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DYNAMIC TESTING OF INNOVATIVE SOLUTIONS TO CHILD OCCUPANT PROTECTION PROBLEMS

Kathleen Weber
John W. Melvin

The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109

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16. Abstract

This report brings together the results of two years of research into the effectiveness of innovative, unconventional, and/or misused child occupant protection systems. Concepts studied and discussed include child restraint securement practices, child restraint orientation relative to the vehicle and the crash, upper torso restraint, and neck and abdominal injury potential. Conclusions and recommendations deal with the dangerous consequences of some installation errors, the performance of seatbelt retractors and tightening devices, CR installation in vans and station wagons, the extended use of rear-facing restraints, the availability and fit of upper torso restraint for children, and the need for further research to guard against possible neck and abdominal injury.

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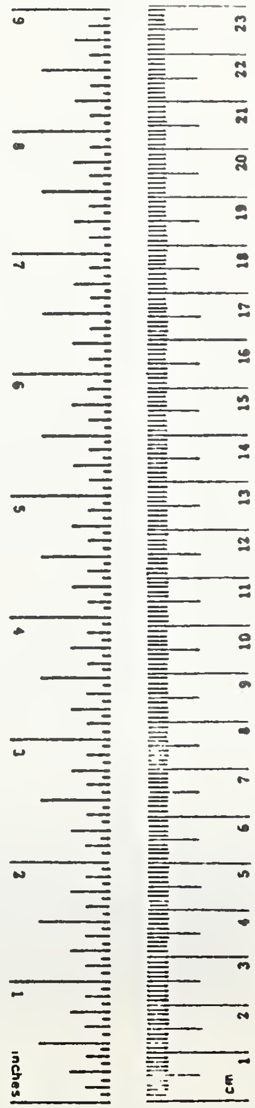
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

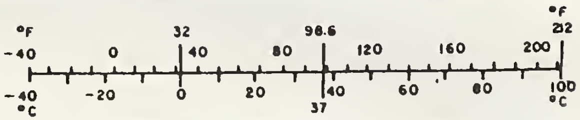
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

With child occupant protection legislation nearly universal in the United States, problems related to real-world use are receiving increased attention, and innovative designs and solutions to these problems are increasingly being developed and suggested. "Innovations" tend to fall into two major groups: (1) unconventional means of restraint used either inadvertently or with the best intentions by the consumer, and (2) restraint devices designed and developed by individual inventors or child restraint manufacturers.

During the course of our regular interaction with consumers, manufacturers, and representatives of local, state, and national child passenger protection organizations, we are continually asked to evaluate these unconventional or innovative child restraint practices and designs. Such evaluation usually necessitates a test in a simulated crash environment. Although many consumer practices can be categorized as misuses of established systems, not all such practices have the same effect on the performance of the child restraint system being misused, and impact tests can usually sort out these differences. Further, even though some misuses or new designs may be dynamically questionable from the outset, often the best way to demonstrate the point is to subject such systems to a crash test. Finally, crash simulations can indicate the relative risk one would be taking when using a marginal system and can identify the weaknesses for possible improvement.

The work reported here is a continuation of a similar program performed under NHTSA contract DTNH22-82-P-07243 and reported by Weber and Melvin (1982). Also included in the current report are the results of a complementary series of tests made possible by grants from representatives of the child restraint and insurance industries.[1] Test results and discussion are presented under four major headings:

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[1]Grantors include Century Products, Kolcraft Products, Questor Juvenile Furniture, Strolee of California, and United Services Automobile Association.

Child Restraint Securement Methods
Child Restraint Orientation
Upper Torso Restraint
Neck and Abdominal Injury Potential

All tests were run according to Federal Motor Vehicle Safety Standard 213 (30 mph, 20 G), unless otherwise noted, and evaluations were based on the standard criteria when appropriate.

The primary criteria for forward-facing restraints are listed below and relate to a dummy simulating a 3-year-old child.

(1) Head Excursion, which is measured from the pivot point between the back and base of the standard bench seat to the leading edge of the dummy head, should not exceed 32 inches. This tends to be the most difficult criterion to meet and thus the most critical for misuse and innovative system tests.

(2) Head Injury Criterion (HIC), which is a mathematical function based on head acceleration and impact time duration, should not exceed 1000. This criterion is rarely exceeded unless actual head impact occurs.

(3) Chest Peak Resultant Acceleration, which is calculated from triaxial chest accelerations, should not exceed 60 G for more than 3 milliseconds. This criterion is rarely exceeded with harness systems but can be critical for shield restraints.

(4) Knee Excursion, which is measured from the pivot point of the standard bench seat to the knee pivot point, should not exceed 36 inches. This criterion is more difficult to meet in reclined forward-facing as opposed to upright forward-facing systems.

The primary criterion for rear-facing restraints is that the angle of the back surface should not exceed 70 degrees from vertical. Other criteria for all types of restraint systems include structural integrity, suitability of the restraining system for the occupant, relative degradation or improvement as compared to a production system under proper use conditions, and potential for injury from some aspect of the restraint configuration not covered by the standard.

CHILD RESTRAINT SECUREMENT METHODS

Field observations of child restraints (CRs) in use have shown that high percentages are not being used as designed. A study reported by Shelness and Jewett (1982) has documented errors in CR installation, or the way in which child restraints are secured on vehicle seats. Consumers and professionals working with CRs are also concerned that optimum securement may not be possible with existing vehicle seatbelt hardware. In addition, the special problem of installing CRs and restraints for handicapped children in vehicles without seats has arisen, as more parents seek to properly restrain their children whenever they travel. This section describes impact tests that address these three areas of concern.

Belt Routing and Tethers

The most common installation error observed in the field is the failure to anchor the tether on those CRs needing a tether to meet FMVSS-213 excursion criteria at 30 mph. The next most likely mistake, observed with both tether and tetherless models, is incorrect routing of the vehicle belt. The combination of these two errors with a tether CR is also a frequent occurrence. The previous test series (Weber and Melvin 1982) showed that failure to anchor the tether resulted in head excursions of 35.4 inches for the Child Love Seat (Fig. 1) and 34.9 inches for the Strolee 599 (Fig. 2). In the current series, a tether CR (without the tether anchored) and a tetherless model were tested with the lap belt misrouted. For comparison purposes, a tetherless CR having an open frame construction was tested while secured with a combination lap/shoulder belt correctly routed. Each test was made with an instrumented Part 572 dummy simulating a 3-year-old child.

LAP BELT THROUGH BASE OF UNTETHERED STROLEE 599 (82D041). This CR consists of a single-walled plastic shell bolted at its base to an elevating metal frame. The lap belt is intended to be routed through an L-brace to anchor the frame, while a tether attached to the shell is intended to hold back the top of the CR. It is quite common, however,

FIGURE 1. 82D036

FIGURE 2. 82D035

to observe this and other frame-type CRs installed with the lap belt threaded through the base of the frame (Fig. 3). It is also common to see this routing error in combination with a failure to anchor the tether. In this test, the CR was installed in this double-misuse manner, but the dummy was snugly harnessed.

During the 30-mph impact, the rivets holding the base to a rear hinge structure failed at belt loads of 1039 pounds (right) and 920 pounds (left), allowing the CR and dummy to pitch forward unrestrained (Fig. 4). We would caution that this was a very severe test of the system. The belt loads at failure were close to typical maximum loads reached during a 30-mph CR test. Also, if the CR had been tethered, no failure would have occurred. This result, however, does indicate that CR manufacturers should be concerned about obvious ways that consumers might misuse their products and should implement appropriate preventive measures. To their credit, Strolee and other manufacturers are now attaching highly visible labels to child restraint frames that point to the correct belt routing location.

LAP BELT THROUGH BASE OF CENTURY 100 (83D003). This CR is designed to be used without a tether and is representative in structural configuration of several other current models, e.g., Astroseat 9100 and 9300, Cosco 78 and 81, Pride-Trimble, and Century 200 and 300. Although the correct lap belt routing for the Century 100 is again through a raised L-brace, it and similar models are often observed with the lap belt through the frame base (Fig. 5). Our experience with design development of tetherless CRs is that the optimum lap-belt anchor path is not at the lower rear corner of the frame or shell, but a few inches above the base. To determine the extent of CR performance degradation in terms of increased head excursion for this commonly seen installation method, the lap belt was routed through the frame base, and the dummy was snugly harnessed.

During the 30-mph impact, there was no structural failure of the solid tubing (maximum belt loads of 1121 and 1040 pounds), and the head excursion was 31.5 inches (Fig. 6). Although this represents an increase of at least two inches over typical results for this model properly installed, it is still within the limits of FMVSS 213.

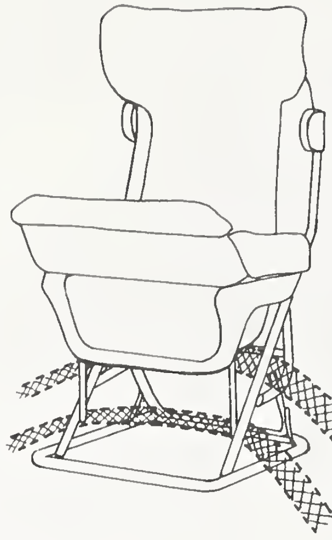

FIGURE 3. Strolee 599

FIGURE 4. 82D041

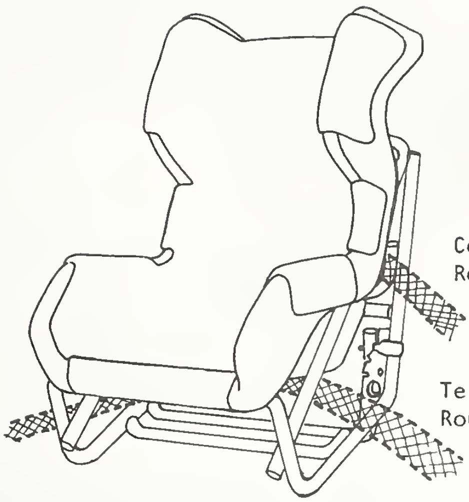

FIGURE 5. Century 100

FIGURE 6. 83D003

LAP/SHOULDER BELT SECUREMENT OF CENTURY 200 (83D013). There is no question that a top tether improves the performance of any child restraint, including those models that meet FMVSS-213 criteria without one. The reluctance of the public to install these devices, however, has resulted in non-use, and we predict an eventual phasing out of tether-CR designs. There is, however, a tether-like device already installed in most front vehicle seats and in rear seats of some imported cars--the shoulder belt. Threaded properly, along with the lap belt, through a frame-type CR (such as those listed above as well as the Kantwet, Collier-Keyworth, and Nissan models), this shoulder belt has the potential of contributing additional securement beyond that provided by the lap belt alone.

