FLIGHT SAFETY FOUNDATION
CABIN CREW SAFETY

Vol. 29 No. 6
Vol. 30 No. 1

For Everyone Concerned with the Safety of Flight

November–December 1994
January–February 1995

SPECIAL DOUBLE ISSUE

FAA Tests Indicate Most Child Restraint Devices Inadequate in Airline Passenger-seat Use

Devices designed for automobile seats do not readily adapt to airplane seats. Most were found to be impractical or useless. Only aft-facing carriers for children weighing less than 20 pounds fully met safety criteria, and even they would create inconvenience for nearby passengers. Nevertheless, FAA officials and other researchers say that any restraint is better than holding a child in an adult's lap during an accident. Advocates of improved restraints argue that children are currently being treated like 'carry-on baggage' and deserve the same safety protection as adults.

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[Editorial note: The issue of child restraints in aircraft cabins has been the subject of study and debate for more than 20 years. In 1992, the U.S. Federal Aviation Administration (FAA) ruled that airlines must allow the use of child safety seats, but did not mandate their use. The decision not to mandate the use of child restraints came despite urging from the U.S. National Transportation Safety Board (NTSB), flight attendant associations and major airlines to adopt such a rule. The FAA said its decision was based in part on research that indicated that mandating the use of child restraints might lead to additional child fatalities in automobile accidents if parents drive their automobiles rather than fly at greater expense (the purchase of an additional seat for the child). Under current FAA rules, infants under the age of two can be held in parents' laps, and airlines generally allow lap-held children to fly at no cost.

Despite evidence that certain types of restraints are deficient and its refusal to mandate child restraint use, the FAA has emphasized that children under the age of two are still safer in a certified child safety seat than when sitting on an adult's lap.

Nora Marshall, of the NTSB's aviation survival factors division, said that the FAA Civil Aeromedical Institute (CAMI) study described in this issue of *Cabin Crew Safety* is important because it clearly identified deficiencies in some restraints. "We need to focus now on solving the problems identified in this research," Marshall said.

Marshall added: "The NTSB still believes that children are better off restrained than unrestrained. Right now, children under two are still being treated like carry-on baggage. For the safety of the child and other passengers, every occupant should be restrained on an aircraft."

Marshall noted that post-accident escape and evacuation factors also play a role in addition to initial survival concerns and threats to the safety of other passengers (who can be seriously injured or killed if struck by children thrown in the cabin by the force of impact).

The NTSB's 1990 recommendation that "all occupants be restrained during takeoff, landing and turbulent conditions, and that all infants and small children below the weight of 40 pounds and under the height of 40 inches be restrained" followed an investigation of the 1989 crash of a McDonnell Douglas DC-10 in Sioux City, Iowa, U.S. Marshall said that an infant in that accident died of smoke inhalation after being thrown from its mother's lap. "That child's chances for survival might have been enhanced if a restraint had kept the child next to the mother," Marshall said. The NTSB accident report said that the 23-month-old boy "went flying down the right aisle toward the rear of the cabin" after the impact jolted the mother upright from a brace position with her son on the floor between her legs. The mother was not injured, but thick smoke prevented her from finding her son, the NTSB report said. The DC-10 made an emergency landing at Sioux City after an engine fan disk fragmented, damaging the aircraft's hydraulic system. Of the 296 people on board, 110 passengers and one flight attendant were killed.

"There is no way that any human being could hold a child during the kind of crash forces that you would see during an accident," said Jeffrey H. Marcus, manager of the FAA's protection and survival laboratory at CAMI. "[Arnold] Schwartzenegger couldn't do it."

Marcus, whose comments came during a Sept. 22, 1994, NTSB hearing on the crash of a USAir McDonnell Douglas DC-9 in Charlotte, North Carolina, U.S., in July 1994, added: "[Unrestrained children] get thrown all over the cabin, bounce all over the cabin and suffer fatal injuries. There is no question that every restraint that we tested offers a much better situation — with the possible exception of the belly belt — than the child just being held in the parents' arms. That is tantamount to no restraint."

Meg Leith, coordinator of air safety and health for the U.S.-based Association of Flight Attendants, agreed. "Even though the study pointed out deficiencies that are problems that need to be solved, we still feel that the use of some form of restaint mechanism, no matter how imperfect it may be, is better than holding a child on your lap. We urge parents to use restraints. Restraints are not a guarantee either, but one's chances are certainly increased. Shouldn't children be provided the same level of protection as other passengers?"

As part of a four-part plan to improve child passenger safety, the FAA has said that it would work with the U.S. National Highway Traffic Safety Administration (NHTSA) to revise standards for child safety-seat testing and labeling.

The following FAA study was launched after the NTSB recommended that further testing be conducted on how existing child restraints perform in crash scenarios and to determine what must be done to better adapt them for airline use. Additional NTSB recommendations relating to child restraints will likely follow completion of an investigation into the Charlotte DC-9 crash. A nine-month-old girl being held in her mother's lap was hurled from her mother's arms and killed in the accident. The plane crashed on approach to the airport during a heavy rainstorm, killing 37 passengers. Fifteen passengers and all five crew members survived the accident.]

