

Crash Protection for Child Passengers

*A Review of Best Practice
by Kathleen Weber*



Child restraint systems provide specialized protection for small occupants whose body structures are still immature and growing. There is a wide variety of systems from which to choose, and different types of restraints are appropriate for children of different ages and sizes. Even with the most appropriate child restraint (CR), however, the way in which it is installed and used can have an effect on its performance. This review describes the theory behind the design of occupant restraint systems and applies these principles to the special needs of children. A distinction is made between child restraints, which themselves provide the restraint structure, and positioning devices, such as boosters, which help the vehicle belt fit the child. Throughout each section, current concepts of best practice are given, including the changes brought on by passenger airbags, and future directions are indicated.

RESTRAINT SYSTEM THEORY

In a vehicle crash, there are actually a series of collisions. The primary impact is between the vehicle and another object, while the occupants continue to travel forward at the precrash speed. Unrestrained occupants then come to an abrupt stop against the decelerating vehicle interior or the ground outside the vehicle. Restrained occupants collide with their belts, or other restraint system, very soon after the primary collision. Finally, there are collisions between the body's internal organs and the bony structures enclosing them, which can be mitigated by the use of occupant restraint systems.

The front ends of vehicles are designed to crush during impact, thereby absorbing crash energy and allowing the passenger compartment to come to a stop over a greater distance (and longer time) than does the front bumper. By tightly coupling the occupants to the passenger compartment structure,

through the use of snug fitting belts, the occupants ride down the crash with the vehicle. For adults, there is usually only one link, such as a lap/shoulder belt, between the occupant and the vehicle. For children, however, there are usually two links: the belt or other system holding the child restraint to the vehicle, and the harness or other structure holding the child.

In the case of belts, which absorb little energy themselves, the tighter they are adjusted prior to the crash, the lower will be the body's initial deceleration into the belts. Other supplemental protection systems, such as padding or airbags, can absorb impact energy between the occupant and the vehicle interior or, in the case of side-impact airbags, provide a layer of protection between the body and an intruding vehicle or other structure. Controlling the rate of the body's overall deceleration reduces not only the forces acting on the

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body's surface but also the differential motion between the skeleton and the internal organs, such as the skull and brain. Hard surfaces or loose seatbelts, on the other hand, stop the body abruptly when they are finally struck and pulled tight, applying more force to the body surface and giving its contents a harder jolt.

Tight coupling to the crushing vehicle addresses only part of the problem, however. To optimize the body's impact tolerance, the remaining loads must be distributed as widely as possible over the body's strongest parts. For adults, who prefer to face the front of the vehicle (or must do so to drive), this includes the shoulders, the pelvis, and secondarily the chest. For children, especially infants, restraint over larger and sometimes different body areas is necessary. Multiple straps, deformable shields, and facing rearward help take care of these needs.

Proper placement and good fit are important for effective occupant restraint. Serious restraint-induced injuries can occur when the belts are misplaced over body areas having no protective bony structure. Such misplacement of a lap belt can occur during a crash if the belt is loose or, with small children, is not held in place by a crotch strap or other positioning device, such as booster belt guides. A lap belt that is placed or rides up above the hips can intrude into the soft abdomen and rupture or lacerate internal organs.^{100,101} Moreover, in the absence of a shoulder restraint, a lap belt worn high can act as a fulcrum around which the lumbar spine flexes, possibly causing separation or fracture of the lumbar vertebrae in a severe crash.^{49,59}

Despite the potential for belt-induced injuries, belt-based restraint systems have significant ad-

vantages over airbag systems. They offer protection in a variety of crash directions, including rollovers, and throughout the course of multiple impacts. Moreover, the force on the occupant is proportional to the mass of that occupant. For example, a man weighing 80 kg will experience a much greater load into

the belts on his chest and pelvis than a child weighing only 20 kg. Even though the child's bony structure and connective tissue may be weaker than the adult's, the child's weight is so much less that the injury potential from contact with belts or other static surfaces is less. Current generation airbags, on the other hand, generate the same amount of deployment force and resistance to deflation regardless of occupant size or proximity to the bag. This puts children and other small occupants at much greater risk of injury than large, high-mass occupants and is among the reasons children should not ride in seats with frontal-impact airbags. The suitability of side-impact airbags for children is a topic of current investigation.

The primary goal of any occupant protection system is to keep the central nervous system from being injured. Broken bones will mend and soft tissue will heal, but damage to the brain and spinal cord is currently irreversible. In the design of restraint systems, it may therefore be necessary to put the extremities, ribs, or even abdominal viscera at some risk in order to ensure that the brain and spinal cord will be protected.

CHILD RESTRAINT SYSTEMS

Child restraint designs vary with the size of the child, the direction the child faces, the type of internal restraining system, and the method of installation. All CRs, however, work on the principle of coupling the child as tightly as possible to the vehicle. Historically in North America, the CR has been attached to the vehicle with the existing seatbelts, sometimes supplemented by an additional top tether strap. The child is then secured to the CR with a separate harness and/or other restraining surface (shield). This results in two links between the vehicle and the occupant, rather than only one. It is therefore critical that both the seatbelt and the harness, for instance, be as tight as possible to allow the child to ride down the crash with the vehicle.

When this system has been properly used and secured, child restraints have been estimated to reduce the risk of death and serious injury by approximately 70%.⁵⁰ By comparison, estimates of fatality reduction to adults in lap/shoulder belts for the same time period averaged about 50%.^{25,43,94} For further comparison, "partially misused" CRs



BUILT-IN CHILD RESTRAINTS

were estimated to be only 44% effective, and lap belts alone with children age 1 through 4 only 33%.⁵⁰ More recent analyses of fatality reduction alone for child restraints, without regard to misuse, still estimated about a 70% reduction for children under age 1 in passenger cars but only a 54% (although steadily increasing) reduction for children age 1 through 4.^{40,95} Seatbelt use by the latter group resulted in a 47% reduction in fatalities. Finally, a recent analysis of children 2 through 5 in crashes indicates that those in seatbelts are 3.5 times more likely to suffer moderate to severe injuries, particularly to the head, than those in child restraint systems.¹²⁹

The following sections first address the installation issues common to all child restraints and then discuss the different types of restraint configurations and types appropriate for children of different size and maturity.

Installation Challenges and Changes

The original function of seatbelts was to restrain only adult-size occupants, and some belt-assembly design parameters are in conflict with those that would best secure CRs. These parameters include belt anchor location, buckle size, and type of retractor and latchplate. These and other issues regarding child restraint compatibility with vehicle belts and seats are addressed in an SAE Recommended Practice (SAE J1819, 1994).¹⁰⁵ Unfortunately, however, not all products comply with this voluntary standard, nor have all problems been solved. Tight installation with a seatbelt continues to be difficult to achieve in many cases.

Built-In Child Restraints

Another approach, pursued in Sweden and eventually in North America as well, is called a built-in or integrated child restraint.^{54,112} Built-ins (figure 1) have the advantage of linking the child directly to the vehicle and eliminating installation errors. The disadvantage, of course, is that integrated restraints cannot be moved to another vehicle nor removed when no longer needed. This drawback, in combination with reluctant or inadequate marketing by dealerships, has resulted in low sales and an expected reduction in availability in the future, although the National Transportation Safety Board has recommended that all automobile manufacturers offer integrated child restraints in their passenger vehicles.⁹⁰

Top Tethers

Some forward-facing restraint designs of the 1970s and early 1980s depended on a top attachment strap and vehicle anchor, in addition to the seatbelt, to meet the federal performance standard (49 CFR 571.213) and keep a child's head from traveling beyond a safe limit during a severe frontal crash. It was found, however, that few people actually installed the anchors in their vehicles.¹⁰³ In 1986 the rule was changed to require mass market restraints to meet the 30-mph crash test requirements without a top tether (51 FR 5335). During this time Canada continued to support the use of tethers by maintaining a more stringent head excursion limit that could only be met reliably by using a tether. In 1989 Canada began requiring vehicle manufacturers to provide readily usable locations for tether anchor installation (SOR/86-975), and these features were included in most U.S. passenger vehicles as well.

As difficulties with belt and seat compatibilities increased and tether anchors became easier to install, interest in tethers again surfaced. In the last few years, U.S. CRs have been increasingly available with standard or add-on tethers for forward-facing use, and new head-excursion requirements in the U.S. (64 FR 10815), which are consistent with Canada's, now require tethers on virtually all forward-facing CRs as of September 1999. New Canadian and U.S. regulations also required factory-installed, user-ready anchors in passenger cars beginning in September 1999 and light trucks and vans in September 2000 (SOR/98-457, CMVSS 210.1; 64 FR 10823, 49 CFR 571.225). There is an effort underway by child restraint advocates to encourage and facilitate the installation of tether anchors in older vehicles as well.⁵⁷

It is anticipated that tethers, which consumers profess to appreciate and want,^{28,97} will signifi-



Figure 1. Built-in child restraint.

cantly improve the perception of installation security, as well as the crash performance of child restraints on which they are used. A few CR manufacturers are also recommending the use of a tether for rear-facing restraints, to be discussed later.

New Anchorages and Attachments

A concept called ISOFIX was first proposed in 1991¹¹⁵ and finally completed as an international standard in 1999.⁴⁴ The original proposal was for standard rigid interface hardware to be available in all vehicles and on all child restraints, so that CR installation would entirely bypass vehicle belts and the CR would not rely on the vehicle seat cushion for support. In addition to a likely reduction in misinstallation and an improvement in crash performance, the creators of the concept hoped there could be an electrical interface to do such things as disable a passenger airbag.

