UMTRI-2003-19

DEVELOPMENT OF SURROGATE CHILD RESTRAINTS FOR TESTING OF OCCUPANT SENSING AND CLASSIFICATION SYSTEMS

Matthew P. Reed
Sheila M. Ebert

University of Michigan Transportation Research Institute

Biosciences Division

September 2003

DEVELOPMENT OF SURROGATE CHILD RESTRAINTS FOR TESTING OF OCCUPANT SENSING AND CLASSIFICATION SYSTEMS

Final Report

by

Matthew P. Reed
Sheila M. Ebert

Biosciences Division
University of Michigan Transportation Research Institute

UMTRI-2003-19

Submitted to:

Alliance of Automobile Manufacturers

September 2003

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTRI-2000-19		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
DEVELOPMENT OF SURROGATE CHILD RESTRAINTS FOR TESTING OF OCCUPANT SENSING AND CLASSIFICATION SYSTEMS	5. Report Date: September 2003 6. Performing Organization Code
7. Author(s): Reed, M.P. and Ebert, S.M.	8. Performing Organization Report No.: UMTRI-2003-19
9. Performing Organization Name and Address: The University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, Michigan 48109-2150 U.S.A.	10. Work Unit no. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address: Alliance of Automobile Manufacturers	13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report describes the design and development of a set of surrogate child restraints that are intended for use in developing and testing occupant sensing and classification systems. Detailed measurements were made of the geometry and mass characteristics of 34 commercial child restraints, including infant restraints, convertibles, combination restraints, and boosters. The restraints were installed in three test seats with appropriately sized crash dummies to obtain data on seat-surface pressure patterns and the position and orientation of the restraint with belt loading. The data were used to construct two surrogate child restraints with removable components. The convertible surrogate can simulate a rear-facing infant restraint with or without a base, a rear-facing convertible, or a forward-facing convertible. The booster surrogate can represent a high-back belt-positioning booster, a backless booster, or a forward-facing-only restraint with a five-point harness. The surrogates were designed to meet geometric and mass targets obtained by taking the mean values for analogous dimensions in each child restraint category. Data analyses showed that the dimensions and performance of the surrogates quantitatively represent the commercial restraints in each category.

17. Key Words		18. Distribution Statement	
Airbags, Child Restraints, Advanced Airbags, Occupant Sensing, Occupant Classification		Unlimited	
19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
None	None	36	

CONTENTS

ABSTRACT 1

1.0 INTRODUCTION 3

2.0 CHARACTERIZATION OF COMMERCIAL CHILD RESTRAINTS 5

- 2.1 Selection of Child Restraints for Study 5
- 2.2 Measurement of Child Restraint Geometry and Mass 8

3.0 IN-SEAT MEASUREMENT OF COMMERCIAL CHILD RESTRAINTS 11

- 3.1 Laboratory Equipment and Procedures 11
- 3.2 Data and Dependent Measures 14

4.0 DEVELOPMENT OF SURROGATE CHILD RESTRAINTS 19

- 4.1 Concept Development 19
- 4.2 Representing Commercial Child Restraints 20
- 4.3 Geometric and Mass Specifications 22
- 4.4 Prototypes 24
- 4.5 Evaluation of Final Prototypes 27

5.0 DISCUSSION 33

6.0 REFERENCES 35

ACKNOWLEDGEMENTS

The authors acknowledge the valuable assistance of Steve Moss and Mike Carlson from First Technology Safety Systems, Inc., who were responsible for the development and fabrication of the hardware. Thanks also to the members of the Joint Working Group convened by the Alliance of Automobile Manufacturers to oversee this work.

FIGURES

Figure		Page
1.	Digitizing child restraint geometry.	9
2.	Data point cloud for one child restraint.	9
3.	Vehicle mockup for testing, second vehicle seat, and standard seat.	11
4.	Testing in the vehicle mockup.	13
5.	Rear-facing infant seat with detachable base.	13
6.	Xsensor pressure distribution measurement system installed under a child restraint.	15
7.	Example of seat surface pressure distribution.	16
8.	Pressure distributions on the seat cushion surface from selected restraints.	17
9.	Geometric data from one in-seat trial.	18
10.	Definitions of child restraint dimensions.	24
11.	The first and second prototypes of the convertible surrogate.	25
12.	Final convertible surrogate prototype.	26
13.	Final booster surrogate prototype.	26
14.	Pressure distributions produced by the surrogates and commercial restraints.	29
15.	Overlay of commercial child restraint and convertible surrogate geometry.	30
16.	Overlay of commercial child restraint and booster surrogate geometry.	30
17.	Schematic of dependent measures representing in-seat child restraint position.	31

TABLES

Table		Page
1.	Child Restraints Used in Program	6
2.	Tested Child Restraints	7
3.	Child Restraint Mass Distributions by Configuration	10
4.	Test Matrix	12
5.	Points Digitized in Mockup Testing	15
6.	Convertible Surrogate Specifications	23
7.	Commercial Restraint and Prototype Surrogate Masses	27
8.	Surrogate and ATD Masses Relative to Targets	28
9.	Performance of the Convertible Surrogate	21

ABSTRACT

This report describes the design and development of a set of surrogate child restraints that are intended for use in developing and testing occupant sensing and classification systems. Detailed measurements were made of the geometry and mass characteristics of 34 commercial child restraints, including infant restraints, convertibles, combination restraints, and boosters. The restraints were installed in three test seats with appropriately sized crash dummies to obtain data on seat-surface pressure patterns and the position and orientation of the restraint with belt loading. The data were used to construct two surrogate child restraints with removable components. The convertible surrogate can simulate a rear-facing infant restraint with or without a base, a rear-facing convertible, or a forward-facing convertible. The booster surrogate can represent a high-back belt-positioning booster, a backless booster, or a forward-facing-only restraint with a five-point harness. The surrogates were designed to meet geometric and mass targets obtained by taking the mean values for analogous dimensions in each child restraint category. Data analyses showed that the dimensions and performance of the surrogates quantitatively represent the commercial restraints in each category.

1.0 INTRODUCTION

The revision of the U.S. Federal Motor Vehicle Safety Standard (FMVSS) 208 adopted in May 2000 mandated changes in airbag systems that are intended to protect vehicle occupants from airbag-induced injury. For the front passenger position, manufacturers must certify that the frontal airbag system complies with the requirements of one of two options. Under the suppression option, the airbag deployment must be automatically suppressed under specified test conditions. Under the low-risk-deployment option, crash dummy performance measures must not exceed specified values during testing with dummies in a variety of positions. The manufacturer must select a certification option for each of the 12-month-old, three-year-old, and six-year-old ATD categories. A dynamic suppression option is also available for the three-year-old and six-year-old categories.

One of the requirements of the suppression option is that the airbag must be deactivated, as indicated by a telltale light on the instrument panel, when any of a list of child restraints is placed in the passenger seat with an appropriate ATD in a variety of configurations. The test configurations include a range of vehicle seat positions and seatbelt tensions. When the suppression test procedures using child restraints were first proposed, the Alliance of Automobile Manufacturers raised a number of concerns, including the following:

Availability – The child restraints selected by NHTSA might not be continuously available during the development of a vehicle.

Consistency – Because child restraint manufacturers can vary some specifications of their products without notice, a nominally identical restraint that NHTSA used for compliance testing might be substantially different from one used by a manufacturer in vehicle development.

Durability – Commercial child restraints are not designed for durability during prolonged testing involving repeated installations with ATDs. The properties of a restraint might change during repeated use in ways that cause it to differ from the restraints that NHTSA might use in testing.

Number of Test Conditions – Because the rule specifies testing with several parameters (seat position, seatbelt tension, etc.) varying over a wide range, hundreds of trials would be required to test all of the restraints on the list in all of the applicable conditions.

Moving Target – In the May 2000 final rule, NHTSA indicated that the list of child restraints would be updated periodically and published a revised list in December 2001. The possibility that the list will be updated annually means that the restraints to be used in certification of a vehicle may not be the same as those available when a vehicle is in development.

In response to these concerns, the Alliance initiated and sponsored the current project to develop a set of surrogate child restraints (SCRs) for use in non-deployment testing of occupant detection and classification systems. Although the original goal was to produce tools for use in the testing required under the suppression option of FMVSS 208, the scope expanded to include a range of occupant sensing and classification applications for which standardized representations of child restraints are valuable.

Responding to these concerns and goals, the SCRs are intended to be:

- quantitatively representative of several categories of commercial child restraints;
- constructed to published and verifiable specifications;
- durable; and
- continuously available;

This report describes the development and initial evaluation of the SCRs, which proceeded in five major phases.

1. Commercial child restraints, including those on the NHTSA list, were obtained. Detailed measurements of the child restraint geometry and mass were taken to create a database from which the SCR specifications could be derived.

2. The child restraints were installed with appropriate ATDs in vehicle seats. The wide range of test conditions spanned those specified in FMVSS 208 for suppression compliance testing. The position and orientation of the child restraints, as well as the seat surface pressure distributions, were recorded.

3. The data from the commercial child restraints were used to develop geometric, mass, and performance specifications for the surrogates based on the mean values for selected dimensions in each child restraint category.

4. First Technology Safety Systems developed the surrogate hardware through several prototype iterations in collaboration with the UMTRI team.

5. The SCRs were measured in the conditions previously used with the commercial child restraints to quantify the representativeness of the surrogates.

