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RESEARCH REVIEW

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Crash Protection for Child Passengers:
Rationale for Best Practice

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Editor's note: This special issue of the UMTRI Research Review *provides the latest research findings on crash protection for child passengers. This issue updates the highly regarded July-September 2000 issue (volume 31, number 3) devoted to the same topic.*

Crash Protection for Child Passengers: Rationale for Best Practice

by Kathleen D. Klinich, Miriam A. Manary, and Kathleen B. Weber

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Child restraint systems provide specialized protection for pediatric motor vehicle occupants whose body structures are still immature and growing. There are many occupant protection systems available and the different types of restraints are appropriately matched to children based primarily on their ages and sizes. Even with the most appropriate child restraint, the way in which it is installed and used can affect its performance. This review describes the basic principles behind the design of occupant restraint systems and applies them to the needs of children. It also includes a brief overview of child restraint testing procedures and their limitations. Each section describes research and insight behind current best practice concepts, primarily from the US perspective.

COURTESY OF NICHOLE ORTON

CHILD RESTRAINT USE AND EFFECTIVENESS

Child restraint systems are highly effective safety devices that protect children against the leading cause of injury and death for those ages 3–18 years. There are four main sequential steps in child restraint best practice: rear-facing harnessed restraint, forward-facing harnessed restraint, booster seat with a lap-and-shoulder belt restraint, and seat belts. Matching the appropriate restraint mode with the child depends on their physical size and maturity level.

Relative to no restraint, rear-facing child restraints are 71% effective and forward-facing child restraints are 54% effective in reducing the likelihood of death and serious injury (Kahane 1986). Forward-facing child restraints reduce odds of an injury by 78–82% compared with lap and shoulder belts (Zaloshnja et al. 2007, Arbogast et al. 2004). Children up to age 2 in forward-facing child restraints are 1.76 times more likely to experience serious injury than children in rear-facing child restraints, with the analysis showing a more distinct benefit for rear-facing children in side impact crashes (Henary et al. 2007). Children aged 2–6 using child restraints without gross misuse had a 28% lower risk of death than children using only seatbelts (Elliott et al. 2006a).

Use of a booster seat reduces risk of fatal injury for children aged 4–8 years by 55–67% relative to the risk to unrestrained children and adults, while

PCPS STUDY

Researchers at the Children's Hospital of Philadelphia in partnership with State Farm Insurance Companies conducted a study called the Partners for Child Passenger Safety (PCPS) from 1998 through 2007. Crashes involving children in 15 states and the District of Columbia were identified through State Farm Insurance claims, and data on the crashes were collected using a validated telephone survey and selected in-depth crash investigations. The survey identified clinically significant injuries, which generally correspond to those AIS2+ and higher such as broken bones and organ injuries. The complete dataset includes 34,732 crash-involved children under age 16 who were in 21,943 crashes. Using statistical techniques to develop weighting factors to represent crashes in the US population, these children's outcomes can be analyzed to represent 531,193 children in 346,485 crashes. This dataset provides valuable information for evaluating actual performance of child restraint models available up to 2007 in real crashes, and a significant portion of the recent data included in this review comes from this study.

children aged 5–14 using seatbelts have a 52% reduction in fatal injury risk relative to unrestrained occupants' risk (Morgan 1999). While proper booster seat use has only a marginal effect on reducing risk of fatal injury compared with the risk of using a seatbelt alone, children aged 4–8 using booster seats have a 55% lower risk of serious injury compared with those using seatbelts alone (Arbogast et al. 2009). In comparison, seatbelts are 37–48% effective at preventing fatal injuries in adults while seatbelts plus frontal impact airbags are 44–54% effective at preventing fatal injuries (Morgan 1999). While child restraints are the most protective restraints available, there can still be catastrophic crashes, particularly those involving severe intrusion into the passenger compartment of the vehicle, where child restraints are not effective and children can sustain severe or fatal injuires.

Tremendous strides have been made to increase child restraint use nationwide, primarily through the enactment of state child passenger safety laws and educational campaigns aimed at parents and caregivers. Since 2000, 49 of 50 states have improved their child restraint laws either by extending the applicable child ages, making nonuse a primary enforcement infraction, or adding other best practice elements to the law. Over the past 25 years, the proportion of children riding unrestrained has decreased from 90% in 1976 (Williams 1976) to approximately 13% in 2008 (NHTSA 2009). However, unrestrained children ages 0–15 years account for approximately 54% of children killed each year in motor vehicle crashes (NHTSA, 2002), indicating that additional gains in safety can be achieved by minimizing nonuse of child restraints further.

Misuse of child restraints remains common, with estimates of misuse ranging from 63–90%. (Decina and Lococo 2005 and 2007, Eby and Kostyniuk 1999, Dukehart et al. 2007) Some errors may have minimal effect on safety, particularly in less severe crashes. However, multiple "small" errors may combine to cause as much of a decrement in performance as a single major error, and become more critical as the severity of the crash increases (Tsai and Perel 2009, Lesire et al. 2007, Weber and Melvin 1983). The effectiveness of child restraints is estimated from their "as used" state, which includes misuse conditions, and thus would be expected to increase if misuse were reduced.

PRINCIPLES OF RESTRAINT SYSTEMS

Vehicle Crashes

Vehicle crashes consist of a series of collisions; the most common type is a frontal impact. The initial impact is between the vehicle and another object, while the occupants continue to move forward at the precrash speed as the vehicle slows down. Unrestrained occupants will continue at the precrash speed until they abruptly stop against the decelerating vehicle interior or surfaces outside the vehicle, experiencing high accelerations and loading. Restrained occupants collide with their restraints, giving them a longer time and distance to come to a stop so that they experience lower loads and acceleration levels.

The front structures of vehicles are designed to crush during frontal crashes, thereby absorbing a portion of the crash energy and allowing the passenger compartment to stop over a greater distance and longer time than does the front bumper. By coupling the occupants to the passenger compartment structure with snug-fitting belts, they will "ride down" the crash with the vehicle frame for a longer time period. For small children to "ride down" the crash, a snug harness couples them to the child restraint, and a tight installation of the child restraint (using seatbelt or LATCH) couples them to the vehicle.

In other crash directions, the occupant motion is primarily toward the point of vehicle impact. Although side impacts usually have a lower change in velocity than frontal impacts, there is much less vehicle structure available to absorb energy between the occupant and striking object. Rear impacts are generally the least severe among all crashes, with restraint provided by the vehicle seat back and head restraint. Rollovers involving more than one-quarter turn of the vehicle project the occupant towards the roof, making restraint use critical to achieving good injury outcomes.


COURTESY OF JINGWEN HU

Restraint Systems

Vehicle seat belts or harnessed restraints that are initially snug allow immediate restraint of the occupant, which maximizes the time of restraint and minimizes the level of loading required to stop the occupant. Other supplemental protection systems, such as padding or airbags, can absorb impact energy between the occupant and the vehicle interior. If belt or harness webbing is loose, the occupant will travel farther before restraint can begin, increasing the level of force needed to stop the occupant in a shorter time period. Advanced seat belt designs balance between loading the occupant and controlling contact with vehicle interior components.

To optimally reduce the risk of injury, the remaining loads must be distributed as widely as possible over the body's strongest components. For adults who face forward, these parts include the shoulders and pelvis. For children, especially infants, distributing the restraint loads over larger and sometimes different body areas is necessary. Multiple straps and rearward-facing orientation help take care of these needs.