As the concept was tested and developed, it became apparent that two lower anchors at the seat bight (the intersection of the seat back and cushion) would be insufficient to isolate the CR from the seat cushion, and alternative additional anchors or reactive devices were proposed and evaluated.⁷⁰ No single system proved to appeal to all markets, however, so the final definition included two rigid lower anchorages “and a means to limit the pitch rotation of the CRS.” The system favored in North America includes a top tether and will be phased into the U.S. market by September 1, 2002 (64 FR 10786, 49 CFR 571.213 and 571.225). The system has also been given the

more user-friendly name of LATCH, which stands for Lower Anchors and Tethers for Children. Canada has a similar proposal, announced in March 1999 (C.Gaz. I, 133:629) but not yet finalized. In both jurisdictions, all CRs will continue to be installable using seatbelts in older vehicles and in seating positions not equipped with the lower anchors. The U.S. regulation, for instance, requires only two positions to have the lower anchors, and unfortunately they are likely to be omitted from the center rear-seat position. That position, if it exists, is required to have a user-ready tether anchor, however.

The ISOFIX standard gives preference to adjustable rigid attachments on the child restraints but also provides for optional nonrigid attachments consistent with the U.S. regulation. Although a rigid interface has the potential advantage of needing only a single operation for installation or removal, and is expected to provide improved performance in many side impacts,^{56,69} U.S. manufacturers and regulators alike prefer to allow the attachment technology to evolve and be tested in the marketplace. Initial applications in North America have therefore appeared as pairs of webbing-based attachments with individual adjustments. Top tethers, which also consist of webbing with a standard hook, will be available for use with either the LATCH attachments or the traditional seatbelt installation. There is, however, a two-level certification test that guarantees the current level of crash performance even without the tether. The LATCH configurations are illustrated in figure 2.

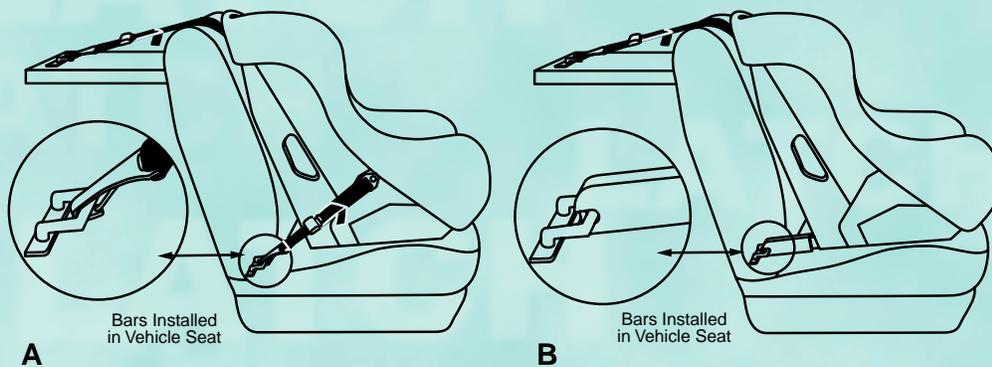


Figure 2. LATCH anchorages and attachments: (A) flexible lower attachments plus tether, (B) rigid lower attachments plus tether.

Restraint Fitting Stations

Australia has often been ahead of other countries in road safety initiatives. In 1985, the Traffic Authority of New South Wales, having determined that restrained children were being injured as a result of incorrect installation and adjustment (fitting) of CRs in vehicles, established a network of stations to assist the



public with this sometimes difficult task.³³ Begun at a local level, restraint fitting stations (RFSs) quickly expanded throughout the populous southeastern states. RFSs are licensed by the appropriate traffic authority, and fitters must attend formal training sessions. To assist personnel at the sites, detailed manuals have been prepared on regulations, use laws, and design, installation, and adjustment of all restraints and auxiliary devices approved for use in Australia. Beyond information and advice, RFSs provide actual installation hardware and services for tethers, shoulder belts, and other special devices that may be required. The stations keep regular hours, and the consumer is charged a nominal fee that varies with the complexity of the installation.

Despite these efforts, a recent pilot observation and interview survey found 29% of infant and child restraint installations to be “poor,” including 18% of those installed by RFSs, and only 24% of participants had taken advantage of the service.⁹³ As restraint installation becomes more uniform and less complex, the author suggests that emphasis should shift away from attachment hardware to proper restraint of the child within the system.

The RFS concept came to the attention of the National Transportation Safety Board, which recommended in 1999 that permanent facilities be established in the U.S. where people could go to obtain information about compatibility and appropriate CRs and have their child restraints checked for correct installation and use.³⁵ The service described is similar to what has been offered by volunteers at car seat clinics or similar check-up events. In response, a major vehicle manufacturer launched such a program at its dealerships. Initially only for owners of its vehicles, the program has expanded during 2000 to include anyone needing help with installing or using child restraints.²⁰

Seating Position and Airbags

From the early days of child restraint regulation, it has been recognized that the center rear seat position is the safest place in the car, since it is farthest from the outside of the vehicle, and current injury data analyses continue to bear this out.¹¹ Because of parental preference and the proven effectiveness of rear-facing CRs, however, infants were often restrained in the front seat, especially when alone with the driver.²⁴ The front-

seat, rear-facing child is the foundation on which Sweden’s child protection record is based.⁵² In addition, with the appearance of booster cushions in the early 1980s and the lack of shoulder belts in rear seats, older children were thought to benefit from sitting in front with 3-point restraints.

All this changed with the coming of passenger airbags around 1990 and the potential for a direct lethal blow of the airbag to a proximate child. This device, intended for the protection of adults, has been estimated to dramatically increase the chance of a child fatality. Depending on the method of analysis, increased risk factors ranging from 34%¹⁰ to more than twice that^{31,51} have been estimated for children in frontal crashes. The Graham et al. double-pair comparison, including all crash directions and all restraint conditions, has yielded a net 63% increased fatality risk among children under 13 in dual vs. driver-only airbag-equipped vehicles.³¹ These fatalities almost always involved head/neck injury from direct blows by the inflating bag and/or the airbag housing cover to children who were unrestrained and/or close to the airbag at the instant of deployment.⁸⁵ A report including 27 children under 13 suffering airbag-related injuries with a range of severity indicates that even properly restrained children are not immune,³⁴ with eye and facial injuries elsewhere reported to be a special problem.⁷¹ Airbag injuries to belted children, who otherwise would likely have been unharmed, are also reported in Canada and include one fatality.⁷⁵

Side-impact airbags are also beginning to appear in increasing numbers, but less than 1% of these are as yet in rear seats.³² There are no studies published thus far that indicate a child properly restrained in a CR is at risk from current side-impact airbags, but laboratory simulations indicate that unrestrained and out-of-position children could be injured.²³ Industry efforts are therefore focusing on developing side airbags and test procedures that will minimize injury risk to such occupants, both adults and children, recognizing that this risk can never be zero.⁷³ As of May 2000, the National Highway Traffic Safety Administration (NHTSA) had recorded 47 crashes involving side-airbag deployments, among which only a single child, age 3 and unrestrained in the front seat, suffered a minor injury from the door-mounted airbag cover flap.⁸⁷

Airbags, however, are not the only factor to

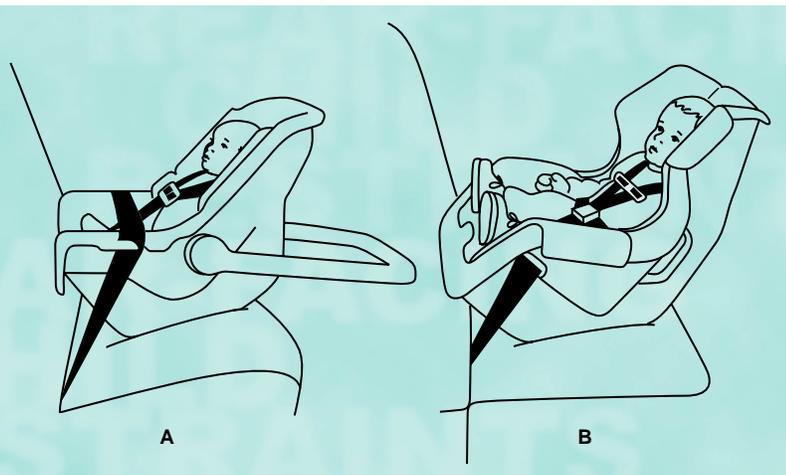


Figure 3. Rear-facing child restraints: (A) rear-facing only, (B) rear-facing convertible.

consider when seating a child in a vehicle. Many statistical studies show that the rear seat is a more benign environment than the front for all occupants, almost without regard to restraint status. Braver et al. found an overall rear-seat vs. front-seat fatality reduction for children under 13 of 35% in vehicles with no airbags and 46% in vehicles with passenger airbags. The only two configurations for which the front seat was better were (1) rear impacts for all ages and (2) when older children with lap/shoulder belts in front were compared to those with no restraint in back.¹² Most recently, Berg et al. studied a large data set of children, among which 40% were unrestrained, and confirmed that either or both rear seat use and appropriate restraint significantly reduce serious injuries and fatalities in serious crashes.⁹

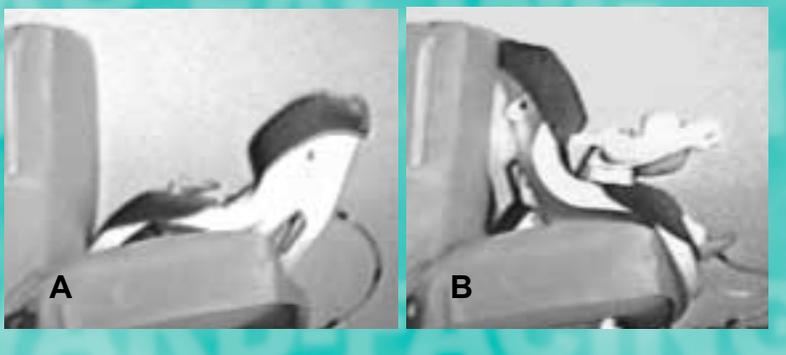


Figure 4. 6-month size dummy during 48 km/h crash test showing (A) head/neck protection in rear-facing child restraint, compared to (B) head exposure and neck tension in forward-facing child restraint.