2.0 CHARACTERIZATION OF COMMERCIAL CHILD RESTRAINTS

2.1 Selection of Child Restraints for Study

Thirty-four commercial child restraints were obtained through retail stores, manufacturers, and Alliance members. Tables 1 and 2 list the child restraints that were used in testing. The list includes all of those on the May 2000 and December 2001 lists in FMVSS 208, except for one restraint (Century Avante SE) that was discontinued by the manufacturer. Table 1 indicates the December 2001 additions to the list. Three of the restraints on the new list were identical to two of the restraints on the original list except for cosmetic changes. In addition to those on the FMVSS list, three convertibles and three boosters were added to represent current trends in child restraint design, including LATCH.

The selected restraints are believed to span a broad range of the geometry and design characteristics of production restraints, but no effort was made to obtain a quantitatively representative sample. During the preliminary phases of the program, consideration was given to selecting restraints for testing based on, for example, physical characteristics or market share. However, the data that would be required to conduct such sampling, such as sales figures and dimensional data for various models, were not available. Because the design approach selected for the surrogates did not require accurate characterization of the extremes of child restraint characteristics, a fairly large sample based on the NHTSA list, albeit somewhat arbitrarily selected, was judged to be sufficient. (See below for a detailed discussion of the surrogate design approach).

Table 1
Child Restraints Used in Program*

Car Bed (1)

Cosco Dream Ride 02–719

Rear Facing Infant Restraints (12)

Kolcraft Secura 43924
Graco Infant 8457
Britax Handle with Care 191
Evenflo Discovery 209
Evenflo First Choice 204
Evenflo On My Way 207
Evenflo Position Right 200***
Cosco Turnabout 02–772
Century Smart Fit 4541**
Cosco Arriva 02-270
Century 560 Institutional 4590
Cosco Opus 35 02603†

Rearward/Forward Facing Convertible Restraints (13)

Britax Roundabout 161
Century Encore 4612
Cosco Touriva 02–584
Evenflo Champion 249
Evenflo Medallion 254
Fisher Price Safe-Embrace 79701
Kohlcraft Performa 23308
Evenflo Horizon V 425†
Cosco Olympian 2803†
Century STE1000 4416†
*Safeline Sit n' Stroll**
Fisher Price Safe Embrace II w/ Latch
Evenflo Triumph

Booster Restraints (8)

Century Next Step 4920
Cosco High Back Booster 02–442
Evenflo Right Fit 245
Britax Cruiser 121
Britax Roadster 9004
Fisher Price Futura
Britax Star Riser Comfy
Evenflo Apollo

* Restraints in *italics* were not in listed FMVSS 208 but were added to represent current trends in child restraints.
† Added to FMVSS 208 in December 2001.
** Equivalent to Century Smart Fit 4543 and Century Assura 4553 without base from December 2001 list.
*** Equivalent to Evenflo On My Way Position Right V 282 from December 2001 list.

Table 2
Tested Child Restraints

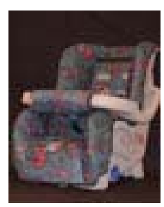
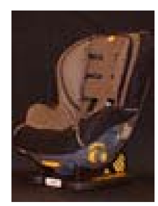
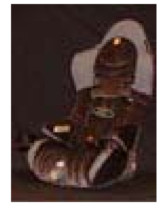
A. Rear-facing Infant Restraints				
 Britax Handle with Care 191	 Evenflo Discovery 209	 Evenflo First Choice 204	 Evenflo On My Way 207	 Evenflo Position Right 200
 Cosco Turnabout 02–772	 Century Smart Fit 4541	 Kolcraft Secura 43924	 Graco Infant 8457	 Cosco Arriva 02-270
 Century 560 Institutional 4590				
B. Convertible Restraints				
 Fisher Price Safe-Embrace 79701	 Evenflo Champion 249	 Century Encore 4612	 Evenflo Medallion 254	 Britax Roundabout 161
 Cosco Touriva 02–584	 *Safeline Sit n' Stroll**	 *Fisher Price Safe Embrace II w/ Latch*	 Kohlcraft Performa 23308	 Evenflo Triumph

Table 2 (continued)
Tested Child Restraints

C. Toddler/Booster Restraints

				
Century Next Step 4920	Cosco High Back Booster 02–442	Britax Cruiser 121	Evenflo Right Fit 245	Evenflo Apollo
				
Fisher Price Futura	*Britax Star Riser Comfy*			

- Restraints in *italics* are not in listed FMVSS 208 but were added to represent current trends in child restraints.

2.2 Measurement of Child Restraint Geometry and Mass

The geometry of each child restraint was measured in each potential usage configuration. For example, rear-facing infant seats with detachable bases were measured both with and without the base, and forward/rearward-facing convertible seats were measured in both configurations. A total of 52 configurations were measured.

The size and shape of each child restraint was recorded using a FARO Arm portable coordinate measurement machine. Figure 1 shows a child restraint being digitized and Figure 2 shows the resulting data. The data document the overall dimensions as well as the prominent contours, belt routing locations, harness slots, and other details relevant to the construction of the surrogates. A set of four permanent reference points was established on each restraint to facilitate data collection in the vehicle mockup. As part of the process of developing design specifications for the surrogates, these geometric data were analyzed to determine a large number of child restraint dimensions (see Section 3 for details of this process).

Figure 1. Digitizing child restraint geometry.

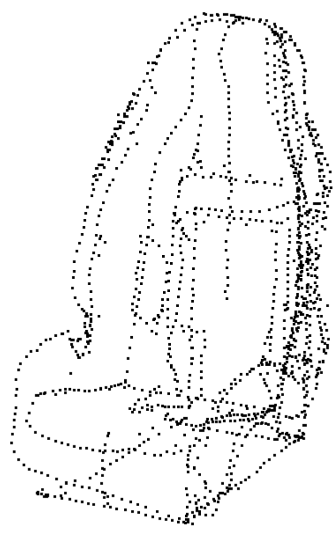


Figure 2. Data point cloud for one child restraint.

The mass and center-of-mass location were determined for each restraint configuration using a scale and a balance table. Table 3 shows the means and standard deviations of masses for each of the four restraint types applicable to the surrogate development. The convertible restraints were heaviest, on average, and also showed the largest variance in mass. The backless boosters were lightest, on average, but only two were measured. Among the other restraint categories, rear-facing infant seats without bases were the lightest, on average, and convertible restraints were heaviest.

Table 3
Child Restraint Mass Distributions by Configuration (kg)

Configuration	Mean	SD	Min	Max
Rear-facing Infant, No Base (N=8)	3.0	0.7	2.4	4.9
Rear-facing Infant, With Base (N=12)	4.9	1.1	3.9	7.2
Convertible (N=13)	5.7	1.4	3.6	8.8
Backless Booster (N=2)	1.5	--	1.4	1.6
Booster/forward-facing only (N=6)	4.3	0.8	3.4	5.2

The centers-of-mass (CM) of the restraints were located fairly consistently near the geometric center of the restraints. However, examination of the CM locations with the child ATDs installed in the restraints showed that the mass and mass distribution of the ATDs dominated the CM location of the child-plus-restraint system and hence the CM locations were not critical design variables for the surrogates.

3.0 IN-SEAT MEASUREMENT OF COMMERCIAL CHILD RESTRAINTS

3.1 Laboratory Equipment and Procedures

A laboratory mockup with a three-point seatbelt that could be fitted with three different seats was developed for measuring the in-seat performance of the commercial child restraints. Figure 3 shows the mockup. Two of the test seats were typical vehicle front seats (from an Opel and a Plymouth), selected to be relatively free of cushion seams that cause artifacts in seat surface pressure distribution measurements. The third seat was based on the cushion foam, covering, cushion angle, and back angle of the sled test buck specified in FMVSS 213 for child restraint testing. The standard seat provided a reproducible test condition for child restraint characterization while the vehicle seats provide more typical seat configurations.

Figure 3. Vehicle mockup for testing (left), second vehicle seat (center), and standard seat (right).

The vehicle mockup was equipped with a standard three-point seat belt equipped with a retractor. The buckle was mounted to the seat frame with a stalk and was located in the same position with respect to H-point as the buckle in the 2000 Ford Taurus. The lower belt anchorage and D-ring were mounted on adjustable fixtures that spanned a wide range of positions centered on the locations measured in the Taurus.

Test conditions were selected to span a wide range of those possible under the airbag suppression option in FMVSS 208. The rule specifies that static evaluation of airbag suppression systems with child restraints may be conducted at full-rear, middle, and full-forward seat positions, and that testing at these seat positions (effectively, at different seatbelt angles) is to be conducted with belt tensions between zero and 134 N (30 lb). Booster restraints are to be installed and the belts tensioned to between 9 and 18 N (2 to 4 lb).

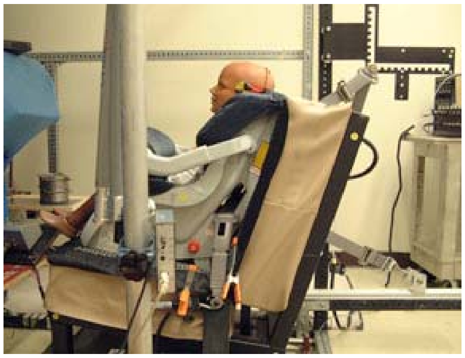
Based on these requirements, the following independent variables and conditions were selected:

- child restraint and configuration (e.g., Evenflo Discovery 209 without base)
- seat type (vehicle 1, vehicle 2, or standard),
- lap-belt angle (13 or 75 degrees with respect to vertical, obtained by varying seat position and belt anchorage location), and
- belt tension (no belt, 15 lb, or 30 lb; no belt and 4 lb for boosters).