To test this idea, a Century 200 was installed using a properly routed lap/shoulder belt (lap portion pretensioned to 14 pounds each side, shoulder portion to 5 pounds), and the dummy was snugly harnessed. Head excursion was 27.6 inches (Fig. 7), which is approximately 2.5 inches less than the excursion measure typically seen with this CR model. This extra restraint is due to the shoulder belt acting somewhat like a tether on one side as it holds the frame back at the point indicated in Figure 8. We caution the reader, however, that the shoulder belt in this test, just as the lap belt in all FMVSS-213 tests, is a static, manually adjustable belt, unlike the inertia-activated shoulder belts found in most cars today. The pretensioning of this belt removes all slack from the system and thus provides restraint sooner than a belt wound on a locking retractor. A comparison of static and retractor lap belts is made from tests described below.

Belt Tightening

The test procedures for FMVSS 213 require that the lap belt used to secure the CR is pretensioned to between 12 and 15 pounds on each side. In an actual automobile, this is only possible with a manually adjustable belt, usually found only in center seating positions. Outboard seating positions are usually equipped with belts having spool retractors that lock under various conditions, depending on the type.

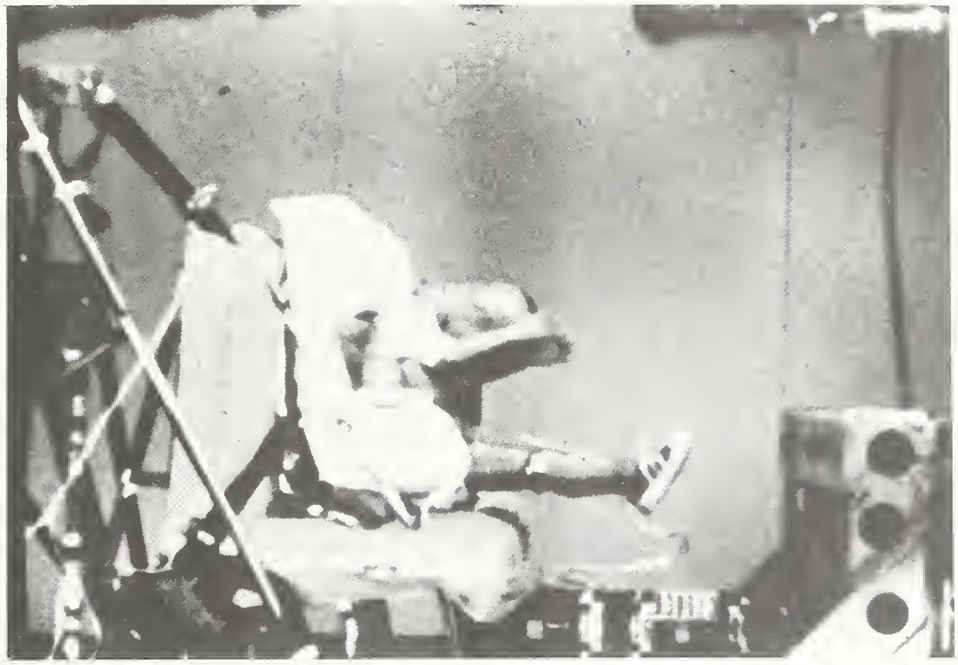

FIGURE 7. 83D013

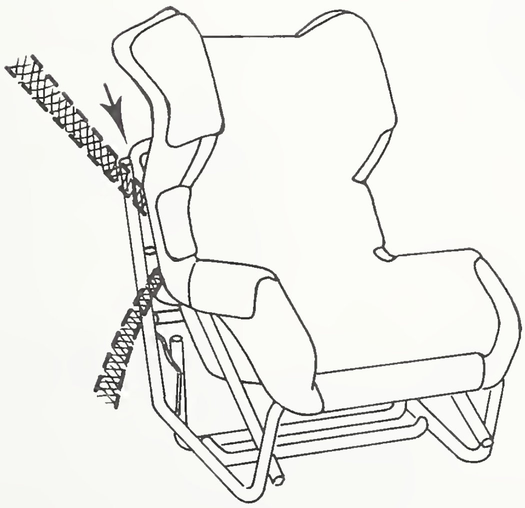

FIGURE 8. Shoulder Belt Routing

In this section, we will address these retractors as they apply to lap belts found in rear seating positions.

Automatic Locking Retractors.[2] The most common rear-seat belt systems use automatic locking retractors (ALRs), which lock after the user pulls out the belt and lets it go slack. These retractors will continue to wind up the remaining slack, but the belt cannot again be pulled out before it has been retracted all the way. When used to install a child restraint, it is recommended that the CR be secured and then pressed into the vehicle seat to allow the ALR to take up as much belt slack as possible. To make a comparison between this real-world securement condition and the FMVSS-213 test conditions, a convertible CR model was tested in both its rear-facing and forward-facing orientation.

REAR-FACING KANTWET 401 SECURED WITH ALR LAP BELT (XP8406). The CR was properly installed on the standard bench seat using a current production ALR lap belt system, and the dummy, simulating a 6-month-old infant, was snugly harnessed. As described above, the CR was pressed into the seat to make the belt as tight as possible. During impact, however, the CR translated forward, placing the rear of the frame over the soft front edge of the seat before the belt became fully tight and thus allowing the back angle of the CR to reach 65 degrees (Fig. 9). Although still within the FMVSS-213 limit, this was an increase of at least 15 degrees over typical results with this model.

FORWARD-FACING KANTWET 401 SECURED WITH ALR LAP BELT (XP8407). Again the CR was properly secured as tightly as possible, and the 3-year-old dummy was snugly harnessed. The CR again translated forward, allowing additional CR rotation, and the head excursion reached 33.3 inches (Fig. 10), which is at least 4.5 inches greater than typical results for this model in an FMVSS-213 test.

The probable cause of the performance degradation of both the rear- and forward-facing systems is the effect of belt spooling on the length of the belt at maximum excursion. Because there is no means by which the belt can be wound very tightly around the retractor reel

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[2]The tests described in this section were conducted with private grants. See footnote 1.

FIGURE 9. XP8406

FIGURE 10. XP8407

during CR installation, whatever looseness there is will be pulled tight only at impact.

Emergency Locking Retractors.[3] Although less common among vehicles on the road than ALRs, emergency locking retractor (ELR) belt systems are beginning to be installed in the rear seats of new automobiles. The locking mechanism on most of these retractors is activated only when the vehicle suddenly decelerates. These are called vehicle-sensitive retractors. Other versions lock when the belt webbing is suddenly pulled out. These are called webbing-sensitive retractors. A few systems incorporate both features to control for secondary low-speed motions.

When used to secure a child restraint, ELR systems have the disadvantage that they cannot be made to lock the belt until a crash, leaving the CR relatively loosely secured prior to impact. This situation also creates a problem on a day-to-day basis, in that the CR may be less stable during cornering than one held by a tight manual or ALR belt. To see the relative degradation during impact conditions, an infant restraint and a convertible CR in both the rear- and forward-facing orientation were tested.

INFANT LOVE SEAT SECURED WITH ELR LAP BELT (XP8408). The restraint was properly installed on the standard bench seat using a current production ELR lap belt system, and the infant dummy was snugly harnessed. For this test, a series of tape loops were attached between the retractor housing and the belt webbing to try to determine the distance the belt might pull out at impact. For this test, the distance was determined to be between 0.5 inch and 1.0 inch. Although there was therefore some additional forward translation of the CR as compared to a standard test, the light weight and flat bottom of this CR design resulted in a back angle of 56 degrees (Fig. 11), which is only slightly greater than typical test results.

REAR-FACING KANTWET 401 SECURED WITH ELR LAP BELT (XP8409). The CR was properly secured and the dummy snugly harnessed. Test results

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[3]The tests described in this section were conducted with private grants. See footnote 1.

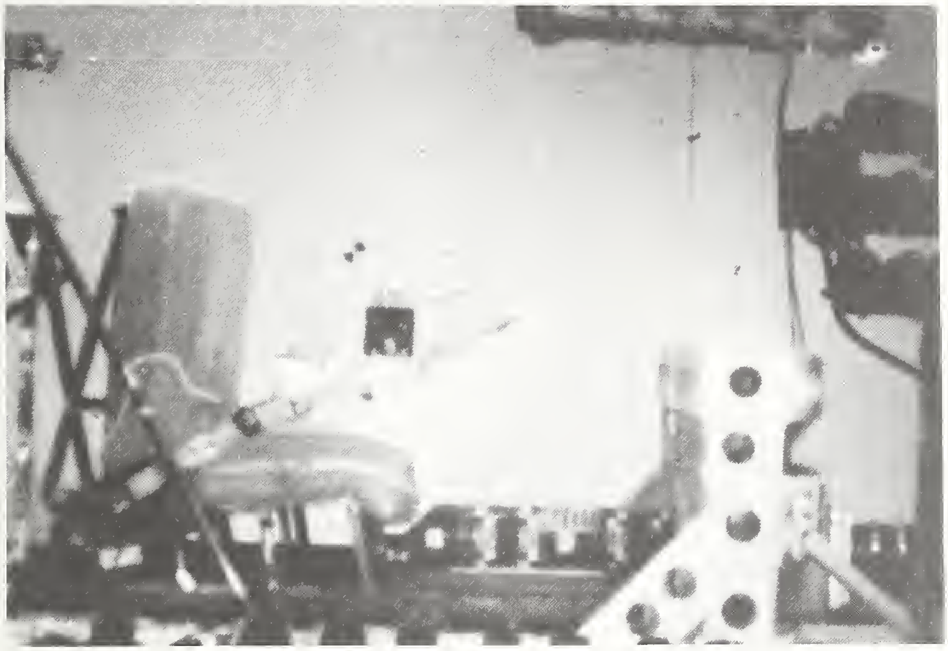

FIGURE 11. XP8408

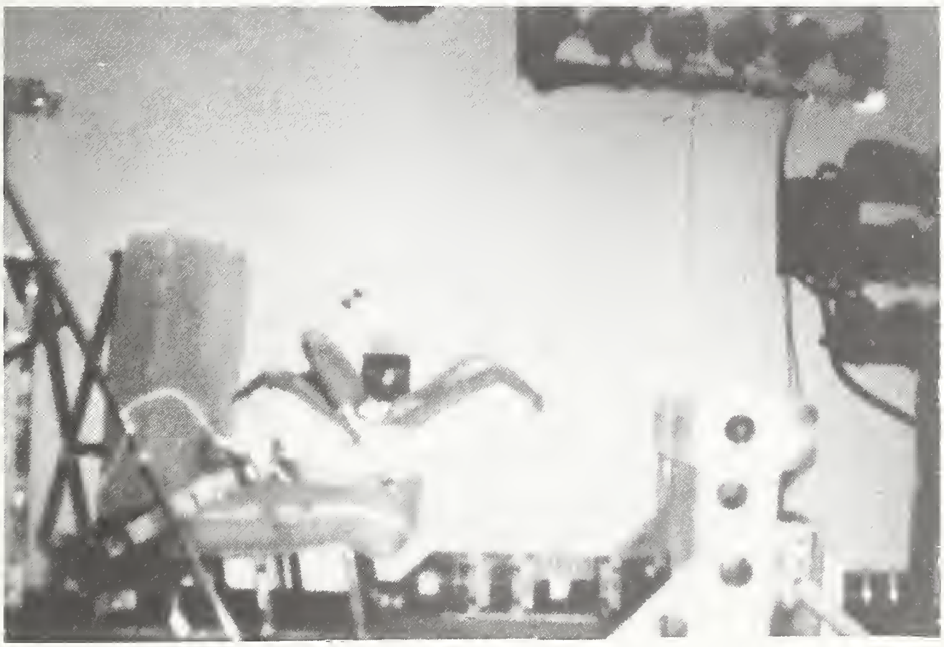

FIGURE 12. XP8409

were similar to those with the ALR (XP8406), with the back angle reaching the FMVSS-213 limit of 70 degrees (Fig. 12). Belt pay-out was again between 0.5 inch and 1.0 inch.