New federal regulations are aimed at ensuring that future airbags will either not deploy when the occupant is too close or would not cause harm if deployment occurs (65 FR 30680, 49 CFR 571.208), but the new systems will not have to be implemented until September 1, 2003. The general message to parents today is to restrain all pre-teens in the back seat, with cautions about behavior and distance from any airbag housing when exceptions must be made. A rear-facing child restraint, however, must never be installed in a seat position with an active frontal-impact airbag.

Rear-Facing Child Restraints

There are two types of restraint systems that face the child toward the rear of the vehicle. One (figure 3A) is designed to be used rear-facing only (RFO), often includes a carrying handle, and may have a detachable base for easier repeated installation. These can accommodate a child up to only 9 or 10 kg (20 or 22 lb), depending on the height of the head/back support. The second type (figure 3B) is a rear-facing “convertible” (RFC) restraint, so named because the same device can be installed in either a rear- or a forward-facing orientation. It is larger than an RFO and can accommodate a child of greater weight in the rear-facing position. Some RFCs are still limited to 10 kg, but many list 13.5 kg (30 lb) as the upper weight limit. Beyond weight, the effective limit for either type is the seated height of the child, the top of whose head should not be above the top of the restraint, to minimize the risk of head-contact and neck-compression injury. When a child outgrows an RFO, it should then be restrained in an RFC until at least the age of one year.^{5,121}

Both types of rear-facing CRs are anchored in place with a seatbelt or LATCH attachments, and internal harness straps or straps plus a shield secure the infant’s body in the shell. In a frontal impact, the crash forces are transferred from the back of the restraint to the infant’s back, which is the infant’s strongest body surface, while the restraint also supports the infant’s head (figure 4A). The movement of the head and neck in unison with the torso during a crash eliminates severe tension and flexion forces on the neck that can occur with forward-facing occupants (figure 4B). Further explanation and field validation of this injury risk are discussed in the context for forward-facing restraints.

REAR-FACING

Properly used, rear-facing child restraints (RFCRs) have proven to be extremely effective in actual crashes,^{80,88,98} and experience in Sweden has shown that children through the age of 3 can benefit as well.^{47,52} These large RFCRs (figure 5) sit away from the vehicle seatback to give the child more leg room and have an additional strap or other device to prevent rearward rotation. These restraints have extremely low injury and fatality rates, with estimates of injury-reduction effectiveness as high as 96% when compared to the unrestrained child. From 1992 through June 1997, only 9 children properly restrained rear-facing have died in motor vehicle crashes in Sweden, and all of these involved catastrophic crashes with severe intrusion and few other survivors.¹²⁶

Airbags and Rear-Facing Restraints

These two restraint devices definitely do not mix. Airbags are stored in the instrument panel and need a certain amount of space in which to inflate before they begin to act as energy-absorbing cushions for larger occupants. A rear-facing restraint in the front seat places the child's head and body very close to the airbag housing. When current airbags deploy in a crash, whether severe or moderate, they emerge in a small folded wad at very high speed—as much as 300 km/h. If an airbag hits the back of a RFCR while it is still inflating, it will strike with considerable force. Accelerations measured at the heads of infant dummies in this situation range from 100 to 200 g,¹¹⁷ with only about 50 g considered tolerable for children represented by a 6-month size dummy.⁷⁸ The sequence shown in figure 6 includes this initial impact and the continuing motion of the RFCR toward the vehicle seatback. Many people mistakenly think that the dangerous aspect of this configuration is the “crushing” of the child's head

against the seatback. Laboratory measurements have found, however, that these forces are not significant, and by then the fatal injury has already occurred.

As of June 2000, ten properly restrained rear-facing infants and another 8 in unsecured or misbelted RFCRs had been killed in the U.S. by deploying passenger airbags in otherwise survivable crashes.⁸⁶ (Another infant was killed by a driver airbag while riding on the driver's lap.⁸⁵) After peaking in 1996, the number of such deaths have steadily decreased, due largely to an intensive public awareness campaign, with the last fatal case recorded in April 1999. Although it may be possible to mitigate this severe interaction with the depowered or multistage airbags that have entered the vehicle fleet, and some believe an infant restraint can be made to deflect and/or absorb airbag forces,¹⁸ the only reliable ways to protect an infant from airbag injury are to disconnect the bag or to restrain the child in the rear seat.

Back Angle for Frontal Impact Protection

For reasonable protection and comfort of a newborn or very young infant, the rear-facing restraint should be installed so that the back surface



Figure 5. Large Swedish rear-facing child restraint.

Figure 6. Airbag deployment sequence showing initial injury-producing impact of airbag against child restraint and continuing motion of child restraint toward vehicle seatback.



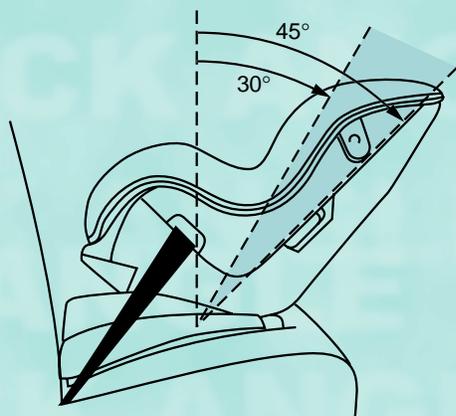


Figure 7. Back angle range for rear-facing child restraint.¹⁰²

is reclined just enough to allow the baby's head to lie back comfortably, but not more than 45° from vertical. Beyond this angle, the force to restrain the child starts to be exceeded by the force to project the baby toward the front of the vehicle. As the child grows, becomes heavier, and can hold its head erect, the angle should be decreased, making the restraint more upright, to provide better crash

protection (figure 7). If a rear-facing restraint is installed in a rear seat with its back against the seat in front, this will help limit a further increase in back angle during a crash and provide the best protection. In Australia, tether straps are routed rearward from RFCRs and attached to an anchor to achieve an even better effect (figure 8A). This tethering not only maintains the initial angle but also allows the child to ride down the crash with the crushing vehicle.

Early designers of RFCRs took care in determining the optimum back angle using dynamic testing and consultation with pediatricians.²⁶ They began with 40° from vertical but decided that a more upright angle of only 15° was needed "to obtain the desired restraint and load distribution."

These tests, however, were apparently conducted without the benefit of straps, which, if snug and routed through slots at or below the child's shoulders, will help contain the child's body during its tendency to ramp up the back of a reclined restraint.

Field experience, feedback to manufacturers, and further input from pediatricians have indicated that an angle greater than 30° from vertical is needed for comfort of a newborn or a resting child to keep its head from flopping over and potentially pinching off the airway. Ensuring that the head is in contact with the CR back is also best for crash protection. At least one major child restraint manufacturer sets its target angle at 35° from vertical through the use of a visual indicator, while others aim for 45°. If for any medical reason a baby needs to be reclined at an angle greater than 45°, however, this child should be restrained in a car bed, discussed below.

Side and Other Impact Directions

In lateral or oblique crashes, rear-facing CRs that are installed with a lap belt will swivel somewhat in the direction of the impact, which was originally considered to be of benefit to the infant occupant.²⁶ Research in support of ISOFIX anchors and improved side impact protection for children, however, indicates that this feature may be a disbenefit for the center or nonstruck side, but that a flexible vs. a rigid installation is probably not significant for the struck side, where impact to the CR and child occurs before virtually any CR movement.^{66,96} More important are deep

side structures and energy-absorbing padding in the head area, so that the head remains confined and the force driving the intruding door is attenuated.^{53,56} On the nonstruck side, rigid or very tight belt attachments that do not slip relative to the CR help maintain the child's position in the CR and away from the impact.^{13,69} For such installations, a tether anchored rearward does not appear to provide significant additional protection in side impacts, but it can improve performance with loose or suboptimal belt-based systems.