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 typically irreversible. In the design of restraint systems, tradeoffs may be necessary that compromise on protection for the extremities or ribs to ensure protection of the brain and spinal cord.

Proper belt placement and good fit are important for effective seat belt restraint when using either the vehicle seat belt or a child restraint harness. 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 also occur during a crash if the belt is loose or, with small children, is not held in place low on the pelvis by a crotch strap or other positioning device, such as booster belt guides. A lap belt that is placed or rides up above the pelvis can intrude into the soft abdomen and rupture or lacerate internal organs (Rouhana 1993, Rutledge et al. 1991). Moreover, in the absence of

CHILD PASSENGER SAFETY TECHNICIAN PROGRAM/ FITTING STATIONS

In the mid 1990s, NHTSA began support of a national standardized child passenger safety curriculum that has created a nationwide network of specially trained personnel to educate parents and caregivers about correct practices in child passenger safety. The course, implemented in 1998, consists of 3-5 days of instruction and demonstrations, culminating in a community car seat check up event. Students demonstrate their mastery of the material with written test and skills demonstrations and then must recertify every two years. Since its introduction, the program has trained over 108,000 technicians, and about 30,000 are currently certified. This group includes first responders, law enforcement personnel, firefighters, parents, researchers, clinicians and social workers. These trained technicians can use their skills to staff permanent fitting stations and car seat check up events as well as serving as community educators.

For more information see ***www.safekids.org***

CHILDHOOD OBESITY AND CHILD RESTRAINTS

Childhood obesity leads to many health problems, but the data are mixed as to whether there is a potential for increased injury rates in motor-vehicle crashes (Haricharan et al. 2009, Zonfrillo et al. 2011). A primary concern is that children may not be able to follow best-practice recommendations for their age (rear-facing until 2 years, harnessed restraint to at least age 4, booster seat until age 8-12 when the seatbelt fits correctly) because they exceed the weight limit of the available products (Trifiletti et al. 2006, Fitzharris et al. 2008, Bahlmann et al. 2009). For example, a three-year-old weighing 36 kg (80 lb) would be too heavy for nearly all forward-facing harnessed restraints, but probably would not sit correctly in a booster that allows increased freedom of movement. For children using child restraints with an acceptable weight limit, the dimensions of the product or the harness system may not fit them appropriately. Another challenge is that pediatric crash dummies represent average sizes of children, and cannot identify how an obese child may interact differently with the restraint.

a shoulder restraint, a lap belt routed above the pelvis will compress the soft tissue and organs of the abdomen and load the spine, possibly causing separation or fracture of the lumbar vertebrae in a severe crash (Johnson and Falci 1990, King 1993). Misusing a lap-and-shoulder belt by placing the shoulder belt behind the back removes torso restraint and allows the same problems seen with lap belts only; placing the shoulder belt under the arm provides minimal torso restraint and can increase direct loading to the abdomen and chest compared with a properly positioned belt (McGrath et al. 2010, Louman-Gardiner et al. 2008).

Despite the potential for belt-induced injuries, belt-based restraint systems have significant advantages over supplementary 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 restraint 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 mass is so much less that the injury potential from contact with belts or other restraint surfaces is also less. In contrast, first-generation frontal airbags produce the same amount of deployment force and resistance to deflation regardless of occupant size, while some advanced airbag systems vary deployment force based on the weight of the occupant.

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 child restraints, however, work on the principle of coupling the child as tightly as possible to the vehicle because it maximizes the time restraint can be applied and minimizes the highest level of force required to stop the occupant. In North America, the child restraint has been traditionally attached to the vehicle with the existing seatbelts. An option available in the US since 2002 is the LATCH system, which stands for Lower Anchors and Tethers for CHildren. After installing the child restraint to the vehicle, the child is then secured in the child restraint with a separate harness. This results in two links between the vehicle and the occupant. It is therefore critical that the seatbelt or LATCH strap be tight and the harness be snug to allow the child to ride down the crash with the vehicle.

Seating Position, Airbags, and Children

From the early days of child restraint regulation, the center rear seat position has been considered the safest place in the car, since it is farthest from the exterior of the vehicle. Analyses of field injury data continue to bear this out (Kallan et al. 2008, Braver et al. 1997, Mayrose and Priya 2008). Before the implementation of frontal-impact airbags for the right-front passenger, infants were often restrained in the front seat to allow monitoring by the driver (Edwards and Sullivan 1997). In addition, until lap-and-shoulder belts were required in rear outboard seats in 1989, the front seat offered the only passenger position with the more complete lap-and-shoulder belt restraint.

When frontal-impact airbags were required in the United States to provide protection for unbelted right-front passengers in the early 1990s, the unintended consequence of a restraint system designed for adults was the potential for lethal loading of children riding in the front seat. (Quinones-Hinojosa 2005, Braver et al. 1998). To date, 28 infants and 152 older children sustained fatal loading attributed to the airbag in the United States (NHTSA 2009). The increased risk of fatality to children in the right-front passenger seating position in vehicles with first-generation airbags is estimated to be 34%–63%. (Braver et al. 1998). These fatalities almost always involved head or neck injury from direct contact with the inflating bag and/or the airbag housing cover delivered to children who were either riding in a rear-facing child restraint or unrestrained and/or were out of position and close to the airbag at the instant of deployment (NHTSA 2000).

The immediate response to the injuries and fatalities to children by first-generation airbags was to recommend that children under 13 years of age use the rear seat. The combination of airbag warnings on child restraints and in vehicles along with educational campaigns has led to high use of the rear seat by children, increasing to 83% of children under age 7, including most children in rear-facing restraints and 50% of children aged 8–12 (Greenspan et al. 2010). Another study indicates that 99% of children under age 1, 98% of children aged 1–3, and 88% of children aged 4–7 rode in rear seats in 2008 (NHTSA 2008). In addition, vehicles are now equipped with occupant detection systems that are meant to automatically turn off the airbag and prevent frontal-airbag deployment with child occupants and occupants who are too close to the deploying airbag. Federal testing requirements have also changed so airbags deploy with less force. Braver et al. (2008) showed that relative to first-generation airbags, second-generation airbags led to reductions in fatal injuries of 65% for children aged 0–4, 46% for children aged 5–9,


COURTESY OF LAURA MALIK

and 32% for children aged 10–12 who were seated in the front seat. Olson et al. (2006) found a 34% reduction in risk for children under 6 between second- and first-generation airbags.

Regardless of what type of airbag system exists in the vehicle, children under age 13 should ride in the back seat (Arbogast et al. 2009, AAP 2011, NHTSA 2011). Despite the improvements in airbag technology, this recommendation remains important because the vehicle fleet still includes vehicles where the airbag can pose a danger. In addition, the rear occupant compartment provides a safer environment during a frontal crash because of intrusion that is more likely to occur in the front occupant compartment (Evans et al. 2009). Several studies have documented the protective effect of the rear seat for belted occupants (Berg et al. 2000, Durbin et al. 2005).