FORWARD-FACING KANTWET 401 SECURED WITH ELR LAP BELT (XP8410). The CR was properly secured and the 3-year-old dummy snugly harnessed. Belt pay-out and forward translation were consistent with previous test results, and the head excursion measured 32.7 inches (Fig. 13). This represents at least a four-inch degradation from FMVSS-213 test results.

Although the belt pay-out measured was significantly less than the additional head excursion, it must also be remembered that the belt starts out with much less tension than in an FMVSS-213 test, and that additional belt length results in greater CR rotation for both the rear- and forward-facing orientations. In the latter case, more CR rotation means greater dummy head excursion. Clearly, the tighter the lap belt is prior to impact, the better the CR will perform.

Belt Tightening Devices. Consumers and child restraint professionals have been concerned about ELRs for some time, but the above tests show that the slack problem also exists with ALRs. Means have been suggested for dealing with the instability aspect of ELRs, including pulling the belt all the way out and wrapping the excess around the CR frame, tying it in knots, or weaving it around a "locking clip."[4] Static tension tests of a standard locking clip used in this fashion (VRTC 1980) have demonstrated that this device is not as strong as the belt itself, and that it will bend under loads of 775 pounds, releasing the belt to unwind with disastrous results. (The same clip used as intended does withstand standard impact tests.) It is also generally known that tying a knot in a rope, string, or fishing line will make the the material more likely to break at that point, and the same is expected to be true of belt webbing.

Toyota has produced a heavier gauge locking clip, which they claim can safely be used to take up belt length in increments of about

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[4]This metal device was designed to clamp the lap portion of a lap/ shoulder belt to the shoulder portion in order to keep the webbing from slipping through a free-sliding latch plate and thus preventing the lap portion from loosening. It cannot "lock" a lap belt alone.

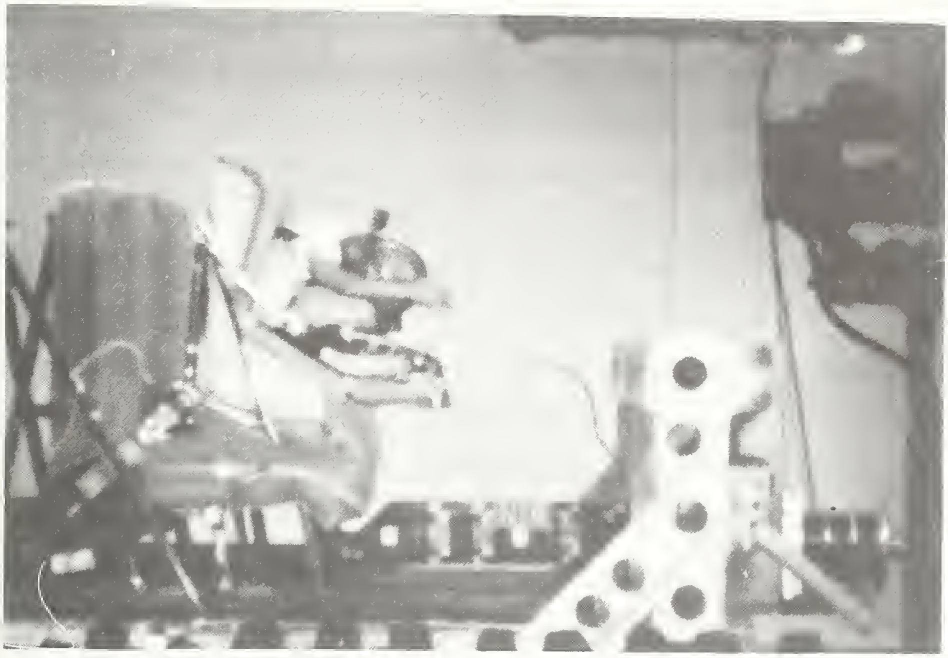

FIGURE 13. XP8410

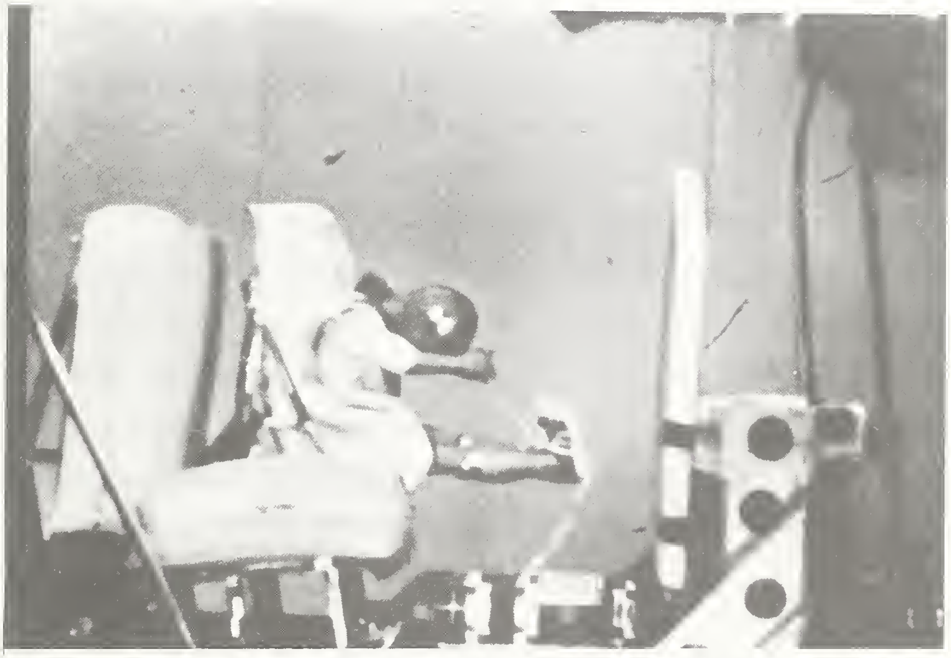

FIGURE 14. 83D005

8 inches for each clip. It is important to note, however, that this and similar methods are merely belt shorteners, not tighteners. It is true that, if shortening the belt by just 8 or 16 inches or by the distance between two pieces of frame tubing will make the buckled belt just tight enough, these methods will work. But what happens if 5.5 or 13 inches are needed to tighten an ELR belt, or just an inch of slack needs to be taken out of a snug ALR belt?

A device was developed at UMTRI that can be attached to a buckled belt to wind up and tighten the belt with a fine degree of adjustment. Details must be withheld at this time for patent considerations, but results of an impact test are reported.

UMTRI BELT TIGHTENER (83D005). A Century 200 was installed on the standard bench seat using a loose lap belt with several inches of slack, and the 3-year-old dummy was snugly harnessed. The tightening device was attached to the lap belt on the right side of the CR, and the webbing was tightened so that load cells on each end of the belt measured between 12 and 15 pounds. The belt was also chalked to indicate pretest position with respect to the tightening device. During the 30-mph impact the device held firm, and post-test examination of the chalk marks showed no permanent belt slippage. The head excursion of 31.0 inches (Fig. 14) was, however, about one inch greater than that typically seen with this CR model secured according to FMVSS 213. Overhead movies also showed that the CR rotated slightly to the left, indicating that some elastic spool-out or additional belt stretch probably occurred. Overall, however, the prototype device performed satisfactorily.

No direct comparisons can be made between this test and the preceding ALR and ELR series because of different CR models and the fact that the belt tightener was applied to a manually adjustable belt. Further testing using a retractor belt system is needed to determine whether or not ALR and ELR systems can in fact be tightened to FMVSS-213 test levels.

Floor Mounting

The popularity of vans and station wagons for family transportation has given rise to the need for a means of adequately securing a CR in the cargo area of these vehicles. Because both forward- and rear-facing CRs depend on the vehicle seatback for rear support and/or rebound restraint, special provision must be made for installation on a van or station wagon floor. The basic concept is that the CR must be secured against both forward and rearward motion by anchoring it with belts through both its forward-facing and rear-facing installation paths. For this reason, only convertible CRs can be used, not infant-only or toddler-only restraints.

When installing the two pairs of belt anchors, care should be taken that (1) the anchors for each belt are spaced as far apart as the CR is wide, and (2) the distance between the two pairs is great enough that the angle of the belts when securing the CR is no more than 45 degrees from the horizontal floor (Fig. 15). Tests using this installation method for a convertible CR in both its rear- and forward-facing orientation and a wheeled travel chair designed for handicapped children are described below.

VAN FLOOR INSTALLATION OF CR (83D009). Two Cosco 78 models were installed on a simulated van floor using the method described above. The 3-year-old dummy was snugly harnessed in the upright forward-facing CR, and the 6-month-old dummy in the reclined rear-facing CR. During impact, belt stretch allowed the CRs to translate forward 1.7 inches, but the rigid floor prevented any forward rotation (Fig. 16). A convertible CR secured in this fashion is therefore judged to be a very tight and effective restraint system.

For application in station wagon cargo areas, we recommend either the forward- or rear-facing orientation for toddlers, as long as there is adequate clearance (2 to 3 ft.) between the front of the child's head and any solid surfaces that the head could hit, but we do not recommend a side-facing installation for reasons discussed in a later section. It is also important to note that the passenger compartment is still the preferred location for child occupants, and that CR installation in the cargo area should only be done if space limitations require it.