In rear-end and rollover crashes, the shoulder straps provide containment

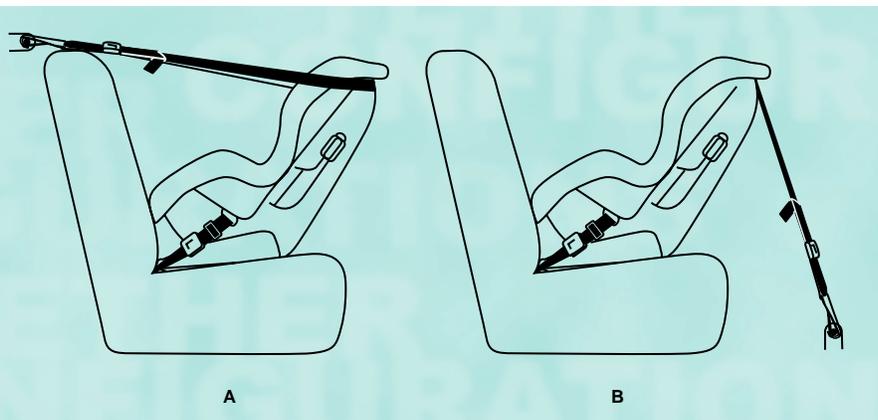


Figure 8. Tether configurations for rear-facing child restraints: (A) Australian method (rearward), (B) Swedish method (forward, down).

CAR-BED RESTRAINTS

and attachment of the child to the RFCR, which may rotate up against the vehicle seatback. Although originally touted as a benefit by the early designers to protect the infant from flying debris,²⁶ many RFOs and most RFCs now have too high a profile next to the vehicle seatback to rotate, without apparent sacrifice to safety. A few RFCs provide a tether strap that can be attached near the floor to the seat in front of the CR to inhibit all such movement in a rear impact or during rebound from a frontal impact (figure 8B). This does induce loading on the neck, but forces are expected to be quite low and have not been known to generate injuries among Swedish children. The benefit in terms of installation stability and a fixed restraint for the larger rear-facing child undoubtedly outweighs the low risk of neck injury.

Harnesses and Fit

RFO harnesses have traditionally been limited to a pair of shoulder straps coming together at a buckle. Recent models, however, include 5-point harnesses, which provide more lateral support and restraint for the infant. RFCs may have 5-point harnesses or a harness/shield combination (figure 9), but the latter should not be selected for use with infants, because they cannot be made to fit a small body tightly and the shield may interact with a small child's neck or face.⁵

Premature and low birth-weight infants may be so small that even RFO restraints seem too big. If the infant's head or body needs lateral support, padding can be placed between the infant and the side of the restraint. Firm padding, such as a rolled towel, can also be placed between the infant and the crotch strap to keep the infant from slouching.⁵ Thick, soft padding should not, however, be placed under the infant, behind its back, or between the infant and the shoulder straps. Such padding will compress during an impact, leaving the harness loose on the infant's body and allowing increased ramping toward the front of the vehicle.

It is common practice to use an RFO with a newborn and continue to use it until it is outgrown by weight or seated height. This usually happens, however, after only a few months and before it is advisable to face a child forward.

It is very important that the child then move to a convertible CR and still be restrained in the rear-facing position. This is a different message than

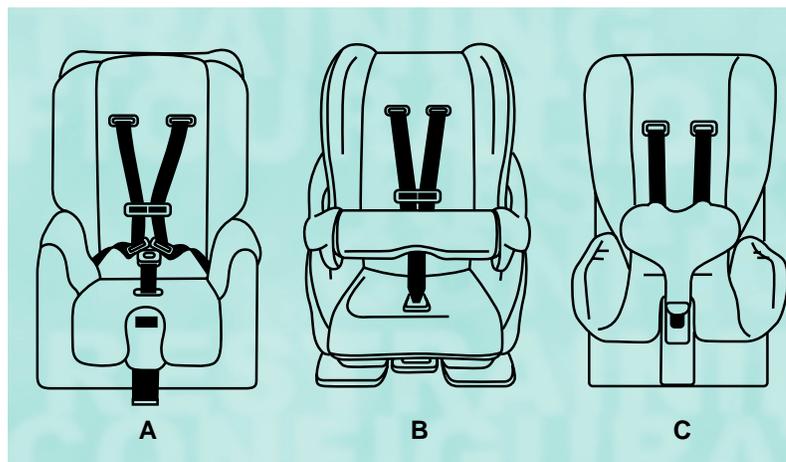


Figure 9. Restraining configurations: (A) 5-point harness, (B) tray shield, (C) T-shield.

the one parents may hear from friends or even some pediatricians or CR manufacturers, who believe that an RFO will take the child through the entire rear-facing period. This is rarely the case.

Car-Bed Restraints

These restraints have historically been used more often in Europe and Australia but have penetrated the North American market because of concerns about premature infants with positional apnea.¹²⁸ The American Academy of Pediatrics currently recommends that infants born at less than 37 weeks gestation be monitored in a semi-upright position prior to discharge to detect possible apnea, bradycardia, or oxygen desaturation.⁴⁷ For infants with documented breathing problems, a car bed is a suitable alternative to an RFO. There are currently three models available in the U.S., accommodating a range of infant sizes, from very low birth weight to an average 1-year-old.

In a car-bed restraint (figure 10), the infant lies flat, preferably on its back or side, and the bed is placed on the vehicle seat, with its long axis perpendicular to the direction of travel and the baby's head toward the center of the vehicle (not next to the door). In a frontal crash, the forces are distributed along the entire side of the infant's body, while a harness or other containment device keeps the baby in place during rebound or rollover. In a side impact, however, the infant's head and neck are theoretically more vulnerable in a car bed than in a rear-facing restraint, especially if the impact is on the side nearest the head and there is signifi-

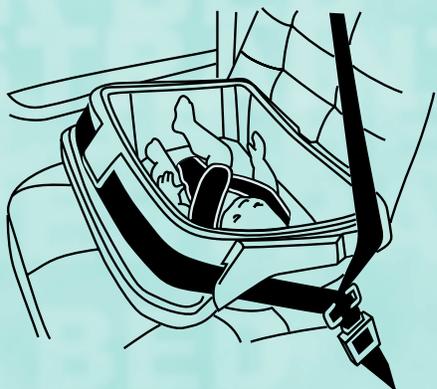


Figure 10. Car bed restraint.³⁰

cant intrusion.¹¹⁸ Experience elsewhere and several years of availability and use in this country, however, have not revealed any protection deficiencies with this configuration.

Potential advantages of using a car bed with an infant with special medical needs are that a baby in the rear seat can be more easily monitored visually by the driver and, according to two manufactur-

ers' statements, the bed can also be installed in a seat with a passenger airbag. Testing available for public scrutiny, however, does not appear to be adequate to prove this assertion under all possible circumstances. Although top-mounted bags will no doubt miss the car bed, it is less certain that no midmount bags will impact the car bed with sufficient force to cause injury. At this time, prudence and caution dictate that car beds be used only in the rear seat unless the airbag is disconnected. If front-seat use is necessary, however, the seat should be in its farthest rearward position.

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protect against rearward bending (extension) of the neck.

Both FFCR types are anchored in place with a seatbelt or LATCH attachments. In addition, many U.S. models made before September 1999, all U.S. models made after that date, and all Canadian models are equipped with top tether straps to be anchored rearward from the CR. These straps significantly reduce the forward motion (excursion) of the child's head and stretching forces (tension) on the neck, discussed further below. The addition of a tether strap, particularly to the taller combination CR/Bs, can extend the usability of these systems for older, heavier children. This capability is currently only allowed in Canada, but consideration is being given to allowing it in the U.S. as well (64 FR 36657).

ers' statements, the bed can also be installed in a seat with a passenger airbag. Testing available for public scrutiny, however, does not appear to be adequate to prove this assertion under all possible circumstances. Although top-mounted bags will no doubt miss the car bed, it is less certain that no midmount bags will impact the car bed with sufficient force to cause injury. At this time, prudence and caution dictate that car beds be used only in the rear seat unless the airbag is disconnected. If front-seat use is necessary, however, the seat should be in its farthest rearward position.

Harnesses and Shields

Convertible child restraints have one of three internal restraint configurations: a 5-point harness, a tray shield with shoulder and crotch straps, or a T-shield with shoulder straps (figure 9). The restraint configuration of the CR/B usually incorporates the 5-point harness to make the conversion to the booster mode easier. Although all of these systems perform well in crash tests, and none stand out as less effective in accident data,⁵⁵ differences among them should be noted.

Forward-Facing Child Restraints

There are two types of restraint systems that face the child toward the front of the vehicle. The most commonly used for children who are just being turned around is the forward-facing convertible (FFC) (figure 11A), because most children are already using these facing rearward. The other type, which will be referred to here as a combination CR/booster (CR/B) (figure 11B), can only be used facing forward and combines features of a child restraint and a belt-positioning booster, to be discussed later. Both types of forward-facing child restraints (FFCRs) are currently limited in the U.S. to restraining a child weighing less than 18 kg (40 lb), which corresponds to children in anywhere from their second through seventh year.¹²⁴ Other effective limits on use include the height of the shoulder strap routing slots, which need to be above the child's shoulders to effectively limit head excursion, and the height of the back, which should be above the child's ears to

The original strap arrangement in early child restraints was the 5-point harness, which was patterned after military and racing harnesses. There is a strap over each shoulder, one on each side of the pelvis, and one between the legs. All five come together at a common buckle. The function of the crotch strap is to hold the lap straps firmly down on top of the thighs, and thus it should be as short as possible. Because the crotch strap is merely a lap-strap positioning device, the primary lower torso restraint is still the combined lap straps. Although simple and effective, early 5-point harness systems were difficult to adjust and buckle around a squirming child, and complaints about twisting and roping of the nylon webbing straps continue today. Easier means of adjusting 5-point harnesses have since been developed, however, and are now incorporated into many models. Some manufacturers have addressed the roping problem by using more expensive polyester webbing, and one has also gone from the usual 38 mm to 50 mm webbing width as well.

