 sled test option). Neck injury measurements were recorded in these tests; however they did not exceed the IARV's established for the 50^{th} percentile male Hybrid III dummy. NHTSA's New Car Assessment Program (NCAP) has also conducted rigid barrier frontal crash tests at 56 kmph with belted 50^{th} male Hybrid III dummies. Preliminary results indicate that many 1998 vehicles with next generation air bags performed satisfactorily in providing occupant protection for belted occupants in high severity collisions. The reader is referred to a companion ESV paper for information on NHTSA's frontal NCAP program [11].

Crash Investigations

In addition to crash testing, NHTSA's Special Crash Investigation (SCI) program is conducting investigations of real world crashes with next generation air bags. As noted earlier in the real world crash investigations section, NHTSA has implemented several early notification mechanisms to identify crashes, and has already initiated 56 investigations since April 1, 1998.

Initially, during the time period of October 1997 to January 1998, the SCI teams selected any case with a next generation air bag deployment. After January 1998, the following criteria was established to focus on cases of immediate interest to the agency.

- A child seated in a position where a next generation air bag has deployed.
- The crash was severe (delta V > 38.6 kmph)
- When a vehicle has driver and passenger in seat positions protected by a next generation air bag.
- When an injured driver or passenger are in a seat position protected by a next generation air bag and transported to a medical facility for treatment.

The agency anticipates investigating 100 crashes based on this criteria in fiscal year 1998 [3].

SUMMARY

Current regulatory steps toward reducing air bag aggressivity to out-of-position occupants fall short of eliminating the fatalities and serious injuries resulting from air bag deployment. NHTSA has initiated an extensive research program on advanced air bag technology to establish the technical basis for new vehicle performance requirements that lead to improved occupant crash protection. Tasks involve the development and certification of alternative test dummy sizes for incorporation into the Federal motor vehicle safety standards. Research is being conducted to establish corresponding injury assessment reference values for each test dummy, particularly in the neck and thorax regions. An advanced air bag technology assessment was conducted by JPL which projected the types of technologies that are being developed and may be available for model years 2001 and 2003. NHTSA conducted evaluations of some of these technologies through participation in the MVSRAC Advanced Air Bag Technology Working Group, and through other cooperative research programs. Test procedures have been developed for assessing overall air bag system performance and aggressivity issues for out-of-position occupants. Crash reconstructions were carried out to better understand and emulate the circumstances that occur in the real world and to enhance test procedure development. NHTSA has also evaluated the occupant crash protection afforded in 1998 model year vehicles with next generation air bags through various crash testing programs, as well as through static out-of-position tests.

FUTURE WORK

Future work in the Advanced Air Bag Technology research program will include improving test dummy biofidelity to support innovative sensor technologies, and the enhancement of injury criterion across the spectrum of occupant sizes. NHTSA will continue to test the performance of advanced air bag technologies, and refine test procedures and criteria to encompass a larger segment of the population, over a greater range of crash scenarios. NHTSA will continue to investigate real world crashes involving vehicles with next generation air bag systems and future advanced air bag systems, as they emerge. Finally, research will be continue to provide rulemaking support as needed.

REFERENCES

1. ____, "Final Regulatory Evaluation: Actions to Reduce the Adverse Effects of Air Bags, FMVSS No. 208, Depowering," National Highway Traffic Safety Administration, February 1997.

2. ____, "Third Report to Congress: Effectiveness of Occupant Protection Systems and Their Use," National Highway Traffic Safety Administration, Report No. DOT HS 537, December 1996.

3. Chidester, Augustus B., and Rutland, Kenneth W., "Air Bag Crash Investigations," 16th International Technical Conference on the Enhanced Safety of Vehicles, Paper No. 98-S6-O-02, Windsor, Canada, June 1998.

4. Kleinberger, M., Summers, L., "Mechanisms of Injuries for Adults and Children Resulting from Airbag Interaction," Forty-First Annual Proceedings of the Association for the Advancement of Automotive Medicine, Orlando, Florida, pp. 405-420, 1997.

5. Klinich, K. D., Saul, R. A., Auguste, G., Backaitis, S., Kleinberger, M., "Techniques for Developing Child Dummy Protection Reference Values, Event Report", October 1996.

6. Phen, R.L., Dowdy, M.W., Ebbeler, D.H., Kim, E-H., Moore, N.R., VanZandt, T.R., "Advanced Air Bag Technology Assessment", May 1998.

7. Rains, G., Prasad, A., Summers, L., "Assessment of Advanced Air Bag Technology and Less Aggressive Air Bag Designs Through Performance Testing", 16th International Technical Conference on the Enhanced Safety of Vehicles, Paper No.98-S5-O-06, Windsor, Canada, June 1998.

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

9. Stucki, S., "Results of Crash Tests to Reconstruct NASS Cases of Child Fatality/Injury from Air Bags," 16th International Technical Conference on the Enhanced Safety of Vehicles, Paper No. 98-S6-O-06, Windsor, Canada, June 1998.

10. Dalmotas, D., "Assessments of Air Bag Performance Based on the 5th Percentile Female Hybrid III Crash Test Dummy," 16th International Technical Conference on the Enhanced Safety of Vehicles, Paper No. 98-S5-O-07, Windsor, Canada, June 1998.

11. Park, B., Morgan, R., Hackney, J., "The Effect of Depowered Air Bags on Frontal USA NCAP," 16th International Technical Conference on the Enhanced Safety of Vehicles, Paper No. 98-S11-O-01, Windsor, Canada, June 1998.