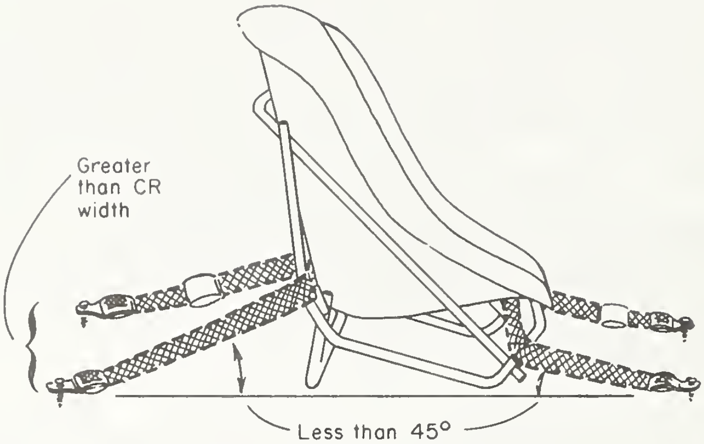

FIGURE 15. Van Floor Installation

FIGURE 16. 83D009

VAN FLOOR INSTALLATION OF TRAVEL CHAIR (83D010). The initial purpose of this test was to stimulate interest in providing a means of strengthening the structure of small wheelchairs that are currently in use and providing a method for their installation that would provide adequate restraint for handicapped children. This work was in fact continued with sponsorship by the Ford Fund of the Ford Motor Company and by the United Cerebral Palsy Foundation of Michigan and is reported by Benson and Schneider (1984).

For the purposes of this report, it is sufficient to indicate that the vinyl straps of an Ortho-Kinetics Travel Chair were replaced by a five-point belt-webbing harness, and a diagonal brace was attached to each side of the frame in an attempt to avoid the need for a top tether. The chair was secured to the floor by two belts in a similar manner to the CR installation above. The impact test showed, however, that the side bracing was not adequate, and flattening of the frame under-structure resulted in a loosening of the belts (Fig. 17). All these problems have since been addressed and solved in the follow-on work.

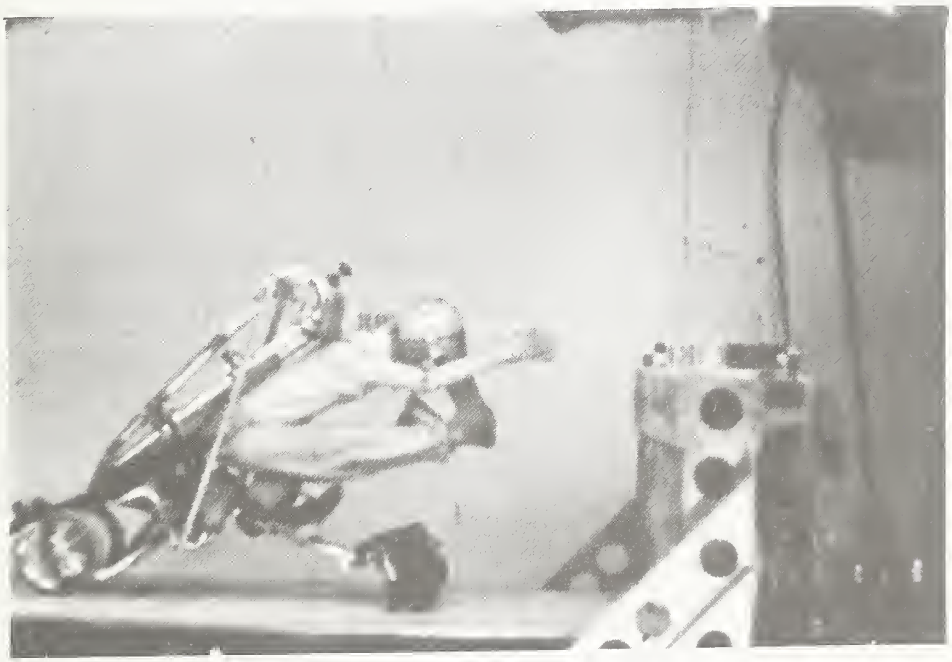

FIGURE 17. 83D010

CHILD RESTRAINT ORIENTATION

The direction in which the child and restraint are oriented with respect to the front of the vehicle and/or the impact itself can have a significant effect on the performance of the restraint system and thus on the outcome for the child. Because the principal direction of force for over half of all crashes is "head-on" plus or minus 45 degrees (e.g., Ricci 1980), and these frontal crashes average higher speeds than other directions, the orientation of the restraint in the vehicle correlates well with its impact orientation in severe crashes. This section deals with rear-, forward-, and side-facing orientations.

Rear Facing Versus Forward Facing

Current child restraint design philosophy in the U.S. is that infants should be oriented in a rear-facing position until they are developed sufficiently to sit up unassisted and weigh at least 17 pounds. This 17-pound threshold emanates from the weight of the 6-month-old dummy used to test infant restraints according to FMVSS 213. The choice of this particular size dummy for development in the early 1970s was based, however, not on biomechanical considerations but on the fact that, at the time, anthropometric data were the most complete for this age child.[5] The original intent was to use the dummy in aircraft restraint testing, but it became incorporated into the automobile testing environment because it was the best infant dummy available. Formal selection of this dummy was made in a 1978 Federal Register notice (43 FR 21490) to accompany a proposal for a new child restraint standard using dynamic test procedures (43 FR 21470). The same notice indicated that this dummy was to be used to test any child restraint designed for infants weighing less than 20 pounds, but not necessarily in a rear-facing orientation.

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[5]This information confirmed in conversation with R.F. Chandler, who participated in the development of this dummy at the Civil Aeromedical Institute (CAMI), Oklahoma City.

Rear-facing restraint systems provide superior crash protection for all ages of children as well as adults than do forward-facing systems, merely because the body's back structure has more bone mass than the front of the chest, and the back as well as the back of the head can be easily and effectively restrained by a broad flat surface. Child restraints secured in a rear-facing orientation add another dimension, in that the child and restraint move together in the direction of impact. This feature has the potential for reducing the loads and orienting their transfer to the body in an optimum direction.

Infant-only restraints (IORs), as distinguished from convertible CRs, are designed to be used only in this rear-facing orientation. As indicated above, the weight of the FMVSS-213 infant test dummy has caused most manufacturers to limit use of these products to children weighing up to 17 pounds, and instructions on convertible restraints also tend to imply such limits on the use of the rear-facing orientation. Because (1) consumers do not generally understand the theory behind rear-facing versus forward-facing restraints, (2) rear-facing use seems to be restricted to children under 17 pounds, and (3) there is, we suspect, some confusion between the designed functions of IORs versus convertible CRs, infant-only restraints are frequently observed facing forward, and larger infants who could still comfortably ride rear-facing in a convertible CR are being turned around to face frontal crashes.

The following series of tests addresses several aspects of the issues raised above, including the consequences of using a popular IOR model facing forward, a comparison of a larger infant dummy in rear- and forward-facing environments, and a rear-facing restraint for older children.

INFANT LOVE SEAT FACING FORWARD (83D001). This restraint system was designed in the late-1960s (Feles 1970), using a 20-pound dummy (hence its higher weight limit), and remains relatively unchanged in basic design to this day. Because the primary restraint mechanism in a frontal crash is through the back of the double-walled shell, shoulder straps were added only for containment during rear-end and angular impact as well as during frontal crash rebound. Rotation of the rear-facing IOR toward the vehicle seatback, which occurs during rebound and rear-end test conditions, also provides some protection through containment. The key feature, however, is that shell and dummy travel rearward together during such impacts.

The shoulder straps provided form a "V" over the infant, coming together at an anchor-point on the shell near a small baby's feet. A strap slide turns this "V" into a "Y" when it is pushed up to the infant's chest. There is, however, no forward pelvic restraint, such as provided by a five-point harness or, to a limited extent, by a "Y" harness with a close-fitting crotch anchor-point. Contrary to popular belief, the lap belt around this IOR anchors only the restraint and is too far from the infant to provide any direct impact protection.

The test dummy, a Part 572 6-month-old, was snugly harnessed in the IOR, with the strap slide located over the chest as shown in the instructions. The restraint was then placed facing forward on the standard bench seat, with its bottom surface flush with the seat cushion, and anchored with a lap belt threaded through the belt slots provided.

During impact, the dummy slid forward relative to the restraint, until its neck caught on the lap belt, its crotch nearly contacting the "foot-end" of the shoulder straps (Figs. 18-19). The shoulder straps themselves may have contributed to keeping the dummy from being ejected over the top of the lap belt, but the primary malfunction relates to the incorrect orientation of the entire system. The critical issue here, however, is that some segment of the consumer public perceives this IOR as being able to provide injury protection in a mode for which no protection was designed. Convertible CRs, at least, provide forward restraint, even if the mechanism is not optimum for an infant body.

HEAVY BABY IN INFANT LOVE SEAT (83D002). In contrast to the misperception leading to the preceding misuse, we have encountered a fear that CRs will not work if used rear-facing with a child slightly heavier than "allowed" by the instructions (Weber 1981). To be able to test the consequences of overloading a rear-facing restraint, among other purposes, UMTRI modified a Part 572 6-month-old dummy (Fig. 20) to simulate a large 1-year-old in size (length=32 in., seated height=20

FIGURE 18. 83D001 Side View

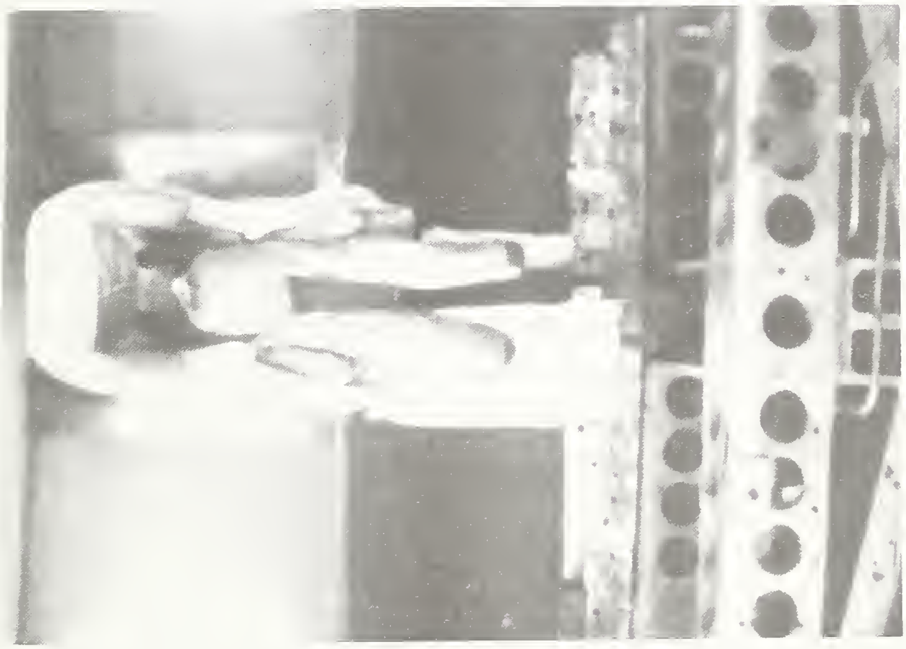

FIGURE 19. 83D001 Overhead View

FIGURE 20. Part 572 6-Month and UMTRI 1-Year Dummies

in.) using foam material, as well as weight (24 lb.) and center of gravity location (58% of length) using lead sheeting (Snyder et al. 1975). Some manufacturers of convertible CRs have already used this dummy to confirm that their models do indeed meet the FMVSS-213 performance criterion even with the extra load.