As side impact airbags have been introduced to the vehicle fleet, more precautions have been taken to avoid the unintended dangerous consequences experienced with frontal-impact airbags. Voluntary testing procedures used by vehicle manufacturers evaluate whether the side airbags pose a danger to an "out-of-position" child next to the airbag module (Side Impact Working Group 2003). Curtain airbags deploy from the vehicle roofline and provide head protection during side impacts and rollovers. Field investigations of crashes have identified almost no unintended injuries to children caused by side or curtain airbags, indicating that the efforts to ensure the safety of their implementation have been effective (Hallman et al. 2009, Arbogast and Kallan 2007).

CHILD RESTRAINT INSTALLATION

Seatbelt

Seatbelt use increased nationwide from 11% in 1982 to 85% in 2010 (NHTSA 2009, Lund 1986), largely due to the enactment and enforcement of state occupant restraint usage laws. During this time, vehicle manufacturers developed seatbelt designs to improve comfort, ease-of-use, and protection for adult occupants. Some of the improvements for adult seat belts conflicted with easy securement of child restraints. For example, a seatbelt anchorage located forward of the vehicle seat bight (the intersection of the seatback and bottom cushion) can provide a more advantageous angle for belt restraint of an adult, but makes it challenging to tighten a seatbelt adequately during child restraint installation. As a result, some issues regarding child restraint compatibility with vehicle belts and seats were addressed in SAE Recommended Practice J1819 (1994) and by the addition of a seatbelt lockability requirement to FMVSS 208 in 1996.

A common child restraint misuse with seatbelt installations is the failure of the installer to lock the seatbelt. Many seatbelts are equipped with an emergency locking retractor, which locks to prevent forward movement of the occupant during a crash event but allows movement of the occupant during normal driving. Use of a seatbelt equipped with an emergency locking retractor alone allows the child restraint to shift during normal driving. To eliminate this problem, some retractors are switchable, and can be converted to an automatic locking retractor, which allows the belt to be locked tightly through a child restraint belt path. They are usually switched by pulling the webbing completely out of the retractor and then feeding it back in to tighten.

Other belt systems use a locking latchplate that allows tight installation of the child restraint in most cases, although it can sometimes be incompatible and loosen during use. Some child restraints are equipped with belt lockoffs that can lock the seatbelt by clamping down on the webbing without use of vehicle hardware. Locking clips are still provided on child restraints without belt lockoff hardware and can be used to prevent transfer of webbing from the shoulder portion to the lap portion of the belt. However, locking clips are often ignored or placed incorrectly (instead of properly positioned within one inch of the latchplate), which may cause them to deform, fly off, and/or introduce belt slack during a crash.

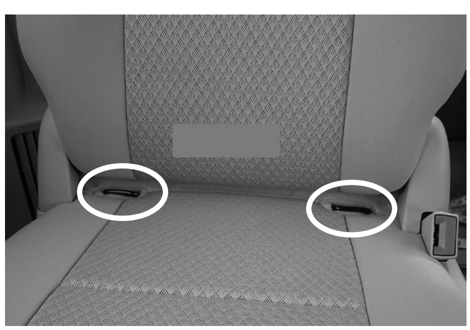
A new challenge in obtaining tight installation of rear-facing restraints using seatbelts has become more prevalent with the presence of lap-and-shoulder belts in all rear seating positions. A tight lap-and-shoulder belt can cause a rear-facing child restraint to tilt sideways as the taut shoulder belt portion pulls up on the belt path. If needed, a child restraint lockoff or a locking clip can be used to allow tightening without tipping.

LATCH

In response to the challenges posed with seatbelt installation of child restraints, the National Highway Traffic Safety Administration (NHTSA) introduced a new child restraint securement system in 1999. The Child Restraint Anchorage System, commonly called Lower Anchors and Tethers for Children, is known as LATCH in the United States and is defined in FMVSS 225 and additions to FMVSS 213. The LATCH concept originated from an effort in the International Standards Organization (ISO), which proposed and adopted a universal child restraint anchorage system called ISOFIX (ISO, 1999a). Implementation of LATCH in the United States began in 1999 and was required in vehicles and child restraints in 2002.

The ISOFIX concept calls for two lower attachment points and a means to "limit pitch rotation of the child restraint". In the United States, LATCH has two distinct components: lower connectors on child restraints that attach to lower anchorage points located at the vehicle seat bight (figure 1), and a top tether strap on forward-facing restraints that attaches to anchor points located on the rear shelf, seat back, floor, cargo area, or ceiling of the vehicle (figure 2).

Most US child restraints are equipped with a LATCH strap consisting of a length of webbing with adjustment hardware and connectors on each end. The two most common types of connectors are hook-on and push-on (figure 3). The LATCH strap is usually routed through the appropriate belt path on the child restraint that would also usually be used to route the seatbelt (figure 4 top) or attached to each side of the child restraint (figure 4 center). The LATCH strap is designed to replace the vehicle seat belt as the primary securement system. Rigid lower LATCH connectors have been manufactured on a few models of US child restraints (figure 4 bottom), but are widely used in Europe where they are required for ISOFIX. Attaching the top tether achieves a more secure installation and reduces occupant excursions when installing a forward-facing restraint with either the LATCH strap or vehicle seat belt. While using the tether improves occupant protection, child restraints in the United States must also pass less-stringent head excursion requirements without the tether



COURTESY OF JAMIE MOORE

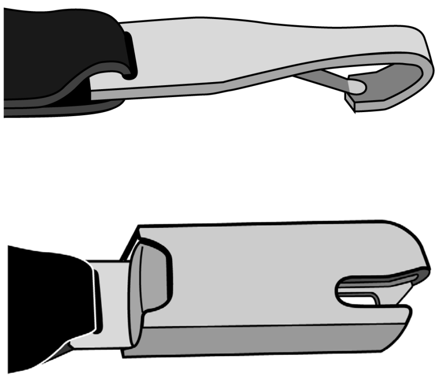
Figure 1. Vehicle with visible lower anchorages.

COURTESY OF JAMIE MOORE

Figure 2. Sedan in which the tether anchorage is located under a marked door on a package shelf (shown closed and open).

to ensure reasonable protection if the caregiver fails to use it.

While many vehicles do allow easier child restraint installation with LATCH compared to seatbelts, in other vehicles the interface with the LATCH hardware makes child restraint installation



COURTESY KATHY CROCKETT RICHARDS

Figure 3. Hook-on (top) and push-on (bottom) LATCH strap connectors.

difficult, and outright incompatibilities between child restraints and particular vehicles have been documented (IIHS 2003, SafeRideNews 2010). New types of misuse have been identified when using LATCH. Top tethers are only used about half the time, even though all vehicles and restraints have had ready-to-use tether hardware since 2001 (Decina and Lococo 2007, Jermakian and Wells 2010). Errors in attaching tethers include connecting them to the wrong hardware, misrouting them with respect to the head restraint, connecting them upside-down, and not tightening them sufficiently. Errors in attaching lower connectors include connecting them to the wrong hardware, connecting them upside-down, and failing to tighten the webbing after connecting. In addition, installers often install the child restraint using both the seat belt and lower LATCH strap, which is only currently allowed by one vehicle manufacturer. Because most US products use the same belt paths to route either the LATCH strap or the seatbelt, the LATCH strap can also be misrouted through the belt paths on the child restraint.

In some vehicles, LATCH has fulfilled the intended goal of making child restraint installation easier, thus reducing misuse and improving effectiveness of the child restraint. However, because of problems in some vehicles, it may still be easier to achieve a better installation using the seatbelt. Best practice dictates that the easiest method providing a tight installation should be used to install a child restraint, keeping in mind that the tether should always be used for all forward-facing installations.