5-POINT HARNESS

In late 1979, a design appeared that replaced the lap portion of the harness with a padded tray-like shield. The shoulder straps were attached to the shield, which kept them from twisting, and the shield was held down by a crotch strap and buckle. This design responded to parents' initial but erroneous perception, held over from early nonrestraining armrests, that "something in front" of the child, besides harness straps, was safest.¹²³ Other manufacturers quickly followed suit. From a restraint theory point of view, the tray shield, which is not usually covered with energy-absorbing padding, is not the best surface for the head to hit, and this contact is more likely the shorter the child and the looser the harness. In a test series with a 12-month size dummy, peak head acceleration was 35% higher for tray shield restraints than for 5-point harnesses,¹¹⁶ and at least one child, weighing 8.6 kg (19 lb), is known to have received a fatal head injury from contact with a tray shield.²¹

In the early 1980s, a Japanese manufacturer developed another variation on the 5-point harness that incorporated a retractor on the shoulder straps. These straps were attached to a flat chest-shield with a relatively rigid stalk, which in turn attached to the child restraint between the child's legs. Eventually, similar designs began to appear on the U.S. market, some with automatic retractors and some with manual strap adjusters, and were referred to as T-shields. Although ease of adjustment and one-handed operation of the T-shield offer convenience for parents, there are some theoretical problems with this restraint configuration. Because the length and angle of the stalk is fixed, it is not possible to adjust the shield to fit close to a small child's body or low across the pelvis. As discussed earlier, a loose-fitting restraining system does not couple the occupant tightly to the crushing vehicle, and higher forces on the body will result. In addition, the lower torso restraint of the lap straps is now replaced by a narrow vertical stalk that concentrates impact forces at the center of the pelvis rather than spreading the forces across

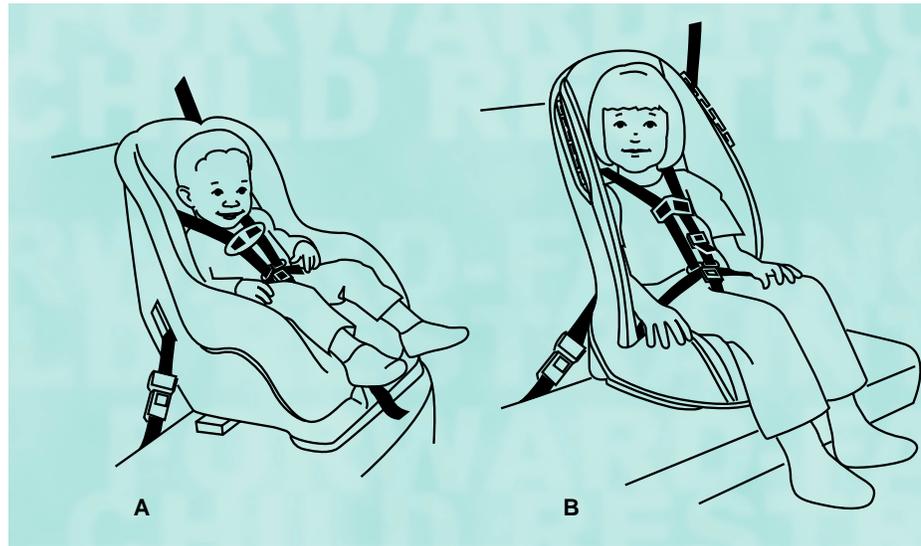


Figure 11. Forward-facing child restraints: (A) forward-facing convertible, (B) combination child restraint/booster as FFCR.

the pelvic breadth, and lateral restraint provided by lap straps is also lost. Another concern is that the throat of a small child may be injured from contact with the top of the shield during a crash, especially in the forward-facing position. In the 12-month-dummy series, neck force was 40% higher for T-shields than for 5-point harnesses, and the pubic load measured with T-shields was 2.7 times higher than that measured with 5-points.¹¹⁶

Neck Injury in Forward-Facing Child Restraints

Facing a child forward for travel is not without risks, but too often it is seen by parents as a goal to be achieved as soon as possible. This goal is inappropriate, but misinformation and lack of understanding about the crash environment and child physiology have been difficult to overcome, even within the medical community. There has long been a concern in bioengineering literature that a child's cervical spine could be pulled apart from the force on the head in a crash when the shoulders are held back.¹⁵ One popular misconception, however, is that muscle strength can overcome this force, and that a child who can hold up its head and sit erect is "strong" enough to face a frontal crash.

In a 50 km/h (30 mph) crash with a 25-g passenger compartment deceleration, for instance, the head of a forward-facing adult or child may expe-



Figure 12. Twenty-month-old child, weighing 13 kg, in a rear-facing child restraint.

rience as much as 60 or 70 g, because the occupant's head stops later and more abruptly than the vehicle's floor pan. Even the strong neck muscles of military volunteers make little difference in such an environment. Rather it is the hardness of the vertebrae, in combination with the tightness of the connecting ligaments, that determines

whether the spine will hold together and the spinal cord will remain intact within the confines of the vertebral column.^{42,107}

Adult cervical spines can withstand severe tensile forces associated with decelerations up to 100 g,⁷⁶ and failure is nearly always associated with fracture. On the other hand, the immature vertebrae of young children consist of both bony segments and cartilage, and the ligaments are loose to accommodate growth.^{63,84} This combination allows the soft vertebral elements to deform and separate under crash conditions, leaving the spinal cord as the last link between the head and the torso. According to Huelke et al.,⁴² "In autopsy specimens the elastic infantile vertebral bodies and ligaments allow for column elongation of up to two inches, but the spinal cord ruptures if stretched more than 1/4 inch." Mathematical models of pediatric spines (age 1, 3, and 6) subjected to various types of loading indicate that, compared to adult spines, the anatomical and material proper-

ties of immature spinal elements make them much more flexible than would be predicted by relative size alone.⁶² Stalnaker notes that the risk of spinal cord injury in children increases with crash severity and decreases with age.¹⁰⁷

Accident experience has shown that a young child's skull can be separated from its spine by the force of a crash,²⁷ the spinal cord can be severed,⁴¹ or the child may live but suffer paraplegia or tetraplegia due to the stretched and damaged cord.^{67,113,122} Eleven cases studied in depth were included in the two 1993 reports. All children with severe injuries were 12 months old or younger, whereas others who suffered less severe injuries, such as C2 odontoid fractures, were over 18 months. All crashes were frontal (10 to 2 o'clock), with velocity changes ranging between 24 and 60 km/h (15 to 37 mph). It must be emphasized that these injuries appear to be rare, although there has been no recent attempt to estimate the risk of occurrence. Because of the potentially severe consequences, however, and the relatively simple countermeasure to such injury among the youngest children, it makes sense to keep them restrained rear-facing as long as possible (figure 12).

Tethers and Crash Performance

In a forward-facing child restraint, a tether can be used to anchor the top of the CR directly to the vehicle and thereby virtually eliminate any pitching motion in a frontal crash. Figure 13 shows a crash sequence comparing the performance of the same model of CR tethered (near side) and untethered (far side) in a 48 km/h crash test with a 3-year size dummy. Note the difference in head excursion, or the distance the dummies' heads



TETHERS

travel forward. In an actual crash, a child would be much less likely to experience head contact with the interior. Among children injured in FFCRs, head and facial trauma predominate.^{55,58} Head contact while the neck is in tension, although again a rare occurrence, can also generate vertebral fractures and dislocations, as well as spinal cord injury, by suddenly stopping the free motion of the head and putting significant compressive and shear loads on the neck.^{76,107} Reduction of head excursion and elimination of head contact is therefore as important for avoiding neck injury as it is for reducing head and facial injury in children.

Laboratory testing with a variety of instrumented dummies has shown that other injury parameters, including head acceleration and neck loading, also decrease in tethered FFCRs compared to nontethered ones in frontal crashes.^{14,68,69,72} The measured reductions are greater for tethers mounted at the top of the CR, especially for the neck tension parameter, than for those mounted lower at the height of the shoulder strap slots. This difference is probably related to the length and shape of the tether routing path, the higher mount generally taking a straighter route to the anchor. The primary tether benefit, however, is that of significantly reduced head excursion, which occurs with either mount location. Tethers are also beneficial in making up for suboptimal vehicle seatbelt configurations and seating contours,⁵⁷ and they give parents a needed sense of installation security.²⁸

In New South Wales, where CR usage is high and FFCRs are routinely tethered, child injuries tend toward minor lacerations or bruising from flying debris, grazing of adjacent structures, or

webbing contact.³⁹ Serious neck injuries without head contact or gross misuse seem to be nonexistent.