Public awareness of the benefits provided by child restraints in automobiles has grown during the past decade. The U.S. National Highway Traffic Safety Administration (NHTSA) estimates that 4.5 million child restraints are sold yearly. The acceptance of approved child restraints by the public may escalate the use of child restraints in commercial air transport.

But there are important differences between airplane seats and automobile seats. The methods and fixtures used to certify child restraints may not measure effectively their performance in an airplane seat. With the advent of dynamic seat performance standards for modern airplane seats, it is important to determine the performance of child restraints in a test condition representing the airplane environment.

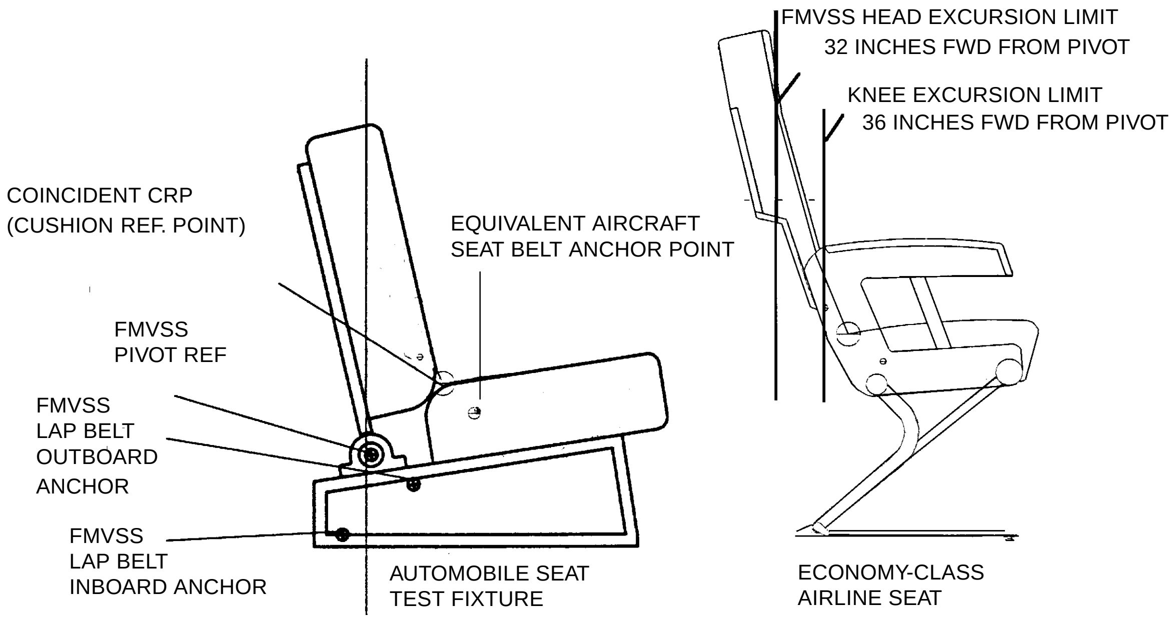
A project was initiated by the FAA Civil Aeromedical Institute (CAMI) Biodynamics Research Section to evaluate approved child restraint devices (CRDs) currently used in commercial air transport operations. There were no specific pass-fail criteria for the CRDs tested during this project. Rather, the objective was to evaluate performance factors such as installation difficulties, physical interface with the airplane seat, retention of occupant and injury potential (analyzed by biomechanical responses from anthropomorphic test dummies [ATDs]). The physical environment surrounding the seat-restraint installation in a transport airplane was represented in the test protocol.

Performance standards for child restraint systems sold in the United States are defined by Federal Motor Vehicle Safety Standard 213 (FMVSS-213).[1] The term "child restraint system" in FMVSS-213 applies to portable and built-in restraints. Indeed, occupant protection must be addressed from a systems approach that includes the vehicle seat, restraints and surrounding structures. For this article, CRD means the portable child restraint as distinguished from the overall passenger seat system.

Aviation Regulatory Policies Accept CRDs

In 1982, the FAA's first policy that allowed the use of CRDs in airplanes was issued in Technical Standard Order (TSO) C100. Formerly, the use of passenger-furnished child restraints was not allowed during takeoff or landing. Voluntary performance standards for child restraints in airplanes had been developed by industry.[2,3] Nevertheless, the FAA's policy, based

Comparison of Automobile Test Fixture and Economy-class Airplane Passenger Seat



Source: U.S. Federal Aviation Administration

Figure 1

on Federal Aviation Regulations (FARs) Part 121.311, stated that child restraints brought on board an airplane must be treated as carry-on baggage. [Part 121.311 regulates aircraft seats, safety belts and shoulder harnesses.]

TSO C100 defined two performance standards for CRDs in airplanes. The first was FMVSS-213 as amended in 1980. The second performance standard was defined in the TSO, specifying an 18 G, 22-feet-per-second dynamic test with the CRD installed on a "representative" airplane seat fixture. A list of TSO-approved CRDs was provided by the FAA.