For the test with the IOR, the UMTRI 1-year-old was snugly harnessed and placed in the rear-facing orientation on the standard bench seat. The lap belt was properly threaded and pretensioned. The extra seated height of this dummy placed the head slightly higher than we would recommend for an actual child, but the harness was long enough to accommodate the larger size. During impact, the maximum back angle reached was 61 degrees (Fig. 21), although the sides of the shell flexed inward considerably under the added load (Fig. 22). In actual use, however, rear-facing restraints are often wedged against the instrument panel, and thus greater loads can easily be withstood. The restriction on size for a child using this particular IOR, therefore, would seem to be limited more by the head height than the weight of the child up to 24 pounds. For convertible CRs, even the head height would not be a problem. We caution the reader, however, that these test results apply only to the Infant Love Seat, and that other CR models should not be used with babies over 17 pounds until such time as they are similarly tested.

SMALL-CHILD/ARMREST INTERACTION (83D006). The purpose of this test was to indicate the potential for injury in a configuration not addressed by FMVSS 213, but the results are particularly interesting in the context of the preceding test. The CR selected for the test was a Century 300, which has a five-point harness and a spring-loaded armrest that is held down by the buckled harness. Although NHTSA tried to eliminate these non-restraining armrests by providing for a "misuse" test in FMVSS 213 (see Melvin 1981), marketing forces within the industry, who believe armrests increase sales, have motivated designers to find a way to retain armrests while complying with the standard.[6]

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[6]The current interpretation of the standard is that an armrest that pops up when the harness is not buckled does not exist at all for the purposes of any FMVSS-213 impact test. Regarding consumer demand,

FIGURE 21. 83D002 Side View

FIGURE 22. 83D002 Overhead View

The other change was to cover the old metal bar with a larger foam pad, but the thickness of this relatively low-density foam directly over the bar is only about one inch. The flat pad, however, extends beyond the bar about 4 inches, giving the impression of a broad protective shield.[7] Although the head interaction seen during a standard test with the 3-year-old dummy is merely with the soft far side of the pad, we were concerned that a shorter dummy, representing a younger child, might in fact contact the armrest at the metal bar.

The 24-pound UMTRI 1-year-old, with head accelerometers added[8] was properly harnessed in the CR, but, to add a little more realism to the test, the harness was adjusted to leave "two fingers" width of slack, which is typical of the tightness used even by conscientious parents. During impact, the head did hit the armrest, resulting in a HIC of 1048 (Fig. 23). The most severe component of the head acceleration was in the A-P (face to back-of-head) direction (108 G), but overhead movies showed that there was also significant loading in the S-I (top-of-head to neck) direction. This is confirmed by the occurrence of an S-I deceleration of the head late in the crash event that is not seen with the 3-year-old dummy. Because of this S-I loading and the fact that the HIC was only slightly over 1000, the primary injury concern may not be for the head but for a combined compression and shear loading of the neck, as the head is stopped but the body continues forward and down.

The crude nature of this dummy precludes any definitive conclusions, but this test does indicate that there may be problems with

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we find the choice of sequential model numbering to be quite misleading. We suggest that the high sales volume of the Century 300 is due less to its armrest than to the fact that is is perceived by the public to be better or more advanced than models numbered 100 or 200. The same can be said for other manufacturers.

[7]Other manufacturers, such as Strolee and International (Astroseat), have provided padded hollow plastic shells around or over the metal bars, which may isolate the bars better from potential head impact. Century has also recently changed to a padded blow-molded armrest cover.

[8]A triaxial accelerometer array was encased in dense foam and placed at the approximate center of gravity of the dummy head, replacing internal packing material.

FIGURE 23. 83D006

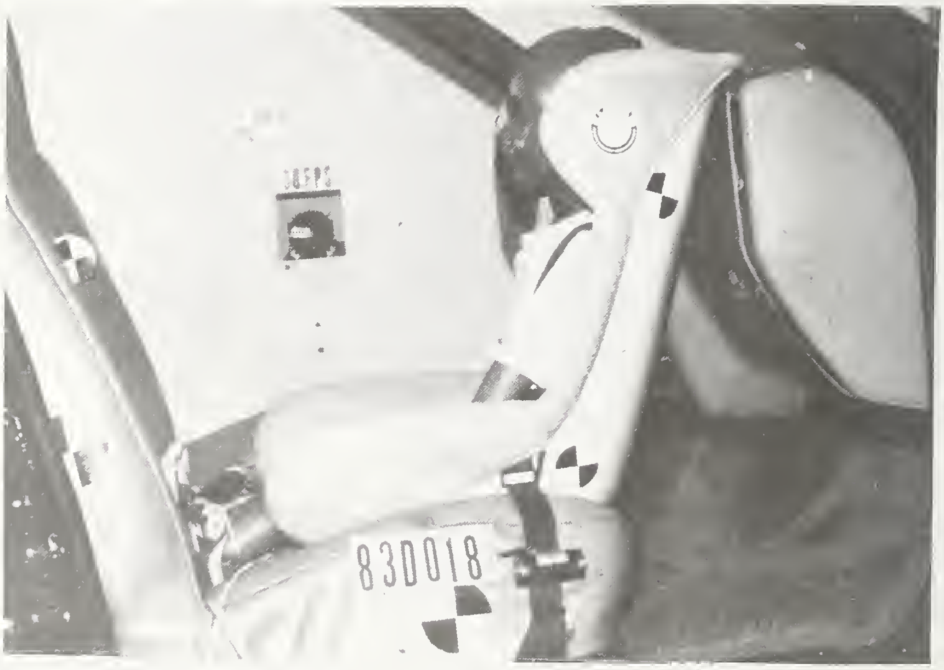

FIGURE 24. 83D018

certain CR designs that are not identified by either the 6-month or 3-year dummy. This gap seems particularly critical in that it relates to children at the age and size that have typically just been turned around to face forward. Again we would like to stress that it is better to keep a child rear facing as long as possible. We therefore recommend that child restraints be tested in all appropriate orientations with a dummy representing approximately a 1-year-old child. These tests may not only extend rear-facing use but also lead to beneficial design changes in forward-facing configurations.

REAR-FACING KLIPPAN TODDLER RESTRAINT (83D018). While the U.S., Japan, and most of Europe have adopted the forward-facing orientation for children past infancy, Sweden has retained the rear-facing orientation for children up to at least age 4, based on early work by Aldman (1964). Because of the need for child leg room, these CRs are positioned farther from the vehicle seatback than are U.S. rear-facing designs, and they therefore require special installation. Instead of being secured by a lap belt, three anchor straps typically tie the CR to the floor and/or seat track behind and on either side of the vehicle seat. In addition, the back of the CR must rest against the instrument panel for front-seat installation or against the back of the front seat for rear-seat installation.

A Klippan "Comfort" was installed in the front seat of a passenger car test buck in the manner described above, and the 3-year-old dummy was snugly harnessed (Fig. 24). During the 30-mph impact test, the restraint and dummy remained in virtually the same place. The notable results were the low accelerations of the head (peak resultant 35 G, HIC 66) and chest (27 G). These can be compared with typical forward-facing accelerations, which range from 60 G to 75 G for head peak resultant, 500 to 700 for HIC, and 40 G to 50 G for chest peak resultant. The reason for the lower accelerations for the Klippan CR is the close coupling between the "vehicle" and the restraint system, primarily due to the initial contact with the instrument panel. Even if the dash were pushed into the passenger compartment in a severe crash, this restraint would provide more effective protection than a forward-facing CR, which might not be able to prevent head contact with the penetrating structure.

The necessity of installing at least one tether anchor and the use in most cases of the front passenger seat make it seem unlikely to us, however, that this CR configuration would be popular in the U.S. At the same time, we would encourage CR manufacturers to voluntarily expand the rear-facing orientation beyond the current 17 to 20 pounds to significantly improve crash protection for small children.

Side-Facing Restraints and Side Impacts

The test configurations discussed in this section are of two types: (1) CRs installed facing the side of the vehicle during a frontal crash and (2) CRs installed facing forward during impact from the side. The primary differences between the two are that frontal crashes tend to be more severe (i.e., higher speeds) than lateral crashes, and the vehicle structures surrounding the child and restraint system are oriented differently by 90 degrees. These differences can have a significant effect on the performance of a child restraint system. Both infant-only and child restraints are addressed, with particular emphasis on head impact protection.

Lateral Infant Restraints. Car beds, secured sideways on a vehicle seat or wedged behind the front seat, are the officially sanctioned method of infant restraint in Europe. The reason these are preferred over the semi-reclined rear-facing restraints used in this country is not clear to us, but it probably has more to do with tradition than with crash protection principles. Although FMVSS 213 includes crash test procedures and criteria for car beds (simply that the dummy's head and torso must be retained within the confines of the car bed), there are no crashworthy car beds currently on the U.S. market. We therefore turn to the European market.

Romer-Britax produces a crashworthy car bed, but it is secured by specially installed belts, rather than the vehicle lap belt, and thus does not conform to FMVSS-213 requirements. Another approach is taken by Klippan, a Swedish manufacturer, which offers an interesting device that converts a household bassinet, "travel bed," or carriage insert into a crashworthy infant restraint.

KLIPPAN BASSINET RESTRAINT (83D008). The Klippan "Baby" is basically a metal frame that is secured by the vehicle lap belt as well as a front tether to the floor. This frame is placed the long way across the vehicle seat, a bassinet is set inside the frame, the baby is laid in the bassinet, and a combination of netting, belts, and buckles holds the bassinet in place (Fig. 25). Heavy pads are provided for placement inside the bassinet at the head and sides to give added strength and impact protection, but there are no harness straps directly restraining the infant. Placement of the system and orientation of the child is critical, however, in that the head must not be next to a vehicle door or other hard surface, but rather as close to the center of the vehicle as possible. This precaution must be taken to guard against potentially severe head and neck injury in a side impact.

To test this system in a frontal impact, the 6-month-old dummy was placed in an old vinyl-sided "travel bed," the heavy padding was added, and the bed was fastened into the Klippan "Baby" frame/netting system as described above. The frame had previously been secured to the standard bench seat with a lap belt and front tether. During the 30-mph impact, the dummy was retained in the bed, and all aspects of the system performed as intended. There was some bending of metal parts, but no failures or breakage occurred. The overhead view of the test (Fig. 26) shows considerable lateral bending of the dummy as the soft bed and netting bowed out under dynamic loading, but this level of bending is judged not to be harmful to a flexible infant.

This approach to infant restraint has the advantage of being convenient for those who use portable bassinets, carriages, or other small beds, but it has the disadvantage of taking up a significant portion of the vehicle's rear seat. There might also be the question of acceptability to the child beyond early infancy. Our own preference for infants is still the rear-facing restraint.