Side Impact Protection

Approximately twice as many crashes with a child fatality are frontal compared to lateral, but side impacts are nearly twice as likely to result in a child fatality as frontal impacts, regardless of restraint status or seating position.^{12,66} The net result is that the number of children killed in each type of crash is about the same. There are also indications that the relative risk in side impacts may be even greater for children in FFCRs, largely because these restraints are so effective in frontal crashes.⁹⁸ Again, however, head and facial injuries predominate for children in FFCRs in lateral impacts.⁵⁵

Only two countries, Australia and New Zealand, currently evaluate child restraints in a side impact, and their test, which is conducted on an open seat, does not reflect the injury-causing intrusion environment in the real world.⁶⁶ Efforts are therefore underway to develop a test procedure that mimics the angle, speed, and shape of side-door intrusion found to be associated with serious and fatal injury to restrained children.^{65,96} Although not conducted with a definitive test, preliminary evaluations of alternative CR anchor systems clearly indicate that a rigid installation to the vehicle and deep side wings containing energy-absorbing padding are critical features of an effective CR in side impact.^{13,56,69} Deep side support and padding are more important on the struck side, while rigid anchors make more difference on the nonstruck side. Again, a top tether, which



Figure 13. Crash sequence showing the relative performance of a tethered (near side) vs. an untethered (far side) child restraint.



is not a rigid attachment, seems to make little difference to side-impact performance compared to the benefit of rigid vs. belt-based lower attachments.

Airbags and Forward-Facing Restraints

Children properly restrained, facing forward, and well away from the airbag should be at no greater risk of injury from deployment than a belted adult in the same seating position. Airbag-related injuries may include skin or corneal abrasions from high-speed fabric impact.⁹⁹ It is unlikely, however, that the CR-restrained child will derive any added benefit from the airbag. As of June 2000, there were 49 fatalities among children age 1 through 5 related to passenger airbag deployment, but none were restrained in a FFCR.⁸⁵ (Four children were buckled in CRs that were not secured to the vehicle, 6 were in belts alone, and 39 were unrestrained.) This is not to say that the configuration is risk-free. It is still important to maintain as great a distance as possible from the airbag housing, and this distance is limited by the forward positioning of the child by the CR itself, even in the most rearward vehicle seat position.

Misuse of Child Restraint Systems

Even with the variety and widespread availability of good child restraint systems, there is still a challenge to get them used and used to maximum advantage. Although suboptimal use in low-severity impacts will not likely result in child injury, proper use may make the difference between life and death in high-severity crashes.⁹⁰ Misuse, intentional or not, can compromise or even negate the protective features designed into a CR. Many such misuses have already been mentioned, and many are a matter of degree. A large observation study in four states found that about 80% of child restraints were not being used as intended,²² but fortunately the majority of these misuses would not have rendered the restraint ineffective. Clearly a failure to anchor the CR or to harness the child is about the same as nonuse, but there are many other opportunities to do the wrong thing. It is therefore important for parents and field technicians to understand the concepts, so that they will know in which direction to aim when perfection cannot be achieved.

With an RFO infant restraint, trying to use it facing forward can result in dangerous loading and

possible ejection, because there is no tested path for the vehicle belt. Although an RFC provides a method for forward-facing installation, the infant's spinal cord is still at risk. Installing either type of RFCR in a seat with an airbag carries a very high risk of death in a crash. Shoulder straps routed above a larger rear-facing child's shoulders may allow ramping above the top of the restraint, with possible head-contact or neck-compression injury. Smaller babies may not reach the top, but the additional movement allowed by high strap routing or a loose harness can induce higher loads on the shoulders or may result in ejection in side or rollover crashes. Use of a strap clip at midchest will keep snug straps in place, but it may not make up for a slack harness in a crash. Finally, the back angle of an RFCR may be the most important factor in its performance and is probably the least understood. If too flat, it cannot restrain; if too upright, a newborn may be unable to breathe. There is no ideal angle for all cases. Rather the RFCR should be as upright as possible, while ensuring that the child's head lies back against the restraint surface, but never more than 45° from vertical. A secure installation is also important, and the extra restraint gained by resting an RFCR against the back of the seat in front is a possible advantage of a rear seat with limited space.

Forward-facing restraints are most dependent on harness tightness and fit, as well as tight coupling to the vehicle. With head injuries being the most common and the most life threatening, the goal is to keep the head from hitting anything. Loose straps or a loose installation will allow the child greater movement toward vehicle interior surfaces and generate higher loads on the child when the system finally pulls up tight. The improvement offered by a tether strap is also degraded by slack. A strap clip at midchest can help keep the harness in place prior to impact, but it should not be considered a substitute for a snug fit. One-piece clips slide down the straps as the child presses forward or may break if sliding is restricted, and many two-piece clips are designed to separate under low loads for extrication purposes. Using either clip instead of the buckle to secure the harness, or routing the straps under the child's arms, could result in ejection or serious injury to thoracic and abdominal organs. Using shoulder strap slots below the child's shoulders effectively introduces slack in a crash, as the

BOOSTERS BELT-POSITIONING BOOSTERS

child's torso bends forward and curls under the straps. Moreover, some lower slots are not adequately reinforced to withstand the forward-facing load.

Problems with nonlocking latchplates on seatbelts led to the development of the locking clip, which can be used to eliminate webbing slippage from the shoulder to the lap portion of the seatbelt to hold the CR tightly in place. Although this clip improves the installation in many cases, it was never intended to withstand severe bending forces during a crash. If it is incorrectly attached to the belt on the outboard side of the CR, rather than next to the latchplate, the clip will likely deform and release the belts, introducing significant slack. The benefit afforded by locking clips in actual practice may be overrated. Anecdotal information and observations at child restraint check-up events have indicted that these clips may be doing more harm than good, because of their likely misapplication. Since model year 1996, seatbelts have been required to incorporate a means of locking lap belt length when used with a CR (58 FR 52922), but some of these systems have not proven as effective as expected. A few CR models include belt locking devices attached to the restraint, but some work better than others. The belt-locking problem is another reason for the adoption of LATCH anchors for child restraint systems.

Improved child restraint design and labeling have largely eliminated seatbelt misrouting that was common a decade ago, while new adjustment hardware and fixed-length crotch straps have made good fit more likely. Color coding of rear-facing vs. forward-facing features by one manufacturer is a welcome approach, and visual indicators for back angle and buckle latching provide useful feedback to parents. Standard methods for evaluating the potential for and consequences of CR misuse have been finalized^{45,46} and should be used by manufacturers prior to launching a new product to make dangerous practices unlikely to occur. In the end, however, children are still dependent on parents or caregivers to take the time to fasten the harness, adjust it snugly, and secure the restraint facing the right direction tightly to the vehicle.

Children with Special Needs

Children with special medical needs also require effective restraint. The same general principles apply, but sometimes their implementation must be different. Car beds for fragile infants is one example, but there are other systems that have been developed for children in hip and body casts, those with tracheostomies or muscle tone abnormalities, and children confined to wheelchairs.¹¹⁰ The American Academy of Pediatrics⁶ and the National Easter Seal Society are sources for additional specific information.

CHILD BOOSTERS AND BELTS

When a child can no longer fit into a convertible or other FFCR, the next step is a booster. Boosters are not restraint systems by themselves, but rather positioning devices that depend entirely on the vehicle belts to hold the child and the booster in place. Thus they facilitate the transition between a child restraint and seatbelts. Results emerging from a large-scale crash surveillance system focused on children show that seatbelts alone are much less effective than FFCRs or belts used with boosters.¹²⁹ There have been two different types of boosters available in the past, but only one is now considered to provide adequate crash protection.

Belt-Positioning Boosters

A belt-positioning booster (BPB) raises the child so that its body geometry is more like that of an adult and helps route a lap/shoulder belt to fit that body size (figure 14). It should have small handles or guides under which the lap belt and the lower end of the shoulder belt are routed^{16,111} (figure 14A), but some merely have a depression or slot for the belt path. The guides function much like a crotch strap, holding the lap belt low and flat across the child's upper thighs, while the in-board guide also pulls the shoulder belt toward the child and makes its angle more vertical, so that the belt crosses the center of the child's chest. Many boosters have high backs that not only give the child rear head support on older-vehicle seats with low backs but also have upper belt guides to optimize the location of the shoulder belt (figure 14B). A clip on the end of an adjustable strap ac-

SHIELD BOOSTERS BOOSTERS

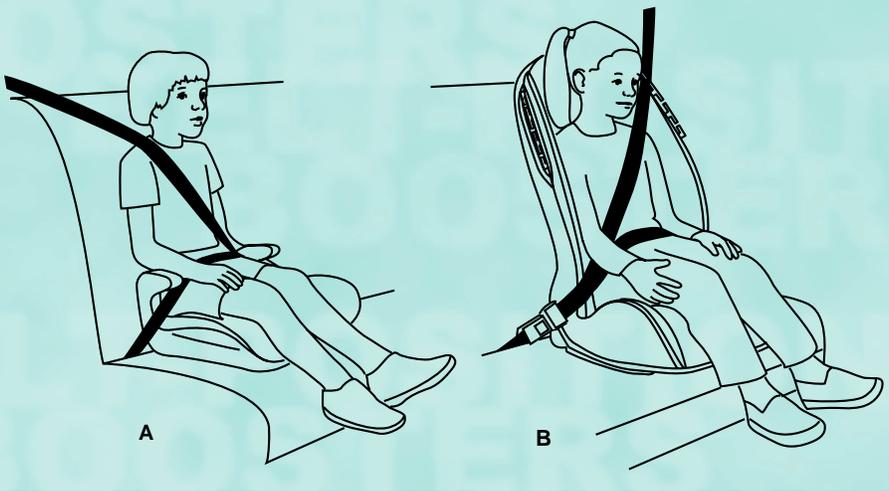


Figure 14. Belt-positioning boosters:
(A) backless booster, (B) high-back booster.

completes this with some backless boosters as well. The cushions of both booster types are also shallower than the vehicle seat cushion, so a child's knees can bend comfortably at the edge. This encourages a child to sit up straight with its back flush with the seatback.⁶¹

Booster cushions were developed in Sweden and Australia in the mid-1970s to allow children to take advantage of the vehicle's built-in upper and lower torso restraint,^{82,92} and they have been used there and elsewhere successfully ever since. Although several models were manufactured in the U.S. in the early 1980s, they soon disappeared again because lap/shoulder belts were not generally available in rear seats where children sat, and parents were therefore required to install a tether anchor for a special Y-harness to provide full protection. Even after outboard rear-seat lap/shoulder belts became standard equipment for passenger cars with model year 1991 (54 FR 46257), it took another four years for federal rules to be changed to allow boosters to be certified for use with lap/shoulder belts (59 FR 37167). In the interim, the market shifted to shield boosters, discussed below, although



the shields of later designs could be removed to create BPBs.