FMVSS 225 specifications include lower and tether anchorage strength requirements evaluated with a quasi-static pull test. When LATCH was first implemented, most harnessed child restraints could only accommodate children up to 18 kg (40 lb). Since then, a number of products have been introduced that allow children up to 23, 29, or even 39 kg (50 lb, 65 lb, 85 lb) to use a harnessed restraint system. Since there is no straightforward way to identify the dynamic strength limits of vehicle anchorages from the quasi-static test data, some vehicle manufacturers have expressed concern that their LATCH hardware should not be used with harnessed child seats for larger children. NHTSA clarified LATCH strength issues in a regulation stating that they consider the strength of lower and tether anchorages (based on static testing) sufficient to secure a child and child restraint with a combined weight of 65 lb (NHTSA 2012). Although many vehicle manufacturers have provided recommended weight limits (that are lower than this value) to a supplementary manual on LATCH used by child passenger safety technicians (SafeRideNews 2011), only one manufacturer currently includes any information about weight limits in their vehicle manuals (Ford 2011). While weight limits on lower anchorages may be appropriate because there is another means (seatbelt) to serve as the main method of attaching the child restraint, setting weight limits on tether use seems misguided because it is a supplement to the main attachment system, and the demonstrated benefits of top tether use in reducing head excursion in a wide range of crashes are much higher than the possible risk of injury caused by hypothetical tether anchorage failure in an extremely severe crash.

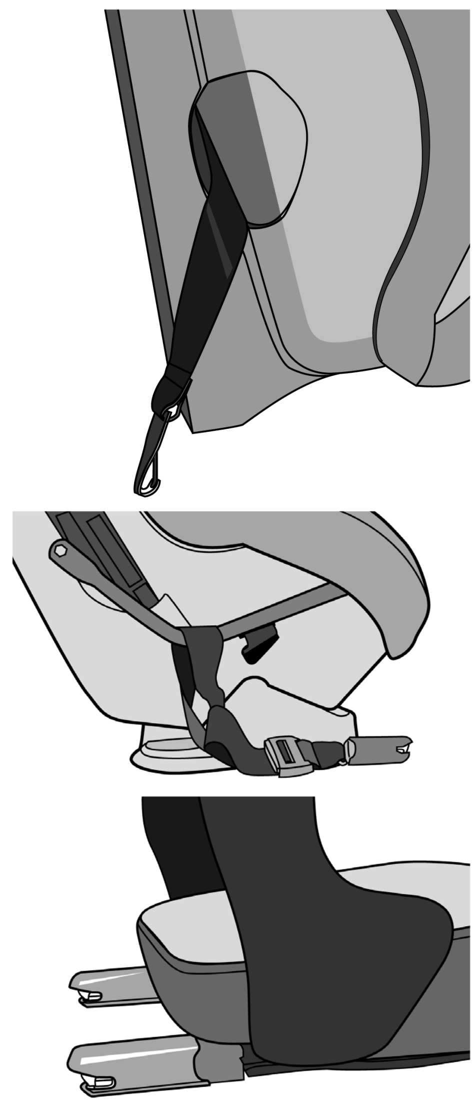


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Figure 4. Implementations of LATCH on US child restraints: LATCH strap routed through belt path (top), attached to bar on each side (center), rigid LATCH (bottom).

CHILD RESTRAINTS ON SCHOOL BUSES

School buses are the safest form of motor vehicle transportation, and recent data based on fatality rates show that they are eight times safer than riding in typical passenger vehicles (NHTSA 2002). The high level of safety is due in part to the special vehicle construction requirements, the high vehicle mass, the conspicuous yellow color, their use primarily during daylight hours on known routes, and the extra training bus drivers receive. School buses were originally designed to transport children ages 6 and older to school. They provide occupant protection using a concept called compartmentalization where the closely spaced seats with extra padding on the seatbacks create a padded compartment to protect the riders. Because federal funding for Head Start requires many children younger than 6 to be transported in school buses using child restraints, buses have some seating positions equipped with either seat belts or LATCH lower anchors. School bus seating manufacturers and NHTSA state that these seats with lap-and-shoulder belts are built to fit a 6-year-old child properly without a booster. Therefore boosters are not recommended at all in school buses. Other publications address details about using child restraints on school buses (SafeRideNews 2009).

Usability and Vehicle/Child Restraint Compatibility

As implementations of LATCH hardware in vehicles and on child restraints have evolved over the past decade, problems with incompatibilities between vehicles and child restraints remain. Caregivers also make mistakes when securing their children in the child restraint harness. Several different rating systems have been proposed to improve the usability of child restraints, reduce misuse, and increase compatibility between the child restraint and vehicle. Except for some label and instruction issues, usability is not an explicit part of FMVSS 213.

NHTSA developed an Ease-of-Use (EOU) Rating system (NHTSA 2006) to provide consumers with information about which child restraints have features that enhance usability. The system has provided strong incentives for child restraint manufacturers to improve products, labeling, and instruction manuals with respect to usability. The rating system includes questions that address each child restraint area related to the most common misuse modes. NHTSA has also proposed a voluntary vehicle/child restraint fit evaluation program to encourage vehicle manufacturers to provide information to consumers about compatibility for vehicle/child restraint pairings (NHTSA 2010). Vehicle manufacturers would submit lists of child restraints that are compatible with a particular vehicle based on a number of key installation factors.

In the field, some misuse modes arise from features and elements of the vehicle environment and others result from interactions between specific child restraint and vehicle combinations. A usability rating scheme has been issued by the ISO Child Restraints Group that has rating forms for all three elements: the child restraint, the vehicle, and specific combinations of the two (ISO 2010, Pedder and Hillebrandt 2007). This rating system currently focuses on ISOFIX (LATCH-type) systems. Some of the vehicle features that are rated in the current version of the ISO document include the vehicle owner's manual instructions on how to identify the number and location of seating positions available for child restraint installation, the visibility and labeling of the LATCH anchors, the presence of other hardware elements that could be mistaken for LATCH anchors, the actions required for preparing the seating position for child restraint installation, and conflicts between LATCH and seatbelts.

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The SAE Children's Restraint Systems Standards Committee has drafted a new recommended practice to improve compatibility between child restraints and vehicles during LATCH installations (SAE 2007). The document defines tools and procedures for evaluating hardware in vehicles and on child restraints to improve their ease-of-use. Factors include measuring the force required to attach LATCH strap connectors to lower anchorages, measuring the clearance around lower anchorages, and recommendations for maximum size of LATCH connector hardware. Since the recommended practice is still in draft form, vehicle and child restraint manufacturers are likely not using the proposed methods regularly.

CHILD RESTRAINT SYSTEMS

There are four main sequential steps in child restraint best practice: rear-facing harnessed restraint, forward-facing harnessed restraint, booster seat with a lap-and-shoulder belt restraint, and seat belts. Matching the appropriate restraint mode with the child depends on their physical size and maturity level. Each successive step offers less occupant protection than the previous mode, so caregivers should delay moving to the next level as long as possible.