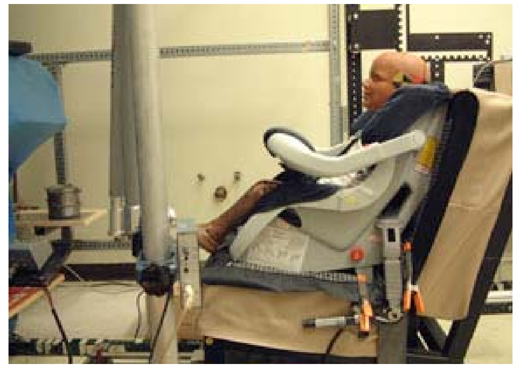
The child restraints were installed in the vehicle mockup using a 6YO Hybrid III, 3YO Hybrid III, or 12-month-old CRABI dummy (a 9MO ATD was used for some preliminary testing). Table 4 lists the test matrix. Figure 4 shows several installations. Many of the rear-facing restraints were tested with a foam “noodle” placed under the rear edge of the restraint base to achieve a 45-degree backrest angle, in keeping with recommended practices for installing infant restraints (NHTSA 2001).

Table 4
Test Matrix

Restraint Type	N	ATD	Vehicle Seat	Belt conditions			Totals
					Angle	Force	
Rear-facing infant, no base	12	12MO		1.	No belt	-	165
				2.	13°	15 lb	
			1. Standard	3.	13°	30 lb	
			2. Seat 1	4.	75°	15 lb	
			3. Seat 2	5.	75°	30 lb	
Rear-facing infant, with base	7	12MO	All 3	All 5			105
Convertible, rear-facing	13	12MO	All 3	All 5			195
Convertible. forward-facing	13	3YO	All 3	All 5			195
Forward-facing toddler	3	3YO	All 3	All 5			45
Booster, with vehicle belt	5	6YO	All 3	All 5			60
						Total	**825**

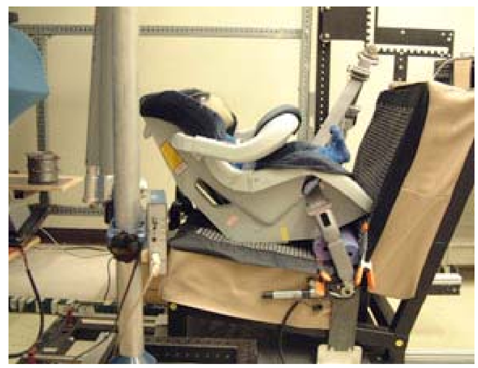


A. Convertible, forward-facing, 13° belt angle



B. Convertible, forward-facing, 75° belt angle

C. Convertible, rear-facing, 13° belt angle



D. Convertible, rear-facing, 75° belt angle

Figure 4. Testing in the vehicle mockup, showing a convertible restraint with 6-year dummy forward-facing and with 3-month dummy rear-facing.

A. Rear-facing infant seat, 13° belt angle

B. Rear-facing infant seat, 75° belt angle

Figure 5. Rear-facing infant seat with detachable base and vehicle belt at two different lap belt angles (angle is measured on the far side).

3.2 Data and Dependent Measures

In each test configuration, the position and orientation of the child restraint and ATD were recorded by digitizing points on the restraint and ATD with the FARO Arm. Recording the reference points on the restraint allowed the detailed geometric data previously recorded for the restraint to be aligned with the in-seat position of the restraint. Table 5 lists the points that were digitized in the mockup.

Pressure distributions were measured using an Xsensor system, comprised of two pressure-sensing mats and a computer interface. Figure 6 shows the Xsensor system applied to a seat. The mats are made from very flexible material about 3 mm thick and conform easily to the deflected seat contour. Each mat contains 1296 capacitative sensors arranged in a 36 x 36 array. Each sensor is square, measuring 12.5 mm (0.5 inch) on each side. For testing, the sensing mats were affixed to the seat using double-sided cloth adhesive tape. Clips were placed on each mat to mark the fore-aft and vertical location of the seat H-point as measured by the SAE J826 (1995) H-point machine.

The Xsensor system was calibrated weekly by placing each mat in a flat chamber with a pneumatic bladder. Inflating the bladder applies a uniform pressure on the mat. The sensor responses to a series of known pressures are stored in a calibration file. As an additional calibration check, a pilot calibration is performed after each set of measurements on a seat. The mats are laid on a rigid, flat surface, and a pressure is applied over a circular area using a known weight. The resulting calibration data are used to adjust the measured values to account for drift in the values during the previous test series. The performance of the Xsensor system is documented in Reed et al. (2000). Figure 7 shows pressure distribution data obtained from one restraint and vehicle seat at a range of belt tensions and angles.

Table 5
Points Digitized in Mockup Testing

Points on Mockup, Seatbelt and Restraints	
▪ 3 reference points on vehicle seat	
▪ 1 point on mock-up frame	
▪ 4 reference points on child restraint	
▪ Center of gravity of the restraint	
▪ Center of gravity of the restraint as measured with the manikin	
▪ Inboard and outboard path of lap and shoulder portions of the vehicle belt	
▪ Outboard angle of the lap and torso portions of vehicle belt	
Points on ATD	
▪ Top of head	▪ Lateral femoral condyle*
▪ Corner of eye*	▪ Left and right suprapatella
▪ Infraorbitale*	▪ Lateral malleolus*
▪ Glabella	▪ Lateral margin of heel*
▪ Acromion*	▪ Distal toe point*
▪ Lateral humeral epicondyle*	▪ Longitudinal line of point over face and chest
▪ Suprasternale	▪ Lateral line of points across face at pupil height
▪ Substernale	▪ Line of points along lateral margin of arm*
▪ ASIS*	▪ Line of points from ASIS to distal toe point*

*inboard and outboard sides measured

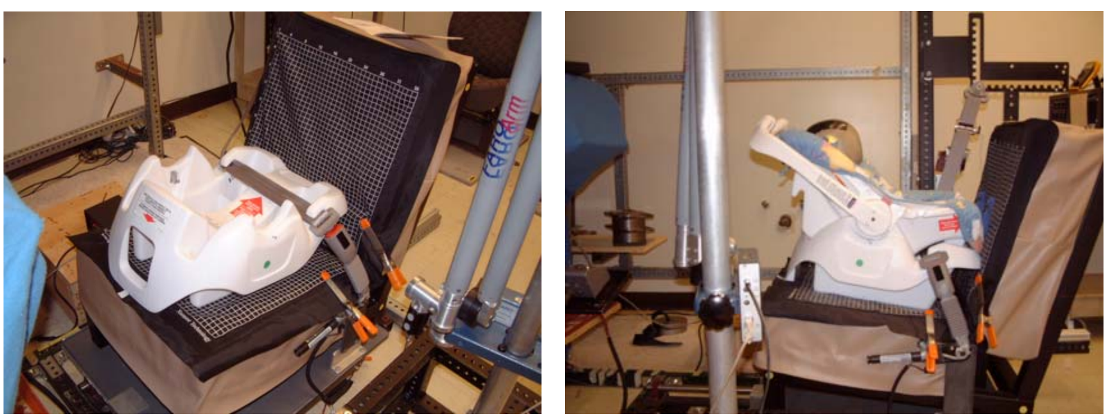
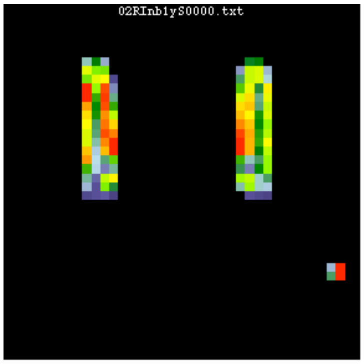
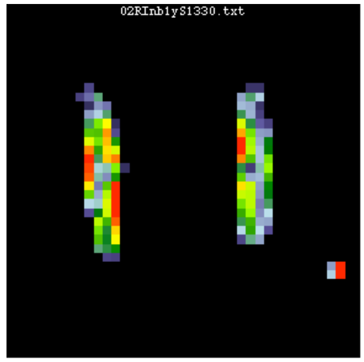


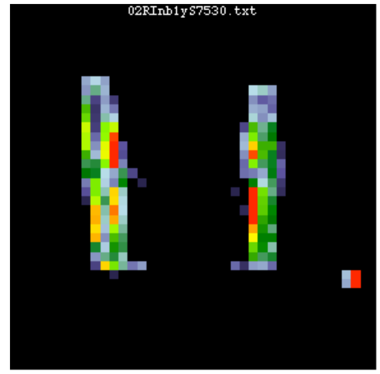
Figure 6. Xsensor pressure distribution measurement mats installed under a child restraint and on seatback.



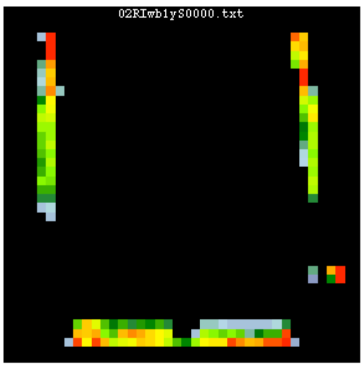
A. Without base, no belt



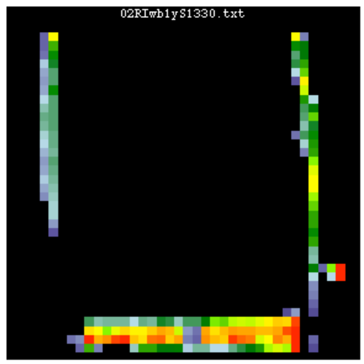
B. Without base, 13° and 30 lbs.