It is only recently that BPBs have seen a resurgence. These are primarily of the high-back design, because many are sold as combination CR/Bs and the public perceives them as safer than backless models. The high back is only useful, however, with low vehicle seatbacks, unless there is also a side structure to provide some head support for a sleeping child or possibly side head protection. Compared to backless boosters, high-backs position the child several inches closer to forward surfaces, are more expensive, and may be uncomfortably upright for long trips. Because

of the back, they are subject to a weight limitation of 4.4 kg (9.7 lb) to avoid injurious loading of the child into the belt by the booster itself. This limit is 10% higher than the heaviest booster in Sweden in 1990,¹¹⁴ but there is no evidence from crash experience that it is too high.

Shield Boosters

Shield boosters (figure 15) were designed to be used in seating positions with only a lap belt, which was the typical rear seat environment in American cars until the last decade and still is for some segments of the population, including many young parents. In most versions, the lap belt went across the front of the shield, transferring the load against the belt to a wider, somewhat flexible surface on the child's abdomen. The low shield provided virtually no upper torso restraint. The primary value of this type of booster was that it raised the child up for better visibility and provided a buffer between the child and an ill-fitting lap belt that might ride up around the child's waist.

The original shield booster, which had a higher shield than later models, was developed in the mid-1960s.³⁷ The high shield acted much like an airbag, restraining the head and upper torso in a frontal crash while deforming to absorb energy. It sat at a fixed distance from the vehicle seatback and was thus comfortable for the child, although it might not be snug against a slender child's body. From a parent's point of view, the restraint was considered easy to use if left buckled in place but was cumbersome to move from one vehicle to another. Some parents also objected that the high shield

DILEMMA LAP BELT DILEMMA

blocked the child's view.

The lower shield, however, concentrated the impact forces on the upper abdomen, rather than spreading them over the entire front of the child's torso, and early laboratory tests with a specially instrumented dummy indicated that these abdominal forces might be excessive.⁷⁹ In crash tests, the child dummy typically wraps around the low shield until the head contacts the legs or the front of the booster. In contrast, an FFCR long available in Europe, which has a flat but deep shield made of energy-absorbing materials, combines the performance of the high shield with the consumer acceptability of the low one.

The lack of upper torso restraint could not be solved by using a lap/shoulder belt with a shield booster unless the shield was removed, as most eventually allowed. The shield itself usually pushed the shoulder belt up and away from the child, making its angle worse with respect to the child's body. Moreover, routine impact tests indicated that, when the upper torso was held back by the shoulder belt, the lower torso moved forward and tended to slide under the shield, which in turn could rotate out from under the belt, depending on its method of attachment.¹²⁰

Shield boosters are no longer considered appropriate crash protection for children. Crash investigations have documented ejections, excessive excursions, and shield-contact injuries in rollover, side, and frontal crashes, resulting in severe head, spinal, abdominal, and extremity injuries.^{74,104,107,127} Marriner et al. have also duplicated ejections in

field experiments, and Meissner et al.⁷⁷ have demonstrated substantial forward excursions with dummies in severe crash tests compared to the BPB alternative. Guidelines from the American Academy of Pediatrics recommend against shield boosters for children under 18 kg (40 lb).⁷ In addition, changes to Federal Motor Vehicle Safety Standard (FMVSS) 213 that require testing with a 6-year-size dummy effective September 1996 have made it virtually impossible to reliably meet both its head excursion and acceleration criteria in order to certify a shield booster for children over 18 kg.

The Lap Belt Dilemma

Until this year, there were no restraint systems that could legally be sold in the U.S. mass market for children over 18 kg that did not depend on a lap/shoulder belt for upper torso restraint. If a family had a vehicle with only lap belts in the rear seat, or had more children over 18 kg than seating positions with lap/shoulder belts, there was no simple solution for providing crash protection beyond the lap belt alone, which has well-understood and documented risks.^{64,90,91}

The use of a BPB with only a lap belt is not recommended, even when that lap belt fits poorly. Children under 18 kg should be restrained in a CR. For those over 18 kg, the risk of head impact and consequent head/neck injury in the absence of upper torso restraint increases the more the child is raised off the vehicle seat. This is due primarily to the longer belt that is needed to go around both child and booster,¹²⁵ and can be exacerbated by compressible booster material.³⁹ With respect to prevention of head contact, it is better for a child to sit directly on the vehicle seat when only a lap belt is available than to sit on a BPB.

A new entry into the U.S. market can restrain a child up to 27 kg using only a lap-belt installation. This is achieved primarily by a low seated height and associated center of gravity, which is suitable for larger children (figure 16). Early products were only available with tray-shield restraining systems, but a 5-point harness model is now available, which should be widely acceptable for use with children over 18 kg, especially in older vehicles or with larger but behaviorally less mature children.

Canada Motor Vehicle Safety Standards (CMVSS) allow FFCRs to be certified for chil-

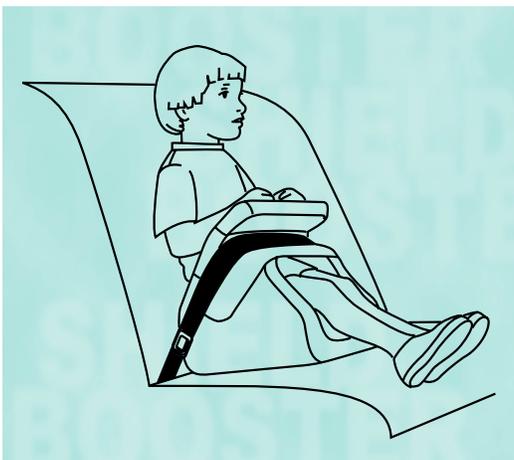


Figure 15. Shield booster (no longer recommended).

SEATBELTS



Figure 16. Child restraint system with low center of gravity for children up to 27 kg.

dren up to 22 kg (48 lb) using a top tether strap, since all CRs may use this device to meet CMVSS 213 (SOR/98-159). U.S. regulations, however, do not. This prohibition also precludes selling a tethered Y-harness with a BPB, which was legal in the early 1980s. A petition requesting NHTSA to modify U.S. regulations to allow certification of tethered FFCRs for children weighing over 18 kg, or to determine other solutions to this problem, has been under consideration for nearly 3 years.¹¹⁹ In the meantime, the best alternatives may be to install lap/shoulder belts in place of rear-seat lap

belts for use with a BPB, or to restrain one child in front with the lap/shoulder belt and a BPB. As last resorts, use the lap belt alone, if it will stay down on the lap, or use an old shield booster.

SEATBELTS FOR CHILDREN

The term seatbelt refers to either a lap/shoulder combination or a lap belt alone. Although the former has become standard equipment in most vehicles, there are still many on the road with only lap belts in rear seats. Vehicle seatbelts are designed primarily with adults in mind, and geometric factors may make good fit difficult for children. Seatbelts are not, however, inherently dangerous, even for young children,^{36,38} and should be used when a more appropriate restraint system is unavailable. Seatbelts are part of a continuum of restraint systems with varying levels of effectiveness for children. In general, more restraint is better than less, and good fit is important for effective restraint performance.

Unfortunately, poor fit of seatbelts often leads to misuse, with shoulder belts placed behind the back or under the arm,^{29,77} which degrades their performance. Even so, statistical analysis of a large Canadian data file indicates that seatbelts reduce fatalities and serious injuries of children age 4 through 14 by 40%.¹⁷ A U.S. injury data analysis, however, confirmed that restrained children age

6 through 12 are not as effectively protected as those through age 5,⁶⁰ and data from an analysis of 1994 fatal crashes showed a similar proportion of fatalities among children age 5 through 9 restrained by seatbelts as among those who were unrestrained.¹

Child Size and Belt Fit

Good fit of a lap belt is as low as possible on the pelvis, touching or even flat across the thighs. A shoulder belt should cross the chest at midsternum and lie flat on the shoulder about halfway between the neck and arm (figure 17). Such fit is dependent primarily on the sitting height of the occupant, and suitable occupant size varies considerably from one specific belt and seat combination to another. Measurements and observations of 155 children age 6 through 12 done by Klinich et al.⁶¹ indicate that a child needs to have a sitting height of 74 cm (29 in) to comfortably and effectively use most lap/shoulder belts, a result consistent with the sitting-height recommendations previously made by Stalnakar.¹⁰⁶ To assist parents in judging their child's size, Klinich et al. also included guidelines for standing height of 148 cm (58 in) and a clothed weight of 37 kg (81 lb), but age was not considered a useful indicator because of the wide variations in anthropometry within each age group. The study also found that 3-point belts fit the taller, thinner subjects better than the shorter, chubbier subjects of the same weight. Each child should therefore be individually evaluated in a particular seat and belt system to determine whether a BPB is still needed or the seatbelt can be used alone.