At the recommendation of a U.S. Department of Transportation (DOT) report issued in 1983, TSO C100 was amended in 1985.[4] The dynamic test procedure was deleted from the TSO. FMVSS-213 was also amended to include a roll-over test for CRDs in airplane seats, and this NHTSA standard was designated by the DOT as the solitary standard for child restraints. "Approved child restraints" for air carrier operations in the United States were devices certified to meet the requirements of FMVSS-213. A CRD labeled as meeting FMVSS-213 could be allowed, at the discretion of the operator of the airline, as a child restraint.

Changes to the FARs in 1992 expanded the definition of approved child restraints to include any CRD that is labeled to meet United Nations or non-U.S. government standards.[5] The 1992 amendments explicitly removed the discretionary allowance of approved CRDs by the operator. Thus, if any approved CRD is furnished for a child holding a ticket, it must be allowed by the operator.

Simultaneously in 1992, the FAA amended Advisory Circular (AC) 91-62, which defined certain types of CRDs approved under FMVSS-213 that should not be used in airplanes. A CRD that positions the child on the lap or chest of an adult seated in a passenger seat should not be used, according to the AC. This is despite the fact a CRD of this type might be labeled to meet the requirements of a recognized international standard or non-U.S. regulatory authority. Other limitations for CRDs, such as seat location and proximity to an accompanying adult, were also contained in this AC.

The new policy information was published by the FAA in the form of a Flight Standards Information Bulletin (FSIB Number 92-23) concurrent with the amended FARs and AC. This FSIB contained the same information as AC 91-62.

Aircraft Seat Regulations Specify Test Criteria

Separate activity by the FAA in the 1980s resulted in improved performance criteria for aircraft passenger seats and crew seats.[6] Regulations adopted in 1988 defined measurable performance standards for assessing occupant protection from crash injuries as well as structural performance of the seat and restraint system. Dynamic impact test conditions and the pass-fail criteria are specified in the FARs. Two test conditions are specified, a horizontal and a vertical impact orientation. The responses recorded from anthropomorphic test dummies occupying the seats during the tests must indicate protection from serious injuries to the head, lower spine, femurs and chest.

Occupant injury caused by contact with structures and furnishings surrounding the seat installation must be considered in the certification procedures for the seat. Thus, impact tests for certification of airplane seats often include a representative seat-installation environment. Performance is measured as a system, rather than an evaluation of the components by separate tests.

The FARs also specify a 50th percentile ATD as the occupant for measuring impact responses. [Percentile is the percent of a distribution that is equal to or below it. A 50th percentile ADT represents an average adult.] The lap belt restraints on seats certified by the FARs must accommodate a range of occupant size from a two-year-old child to a 99th percentile male. There is no requirement for seats to accommodate CRDs, nor is there an FAA requirement to assess injury protection for occupants in CRDs installed in passenger seats. Thus, new airplane seat-performance regulations focus on adult-occupant injury protection. Providing additional protection by means of a CRD is at the option of the accompanying adult.

Child Restraint Performance Standards Define Approval Methods

The approval method in FMVSS-213 strictly specifies the test fixtures, procedures, impact conditions and pass-fail criteria. There is no provision for the performance of the CRD in a vehicle environment other than that for the defined test method. The fixtures used to certify CRDs do not represent the installation of a CRD in an airplane passenger seat.

Significant differences exist between fixtures specified in FMVSS-213 and the transport airplane passenger seat. Figure 1 (page 3) illustrates some of these differences, which can affect the overall performance of a CRD when dynamically tested. Some of the most notable differences are:

- Lap belts on the FMVSS-213 fixture are attached at locations that are geometrically different from those of a typical airplane passenger seat. The inboard and outboard belt anchor points on the automotive test fixture are at different heights. A line passing through the belt anchor points is not parallel to the lateral line defined by the seat back pivot axis. The lap belts on an airplane seat are usually located near a horizontal lateral line passing through the cushion reference point (CRP). This difference results in a more vertical lap belt path in an automobile compared with the CRD in the airplane seat.

- The seat back on the FMVSS-213 test fixture does not rotate forward in a manner representative of airplane passenger seats during the impact. It is common for airplane passenger seats to have breakover seat backs as a convenience feature. On seats with breakover backs, the seat back can be rotated forward to a horizontal position by pushing on the seat back, nominally with 30 pounds of force applied at the top of the back. (Regulations prohibit the installation of seats with breakover backs at certain locations in the cabin.) The combined effects of breakover seat backs and aft-row-occupant impact forces transferred through the seat back are not evaluated by FMVSS-213.

- A specific restraint system is not prescribed by FMVSS-213. Modern automobile restraints use a short fixed-length strap on one side. The tension of the belts and shoulder straps is automatically adjusted by the retractor mechanism in the inertia reel. Typically, an automobile buckle is positioned to the inboard side of the occupant when in use. Airplane passenger seat belts are manually adjusted, and the range of adjustment is limited. The buckle on an airplane passenger seat is centered over the lower abdomen when adjusted by an adult occupant.

- The buckle release mechanisms differ. Modern automobile buckles are smaller and have a push-button release. Airplane buckles are usually as wide as the two-inch webbing of the belts and have a lift-latch type release. Space above the buckle is required to lift the release plate when removing the belts.

- The available lateral space for the installation of a CRD on airplane seats is limited to the distance between the arm rests. On most economy-class seats, the arm rests can be raised to a stowed position, which provides additional space. Nevertheless, seats in some rows have nonstowable arm rests that may prevent installation of some CRDs. The FMVSS-213 fixture has no arm rests and provides a wide unobstructed cushion for CRD installation.