Rear-Facing Child Restraints

Both the American Academy of Pediatrics and the National Highway Traffic Safety Administration now recommend that children remain rear facing until they outgrow their restraint. This means that most children can remain rear-facing through age 2 years, based on average child sizes and the capacity of most rear-facing convertible restraint products on the market. US crash data show that children aged 1–2 years are 5.53 times safer in a rear-facing restraint than in a forward-facing restraint in side impacts and 1.23 times safer in frontal impacts (Henary et al. 2007). These recent US data support Swedish data showing benefit for children rear-facing through age 4, with rear-facing restraints reducing AIS2+ injury by 90% compared with unrestrained children (Jacobsson et al. 2007, Isaksson-Hellman et al. 1997). Because earlier rear-facing child restraints did not accommodate larger children, older education materials may contain outdated information stating that children can begin using forward-facing restraints at age 1 or 10 kg (20 lbs), which is no longer considered a safe practice.

COURTESY OF KATHLEEN KLINICH

Types of rear-facing restraints

Two types of restraints, infant restraints and convertibles installed rear-facing, are commonly used to orient the child to face the rear of the vehicle. Infant restraints can only be used rear-facing and most have a separate base which remains in the vehicle to facilitate repeated installation (figure 5 top), but most can also be used without the base and secured with the seatbelt (figure 5 middle). The infant restraint base can be installed with either lower anchorages or the seatbelt. These products usually have a carrying handle. Traditionally, these products have accommodated children up to 9 or 10 kg (20 or 22 lb), but there are now many models that can accommodate children up to 13 kg (30 lb).

A rear-facing convertible is shown in figure 5 (bottom). These can be used rear-facing up to 13–20 kg (30–45 lb), then converted for forward-facing use. Convertibles tend to be larger than infant seats. While most children will outgrow their rear-facing restraint because they reach the allowable maximum weight limit for their use, some children will outgrow their rear-facing product because the top of their head is within 2.5 cm (1 inch) of the top edge of the child restraint back support. It is common practice to use an infant restraint for a newborn until it is outgrown by weight or seated height. For a product with a 9 or 10 kg (20 or 22 lb) weight limit, this means that most children would outgrow the device within the first year and should then be moved into a convertible child restraint used rear-facing.

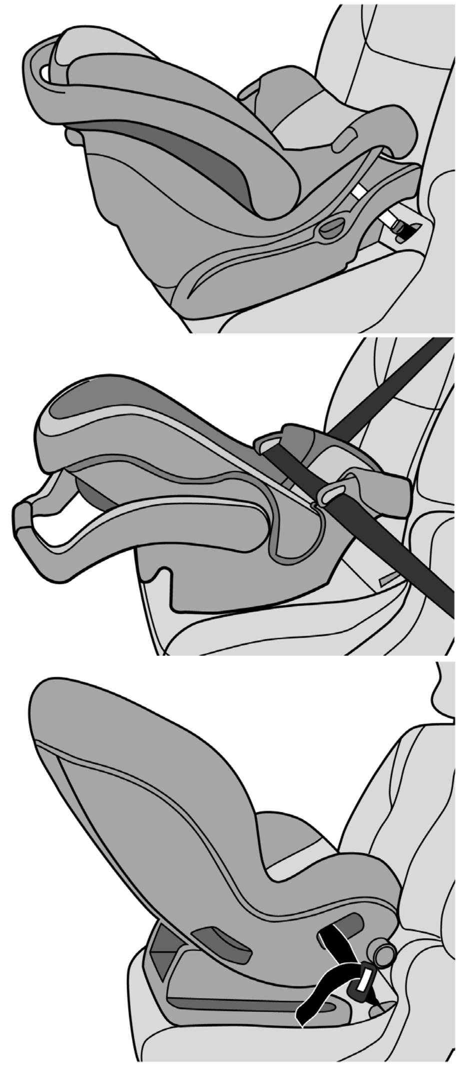

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Figure 5. Infant seat with base installed with LATCH (top); infant seat without base installed with belt (center); rear-facing convertible installed with LATCH (bottom).

Rear-facing restraints use an internal harness to secure the child into the shell. In a frontal impact, the restraint forces occur where the back of the child meets the restraint so that the restraining load is distributed across the entire back and head of the infant.

CHILD RESTRAINTS ON AMBULANCES

Ambulances pose special challenges for correct child restraint installation. Often there are no forward-facing vehicle seats within the transport cabin where a child restraint can be installed per the manufacturer's instructions. If the child needing transport is uninjured, the best practice approach would be to call for a conventional passenger vehicle with an appropriate child restraint to transport the child. If the child is a patient who requires care during transport, methods have been proposed for securing certain types of child restraints to the patient gurney (Bull et al. 2001). Some ambulances are equipped with captain's seats that have built-in child restraint systems.

The infant's head is well supported in this mode, and the movement of the head and neck happen in unison with the torso during a crash to eliminate severe tension and flexion forces on the neck that can occur with forward-facing occupants. Figure 6 shows the difference in kinematics between the same child restraint used rear-facing and forward-facing in a simulated frontal impact. Peak axial neck forces are four times higher in the forward-restraint compared to the rear-facing restraint.

Figure 6. During a frontal crash simulation (times 0, 60 ms, 90 ms), the back of a rear-facing restraint (farther from camera), supports the head and back of the child. In the forward-facing child restraint (closer to camera), the head is pulled away from the restrained torso.

Using a rear-facing infant restraint facing forward can result in dangerous loading and possible ejection because the belt path has not been designed for loading in this mode. Similar consequences could occur if a convertible restraint is installed rear-facing using the belt path for forward-facing (or vice versa). Restraining an infant or toddler forward-facing too early increases the risk of injury to the spinal cord as the child's disproportionately large/heavy head is stopped from forward motion by a tension load applied in the cervical spine.

Regulatory tests differ globally with regard to the extended rear-facing position. In Europe, dynamic tests for both frontal and rear impacts (R44/04) require additional attachment and stabilization elements to conform to the requirements. Swedish rear-facing child restraint designs differ from US products, in that they often use a support leg (figure 7) and strap attachment to the front seat or are placed in the front seat against the instrument panel with the airbag deactivated to limit forward rotation of taller or heavier children. These extra requirements are less known in EU countries outside Sweden, which may lead to a higher risk of incorrect installation. In addition, these seats are approved for use in specific vehicles, not across all models.

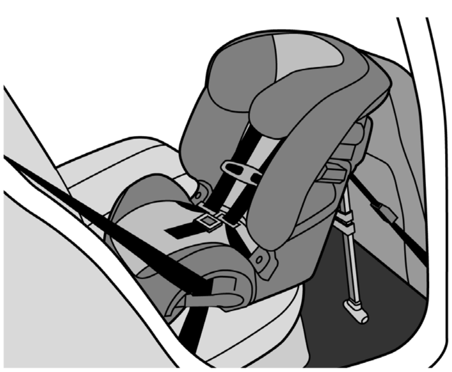
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Figure 7. European child restraint with support leg.

Rear-facing restraint recline angle

The angle of installation is one of the most critical factors for correct restraint of children riding rear-facing. If the restraint is too upright, newborn infants may not be able to breathe because their heads drop forward during travel. If the restraint is too reclined/flat, the child will not be effectively restrained by the back of the child restraint. Ensuring that the child's head is in contact with the child restraint back support is also best for crash protection.