FIGURE 25. 83D008 Pre-Test

FIGURE 26. 83D008 Overhead View During Impact

Side-Facing Installation in Station Wagons.[9] Most, if not all, CR instructions say to use the restraint system only on forward-facing vehicle seats. Some full-size station wagons, however, have side-facing seats in the rear, which are equipped with belts and which many parents would like to use for child restraint installation. The question has been raised as to whether there is any justification for this restriction, other than the fact that FMVSS 213 addresses only forward- and rear-facing restraints in frontal crashes.

We would first eliminate the rear-facing CR from installation on a side-facing seat, because the infant would be facing side window glass, rather than the soft seatback cushion. The forward-facing installation mode on a side-facing seat, however, seemed to deserve actual impact testing. Two such tests are described, the first with a single CR and the second with two CRs side by side. The third test addresses side-facing installation in a station wagon cargo area that has no seats. All tests were run at the standard 30-mph/20-G severity level for frontal impacts. These tests were therefore much more severe tests of the CR systems than the typical lateral impact test of 20 mph and 16 G.

CR INSTALLATION ON SIDE-FACING SEAT (XP8411). A Century 100 was installed with a lap belt on a vehicle bench seat oriented sideways on the impact sled. A platform was constructed next to the seat to simulate the actual interior floor geometry of a full-size station wagon having this type of seating configuration. The 3-year-old dummy was snugly harnessed in the CR. During impact, the CR rotated sideways about 45 degrees, allowing the head to contact the raised "floor" (Fig. 27). It is significant that the side wing next to the head deflected completely out of the way and provided no impact protection. The HIC was 970 and was due not only to the contact on the side of the head (right-left acceleration 54 G) but also to the flailing of the head during CR rotation (S-I acceleration 88 G). (Chest accelerations were not excessive.) The inability of the lap belt to adequately control the motion of the CR on the soft seat as well as the inability of the harness and shell to adequately control the motion of the dummy

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[9]The tests described in this section were conducted with private grants. See footnote 1.

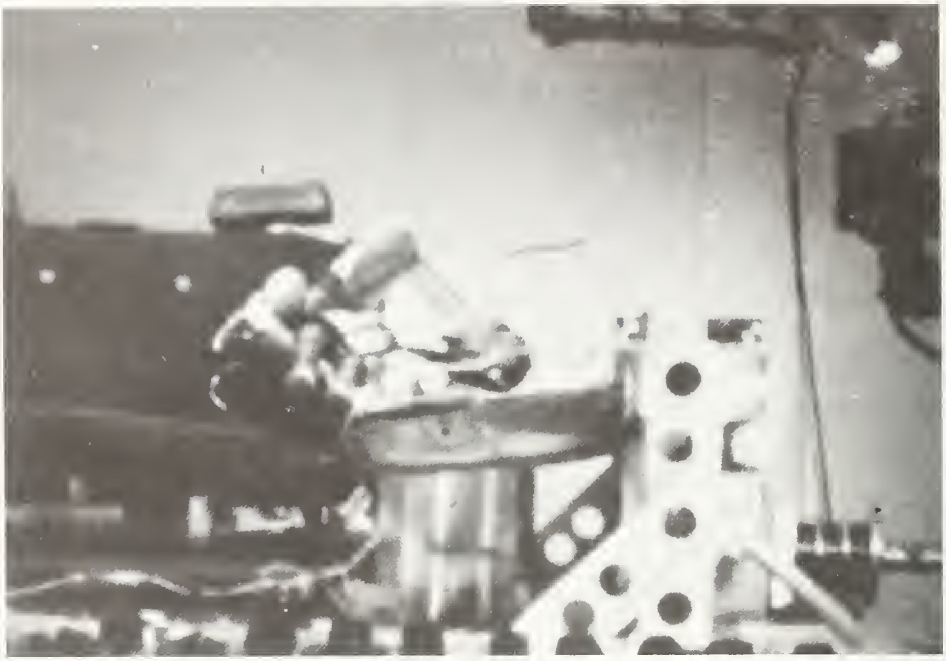

FIGURE 27. XP8411

FIGURE 28. XP8412

represent significant degradations over expected performance in either a forward-facing orientation or a lateral impact at 20 mph. It is probable, however, that a child so restrained would survive most actual crashes virtually unharmed, as long as the head was not close to a hard vertical surface. It is also clear that a CR installed in this configuration would provide better protection for a child than would a lap belt alone in the same situation. Therefore, although we do not recommend installing CRs on side-facing seats for regular use, if vehicle occupancy demands use of such seating positions, a child in a CR is likely to fare all right.

INSTALLATION OF TWO CRS ON A SIDE-FACING SEAT (XP8412). The purpose of this test was to determine if there might be any interaction between the dummies and/or the CRs that would indicate an adverse effect on the more rearward passenger. Three-year-old dummies were snugly harnessed in a Strolee 612 and a Cosco 313, and both CRs were secured to the vehicle seat by lap belts. The Cosco was placed on the impact side. The results of the impact were similar to those of the previous test, with the CRs effectively isolating the dummies from each other (Fig. 28). The HIC for the Strolee dummy was 845, with the S-I component being 53 G, significantly lower than that of the previous test. It therefore appears that two CRs installed side by side are no worse for the second child.

CR INSTALLATION SIDE-FACING IN STATION WAGON CARGO AREA (XP8414). A Century 200 was installed with a single lap belt on a rigid floor simulating the cargo space in a station wagon. The CR was backed up by a simulated vehicle side panel and placed next to a simulated rear seatback with padded upper edge. For the purposes of this test, it was assumed that the "seatback" locks would hold; otherwise the results would be similar to the previous tests in which no substantial structure was in the path of the CR. During the 30-mph impact, there was much less lateral rotation because of both the rigid floor surface and the proximity of the fixed "seatback" (Fig. 29). Again the side wing next to the head was pressed out flat (Fig. 30), but in this case there was nothing in the head's path to hit. The combination of non-contact and the relatively controlled motion of the dummy resulted in a HIC of 521.

FIGURE 29. XP8414 Side View

FIGURE 30. XP8414 Overhead View

The problem here, however, is the way in which that dummy motion was "controlled." The sudden stop against the fixed "seatback" resulted in a lateral chest acceleration of 105 G, enough to be lethal. Although child restraints can provide some side impact protection (further discussion on this relative to tests described below), the important factor here is that lateral installation has placed the vehicle seatback in an orientation relative to the CR for which it was not designed.

Fortunately, in this case, there is a better alternative. That is to install the CR(s) rear facing, backed up against the rear seatback, using the two-belt method described previously for vans (83D009). A single belt through the path normally used for forward-facing installation is not adequate, because of the possibility that the seatback latches may not be able to hold under the forces of a severe crash. It would be possible, however, to attach one pair of belts to the rear-seat belt anchors already in the vehicle, so that only one new set of anchors would need to be installed to hold down the front of the CR.

Side Impact Protection. In the previous tests, we saw that flexible plastic side wings provided for children to rest their heads against are easily bent outward by the head during 90-degree, or "pure lateral," impacts. In addition, we have seen in other test series (Melvin 1976) that, when CRs are impacted at 60 degrees, the head not only deforms the side wing somewhat but also travels out around it, leaving the head completely unprotected from intruding structures.[10] The best solution to the problem of side impact protection for the head would of course be to have all children (as well as adults) wear helmets. But this is not likely to be practical. The question has been raised, however, as to whether these side wings would or could act like a partial helmet if somehow trapped between the head and an intruding structure, such as a door pillar. The following two tests address the

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[10]In fact, the 60-degree impact is a much more realistic test, because there is nearly always a forward component in any side impact, due to the fact that the vehicle is probably traveling forward at the time. A pure lateral impact could only occur if the vehicle were standing still or if it were hit to the rear of 90 degrees while traveling forward. These are both fairly rare events.

potential benefits of CR side wings by comparing dummy response with and without the wings. Because these tests were to simulate a side impact to a forward-facing CR, they were run at lower speeds (approximately 19 mph) than previous tests.

CENTURY 100 WITH SIDE WING REMOVED (84D022). The side wing head rest was cut from a Century 100, the CR was installed on a vehicle bench seat oriented sideways on the impact sled, and the 3-year-old dummy was snugly harnessed. A rigid wall with surface padding of 1/2-inch Ensolite was placed next to the CR to simulate a vehicle side panel being impacted in the direction of the CR. During impact (Fig. 31), the lateral acceleration of the head exceeded 250 G and could not be measured by the instrumentation used. The HIC exceeded 2750. Lateral chest acceleration was 177 G, the dummy's shoulder having been exposed as well by the removal of the wing. This baseline test is also an indication of the relative vulnerability of a child in a booster or a lap belt alone.

CENTURY 100 WITH SIDE WING INTACT (84D021). A nearly identical test except for the existence of the side wing shows that this structure does provide some cushioning for the head and shoulder if it remains in place between the dummy and the impacted surface (Fig. 32). Although the lateral head acceleration was 113 G, the HIC was only 845, a significant decrease from the previous test. There still appears to be a problem with the chest, however. Although the lateral acceleration was reduced to 87 G, this level is still unacceptable.

In evaluating restraint systems, we consider whether the dummy's motions are adequately controlled to keep it from hitting injury-producing surfaces and whether the means of control is itself non-injurious. In the case of a near-side impact, it is nearly impossible for any restraint system to control the motions of an occupant enough to keep him or her from interacting with the interior of the vehicle. A child restraint has the potential of providing relatively thick sections of high-density padding within a double-walled side shell structure, but these would also need to be rigidly supported by the frame so that they would remain in place when needed. Even this would only be a partial solution, however, because more exterior rigidity and more interior

FIGURE 31. 84D022

FIGURE 32. 84D021

padding depth would be needed for complete protection than could be provided by any portable child restraint. Further side impact protection must come from the vehicle itself. We are hopeful and optimistic that current research on side impact protection for adults will soon result in vehicle side structures and interior padding that will benefit all occupants in lateral crashes.

UPPER TORSO RESTRAINT

Shoulder belts, full shields, and inflatable cushions can all provide the very valuable function of keeping the body relatively upright and thus restricting the forward travel of the head. Shoulder belts, both single-diagonal and vertical pairs, also share the body's load with that on the lap belt, reducing the risk in severe crashes of pelvic fracture or damage to soft abdominal tissue. Upper torso restraint systems can also be designed to provide upper body support for handicapped individuals during everyday travel. Although diagonal shoulder belts are easy to use and comfortable if they fit properly, their anchorage geometry as found in the family car may not be optimum for small children. Ways to alter this geometry as well as an alternative upper torso restraint for children have been explored. These topics are addressed by the tests described in this section.