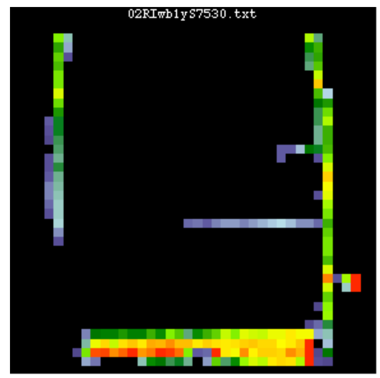
C. Without base, 75° and 30 lbs.



D. With base, no belt



E. With base, 13° and 30 lbs.



F. With base, 75° and 30 lbs.

Figure 7. Example of seat surface pressure distribution for a rear-facing infant restrain in a range of belt conditions on the standard vehicle seat. Rear of vehicle seat is at bottom of images. Dot on right margin marks the fore-aft H-point location. Areas of higher pressure are shown in red and yellow; blue indicates lower pressure.

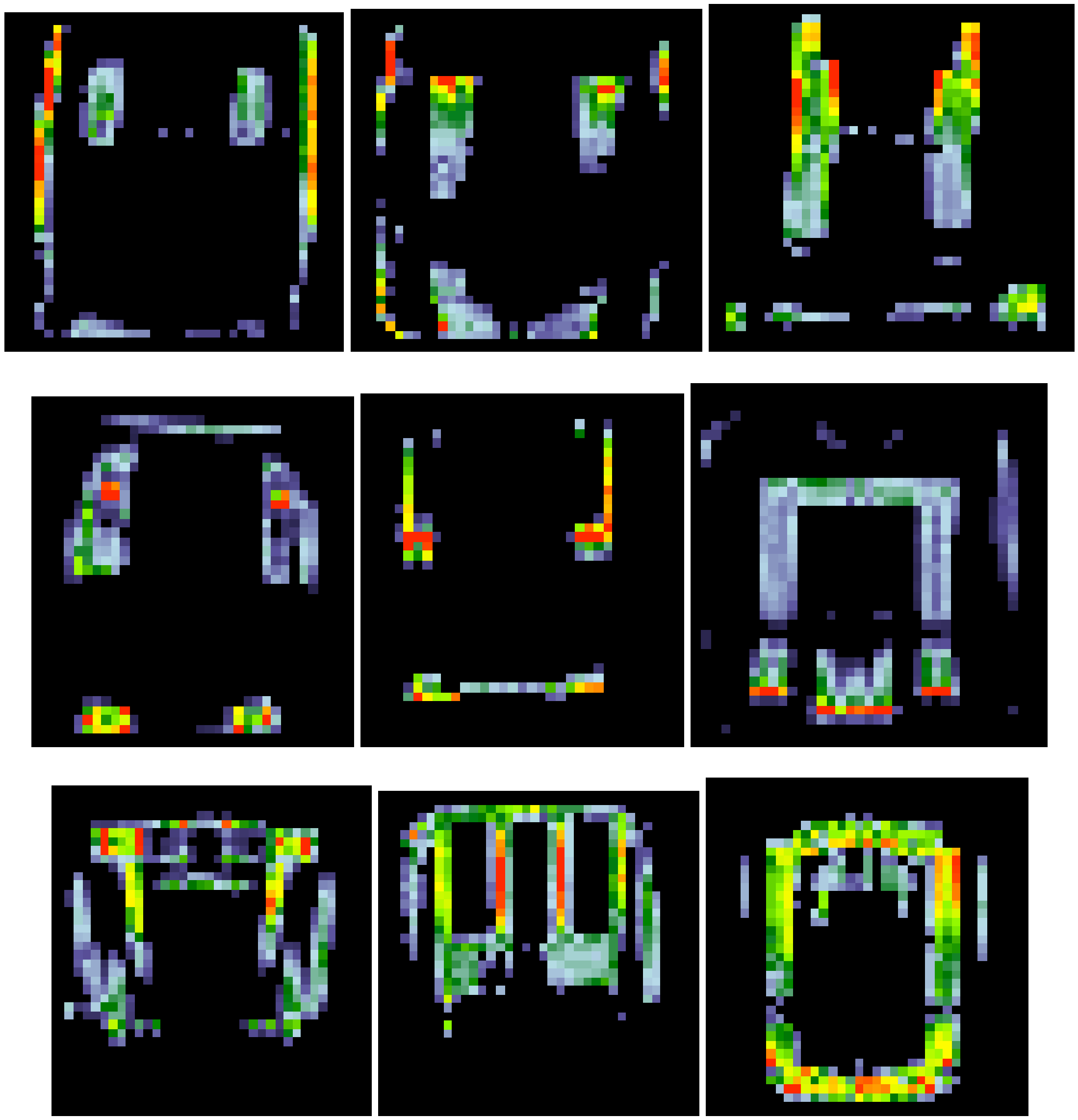


Figure 8. Pressure distributions on the seat cushion surface from selected restraints in three categories: rear-facing infant restraints (top), forward-facing convertibles (middle), and forward-facing harness and booster restraints (bottom). Red indicates areas of highest pressure, yellow and green are medium pressure values, and blue indicates low pressure. Data are from the 13-degree, 15-lb belt condition in vehicle seat number one.

The data gathered in the mockup were analyzed to (1) determine the effects of the independent variables on the position and orientation of the child restraints, and (2) to develop in-seat performance measures for the surrogate child restraints. To facilitate the analysis, the detailed child restraint geometry measured with the FARO Arm (see section 2.1) was aligned with the in-seat data by means of the four reference points on each child restraint. Figure 9 shows an example of alignment of in-seat and platform measurements.

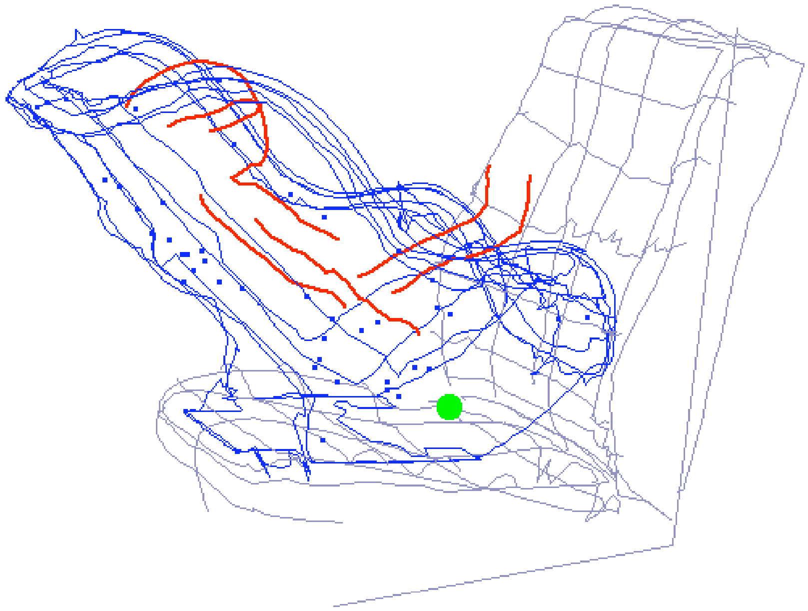


Figure 9. Geometric data from one in-seat trial obtained by combining in-seat measurements with previously measured restraint geometry aligned to reference points. Contour streams on ATD and seat surface contours are also shown. Large dot is seat H-point.

4.0 DEVELOPMENT OF SURROGATE CHILD RESTRAINTS

4.1 Concept Development

The program began without a clear indication of the number of surrogate restraints that would be required. Initial discussions with the Joint Working Group indicated that a surrogate was believed to be unnecessary for the car bed because only one was on the NHTSA list. With the car bed excluded, surrogates were needed to represent seven distinct child-restraint configurations:

1. rear-facing infant restraints without removable bases,
2. rear-facing infant restraints with removable bases,
3. rear-facing convertible restraints,
4. forward-facing convertible restraints,
5. forward-facing-only restraints (toddler restraints with harnesses),
6. backless boosters, and
7. high-back boosters.

Representing these categories with selected commercial restraints would require a minimum of four restraints: a rear-facing infant restraint with a base, (configurations 1 and 2) a convertible (configurations 3 and 4), a backless booster (configuration 7), and a combination restraint that can be used forward-facing with a harness or as a belt-positioning booster (configurations 5 and 8).

Although this initial categorization suggested a need for four distinct surrogates, analysis of the geometric data from commercial restraints suggested that it would be feasible to create two surrogate systems with removable components that could represent all seven categories. The *convertible* surrogate, consisting of a cradle component with base that can be removed and mounted at two different locations, could represent all infant and convertible configurations. A *booster* surrogate, with a removable back could represent the booster and forward-facing-only configurations.

Initial design assessments suggested that it might not be feasible to construct durable surrogates that also met the surrogate mass targets. Because application of the molding technology typically used to manufacture commercial restraints was not feasible for constructing surrogates, the initial surrogate concepts targeted the combined mass of the ATD-plus-restraint system. Representing the occupant shape using lightweight inserts would allow the surrogate restraint hardware to be substantially heavier and more robust than would be the case if the hardware had to meet mass targets developed from unoccupied commercial restraints.