- Non-U.S. standards for child restraints differ from FMVSS-213. Canada and Australia require a tether strap to secure the CRD to a fixed point on the vehicle. The requirement for a tether strap will prohibit the installation of these devices on transport passenger seats unless the device has been approved for airplane use without the tether by the responsible authorities. Test fixtures and impact severity are also different among the non-U.S. standards. Nevertheless, non-U.S. approval methods also rely on automobile test procedures to measure performance. Thus, the effects of differences between automobile seats and airplane seats apply to non-U.S.-approved CRDs as well those approved in the United States.

Table 1
Child Restraint Device Types Evaluated in Test Program

CHILD RESTRAINT IDENTIFIER	MODEL	TYPE	OCCUPANT DESCRIPTION
A	CENTURY COMMANDER	BOOSTER	30 TO 60 POUNDS
B	KOLCRAFT TOT-RIDER QUICKSTEP	BOOSTER	
C	CENTURY CR-3	BOOSTER	
D	COSCO EXPLORER 1	BOOSTER	
E	BRITAX (UK AUTOSEAT)	CONVERTIBLE	AFT-FACING LESS THAN 20 POUNDS FORWARD-FACING 20 TO 40 POUNDS
F	KOLCRAFT DIAL-A-FIT II	CONVERTIBLE	
G	FISHER PRICE CAR SEAT	CONVERTIBLE	
H	EVENFLO WONESTEP 402	CONVERTIBLE	
J	CENTURY 3000STE	CONVERTIBLE	
K	EVENFLO W7	CONVERTIBLE	
L	CENTURY 2000	CONVERTIBLE	
M	COSCO TLC INFANT CAR SEAT	AFT-FACING	LESS THAN 20 POUNDS
N	EVENFLO JOYRIDE CAR SEAT	AFT-FACING	
P	CENTURY 580 INFANT CAR SEAT	AFT-FACING	
Q	CENTURY 4500 INFANT LOVESEAT	AFT-FACING	
R	CENTURY 4560 SDL	AFT-FACING	
S	AVIATION FURNISHINGS CARE CHAIR 2040	FORWARD-FACING	6 TO 36 MONTHS
T	LITTLE CARGO	HARNESS	25 TO 40 POUNDS
BELLY BELT	LAP-HELD CHILD RESTRAINT		0 TO 24 MONTHS
LAP BELTS	GENERIC—STANDARD LAP BELTS		ANY AGE

Source: U.S. Federal Aviation Administration

There are similarities between the pass-fail criteria in FMVSS-213 and FARs Part 25.562. [Part 25.526 regulates seating and restraint conditions needed to meet the dynamics of emergency landing conditions.] Both have requirements for structural integrity. Head injury protection, measured by the Head Injury Criteria (HIC), is specified in both regulations. The HIC is determined from a numerical computation performed on head-acceleration data. If the value resulting from the HIC computation exceeds 1,000, which is considered as an indication of the onset of serious injury, the criteria in the regulations are not met. Under the FARs, the HIC applies only in cases of head contact with surrounding structures. Certification of airplane seats often includes representative structures and furnishings near the seat installation. HIC is also computed from the FMVSS-213 test procedure. Nevertheless, no structure is placed in front of the CRD in testing for the automotive standard. The only potential head-strike structures are the CRD and the padded seat fixture. A maximum head-forward excursion limit of 32 inches (82 centimeters) from the seat-back pivot axis is specified in FMVSS-213. This forward excursion distance represents the clearance for a CRD installed on the front passenger seat in an automobile.[7]

The impact severity for the horizontal test condition in Part 25.562 is significantly less than the required test in FMVSS-213. The peak deceleration in FMVSS-213 is a minimum of 24 Gs. The minimum peak acceleration in Part 25.562 is 16 Gs. The FARs require a second test condition in a vertical-impact orientation. For transport category aircraft, the vertical-impact severity is less than the horizontal test severity. Its main purpose is to ensure that occupant spinal loads do not exceed a specified criterion of 1,500 pounds.

Another important difference exists between the pass-fail criteria of the two regulations. Any evidence that the lower torso restraints load the abdominal region above the pelvis is cause for rejection by the FARs. FMVSS-213 does not prohibit abdominal loading. In fact, the primary load path for some CRDs is directly into the upper abdominal region.

Three Performance Factors Were Examined

Three performance factors were examined by dynamic-impact sled tests with CRDs.

Fit and Adjustment. The compatibility of the CRD with a passenger seat and lap belt was addressed by this factor, including proper adjustment of the CRD installed in a passenger seat. Ergonomics and potential misuse or incorrect installation were also considered.

Figure 2. Three-year-old ATD wearing harness-type restraint device.

Dynamic Performance. This factor was based on an evaluation of impact test results with the CRD installed in an airplane passenger seat. The dynamic test condition was the 16 Gpk (peak G of the test), 44-feet-per-second impact pulse as defined in Part 25.562. The evaluation included dynamic displacement, interaction with breakover seat backs and compatibility with the lap belts. Occupant head excursion was also included in this factor.