Boosters and Belts

Booster seats are designed to be used with lap and upper torso restraint. Most booster designs consist of a firm, elevated seating surface with no back. They are different from ordinary cushions in that they have seatbelt guides on each side. These guides, which also double as convenient carrying handles, provide (1) a sturdy location for the seatbelt to restrain the booster and keep it from sliding out from under the child and (2) a seatbelt positioning aid to place the lap portion low and flat across the child's thighs and to decrease the angle of a diagonal shoulder belt so that it lies comfortably on the child's shoulder and chest.

Upper torso restraint is most easily provided if a vehicle lap/shoulder belt is available. Unfortunately, rear seats are rarely equipped with such belts today, although the influx of foreign cars having rear-seat shoulder belts may change that situation. In any case, the alternate method requires installation of a tether anchor for a special pair of shoulder straps through which the lap belt is threaded. Based on CR tether observations (Shelness and Jewett 1984), our own informal observations of boosters, and inquiries from consumers, we suspect that boosters are frequently used with only a lap belt. The first test described below shows the consequences of using a booster without upper torso restraint compared to using a lap belt with the dummy sitting directly on the vehicle seat. The other two tests address the problem of shoulder belt geometry for small children with and without a booster.

BOOSTER WITH LAP BELT ONLY (83D004). Boosters are required to meet the FMVSS-213 criteria when tested at 20 mph using only a lap belt restraint. This is usually referred to as the "misuse" test. Although the 3-year-old dummy, lap-belted on the standard bench seat, stays within the 32-inch head excursion limit at 30 mph, the insertion of a booster under the dummy significantly increases that excursion at the same test speed (Fig. 33). The head excursion of the lap-belted dummy was 31.1 inches, while the head excursion with lap belt and booster reached 34.4 inches, an increase of over three inches. In addition, a comparison of the arcs described by each dummy's head shows a greater difference (3.7 inches) at about 60 degrees from vertical than at maximum forward excursion (Fig. 34). Thus a child lap-belted on a booster in the rear seat runs a greater risk of hitting his head on the seatback in front of him than does a child lap-belted directly on the vehicle seat. Seatbacks, especially those with adjustable headrests or ashtrays mounted on the back, can expose such a child's head to injury-producing hardware.

The increase in head excursion is due primarily to the longer belt needed to go up and around both the child and the booster. As the belt is pulled tight during impact, the leading edge of a longer belt is higher and farther forward than the leading edge of a shorter belt at the same belt angle. The head of the child, whose body is rotating around this leading edge, will also describe an arc that is offset higher and farther forward from that of an unboosted child, thus exposing the head during a crash to a different, and possibly more hostile, head-impact environment. Because head impact protection is so critical, we think it unfortunate that a concern over possible submarining has caused the Canadian government to prohibit the sale of

FIGURE 33. 83D004

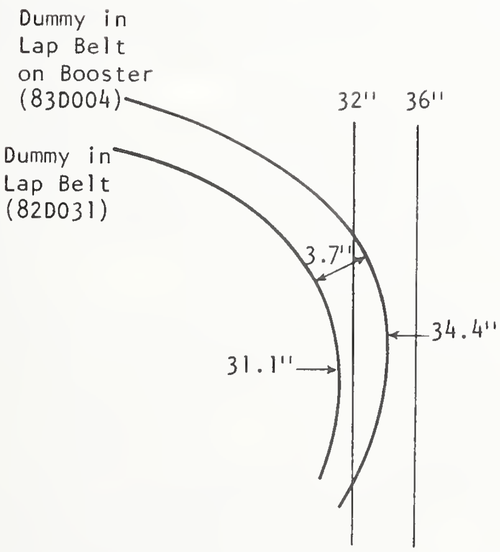

FIGURE 34. Head Arc Comparison With and Without Booster

these add-on shoulder straps and thus encourage lap-belt-only use in the absence of rear-seat lap/shoulder belts.

KLIPPAN HIGH-BACK BOOSTER (83D017). Even with the aid of the booster's seatbelt guide, the shoulder belt may rub uncomfortably on a small child's neck. In addition, the head of a larger child, when he or she is sitting on a booster, may be positioned above the top of a low vehicle seatback. To address both these problems, the Swedish Klippan "Kombi" provides an adjustable (and removable) back support structure with a padded headrest/restraint and a second belt guide just above shoulder level. This booster system can be used only with a lap/shoulder belt, because no alternate method of upper torso restraint is provided.[11]

To test the system under extreme conditions, a 10-year-old dummy (TNO, The Netherlands) weighing 70 pounds was harnessed in the Klippan booster with a lap/shoulder belt (Fig. 35). Unfortunately, the combination of structural problems with the booster and a dummy with unrealistic rotational flexibility (Roy et al. 1982; Clark 1983) led to unsatisfactory results (Fig. 36). Not only did the dummy rotate out of the shoulder belt during the impact, but the press-fit metal head restraint flew off the high back. Although the concepts were good, their execution was lacking. We refer the reader instead to the Cosco version (see footnote).

SHOULDER BELT ADJUSTMENT STRAP (83D007). There is some controversy over the potential for neck injury, either strangulation or dislocation, when children use diagonal shoulder belts. The old rule of thumb was that they should not be used with children less than 55 inches tall (an average 11-year-old, sitting height 29 inches). In recent years, however, the anchor points of shoulder belts have been lowered, significantly changing belt geometry. Because individual vehicles vary greatly, it is more meaningful to give parents guidelines that can be applied on an individual basis.

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[11]Independently, Cosco has also developed an adjustable high-back booster, the Travel Hi-Lo. Available on the U.S. market, it can be used with either a lap/shoulder belt or a tethered shoulder strap assembly that is threaded through the high back.

FIGURE 35. 83D017 Pretest

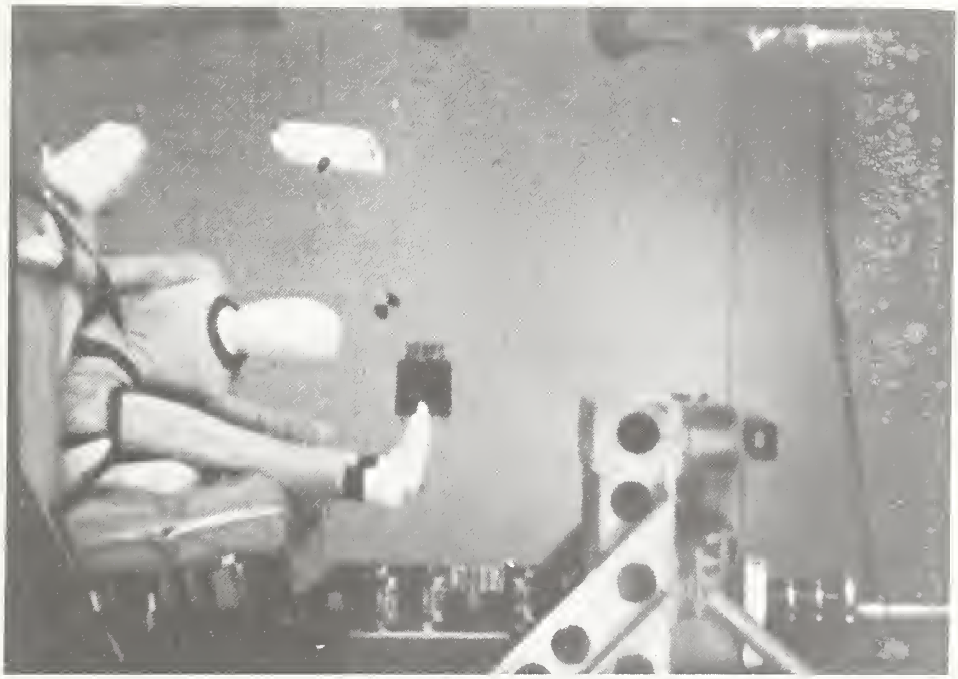

FIGURE 36. 83D017 During Impact

Shoulder belts are just that--they are designed to restrain the body at the shoulder bony structure. If a belt lies across a child's face or flat on the neck, it will not do the job it was designed for and should not be used. If, however, it can be made to lie flat on the shoulder, even though its edge may touch the neck, it will provide non-injurious restraint and should be used.[12] Our own measurements in current vehicles indicate that children with a sitting height as low as 20 inches (an average 2-year-old) can be properly restrained in a lap/shoulder belt, especially if the child is positioned close to the lower end of the belt. One means of adjusting this geometry is the booster, with or without the upper belt guide. Another method is a shoulder belt adjustment strap.

This simple strap, constructed for this test, was patterned after an Australian design called "Sit-Safe" made by Safe-N-Sound of New South Wales. Properly positioned between the shoulder and lap belts, the strap pulls the shoulder portion down without pulling the lap portion up. Figure 37 shows the geometry of the unmodified shoulder belt on the 3-year-old dummy, and Figure 38 shows the same belt with the adjustment strap. During the 30-mph impact test this system provided effective restraint geometry for the 3-year-old dummy, with no evidence of the lap belt being pulled up to cause submarining (Fig. 39). Acceleration measures were of some concern, however. This triangular belt system has more "play" than does a lap/shoulder belt alone, but at the same time it is relatively stiff. The effect is a higher S-I head acceleration from the head whipping forward (67 G) as well as a higher HIC (931) than occurs in tests of boosters with lap/shoulder belts. Even so, this strap provides a better alternative than placing the shoulder belt behind the child and thus eliminating the upper torso restraint entirely.

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[12]As with any belt restraint, risk of injury from the belt itself is reduced directly with the pre-impact tightness of that belt. Cases of severe neck injury from diagonal belts are known to have involved very loose belts that cause sudden excessive loads on the neck (Corben and Herbert 1981; Appleton 1983).

FIGURE 37. 83D007 Shoulder Belt Without Adjustment Strap

FIGURE 38. 83D007 Shoulder Belt With Adjustment Strap, Pre-Test

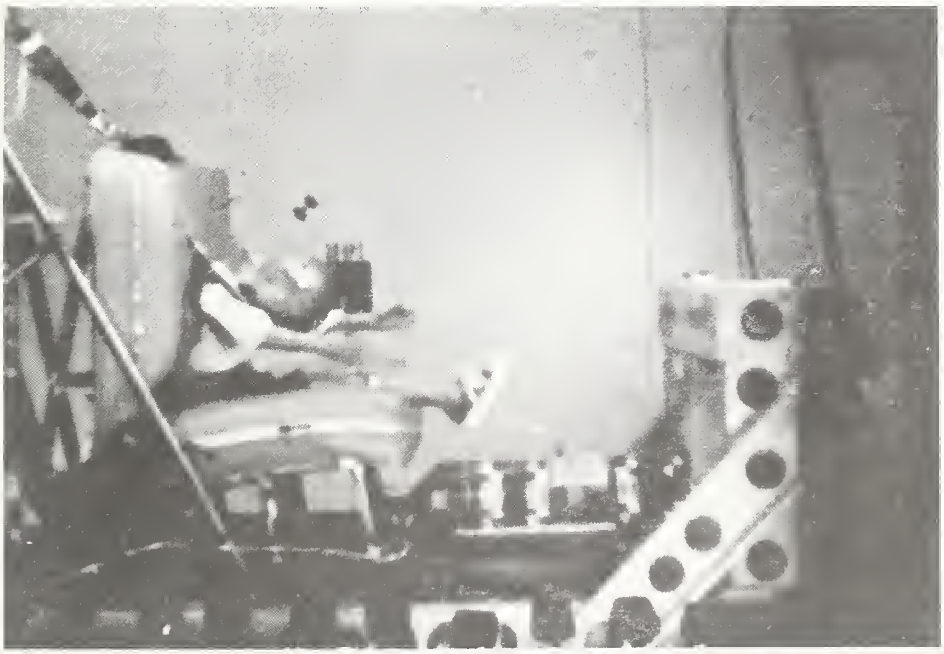

FIGURE 39. 83D007 at Impact

Experimental Load Distribution

Two experimental upper torso restraint systems, constructed specially for this project by Suzanne Klich, Vincentown, New Jersey, were tested at 30 mph. The first is a netting vest restraint for older handicapped children and the second is an inflated pad for protection of otherwise unrestrained children in rear seats.