However, after two generations of the surrogate prototype, the engineers at FTSS who were overseeing the hardware development identified materials and construction methods for both the convertible and booster surrogates that would allow them to meet the unoccupied mass targets with the desired durability. The final prototypes are therefore intended for use with ATDs rather than special-purpose inserts.

4.2 Representing Commercial Child Restraints

Perhaps the single most important issue in the design of the surrogates was the specification of the manner in which the surrogates would represent commercial child restraints. The surrogates are intended for use as an alternative to testing with a large number of commercial restraints that differ widely in size, shape, and weight, among other parameters. How can a small number of surrogates be considered "representative" of the spectrum of current and future restraints?

A quantitative assessment of the representativeness of the surrogates must be based on a suitable parameterization of the problem. Specifically, what characteristics of child restraints are important for occupant detection and classification? Based on an examination of the technologies available or proposed for use in occupant detection and classification systems, and particularly those applicable to airbag suppression systems, four primary characteristics of child restraints (with occupants) were identified as being of potential importance.

1. *Overall dimensions and volume* are potentially important for any system that measures the spatial characteristics of the occupant, such as those using camera-based, laser-scanning, or infrared range-finding technologies.

2. *Mass* is important for systems that include weight sensors.

3. *Seat surface pressure distribution* measurement has been proposed as a general-purpose technology for use in occupant classification. Several prototype occupant classification systems using pressure distribution measurement were available to the industry at the time this program was begun.

4. The *electric field characteristics* (capacitance) of the occupant are important for some systems.

Because the electric field characteristics of the restraint-plus-occupant system are primarily determined by the occupant characteristics, the electric-field performance was eliminated as a design criterion for the surrogates. Based on this assessment of the child-restraint characteristics likely to be important for occupant classification systems, the surrogates were intended to be representative of commercial child restraints with respect to spatial dimensions, mass, and seat surface pressure distributions.

The purpose of the suppression test procedures in FMVSS 208 is to verify that the airbag deployment will be suppressed under a number of different child restraints and installation conditions. Under the suppression option of FMVSS 208, a successful system must suppress deployment for any condition with a child restraint, but activate the airbag when a normally positioned small adult female ATD is present. For any particular system, some suppression conditions may be harder to accurately classify than others. For example, a system that uses a centrally located weight sensor in the vehicle seat pan might have the greatest difficulty distinguishing between a normally positioned adult and a six-year-old ATD in a booster when the booster is particularly narrow. Another system that uses a camera-based image processing system might have the greatest difficulty with a large forward-facing convertible restraint. The particular child restraints that are difficult to accurately classify for a pressure-distribution-based system may depend on the location of the pressure sensors within the seat pan and how the contouring of the vehicle seat interacts with the structure of the base of the child restraint.

In general, the characteristics of a child-restraint configuration that are difficult to accurately classify differ, perhaps widely, for different systems. This means that it is not possible to select, *a priori*, a small set of child restraints that present a quantitatively extreme challenge for any classification system. What is extreme for one system will not necessarily be extreme for another system.

In constructing a set of surrogates, we might nonetheless attempt to produce surrogates that are extreme on some set of characteristics, reasoning that this approach will ensure that systems whose compliance is based on the surrogates will be likely to achieve good performance (i.e., reliable occupant classification) with commercial child restraints. There are, however, two serious problems with this approach.

First, selecting and justifying quantitative extremes is problematic because of problems with measurement selection and definition and correlation among dimensions. For example, suppose child restraint width was identified as an appropriate parameter for a surrogate to represent in the extreme. What width dimension would be most appropriate to use? Some systems might measure width using seat surface pressure, others by optical silhouette. Should a “large” restraint be tall as well as wide? Some systems might be challenged only by a wide restraint that was unusually short.

Second, there is also no mechanism in place to identify, sample, and characterize the entire set of child restraints available for sale in the U.S. Consequently, it is difficult to estimate extreme values or tail percentiles of the distributions of child restraint dimensions. One could pick a value for a “large” restraint width, for example, but it would be difficult to justify the selection on a quantitative basis. The extreme values of distributions of child restraint dimensions can change rapidly with the introduction of one or a few new models. For example, several manufacturers recently introduced convertibles that were significantly larger than the largest convertibles previously offered in the U.S.

Because of these problems with attempting to represent extremes in the design of the surrogates, the surrogate designs targeted the mean values for dimensions within each restraint category. Mean values are more robust than tail percentiles to non-representative sampling and to trends in child restraint design. Even if the sample of child restraints measured in this study is not fully representative of the population of child restraints on any particular dimension, it is likely that the mean value from a complete census of restraints would not be substantially different from the value obtained in this study. Targeting the mean provides a quantitative rationale for the selection of child restraint dimensions, ensures that the dimensions will be internally consistent, and results in a design that is likely to lie near the reference dimensions for the population for many years.

The goal of targeting mean dimensions and performance was met to varying degrees in the construction of the surrogates. For the convertible surrogate, relatively large numbers of commercial exemplars were available so that the mean values could be calculated with reasonable precision. In comparison, smaller numbers of boosters were available and the boosters and some of the combination restraints differed widely in their styling, making representation using geometric averages problematic. This problem was addressed by obtaining relevant dimensions from exemplar restraints as appropriate for the particular booster-surrogate component (see below).

A bigger problem with representativeness arose with respect to pressure distribution. Although seat surface pressure distribution has been proposed as a useful approach for characterizing occupants (see discussion in Reed et al. 2000), the data gathered in this program showed that the seat surface pressure distributions produced by child restraints vary widely. Even within a restraint category (rear-facing infant seats without bases, for example), many different patterns were observed. Consequently, the surrogate child restraint pressure distributions were designed to be representative of only the overall length and width of the contact area with the seat. Due to the variance across restraints, it is not meaningful to create a pressure distribution that targets the means of additional pressure distribution parameters.

4.3 Geometric and Mass Specifications

The convertible surrogate was designed to the mean values of the dimensions listed in Table 4. Because the convertible is intended to represent four different restraint categories (see above), some compromises were necessary. In particular, the back length and overall height of the surrogate are the averages of the values for the infant and convertible categories. The average back length differed by about 50 mm between the two categories. The cradle component, to which the ATD is harnessed, has a back length that is midway between the values for the two categories. The cradle is then mounted on the base such that the overall height and length of the cradle+base+ATD system meets the mean targets for both the forward-facing convertible and rear-facing infant (with base) configurations. As constructed, the surrogate meets the geometric targets within a few millimeters, except that the inside width was expanded from 270 to 285 mm to allow the 3YO Hybrid-III ATD to fit easily.

Table 6 lists the target values for the convertible surrogate dimensions defined as shown in Figure 10. As noted above, testing in vehicle seats indicated that it was not possible to create a surrogate that produced a quantitatively representative pressure distribution because the pressure distributions produced by the commercial restraints were so variable. The surrogates therefore have square bases with length and width dimensions that are mean values for the categories and hence produce pressure distributions that are representative in terms of these basic “footprint” dimensions (base length and base width). Note also that the final physical prototype is the geometric standard. Any discrepancy between the values in Table 6 and the prototype should be resolved in favor of the prototype.

Table 6
Convertible Surrogate Specifications Based on Measurements from
Rear-Facing Infant Restraints and Forward- and Rear-Facing Convertibles

Dimension*	Target	Mean	SD	N	Notes
Inside Width	270	272	16	20	Compressed padding **
Outside Width	430	429	29	20	Includes handles
Cushion Length	280	276	24	20	On centerline
Back Length	490	486	56	20	On centerline
Back Angle (RF)	45	48	6	20	On horizontal base
Cushion Angle (RF)	35	38	10	20	On horizontal base
Back Angle (FF)	25	23	5	9	On horizontal base
Cushion Angle (FF)	15	16	5	9	On horizontal base
Base Length	330	329	62	16	Centerline
Base Width	275	272	51	16	Max
Total Length (RF)	650	647	46	20	Includes handles down
Total Length (FF)	550	546	39	9	Prototype = 537
Overall Height (NB)	360	276	47	11	#
Overall Height (WB)	360	348	48	7	#
Overall Height (RF)	475	473	35	7	Cradle +115 mm base
Overall Height (FF)	610	608	45	9	Cradle + 90 mm base
Bight Height (NB)	13	46	17	11	Cradle bight height
Bight Height (WB)	13	69	38	7	Cradle bight height
Bight Height (RF)	128	118	36	9	Cradle bight + base
Bight Height (WB)	103	87	36	9	Cradle bight + base

* Dimensions in mm or deg. WB = rear-facing infant without base, WB = rear-facing infant with base, RF = rear-facing convertible, FF = forward-facing convertible.

This dimension is difficult to meet with single-cradle concept, because the cradle is about 80 mm taller than the average infant restraint without base (NB). However, the cradle matches the average infant restraint with base (WB) fairly well.