Occupant Protection. Occupant protection was assessed from biomechanical responses measured from the child ATDs. Included were head and chest accelerations required for approval under FMVSS-213. The pass-fail criteria in the automotive regulation require that the resultant chest accelerations not exceed 60 Gs for more than three milliseconds. Potential head injury was assessed by the HIC. Head acceleration data were acquired only in tests where head contact with structures occurred. An experimental method to measure abdominal forces induced by the CRD was also evaluated.

CRD Test Specimens Included Six Types

Table 1 (page 5) lists the models of child restraints evaluated in this test program. The CRDs provided for this dynamic test project were classified into five types, and normal passenger-seat lap belts were included as the sixth type of restraint system. The six types of CRDs are described by the following:

1. Booster Seat. Booster seats are designed for children who weigh 30 pounds to 60 pounds. These seats are a raised platform base on which the child sits. A front shield, over which the lap belt is routed, covers the abdominal area of the occupant. Booster seats do not have a back or side shell. There are no integral belts to restrain the child. Depending on the model, some booster seats can be used without the front shield if a shoulder strap is available. Four booster seats were tested in this project. All were labeled as meeting FMVSS-213 requirements and certified for use in airplanes.

2. Forward-facing Convertible Carrier. These devices are designed to be installed facing forward in the vehicle seat for children weighing more than 20 pounds. For children who weigh less than 20 pounds, the convertible carrier CRD is installed facing aft. Many of these CRDs have a maximum occupant weight restriction of 40 pounds. All convertible carriers provide shoulder straps as part of the CRD. This type of CRD has a back- and side-protection shell. Not all models of convertible carriers have a rigid front shield. Some have a padded "Y" plate integral to the shoulder straps on the CRD. These devices are usually installed by routing the vehicle lap belts through a path provided on the back of the forward-facing CRD. Six FMVSS-213-approved convertible carriers and one U.K.-approved (ECE-44) convertible carrier were tested.

One forward-facing carrier included was a CRD designed specifically for use in an airplane passenger seat. CRD S (Table 1) was designed for forward-facing installation. The range of occupant size for CRD S was children between the ages of six months and three years. It includes an integral five-point restraint with a rotary release buckle. The seat back is hinged to allow the device to fold for storage in an overhead bin. This device met the European Community Standard (ECE-44) for child restraints.

3. Aft-facing Carrier. These CRDs are only for children weighing less than 20 pounds. There is no shield over the chest or abdomen of the child. Adjustable shoulder straps are integral to the CRD. Typically, an aft-facing carrier is installed by tightening the vehicle seat lap belt through slots on the top side of the CRD. This type of device should not be installed forward- or side-facing, i.e., the CRDs are nonconvertible. Five aft-facing nonconvertible carriers were tested. All five aft-facing CRDs were sold in the United States and certified for use in airplanes.

4. Torso Harness. The fourth type of CRD is a torso harness designed for children weighing between 25 pounds and 40 pounds. These are forward-facing restraints fabricated with webbing. There is no rigid shell or platform with these harness devices. The CRD attaches to the vehicle's lap belt by passing the belt through a loop sewn on the back side of the harness. Harness systems are relatively new products. They have the convenience of being lightweight, compact and easy to install. There are at least three models that currently meet the requirements of FMVSS-213 and are certified for use in airplanes.

5. Lap-held Child Restraint. Commonly identified as the "belly belt," this device restrains a small child (less than two years old) on the lap of an adult. Although not approved for use in automobiles by any standards, the belly belt is certified for use in airplanes by the U.K. Civil Aviation Authority.

6. Passenger Seat Lap Belt. Children of any age are allowed to be restrained by the lap belts provided on the passenger seat. Therefore, tests with normal lap belts were conducted for comparison with the add-on devices described in types 1 through 5.

Anthropomorphic Test Dummies (ATDs) Were of Three 'Ages'

Four types of child ATDs were used in these tests. Two were standard child ATDs as defined in 49 Code of Federal Regulations (CFR) Part 572: the ATD representing a three-year-old specified in Part 572-C (Figure 2, page 6) with instrumentation, and an ATD representing a six-month-old, the noninstrumented "bean bag" specified in Part 572-D. The third type was an articulated ATD representing a six-month-old, identified as the "Child Restraint and Air Bag Interaction" (CRABI) dummy being developed by the Society of Automotive Engineers (SAE) Infant Dummy Task Group.[8] The CRABI dummy has provisions for head and chest instrumentation. The fourth ATD was an experimental ATD representing a two-year-old, identified as CAMIX.

The CAMIX ATD measures abdominal pressure loads induced by restraint systems during dynamic tests. The ATD includes articulated limbs, a cast metal pelvis and an abdominal cavity for fluid-pressure instrumentation. The pressure-measurement system was based on a water-filled intravenous fluid bag. A pressure transducer was attached to the fluid bag by a plastic tube. Abdominal pressure instrumentation was also installed in the six-month-old CRABI ATD for selected tests.