To achieve the best fit, the child should be sitting fully upright with its pelvis as vertical and as far back into the seat as possible, and preferably with its feet touching the floor. This will help place the lap belt in front of the pelvic bone below the anterior-superior iliac spines and will minimize the possibility of the belt sliding up and intruding into the soft upper abdomen. The lap belt must not be placed or be allowed to ride up around the waist. Klinich et al.⁶¹ found that children whose upper legs were too short for their knees to bend over the front edge of the seat tended to slouch their pelvises forward and slide under the lap belt. If an erect seated posture cannot be achieved, or if the shoulder belt crosses the throat, the child needs to use a BPB.

SHOULDER BELT POSITIONERS

Shoulder belts that touch the side of the neck are not likely to cause injury unless they are very loose.^{8,19,89} Although individual cases of vertebral and spinal cord injury are reported in the medical literature, there is usually insufficient information to determine crash and restraint conditions. Until an independent evaluation of these cases has been done, similar to that for the forward-facing infant, the actual mechanism of injury and guideline for prevention are largely speculative. In any case, the shoulder belt should not be routed behind the child's back, because the fit of the remaining lap portion will not be the same as a lap-only belt, and the belt will likely ride too high on the in-board side. Finally, the shoulder belt should never be routed under the arm, because the resulting belt forces on the side of the thorax are known to result in serious internal injuries in a crash.^{29,108}

Shoulder Belt Positioners

Various unregulated devices have appeared on the market in the last several years to pull a shoulder belt away from a short occupant's neck. Although possibly useful for a small adult, who might need only a minor modification of the belt geometry, they are not suitable for children. Most of these devices connect the shoulder belt to the lap belt in front of the body in some fashion, thereby changing and often degrading the performance of the original belt system.¹⁰⁹ Effects include increased head and chest acceleration and increased roll of the upper body out of the shoulder belt. In addition, some devices made of plastic break on impact, and others made of metal bend significantly under load. Others made of soft materials may be effective in pushing the belt away from the neck but can also be easily misused to push the shoulder belt onto the arm. Most important for children, however, they do nothing to improve the positioning of the lap belt on a small body and may actually lift it higher, and the slouching problem with short legs remains. Shoulder belt positioners should not be used in place of BPBs.

The NHTSA test series¹⁰⁹ used 3-year, 6-year, and 5th-percentile female dummies.⁸¹ Although there were only minor variations in performance in most tests with the 6-year dummy, compared to those with the 3-year and small female dummies, and not all degradations would be considered failures, these results should not be consid-

ered a definitive endorsement.

The test procedure was limited in realism by the nearly ideal test bench, belt geometry, and dummy positioning used, and the stiff thoracic and spinal structures of the child dummies virtually precluded their sliding under the lap belt. If these devices are to be regulated in the future, it will be necessary to develop performance criteria beyond those in the current child restraint standard (49 CFR 571.213), to use more sophisticated dummies, to use realistic seat cushion shapes and belt anchor geometries, and to incorporate a belt fit criterion that ensures the lap belt will be properly located on the upper thighs.

A provision in the European child restraint regulation, which says "devices utilizing a lap strap must positively guide the lap strap to ensure that the loads transmitted by the lap strap are transmitted through the pelvis" (E/ECE/324/Reg44/6.2.2), has been interpreted to include not only boosters but other belt-positioning devices as well. Few, if any, of the current shoulder belt positioner designs would qualify.

Lap vs. Lap/Shoulder Belts

Restraint theory leads to the conclusion that lap/shoulder belts would be better for children, even if fit is not optimal, than a lap belt alone. This assumption was made by Johnson et al.⁴⁸ for an analysis of police-reported data on children over age 4, but the data did not show a significant difference in injury reduction by belt type. Other analyses with more detailed usage and injury information also found no significant differences in overall injury severity and rates among children in different types of belts.^{2,3,29,38} Head and facial injury patterns were similar, although Henderson et al. found that the injury source differed by seating position as well as by belt type. Halman³⁶ looked at the Injury Severity Scores (ISSs) of 200 school-age children in a Transport Canada data base and determined that there was no statistical difference between those in rear-seat lap belts vs. front-seat lap/shoulder belts, and that both types



Figure 17. Good lap/shoulder belt fit.

AIRBAGS

of restraint systems reduced ISSs for children comparably to the reduction for adults.

A complicating factor in past comparisons of lap vs. lap/shoulder belt effectiveness was that seating position (outboard vs. center, front vs. rear) was necessarily mixed in with belt type. Data analysis by Braver et al.¹² showed a 32% reduction in fatalities for children 5 through 12 in rear-seat lap belts compared to those in front-seat lap/shoulder belts in pre-1988 cars, but an even greater reduction (44%) when lap/shoulder belts were compared for both front and rear in newer cars. (The 95% confidence intervals overlap, however.) A reduction of 24% is also given for all restrained children in the rear-center vs. the rear-outboard positions. These results imply some benefit from the lap/shoulder belt that may be masked by its outboard location and/or front seating position.

When comparing only abdominal and lumbar spine injuries, ten years of Australian data indicated the relative risk for children in rear-seat lap belts was twice that of rear-seat lap/shoulder belts.⁶⁴ The Gotschall et al.²⁹ series showed a similar occurrence of soft tissue injury in the abdominal region by belt type, but the lumbar spine fractures were limited to the lap-belted children. Included in the latter were children who had put the shoulder belt of the 3-point system behind their backs. From these studies, it might be concluded that the pelvis can slide under either configuration, but that the upper torso must be thrust over a high lap belt to break the spine.

The question of fatality reduction effectiveness of rear-seat lap vs. lap/shoulder belts has recently been addressed in an extensive double-pair analysis by Morgan,⁸³ in which children of age 5 through 14 were included and evaluated separately. The conclusions for rear-outboard occupants in this age group are that lap-belted children were 38% less likely to die than unrestrained children, while lap/shoulder-belted children were less likely by 52%. The lap/shoulder belt was found to reduce fatalities 26% over lap belts alone for children 5 through 14 in all crashes and 31% in frontal crashes, and children derived more relative benefit from the lap/shoulder belt than did the adult groups. Further analysis with supplemental cause of death data indicated that both types of belted children were somewhat more likely to receive abdominal injuries than unrestrained children, but the increase for the adult groups in lap belts was much greater.⁸³

Finally, both belt systems markedly reduced fatal head injuries, but these were still twice as likely among lap-belted than lap/shoulder-belted children (64 FR 36657). This study makes it clear that shoulder belt use is very beneficial for older children.

Airbags and Seatbelts

Children in seatbelts may be at greater risk of injury from airbags than their younger siblings restrained in FFCRs, because the former are able to lean forward in their shoulder belt or even put the belt behind their back. This behavior may place their head in the path of the deploying airbag or allow their upper body to be thrown forward during precrash braking. Among the 28 children age 6 through 11 who were killed by passenger airbag systems as of June 2000, five had the shoulder belt behind their back, one was leaning forward in his belt, and the cases of another two in lap/shoulder belts are still under investigation. The other 20 were unrestrained.⁸⁵

CONCLUSION

The consistent and proper use of restraint systems by infants and children in passenger vehicles can prevent hundreds of deaths and thousands of injuries each year. Infants require the most special treatment, with restraint systems designed to apply crash forces to their backs or the full length of their bodies. Children over 1 year also benefit from specially designed restraints that snugly conform to their small body shape, while providing elevation so that they can see the world around them. Seatbelts can provide good restraint for older children, particularly when adapted to their body size by a booster, and provided that attention is paid to good belt positioning and fit. It is important to understand both the theory behind the design of restraint systems and how this theory has been applied to be able to evaluate child restraint performance in a crash, to develop improved restraint systems, and to provide informed guidance concerning child restraint selection and use.

ABOUT THE AUTHOR

Kathleen Weber is project director of the Child Passenger Protection Research Program in the University of Michigan Medical School, Pediatric Surgery Section. She works with manufacturers, consumer groups, and government agencies to evaluate and improve the effectiveness of all types of child restraint systems. Ms. Weber's first research study concerned the comfort and convenience of restraint systems for infants, but she later changed her focus to crash testing. Ms. Weber chaired the Society of Automotive Engineers committee on the interaction of child restraint systems with airbags, and she was instrumental in bringing to public attention the dangers of airbags to restrained infants. She has also served on two Blue Ribbon Panels advising the government on child restraint compatibility with vehicles and on restraining older child pas-



sengers. Ms. Weber currently serves on the SAE Children's Restraint Systems Standards Committee and the International Standards Organization working group on child restraint systems. She has published numerous papers on such topics as compatibility, restraint systems for children with special needs, child restraint and airbag interaction, and neck injury in restrained children, and she has written a frequently cited paper on the state of the art of child passenger protection, which is updated by this article.

In June 2000, Ms. Weber was recognized at the International Child Passenger Safety Technical Conference with the first Dana Hutchinson Award for contributions resulting in a significant improvement in the field of child passenger safety.

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