** Expanded to 285 mm to provide better fit for 3YO ATD.

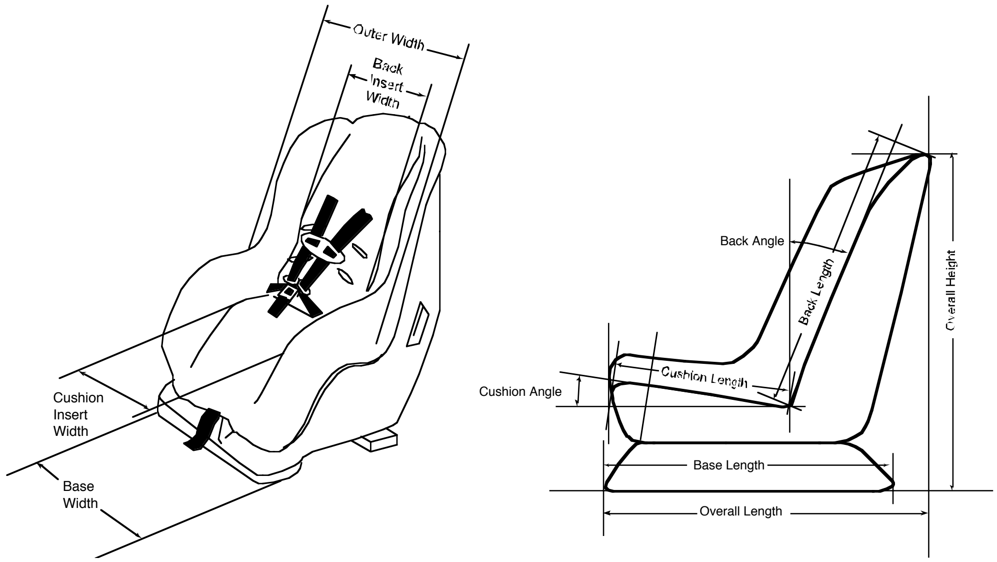


Figure 10. Definitions of child restraint dimensions in Table 6.

In developing the booster surrogate, a greater emphasis was placed on functional equivalence than on quantitative representativeness. This direction was chosen in part because the small number of restraints that were tested included substantially different design approaches that could not be readily averaged to obtain a mean design. The booster surrogate incorporates a base designed to be typical of backless boosters and a back component that provides a frontal profile typical of forward-facing-only restraints, some of which can also be used as belt-positioning boosters. The depth of the back component is typical of the depth of forward-facing-only restraints, but represents the thinner, less obtrusive high-back boosters less accurately. However, the appearance of restraints in these two categories to occupant classification systems may be similar because, in both cases, the size and shape of the occupant dominates the geometry of the system above the base.

4.4 Prototypes

Figure 11 shows early prototypes of the convertible surrogate. The first version was constructed using PVC and served as a proof-of-concept. Installations of the prototype with the base in a range of positions confirmed that it was feasible to use a single surrogate to represent the range of restraints from rear-facing infant seats through forward-facing convertibles. The second prototype was constructed from a much lighter wood/carbon-fiber laminate. The various configurations of this prototype were close to the mass targets and demonstrated that it would be feasible to construct surrogates that were light enough to be used with ATDs rather than separate inserts to represent the occupant's shape.

The booster surrogate was developed with a single prototype. Only minor revisions and additions were made after the initial build. The contour of the bottom surface was changed slightly to fit better in vehicle seats, a harness was added, and the back pivot system was improved.

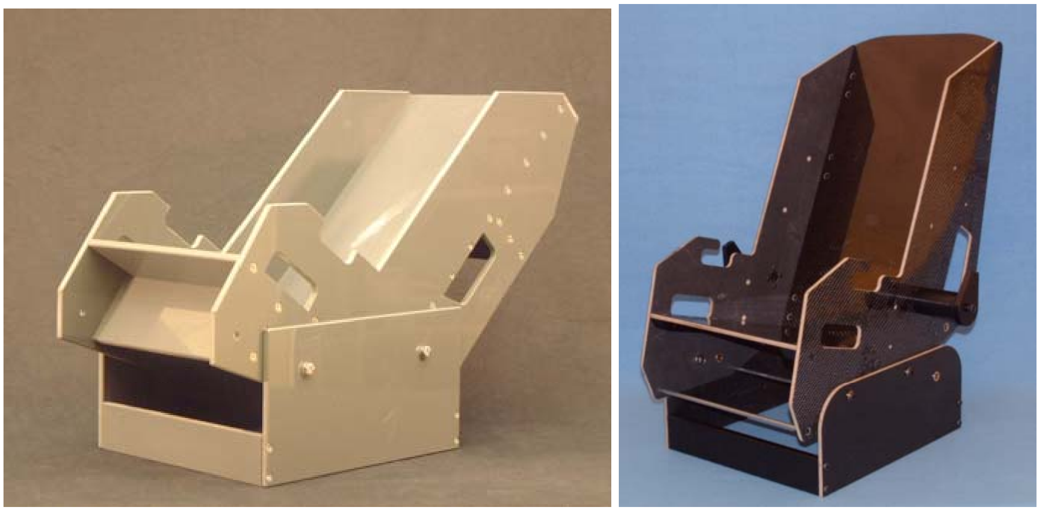


Figure 11. The first (left) and second (right) prototypes of the convertible surrogate.

Figures 12 and 13 show the final prototype child restraints in each of their configurations. The eight configurations identified in section 4.1 are represented, except that the rear-facing infant and rear-facing convertible configurations are represented by a single surrogate configuration. The convertible surrogate is constructed using a foam-core carbon-fiber laminate that is light yet strong. The laminate is reinforced with plastic brackets and metal hardware at key locations. Edges and belt paths are protected by moldings. A harness provides stability and consistent positioning for the ATD. (Note that the chest clip that would be used on a real child restraint is not included on the surrogate to facilitate ATD installation and removal.) The convertible surrogate has a base that can be removed to simulate a rear-facing infant seat without a base, or attached at two different angles to simulate a forward-facing convertible or a rear-facing restraint (convertible or infant restraint) with a base. The convertible surrogate can be used with ATDs up through the 3YO.

The convertible surrogate has three paths for the vehicle belt. For rear-facing applications, the belt can be routed under or over the thighs of the ATD, simulating typical convertible and rear-facing infant belt paths, respectively. For forward-facing applications, the vehicle belt routes behind the backrest of the restraint like many convertibles.   A handle is included to allow handle-up testing with a blanket as required under FMVSS 208.

The primary components of the booster surrogate were molded using acrylonitrile-butadiene-styrene (ABS). Metal and plastic fittings are used to attach the removable back component to the base.   Using the base alone simulates a backless booster. The back can be locked at a fixed angle to represent a forward-facing-only harness restraint or allowed to pivot to represent a high-back belt-positioning booster. For the forward-facing-only configuration, the ATD is secured by a harness and the vehicle belt passes through routing holes behind the backrest surface.

Figure 12. Final convertible surrogate prototype, from top to bottom, as a rear-facing infant seat without base, rear-facing infant/convertible with base, and forward-facing convertible with 3YO and 12-month ATDs.

Figure 13. Final booster surrogate, from top to bottom, as a high-back booster, forward-facing-only restraint, and backless booster.

4.5 Evaluation of Final Prototypes

Table 7 shows the final mass values for the prototype surrogates. The most meaningful way to assess the mass of each surrogate is to consider the mass of the surrogate-plus-ATD system. Table 8 lists the target values from the measurements of commercial restraints along with the prototype and associated ATD masses. Cases in which the system mass is less than the target values are not considered to be problems, because the system can be easily ballasted up to any desired weight. Of more concern are the booster and forward-facing-only configurations, which exceed the mass targets. However, the target values were established from only a few commercial restraints, and the ATD-plus-surrogate systems exceed the targets by only two percent.

Table 7
Commercial Restraint and Final Prototype Surrogate Mass (kg)

Category	N*	Min	Max	Mean (Target)	Prototype
Rear-Facing Infant, No Base	8	2.4	4.9	3.0	3.0
Rear-Facing Infant, With Base	12	3.9	7.2	4.9	3.7
Convertible	13	3.6	8.8	5.7	3.7
Backless Booster	2	1.4	1.6	1.5	2.0
Highback/Forward-Facing Only	6	3.4	5.2	4.3	5.0

* Number of commercial restraints measured.

Table 8
Final Prototype Surrogate plus ATD Mass† Relative to Targets (kg)

Category	Restraint	ATD	Total (Target)	Prototype	±%
Rear-Facing Infant, No Base	3.0	10.0	13.0	13.3	--
Rear-Facing Infant, With Base	4.9	10.0	14.9	13.7	- 8%
Convertible	5.7	15.5	21.2	19.2	- 9%
Backless Booster	1.5	21.4	22.9	23.4	+2%
Highback/Forward-Facing Only	4.3	21.4	25.7	26.4	+2%

† ATD masses are 10 kg for the CRABI 12MO, 15.5 kg for the 3YO, and 21.4 kg for the 6YO.

As noted above, the seat surface pressure distributions varied widely across commercial restraints within each category. Consequently, the seat surface pressure distribution for the surrogates was designed to be representative only in the overall length and width of the part of the base that contacts the seat. These dimensions were obtained from the digitized measurements of the commercial child restraints. Figure 14 compares the surrogate pressure distributions on one seat along with examples from child restraints that produced similar and dissimilar distributions.

The surrogates were installed in each of the mockup test conditions to evaluate their performance and ease of installation. The primary consideration was the extent to which the position and orientation of the surrogate and ATD matched the data obtained with commercial restraints. Figure 15 shows the convertible surrogate geometry overlaid with the data obtained from testing with commercial child restraints in each of the four categories represented by the convertible surrogate.