Focusing on crash protection, if the back support angle is more reclined than 45°, the reaction force to restrain the child in a frontal crash starts to be exceeded by the force projecting the baby upwards along the seatback and toward the front of the vehicle. As the child grows, gains weight, and can hold its head erect, a more upright restraint angle would provide better crash protection (figure 8).

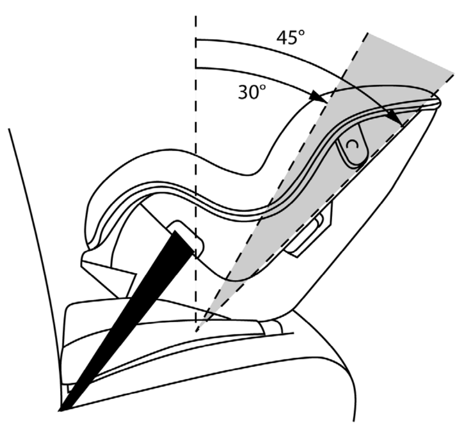

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Figure 8. Back angles for optimal protection. A more upright, 30° angle is more protective for older children in a crash while younger infants and those without good head control need a more reclined support angle of 45°.

For the youngest infants, providing the best crash protection must be balanced with providing an angle that prevents the head from flopping over and potentially pinching off the airway. A back support angle of 45° from vertical is considered the maximum angle that can achieve these two aims. To

CHILDREN WITH SPECIAL NEEDS

Children with special medical needs also require effective occupant protection. The same general occupant protection principles apply, such as rear-facing as long as possible, tight installation of the child restraint, and snug harness adjustment. Given the needs of these children, however, sometimes their occupant protection system must be different or include additional postural support elements. Car beds are one example, but there are other systems to address most of the commonly encountered healthcare issues, including children in hip and body casts, those with tracheotomies or muscle tone abnormalities, and those who use wheelchairs for ambulation. A national curriculum titled "Safe Travel for All Children: Transporting Children with Special Health Care Needs," ***www. preventinjury.org*** and the American Academy of Pediatrics (1999) offer additional information.

For children who use wheelchairs and cannot transfer to a child restraint, the best practice is to use a wheelchair that meets a voluntary crashworthiness standard (RESNA WC19), which means it is designed to perform as a motor vehicle seat. The wheelchair is attached to the vehicle with a crash tested securement system, most often a four-point tiedown that complies with RESNA WC18. The child in the wheelchair must be provided with a crashworthy belt system that is properly fitted to their body. Most belts attached to the wheelchair are meant for postural positioning and may not protect a child during a crash. For more information about wheelchair transportation safety, see ***www.travelsafer.org*** or ***www.rercwts.org.***

account for the differences in vehicle seat angle, child restraint manufacturers often provide a means to indicate and adjust the installation angle. At least one major child restraint manufacturer sets its target angle at 35° from vertical through the use of a visual indicator, while others specify angles closer to 45°. Unfortunately, indicators provided on rear-facing child restraints are primarily based on the angle where the restraint performs best in regulatory testing. Manufacturers may not fully consider that the angle providing the best orientation for a newborn may not be the best choice for a larger toddler. If the installation angle required by child restraint instructions places a newborn too upright, either a different rear-facing child restraint or a car bed should be used.

If a rear-facing restraint is installed in a rear seat with its back initially against the seat ahead, this will help limit rotation during a crash and provide improved protection, partly because the child restraint will not suddenly strike the seatback as it would if there were an initial gap (Tylko 2011, Sherwood et al. 2005). However, some child restraint manufacturers prohibit contact with the front seat because of concerns about adverse interaction between the child restraint and front seatback in a rear impact. In some vehicles with advanced airbags, vehicle manufacturers also prohibit contact between a rear-facing child restraint and the right-front passenger seat because it could interfere with occupant sensing systems.

Tethering rear-facing

Following practices common in Australia and Scandinavia, some rear-facing child restraints in the United States provide the option to use a tether to help secure the child restraint to the vehicle, although all rear-facing child restraints sold in the United States need to meet the federal regulation without a tether. FMVSS 213 does not include any testing of a rear-facing child restraint with a tether, nor does FMVSS 225 cover tether anchors that may need to be located forward and below a vehicle seating position for use with a rear-facing child restraint.

The Australian tethering method, shown in figure 9 left, routes the tether rearward, towards the back of the vehicle, to the standard tether anchorage used for forward-facing installations. This tethering more effectively limits forward rotation of the restraint in a crash, minimizes movement into the front seat, and allows the child to better ride down the crash with the vehicle. The traditional Swedish method, shown in figure 9 right, routes the tether down and forward to a point on the floor in front of the vehicle seat. This approach helps adjust the initial restraint angle and limits rotation towards the rear of the vehicle on rebound (Sherwood et al. 2005).

In a laboratory study comparing the methods of rear-facing tethering, any type of rear-facing configuration (no tether, Australian tether, or Swedish tether) provided superior protection compared to forward-facing restraint with tether. Among rear-facing tethering options, the Australian tethering method produced the lowest accelerations and excursion to the dummy head and chest among the methods evaluated. None of the tethering methods produced potentially injurious neck loads, based on the neck loading levels established in FMVSS 208, during the rear impact test events (Manary et al. 2006).

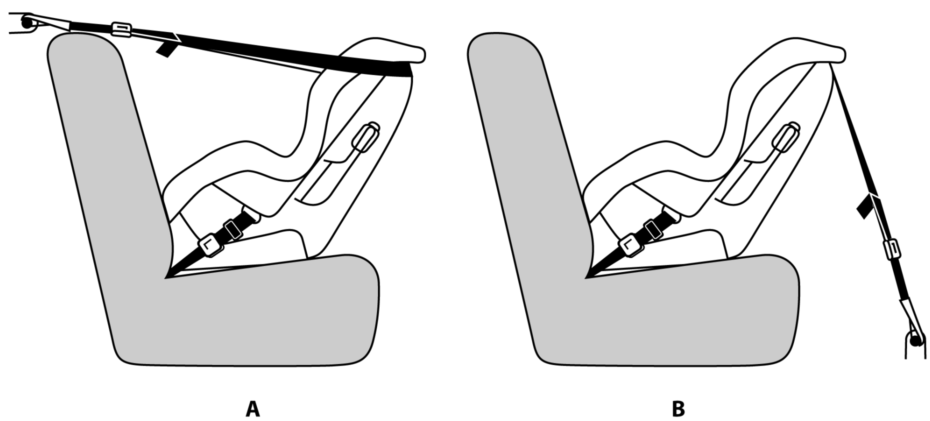

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Figure 9. Tethering rear-facing child restraints: Australian method (left) and Swedish method (right).

Rear-facing restraints in side impacts and other impact directions

As in frontal impacts, the most important priority for reducing injury in side impact is to minimize or eliminate the head strike. If the child's head contacts something, it should be a surface designed to absorb energy and limit injury. A typical rear-facing restraint will rotate toward the struck side of the vehicle more than a forward-facing restraint simply because of the increased distance between the combined center of mass of the occupied restraint and the belt path. Despite this greater motion toward the intrusion, rear-facing child restraints are over five times better at preventing injury in side impacts than forward-facing child restraints (Henary et al. 2007).