There were no established injury criteria for this abdominal pressure measurement, but avoidance of loads in the soft tissues of the abdomen was considered a critical factor in restraint performance. Previous studies to measure abdominal intrusion and pressure in CRD tests have identified this factor as an important component of restraint performance.[9,10] Part 25.562 requires lap belt restraints to remain on an adult ATD's pelvis during the impact test. Any indication that the belts move above the prominence of the anterior iliac spine of the test dummy, thus loading the abdomen, is cause for rejection of the seat certification.

A 50th percentile Hybrid II male, specified in Part 572-B, was used in tests to evaluate the lap-position belly-belt CRD. The 50th percentile ATD was also used to induce aft-row-occupant impact loads on breakover seat backs.

Passenger Seats Were Economy-class Standard

Economy-class triple-position air transport passenger seats were obtained for this project. The seats, typical in construction and dimensions of passenger seats currently in service, were complete assemblies with armrests, backs, tray tables and cushions. Standard passenger-seat lap belts were provided with the seats.

The only modification made to the seats was a seat-back breakover-lockout plate that was installed on selected tests to inhibit forward rotation of the seat back. For tests with seat-back breakover, the breakover mechanism was adjusted to allow forward rotation of the seat back with a 30-pound horizontal force applied at the top of the tray table.

This project was conducted at the CAMI Biodynamics Research Section dynamic impact laboratory. Fixtures and test specimens were installed on a ten- by five-foot sled, mounted on a 150-foot rail track. The sled is accelerated gently (<0.4 G) to the impact velocity by means of a falling weight attached through a wire rope and pulley system. A controlled deceleration pulse is produced with a wire brake mechanism.

Fixtures were installed on the sled to mount the seats in forward orientation. There was no yaw or pitch relative to the impact vector. The fixtures on the sled permitted single-row and double-row installations of the passenger seats. Double-row tests were conducted with 32-inch seat pitch, which is representative of an economy-class cabin. [Seat pitch refers to the distance between a point on a seat and the equivalant point on the seat forward or aft of it.] In most tests, more than one CRD was installed in the triple-position passenger seats. Vertical-impact tests were all conducted on single-row seats.

Photometric cameras were positioned on both sides of the impact area to provide accurate coverage of the left and right seating positions when multiple-occupant tests were conducted. High-speed video recordings were obtained from a "best view" camera perspective for qualitative analysis.

Three Types of Seat Configurations Were Tested

The primary variable of the tests was the configuration of the passenger seats. Three types of configurations were conducted: (1) single row, (2) double row and (3) vertical orientation. These configurations are defined as follows:

Single-row Tests. Single-row test configurations were conducted to evaluate the CRD's performance without interaction from aft-row occupant loads. Important measurements obtained from the single-row tests were the maximum excursions of the CRD and ATD. Both locked and unlocked seat backs were included in the single-row tests. This test configuration is similar to the FMVSS-213 test orientation.

Double-row Tests. A number of different variables were investigated using the double-row test setup. With CRDs installed in the forward-row seats, it was possible to evaluate the effects of an adult occupant in the aft row impacting the forward seat back and its occupant. Placing the CRDs in the aft row provided head-impact responses if the deflection of the CRD resulted in head contact of the child ATD against the forward-row seat. The placement of CRDs in the aft row also provided data regarding installation problems, such as contact interference with the forward row seat and cross-aisle blockage. Double-row tests were also conducted with the belly-belt CRD.

Vertical Orientation. The impact orientation for vertical tests was that specified in Part 25.562. This is not a pure vertical impact condition. The impact-velocity vector is angled 30 degrees below the horizontal axis of the vehicle. In this orientation, 86 percent of the impact-momentum vector is parallel with the vertical axis of the seat. Only aft-facing CRDs were tested in the vertical orientation.

Most CRD Types Performed Poorly

Of the four booster CRDs tested in this series, three had fit and adjustment problems. Installation difficulties with one CRD were attributed to the limited width between arm rests on the airplane passenger seat. The incompatibility between the buckle and the webbing path molded in the front shield on two booster CRDs altered the web path and buckle position of the tightened lap belts. The resulting variance in the webbing path over the front shield did not comply with the manufacturer's instructions, indicating that they cannot be correctly installed in an airplane seat.

One of the four booster CRDs failed structurally during the 16 Gpk, 44-feet-per-second test. The potential for head impact on a forward-row locked seat back at 32-inch pitch was measured from photometric data with three-year-old ATDs tested in the three other booster CRDs. The maximum forward head excursion from tests with two of the CRDs exceeded the distance allowed in FMVSS-213, which has a more severe impact test condition.

The peak abdominal pressure response from the CAMIX ATD was significantly higher in the test with seat-back breakover and aft-row-occupant impact on the seat. The highest peak chest acceleration from a three-year-old ATD was also measured in the same test configuration. Data from tests conducted with no aft-row-occupant impact did not exhibit a significant effect on abdominal pressure or chest acceleration due solely to seat-back breakover.

The following results and observations from this series are arranged by CRDs as classified above. The performance of each class of CRD is summarized according to performance factors.

Forward-facing Convertible Carriers. Eight models of CRDs were tested, including one non-U.S. device built specifically for use in an airplane passenger seat. The test matrix included five double-row tests with the CRDs installed in the rear seat. The forward-row seat was unoccupied and the seat backs were locked in the double-row tests. All tests of forward-facing convertible seats were conducted with the standard three-year-old ATD instrumented to measure head and chest accelerations. The two single-row tests were conducted to measure the three-year-old ATD's head excursion with this type of CRD.