When placed rear-facing without the base, the convertible surrogate matches the size, shape, position, and orientation of the rear-facing infant restraints well. The side-view profile of the surrogate, when tested rear-facing with the base, differs in the area below the backrest from most of the commercial rear-facing infant seats with bases. However, the overall height of the restraint and its forward-most protrusion match the commercial restraints well. As was the case with many of the rear-facing commercial restraints, the convertible surrogate was tested rear-facing with a foam noodle placed under the rear edge of the restraint base to achieve a 45-degree backrest angle (NHTSA 2001).

As shown in the lower-left portion of Figure 15, some of the commercial convertibles were taller and some extended more forward than the surrogate when installed rear-facing. However, the figure illustrates a large amount of variability in these dimensions for the commercial restraints and shows that the top-of-backrest point on the surrogate lies near the center of the distribution of the same point on the commercial restraints. When tested forward-facing (lower-right image in Figure 15), the uppermost point on the surrogate was lower than the uppermost point on most of the convertibles, but the ATD head height in the surrogate and commercial restraints matched well. The difference in backrest height is due to the compromise described earlier that was required to obtain good fit to both the infant and convertible restraint geometry. Overall, Figure 15 shows that the size, shape, position, and orientation of the convertible surrogate in its various configurations lie within the range of the commercial restraints.

A similar qualitative analysis was performed with the booster surrogate. Figure 16 shows an overlay of data from vehicle-seat installations of the booster surrogate and commercial boosters tested with the 6YO ATD and vehicle belt. The overall size and shape of the booster surrogate lies within the range of the commercial restraints, and the resulting ATD positions are similar. A quantitative analysis of the booster surrogate performance in the vehicle seat was not performed because of the small number of commercial restraints to which the values could be compared.

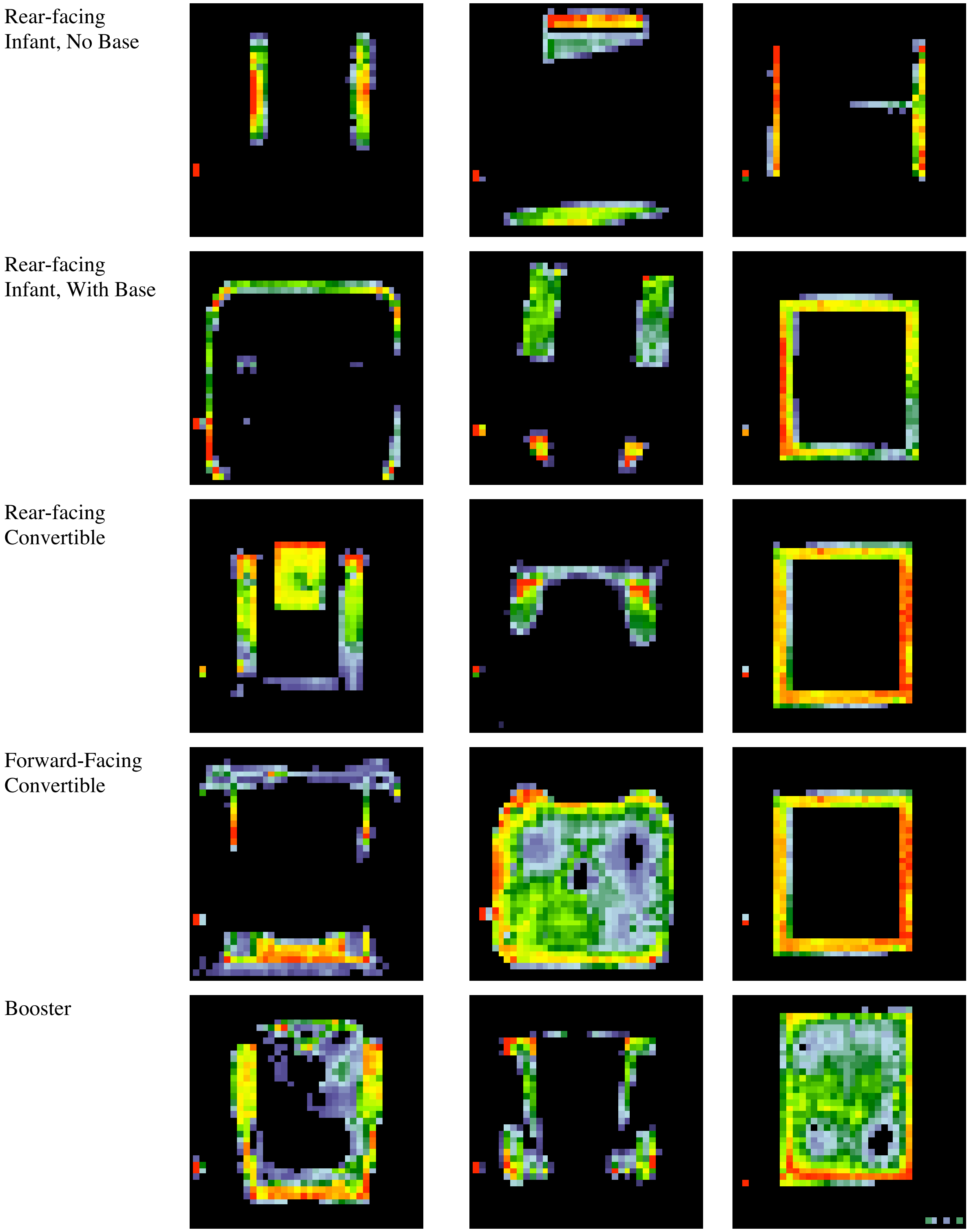


Figure 14. Comparison of pressure distributions produced by the surrogates and commercial restraints on the standard seat with 13-degree belt angle and 15-lb belt tension. The right column shows pressure distributions from the surrogates. The left column shows a pressure distribution from a commercial restraint that is somewhat similar to the pressure distribution produced by the surrogate. The center column shows a pressure distribution from a commercial restraint in the same category that is substantially different from the surrogate pressure distribution.

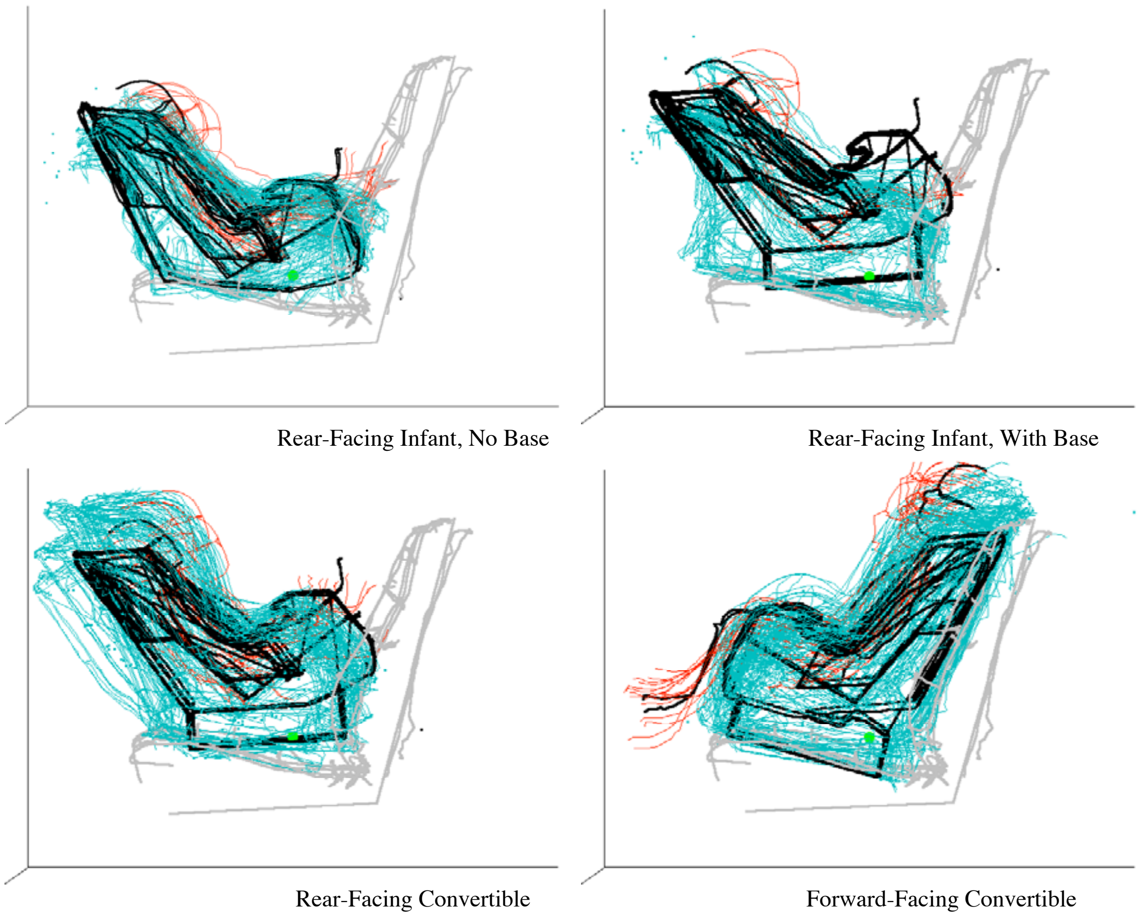


Figure 15. Overlay of convertible surrogate geometry (thick lines) with data from commercial child restraints (thin lines) in a vehicle seat.