Most side impacts also have a frontal deceleration component so the occupant usually moves toward the front and side of the vehicle simultaneously. When this happens, the head of the child in a rear-facing restraint will be directed further within the protection offered by the side wings of the restraint. This differs from a forward-facing child restraint, where the child's head tends to move forward and around the sidewings and be more vulnerable to injury from the intruding vehicle or door structure. Several laboratory studies have demonstrated that a more rigid installation between the child restraint and vehicle, such as that provided by rigid LATCH attachments, also works better to keep any child restraint in position and prevent the head from contacting vehicle interior components (Klinich et al. 2005).

In rear-end and rollover crashes, the shoulder straps act to contain the child within the rear-facing restraint, which may rotate up against the vehicle seatback. This motion was originally touted as a benefit by the early designers to protect the infant from flying debris (Feles 1970). Since most rear-facing restraints are now larger and taller, this gives them greater potential to allow contact between the child's head and interior vehicle components in a rear impact or rollover. However, injuries from this mechanism have not been documented in the field.

Harnesses and fit

Most rear-facing child restraints are now equipped with a five-point harness, although the original designs for rear-facing infant restraints were usually equipped with a three-point harness that did not include pelvic straps. Premature and newborn infants may be so small that many rear-facing restraints seem too big. Manufacturers have added lower shoulder harness positions and greater harness adjustability to improve the fit for tiny infants. Some child restraints come with padded inserts that position the infant's body for improved harness fit and offer lateral support, but are removed for use with older children. Padding that pushes the infant's head toward its chest should not be used. If the infant's head or body needs lateral support beyond that provided by the child restraint, 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 (AAP 2011a). Supplemental thick, soft padding, which has not been provided by the child restraint manufacturer, should not 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 sliding upward/forward toward the front of the vehicle and increasing the risk of occupant ejection.

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In a rear-facing restraint, shoulder straps should be routed to restraint slots that are at or below the shoulders of the child. If shoulder straps are positioned above the shoulders of a child in a rear-facing restraint, the child can slide up the seatback during impact so the head is beyond the top of the restraint, increasing risk of injury from head contact. Smaller babies' heads may not reach the top of the restraint, but they could experience higher loading through the shoulders when stopped against the shoulder straps. Loose harnesses increase the chance of ejection and lead to increased loads once the child begins loading the harness. Use of a chest clip helps keep the harness positioned on the shoulders but cannot compensate for a loose harness during a crash.

Rear-facing restraints and frontal airbags

Frontal impact airbags and rear-facing child restraints do not mix. Even with advanced airbag systems, rear-facing restraints should never be installed in the right-front passenger seating positions. Installing any type of rear-facing child restraint in a seating position with a frontal impact airbag carries a high risk of injury or death during a crash. Frontal impact passenger 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 hardware. When current airbags deploy in a crash, whether severe or moderate, they emerge in a small folded package at very high speed—as much as 300 km/h (186 mi/h). If an airbag hits the back of a rear-facing child restraint 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, (Weber 1993, Klinich et al. 2002) with 50 g considered the threshold for injury for children represented by a 6-month size dummy (Klinich et al. 2002, Melvin 1995). The sequence shown in figure 10 shows the initial impact of the airbag into a rear-facing child restraint, which laboratory measurements have demonstrated is the cause of fatal head injury in crashes. Although the airbag could also propel the infant and rear-facing child restraint into the vehicle seatback, the head injury from the airbag would already have occurred with the initial airbag contact into the back of the restraint.

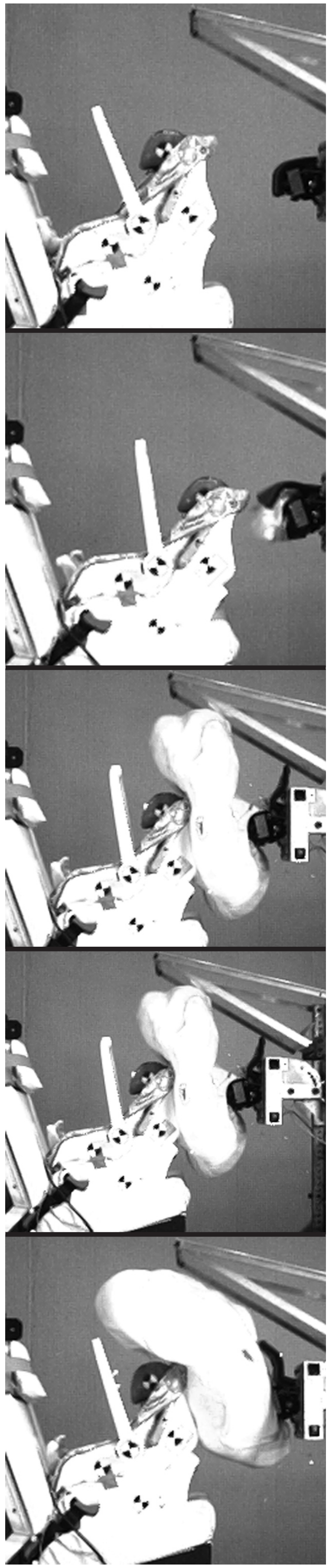

Figure 10. Laboratory reconstruction of airbag deployment into rear-facing infant restraint that resulted in infant fatality. T0, 95, 100, 110, 120 ms

Car Bed Restraints

For infants with documented breathing problems or who cannot otherwise tolerate the semireclined positions, a car bed is a suitable alternative to a rear-facing infant restraint. The three models currently available in the United States accommodate infants ranging from birth weight to 15 kg (35 lb). In a car-bed restraint (figure 11), the infant lies flat, preferably on its back. The car 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). Depending on the car bed model, the infant can be placed on its back, which is preferred, on the stomach, or on the side. In a frontal crash, the occupant restraint forces are distributed along the entire length 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 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 significant intrusion (Weber 1990). Field data from the United States and other countries are sparse but have not revealed any protection deficiencies with this configuration.

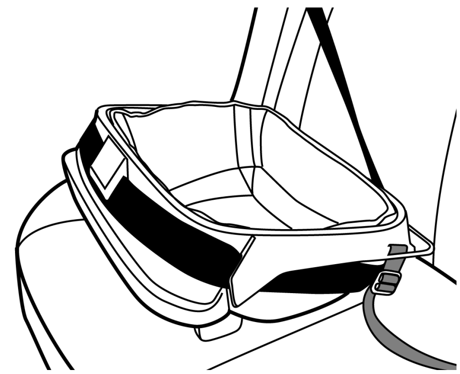

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Figure 11. Car bed restraint installed with seatbelt. This model is equipped with a strap (gray) to help keep the seatbelt in place.

The American Academy of Pediatrics prefers the use of the semireclined, rear-facing position, but recognizes the issues of positional apnea (Degrazia et al. 2010, Nagase et al. 2002). It currently recommends that all infants born at less than 37 weeks gestation be monitored in a semiup–right position prior to discharge from the hospital to detect possible apnea, bradycardia, or oxygen desaturation (AAP 1999b).

Forward-Facing Child Restraints

Types of forward-facing child restraints

There are two main types of harnessed restraint systems that face the child toward the front of the vehicle. One is a convertible child restraint used forward-facing (figure 12 top). The other is referred to as a combination child restraint. Combination seats (figure 12 bottom) are initially used with a harness; the harness is then removed to convert the restraint into a belt-positioning booster. In addition, a few products have been designed for only forward-facing harnessed use.