NETTING VEST (82D042). Vest restraints are popular for handicapped children who need special upper torso support as well as crash protection. They require the installation of one or two tether anchors in addition to the use of a lap belt. Vests constructed of belt webbing material are commercially available from Rupert Industries. The experimental system tested here was instead constructed primarily of a heavy nylon netting material, with belt webbing used only at anchorage points (Fig. 40), the theory being that crash loads would be distributed over the chest rather than concentrated in narrow areas. In addition, leg straps were provided to hold the vest down and reduce the risk of submarining.

Due to the size and limited adjustability of the vest provided, it was necessary to use a 5th percentile female dummy, which roughly simulates a 13-year-old child in height (58.5 inches) and weight (105 pounds). Although the stitching at the tether attachment failed late in the impact (load at failure 1733 lb.), it was still possible to see that the vest would have performed well otherwise, there being no evidence of submarining. It is questionable, however, whether the netting provided any real load distribution. It is more likely that the loads were still concentrated in the vertical paths between anchor points, but there is no evidence that this concentration would itself be injurious.

INFLATED PAD (83D019). Three air-inflated bags made of polyurethane-coated nylon fabric were constructed and installed in front of the TNO 10-year-old dummy in the rear seat of a passenger car buck (Fig. 41). Their purpose was to provide some occupant motion control for an unrestrained child (see Clark 1984). The front seatback was anchored with cables to prevent forward deformation. During impact the dummy contacted the bags but experienced severe rebound from their

FIGURE 40.   82D042

FIGURE 41.   83D019

elastic structure, and the head contacted the roof of the buck. It was clear that a much more sophisticated design having multiple chambers and flap valves was needed to slowly arrest the dummy and thus reduce rebound.

NECK AND ABDOMINAL INJURY POTENTIAL

The child restraint standard, FMVSS 213, was written to deal with a relatively limited variety of restraint configurations that existed in the late 1970s. These included five-point harnesses, with and without narrow armrests, and full shields, exemplified primarily by the Ford Tot Guard. The Bobby-Mac series also had a shield, but its function was more for structural support of the shell (much as a tether would do) rather than for direct restraint of the child. In December 1979, Kantwet introduced a variation on the five-point harness that improved considerably the ease of use. This design, along with the specter of a Japanese design by Takata, had a significant effect on the entire child restraint industry.

Although we applaud the evolution of child restraint design in the direction of increased convenience for the user, we are concerned that the standard does not provide adequate guidance for the designer to determine how alterations to traditional restraint configurations might also alter their effectiveness. Returning to a concept expressed earlier, an effective restraint system controls an occupant's motion by a means that is itself not likely to be injurious. We know from extensive field experience that properly positioned and adjusted five-point harnesses do just that, and the same is true of a properly fitting Tot Guard shield. Although we have no evidence from field experience that variations of these configurations are any less effective, it may be too early to tell for some designs, and other designs are not yet even on the market. Rather than risking an unnecessary injury to a child, we would prefer to see test procedures developed that would provide child restraint designers with the information they need to be confident that their systems will be effective prior to use in the field.

The areas not addressed by FMVSS 213 that are of greatest concern to us are the potential for injury to the neck and abdomen from the restraint systems themselves. During this project, some preliminary efforts were made toward developing suitable test devices, procedures, and criteria to address these issues. Our approach and recommendations for further research are described below.

Neck. We know from the success of harness restraints in actual crashes that the neck is capable of holding onto the head without sustaining injury to itself when the shoulders are held back by belts. The popular fear that the neck will stretch or snap as the head flails forward and rotates down is not supported by crash experience. A different and potentially injurious situation occurs, however, if the head is stopped unnaturally during this flailing/rotating motion. This can happen if the head contacts the instrument panel or a relatively unyielding armrest before the shoulders have come to a complete stop and/or the head is midway through its downward rotation. The result of such sudden interruption of the head's natural kinematics may be compression and/or shear loading of the neck that could produce neck fracture.

A similar situation could also occur with a shield-only restraint that stops the head abruptly but late in the impact event. Here it is important to understand how the Tot Guard shield works. This relatively high but flexible surface provides restraint for the entire front of a child's body, including the abdomen, chest, shoulders, and head. During a frontal impact, the body gradually increases its contact with the shield and, at the same time, the shield deforms downward with the upper torso and head to provide a progressive arresting of the body's motion. This "soft landing" is due to both the energy-absorbing characteristics of the large flexible shield and the extensive distribution of crash loads over the entire upper body. Such a system has virtually no risk of injurious neck loading. If, however, this basic design is modified with respect to height or flexibility, the effect on head motion and interaction with the shield must also be considered.

Using a commercially available triaxial neck load cell, we attempted to measure the forces on the neck with different restraint configurations. Although some significant differences were indicated, questions regarding the mechanical characteristics of the dummy's neck along with insufficient documentation of the load cell's design rendered the results inconclusive. We do believe, however, that these problems can be overcome and that further work is needed regarding the effect of head interaction with a restraint system on potential neck injury.

Abdomen. The lap portion of a five-point harness is intended to be low on the pelvis if not actually flat across the thighs. A short crotch strap assists in this placement by keeping the lap straps from riding up above the pelvic bone. It is important that variations of the five-point harness, which substitute a padded shield for the lap straps, or low shields that have no shoulder straps at all also conform to the basic principle of restraining the lower torso through the pelvic bone. If, on the other hand, the restraining surface, either belt or shield, applies its load to the upper abdomen, penetration of this soft body region can occur.

It has been shown in experiments with animals that deformation or penetration of the abdominal contents along with significant force or pressure generation in the deformed organs can result in injury to these organs (Melvin et al. 1973; Trollope et al. 1973). In addition, organs such as the liver may undergo severe damage due to pressure generation alone at high impact velocities. It would therefore be useful for the child restraint designer to have a device within the dummy abdomen that could indicate degree of penetration, dynamic pressure level, and rate of penetration.

A prototype device using fluid flow and fiber optic techniques was developed, installed in a 3-year-old dummy, and used in tests of three different restraint configurations. Although the tests indicated the feasibility of such a device, durability and capacity problems precluded the generation of any valid test results. A plan for redesign and fabrication of a new prototype has been developed, but funding limitations did not allow further work under the current contract.

Because concerns such as these regarding potential neck and abdominal injury have been raised, and because it is quite possible that the non-traditional restraint configurations do in fact pose no special injury risk to child occupants, we think it important that methods to evaluate such injury potential be developed, if only to set aside these concerns. For future designs, the additional information would allow the designer to explore a wider range of innovative systems while remaining confident that restraint effectiveness will not be compromised.

CONCLUSIONS AND RECOMMENDATIONS

Dynamic testing of innovative or unconventional child occupant protection systems remains the best approach for obtaining definitive answers regarding restraint effectiveness. "Effectiveness," as used in this report, refers to the ability of a restraint system to adequately control occupant motion by a means that is itself not injurious. This impact testing procedure is limited, however, by gaps in our knowledge about biomechanical response characteristics and injury tolerance of children as well as by the lack of sophistication of the child dummies available.

Although it may not be possible to say with certainty that a child would or would not be injured in a given situation, it is usually possible to make reasonable evaluations by comparing the performance of a new configuration to that of a system having a proven record in the field. An analysis of performance measures from existing effective CRs was in fact the method used to determine excursion limits in FMVSS 213. By expanding and building on our knowledge of effective restraint systems, tools can be developed to better evaluate innovative systems.

Based on a combination of field experience and test results reported here, we can make the following conclusions and recommendations:

1. Seatbelt routing errors can have a significant effect on CR performance. Child restraint educators need to continue to emphasize the importance of proper securement methods, and manufacturers should continue to try to anticipate these errors, take steps to minimize their likelihood, and work toward reducing the severity of the potential consequences.

2. The use of retractor seatbelts can result in a significant degradation of CR performance in both the rear- and forward-facing orientations. The development of devices to tighten these belts is worth exploring along with improvement in the retractors themselves to make them more compatible with child restraints.

3. Effective installation of convertible CRs on the cargo floor of a van or station wagon, in either a rear- or forward-facing orientation, can be done using two separate lap belts that secure the restraint through each belt path. Side-facing installation is not recommended, especially if the CR would be close to a hard vertical structure and if forward- or rear-facing installation is possible.

4. Installation of a forward-facing CR on a side-facing vehicle seat is not recommended for regular travel, but the CR would provide a child with added protection over riding in the same seat using only a lap belt. These seating positions should only be used if the number of passengers requires it.

5. Rear-facing restraint configurations are generally more effective than forward-facing ones. CR manufacturers should take steps to extend their weight limits for rear-facing children, and child restraint educators should encourage parents to take advantage of this configuration as long as possible.

6. Upper and lower torso restraint is significantly more effective than lower torso restraint alone. In the absence of a special child restraint, children should use vehicle lap/shoulder belts, when available, as long as the shoulder portion can be made to lie flat on the shoulder. Placement of the child on the seat, boosters, high-back boosters, and other innovative devices can assist in shoulder-belt location on a small child.

7. Neck and abdominal injury potential are not addressed by FMVSS 213. Test devices, procedures, and criteria related to these body regions are needed to assist CR designers in developing the most effective restraint systems for children.

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AVAILABILITY OF DATA APPENDIX AND TEST FILMS

An appendix to this report containing computer plots of the sled, head, and chest acceleration data and belt loads for all tests is available from the authors upon request.

A ten-minute film containing footage from thirteen of the tests reported here, which emphasizes real-world use and misuse, is available from the authors for $50.

Please address inquiries to:

Kathleen Weber
University of Michigan
Transportation Research Institute
2901 Baxter Road
Ann Arbor, Michigan 48109
(313) 763-3462