Two of the forward-facing convertible CRDs could not be secured satisfactorily in the airplane passenger seat. HIC results were above 1,000 in double-row tests with six of the eight forward-facing convertible CRDs tested in this series. Fit and adjustment problems, particularly with the interface to the airplane seat lap belts, resulted in forward excursion of the CRDs during dynamic tests. There were no significant structural failures. Peak chest accelerations were less than the maximum of 60 Gpk defined in FMVSS-213.

By moving the seat-belt anchor point on the passenger seat aft to the seat-back-recline pivot bolt, a more effective load path for restraining the CRDs was demonstrated. Head excursions were significantly reduced with the modified anchor point. No forward-seat head contact resulted for any of the three CRDs tested with the new anchor point. This modified belt installation also reduced the difficulties of installing a CRD in the confined space of a passenger seat.

Aft-facing Carriers. Eight aft-facing CRDs were tested in this project. Two tests with aft-facing CRDs were performed in the vertical orientation. The vertical tests were conducted under the impact conditions specified in Part 25.562, i.e., 14 Gpk with a velocity of 35 feet per second.

There were two types of aft-facing CRDs. The first type was the nonconvertible "aft-facing-only" CRD. The second type was the convertible carrier CRD installed facing aft in the airplane passenger seat. Three horizontal tests in this series were double-row, with one aft-facing CRD in the forward row and one in the aft. The seat back on the forward-row seat was locked. Seat-back breakover was allowed to occur on the aft row. A standard six-month-old ATD was placed in the forward-row CRD, and the CRABI ATD was restrained in the aft row. Four single-row tests with the CRABI ATD completed the horizontal test matrix.

Applying the three performance factors of this project, the five nonconvertible aft-facing CRDs tested in this series performed well. This is the easiest type of CRD to install in an airplane passenger seat. Some of the convertible CRDs could not be secured facing aft in the airplane seat if the insert fitting on the fixed-length belt was situated in the guide slot on the CRD. The interference prohibited buckling of the belts on some CRDs, and prevented the webbing lock mechanism internal to the lap belt buckle from engaging on others. Both types of aft-facing CRDs overhang the airplane seat cushion, and passage in the space between seat rows was blocked by the CRD. These CRDs' overhang may also interfere with the forward-row seat-back-recline motion.

The dynamic performance and occupant protection for both types of aft-facing CRDs conformed to the requirements of

FMVSS-213. Also, retention of the CRD in the airplane seat and restraint of the ATD were considered acceptable based on the vertical tests of these devices.

Harness Restraints. One harness-type restraint device, CRD T, was tested. Shown in Figure 2 (page 6), this model was designed for children of 25 to 40 pounds. The CRD was constructed as a torso harness with padded adjustable straps over the shoulders and around the waist. A Gz strap (crotch strap) was included on this CRD. The shoulder and abdomen straps were attached to a rectangular metal plate, approximately 10 inches by nine inches, positioned on the back of the ATD. The airplane-seat lap belts were routed through a loop of webbing attached to the metal back plate on the CRD according to the manufacturer's instructions. Two single-row tests with this device were performed.

Because of the limited adjustment range and anchor location of the airplane-seat lap belts, the harness restraint could not satisfactorily restrain the motion of the three-year-old ATD. When the CRD was installed according to the manufacturer's instructions, the loose tension of the lap belts did not provide a secure restraint. The experiment with an air mattress as a spacer between the ATD and the seat back on these tests did not significantly affect the poor interface between the harness and lap belts. Gross displacements, forward and down, were observed in the first test. Modifying the seat and rigging the lap belts through an elaborate wrap-and-twist procedure produced improved results in the second test. Nevertheless, the modified installation method would not be practical or even possible with most airplane seats.

Lap-held Child Restraint (Belly Belt). The belly belt, a short loop of webbing with standard buckle hardware installed on the ends, is buckled around the child's abdomen. It is secured to the adult's belt by routing the seat belt through a small loop of webbing sewn on the belly belt. Thus, the child is restrained by an abdominal belt attached to the adult's lap belt.

The belly belt is not certified under any automotive standard. In fact, carrying a child on the lap in a moving automobile is illegal in the United States. Some belly belts are labeled as meeting the requirements of FAA TSO C22, basically a static strength standard for aviation restraints. There are no known performance standards for the belly belt.

Two key effects of the belly-belt restraint were investigated in these tests. First, the ATDs were instrumented to measure abdominal pressure resulting from restraint loads concentrated on the abdomen. Second, tests were conducted to observe and measure potentially injurious contact forces on the lap-held child created by the adult flailing and impacting the forward-row seat. The effects of aft-row occupant impact combined with seat-back breakover were included in the fourth test.

The data and observations from the four tests with the belly belt did not produce any favorable results. The impossibility of protecting a small child sitting on the lap of an adult restrained by a seat belt was confirmed in these tests. Severe contact with the forward-row seat back was observed during double-row tests. The recorded head impact of the six-month-old CRABI ATD resulted in an HIC above 1,900. Abdominal pressures from the CAMIX ATD were 50 percent greater than data from booster-seat tests under similar conditions. Aft-row-occupant impact on the breakover seat back resulted in a definitive peak in the abdominal pressure data. Based on biomechanical data as well as observations of the films from these tests, the belly belt should not be used to protect small children.