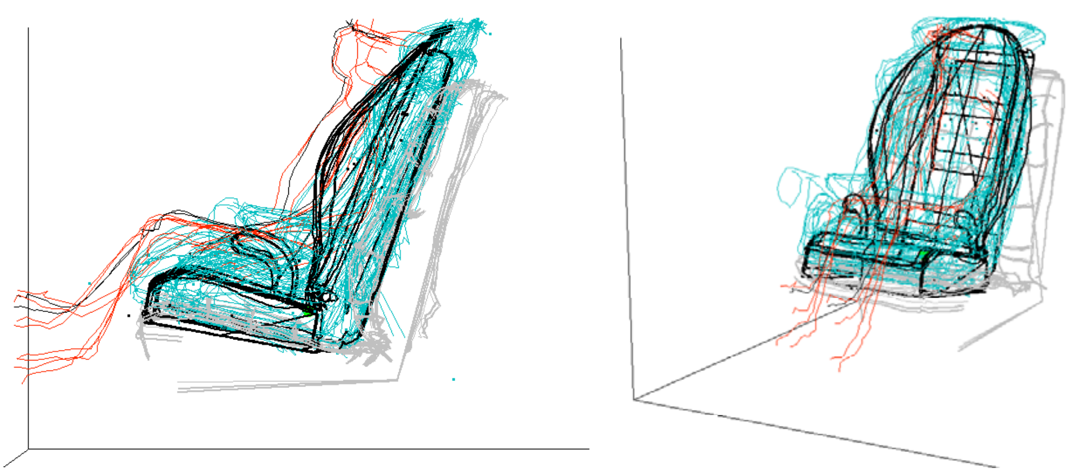


Figure 16. Overlay of booster surrogate geometry (thick lines) with data from commercial child restraints tested with the 6YO ATD and vehicle belt.

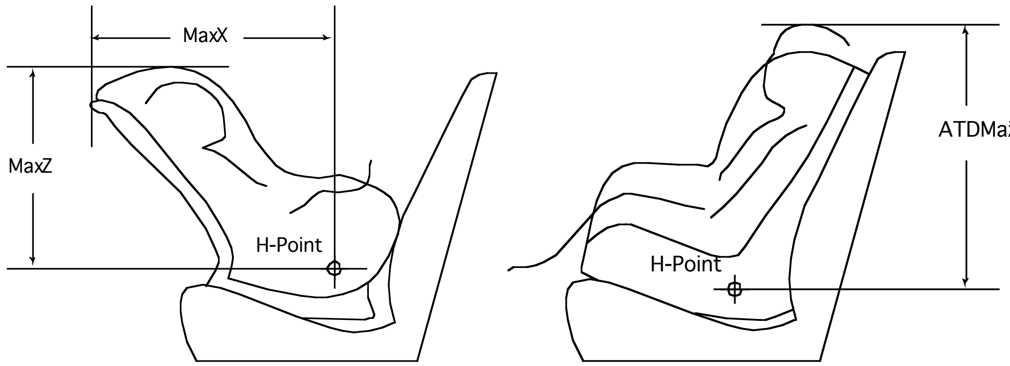


Figure 17. Schematic of dependent measures representing in-seat child restraint position.

Table 9 compares the in-seat position of the convertible surrogate in the standard seat with the commercial restraints for the rear-facing infant (no base), rear-facing infant, rear-facing convertible, and forward-facing convertible categories. The table shows the fore-aft position of the most-forward point on the restraint (MinX) the height of the highest point on the restraint (MaxZ), and height of the highest point on the restraint or ATD (ATDMaxZ). Figure 16 illustrates these dimensions, which were measured with respect to seat H-point. Restraint handles and other removable components on the commercial restraints were neglected in computing these dimensions. Values for the surrogate in the corresponding configuration are shown in Table 9 along with deviations from the commercial-restraint means. The score column lists the difference between the value for the surrogate and the mean value for the commercial restraints divided by the standard deviation of the values from the commercial restraints. Scores between 1 and –1 indicate that the surrogate is well within the distribution of commercial restraints for the category.

For the category of rear-facing infant restraints without bases, the surrogate scores are within a half standard deviation of the commercial targets, indicating good spatial correspondence between the surrogate and the commercial restraints. For the rear-facing infant restraints with bases, the surrogate was higher than the average value for the commercial restraints, but the ATDMaxZ correspondence was good (score = 0.21). The surrogate configuration that represents the rear-facing convertible configuration is the same as the one matching the rear-facing infant (with base) configuration. The surrogate is slightly lower than the rear-facing convertibles, in keeping with the idea of representing the average of both the rear-facing infant seats and larger rear-facing convertibles with the same surrogate configuration. In both cases, the ATD head heights are within a half standard deviation of the commercial restraint mean.

For the same reason, the forward-most point on the surrogate, when representing a rear-facing convertible, is about 1.7 standard deviations rearward of the average value for the rear-facing convertibles and about 0.8 standard deviations forward of the average value for rear-facing infant seats with bases. When representing a forward-facing convertible, the highest point on the surrogate is more than one standard deviation below the mean value for the category, but the ATD head in the surrogate is very close to the mean value for the commercial restraint category, indicating that the frontal profile of the ATD-plus-surrogate system will be typical for the category.

Table 9
Performance of the Convertible Surrogate Relative to Commercial Restraints
in the Standard Seat with 15-lb Belt Tension and 13-Degree Belt Angle

Configuration and Measure*	Commercial Restraints		Surrogate		
	Mean	S.D.	Value	Deviation	Score†
RInb (N=12)					
MinX	-448	38	-440	8	0.22
MaxZ	325	53	350	25	0.48
ATDMaxZ	486	44	468	-18	-0.41
RIwb (N=8)					
MinX	-454	39	-422	32	0.82
MaxZ	358	41	434	76	1.85
ATDMaxZ	535	52	546	11	0.21
CNrf (N=11)					
MinX	-494	43	-422	72	1.68
MaxZ	472	50	434	-38	-0.76
ATDMaxZ	560	50	546	-14	-0.28
CNff (N = 9)					
MinX	-337	27	-324	13	0.49
MaxZ	518	63	591	73	1.16
ATDMaxZ	588	47	591	3	0.07

* Configurations are rear-facing infant, no base (RInb), rear-facing infant with base (RIwb), rear-facing convertible (CNrf), and forward-facing convertible (CNff). Measures are defined in Figure 17.

† Difference between surrogate and commercial-restraint mean divided by commercial-restraint standard deviation. A score between 1 and –1 indicates that the surrogate is less than one standard deviation from the mean value for the commercial restraints.

5.0 DISCUSSION

The prototype surrogate child restraints described in this paper are quantitatively representative of a wide range of child restraints with respect to geometry and in-seat performance. The surrogates were designed to mean values of a large number of geometric parameters and are subjectively and objectively typical of commercial restraints on many parameters that are likely to be important for occupant classification systems. However, the data gathered in this study illustrate clearly that any individual model of child restraint can deviate markedly from the average values in each category. The importance of this variance for occupant classification must be assessed with respect to a particular implementation of an occupant classification system. Even the same sensing technology, when applied in different vehicles, will be challenged by different restraint characteristics. The approach in the development of the surrogate child restraints, as in the development of crash dummies, has been to produce a small set of surrogates that span an important range of different characteristics (size and mass, for example), while recognizing that the true population varies much more widely.

The surrogates are intended only for non-deployment testing. They are not appropriate for testing that involves significant loading, although the surrogates are robust enough to be used in non-crash dynamic environments, such as testing the rough-road performance of a weight-based occupant sensing system. The surrogates can be used in LATCH-equipped seating positions by use of a LATCH retrofit kit. However, the primary application of the surrogates is for testing in front seating positions that are not equipped with LATCH.

In many vehicle seats, rear-facing infant seats are propped up using a foam noodle or a rolled-up towel to obtain an acceptable backrest angle. This practice evolved because of a substantial difference between the FMVSS 213 seat pan angle and typical vehicle seat pan angles. The flatter pan angle used for the FMVSS 213 buck (8 degrees) led to child restraint backrest angles that are too upright when placed on many vehicle seats. A revision of FMVSS 213 in 2003 changed the pan angle to 15 degrees, which can be expected to lead to changes in the relationship between the base and the backrest for some future restraints. The design of the convertible surrogate, with a separate base component, would allow these changes to be reflected with only minor modifications. Either the base can be mounted on the cradle at a different angle, or the base itself can be modified to a different angle.

One central issue that has not been addressed in this work is whether airbag systems developed and certified using surrogate child restraints would provide performance advantages or disadvantages relative to systems developed and certified under the current FMVSS requirements. If manufacturers were allowed to certify their occupant sensing and classification systems using the surrogates, rather than the restraints listed in FMVSS 208, would the field performance of the airbag systems differ? Further study will be necessary to determine how systems designed using these surrogate child restraints perform when tested with a wide range of commercial restraints.

5.0 REFERENCES

Code of Federal Regulations (2002). Federal Motor Vehicle Safety Standard 208: Occupant Crash Protection. 49 CFR 571.208.

National Highway Traffic Safety Administration (2001). Standardized child passenger safety training program. Summer 2001 Edition. U.S. Department of Transportation, Washington, DC.

Reed, M.P., Ebert, S.M., Lehto, M.M., and Schneider, L.W. (2000). Development of Anthropometric and Performance Standards for Occupant Classification Test Devices (OCATD). UMTRI-2000-38. University of Michigan Transportation Research Institute, Ann Arbor, MI.