Normal Lap Belts. The first test was conducted with the two-year-old CAMIX ATD restrained by lap belts. Seat-back breakover and aft-row-occupant impact forces were not included on the first test. The second test had three-year-old ATDs restrained by the normal lap belts in the forward and aft row of a double-row test. A third test had an adult ATD in the aft row with a lap-belt-restrained three-year-old ATD in the forward row. The final test with normal lap belts included the CAMIX restrained in a seat with a breakover back in the forward row, and an adult ATD in the aft row.

The six-month-old test dummies were too small for the minimum adjustment range of the lap belts. Also, children weighing less than 20 pounds cannot be safely restrained in a forward-facing restraint.

The fit and adjustment of airplane-seat lap belts used to restrain the three-year-old ATDs was satisfactory, although the lap belts were near the minimum adjustable length with this size occupant. Results from dynamic tests indicated that the basic performance of lap belts with three-year-old, 33-pound occupants was marginal by existing standards.

Accommodation of the CAMIX ATD in lap belts was considered marginal. A tight fit was not achieved with the minimum-length-adjusted belts. The relatively loose fit of the belts and the smaller pelvis of the CAMIX resulted in a greater head excursion than was observed with the three-year-old ATDs.

A head strike against structure in the seat that a three-year-old ATD occupied was recorded during two tests. The HIC result calculated from one of the head strikes was 1,002, which is unacceptable in both FAA and NHTSA regulations. Slight variations in the seat pitch or dynamic deflection of the seats could result in head contact with the forward-row seat. Motion analysis of the three-year-old ATD's head path during these tests revealed the potential for high-velocity head impact on the forward-row seat. If the seat pitch was reduced or the seat back did not move during the impact, the ATD's head would impact the tray table with a relative velocity of approximately 38 feet per second.

Abdominal loads measured with the CAMIX ATD restrained in lap belts were affected by seat-back breakover and aft-row-occupant impact. The lap belts remained across the pelvis throughout the impact and did not appear to directly load the abdomen. Nevertheless, a significant peak was noted in the abdominal response coincidently with the aft-row occupant striking the seat back.

Caution should be exercised when comparing the performance of lap belts vs. automotive CRDs presented in this report. The restraint load distribution for lap belts is concentrated across the two-inch-wide path across the pelvis. These loads are usually distributed over multiple load paths with wider surfaces in automotive CRDs. Thus, the local contact forces are lower with automobile CRDs. Also, injury mechanisms other than head and chest accelerations should be considered for lap-belt-restrained children.[11] Automobile accident studies have identified potential injuries to the abdomen and spine associated with belt-restrained children.

Poor Adaptation Is Main Problem

Based on the results from the series of impact tests conducted in this project, the performance of certain types of child restraint devices does not enhance safety for children in transport airplane passenger seats. Protection for children restrained in certain types of CRDs traveling by automobile cannot be equalled in an airplane seat. A level of safety, as defined in Part 25.562, equal to that provided for adult passengers cannot be demonstrated with some CRDs when tested in transport airplane seats. In fact, these tests demonstrated that some types of CRDs should not be used in airplane passenger seats.

The main reason for the unsatisfactory performance of some types of CRDs in airplanes is that CRDs are designed to meet an automotive requirement, FMVSS-213, and do not necessarily adapt properly to an airplane seat. Test fixtures, restraints and pass-fail criteria specified in the automotive standard do not serve as a valid test for a CRD in an airplane seat. In particular, the restraints on airplane seats differ significantly from those on the test apparatus in the automotive standard in anchor point geometry, tension adjustment and buckle hardware. These differences can adversely affect the performance of a CRD designed primarily for the automobile.

In addition to the performance of CRDs exposed to impact test conditions, the accommodation of some CRDs is not satisfactory in airplane passenger seats. Models that require 17 inches or more of lateral space for installation may not fit in seats with fixed arm rests. Forward overhang of aft-facing devices can block the passage of adjacent passengers and interfere with the seat-back recline motion of the forward row seat. Depending on the specified path for routing the lap belts to secure the CRD to the seat, interference with lap-belt buckle hardware can prohibit proper installation.

The airplane seat structure and narrow seat pitch in the economy class cabin are additional reasons for unsatisfactory performance with some CRDs. In the FMVSS-213 test procedure for forward-facing seats, the excursion limit for the ATD's head exceeds the distance to the forward-row seat back in typical economy-class cabin seats. Also, the consequences of seat-back breakover on airplane passenger seats, combined with aft-row-occupant impact on the seat back, are not considered in the automotive test procedure.

These conclusions do not mean that it is dangerous for children to travel in commercial transport airplanes. Commercial aviation is a very safe mode of transportation. Rather, this information is presented to identify a particular component of passenger safety, child restraints, that may not meet the expected levels of performance in an accident. The observations in this report are provided to encourage the aviation community, restraint manufacturers and government agencies to further enhance safety for children traveling in airplanes.♦

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