Historically, forward-facing restraints were made for use with a harness for a child up to only 18 kg (40 lb). However, many current models now accommodate children up to 30 to 40 kg (65 to 90 lb) using the harness system. These higher-weight harness systems may include higher slots for routing the harness straps at or above the shoulders of a larger child, as well as higher seatbacks that need to extend to a height at or above the child's ears to protect against rearward bending of the neck. Both forward-facing child restraint types are installed with a seat-belt or LATCH lower attachments. In addition, all current forward-facing child restraints recommend use of the tether with any installation to reduce head excursion during a crash, and some manufacturers require tether use for the heavier children.

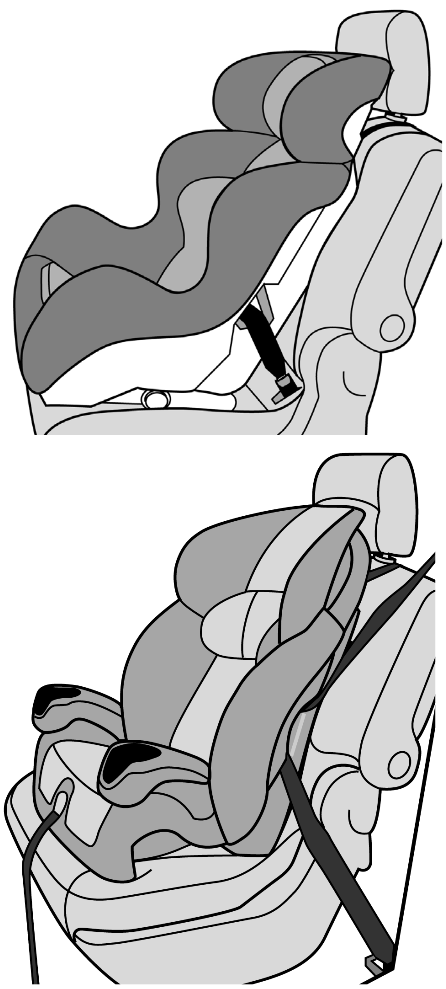

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Figure 12. Convertible child restraint installed forward-facing with LATCH (top) and combination restraint used with harness and installed with seatbelt (bottom).

Harnesses and shields

The ability of a forward-facing restraint to provide effective protection depends on harness fit and snugness as well as tight coupling to the vehicle. Current child restraints are equipped with a five-point harness, although a few child restraint models still secure the child with a tray shield and shoulder straps (figure 13). The five-point harness styles are generally preferred because they permit a snug fit around the child. However, the tray shield style may be helpful for caregivers with a lack of dexterity who may be unable to appropriately buckle the harness.

The five-point strap harness arrangement is generally styled after military and racing harnesses. Straps go over each shoulder and the lower portions form a lap belt across the thighs as two latchplates connect to a central buckle. The buckle, which is on the end of the crotch strap, is routed between the child's legs, and serves to hold the lap straps down on top of the thighs, so it should be as short as possible. Most current products have a single pull harness adjustment strap or knob that makes it easier to tighten the harness so it is snug around the child compared with earlier designs. Loose harness straps will allow the child greater movement toward vehicle

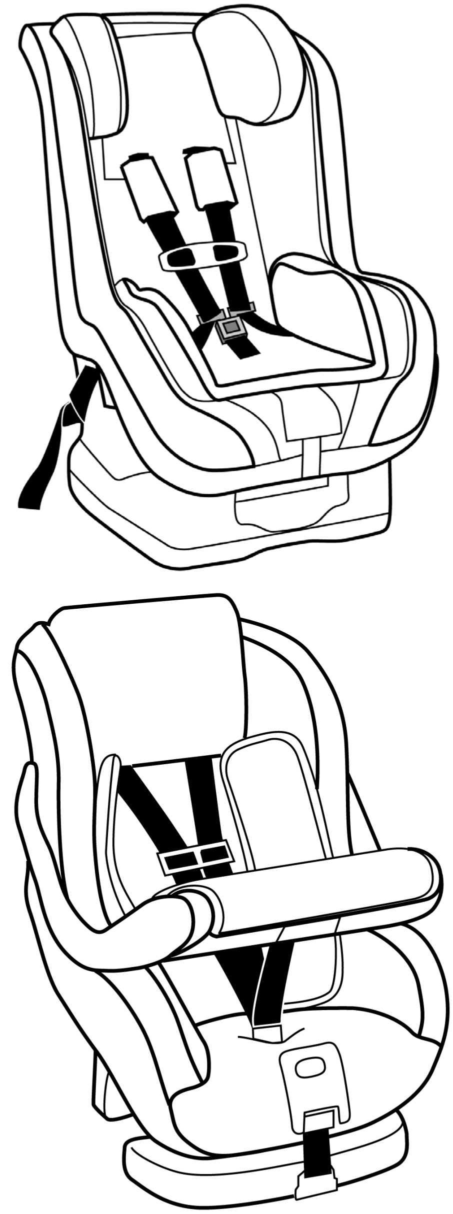

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Figure 13. Child restraints that secure child using harnesses (top) or tray shield (bottom).

interior surfaces and generate higher loads on the child when the system finally pulls up tight to resist movement. Failure to buckle the harness or route the harness properly could result in ejection or serious injury to thoracic and abdominal organs.

The shoulder straps of the forward-facing harness should be routed to shell slots located at or above the child's shoulders. For forward-facing restraints, erroneously placing the harness shoulder straps in slots located below the shoulders has the consequence of introducing slack in the harness, as the child's torso can move forward before the straps begin restraining the shoulder and also creating increased compression loading in the spinal cord. Using harness slots not specified for forward-facing use may lead to child restraint shell failure, as some lower slots on convertible restraints are not reinforced for loading in frontal mode.

Neck injury in forward-facing child restraints

A transition to a forward-facing child restraint should not be celebrated but delayed as long as possible. A child "graduating" to facing forward actually experiences a decrease in protection from riding rear-facing, which is the safest mode of restraint available for children. While education about the benefits of extended rear-facing restraint use has become more widespread, there are still misconceptions even within the medical community about the appropriate timing for the transition to forward-facing restraints.

A forward-facing child with shoulders held back by a harness during a significant frontal impact can experience severe loading of the cervical spine as the mass of head extends forward and is stopped by the neck. In a 48 km/h (30 mph) crash with a 25-g passenger compartment deceleration, for instance, the head of a forward-facing adult or child may experience as much as 60 or 70 g, because the occupant's head stops later in the event and more abruptly than the vehicle's floor pan. Even the strong neck muscles of military volunteers make little difference in outcomes in such an environment. Rather it is the skeletal strength 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 (Huelke et al. 1992, Stalnaker 1993). Adult cervical spines can withstand severe tensile forces associated with decelerations up to 100 g (McElhaney and Myers 1993) and failure is nearly always associated with vertebral 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 (Kumaresan et al. 1998, Myers and Winkelstein 1995). This combination allows the soft vertebral elements to deform and separate under crash conditions, leaving the spinal cord as the only fragile link between the head and the torso. This flexibility allows children to sustain spinal cord injury without fracture to the vertebrae, which is extremely rare in adults. Mathematical models of pediatric spines (age 1, 3, and 6 years) subjected to various types of loading indicate that, compared to adult spines, the anatomical and material properties of immature spinal elements make them much more flexible than would be predicted by relative size alone (Kumaresan et al. 2000). Crash experience has shown that a young child's skull can be separated from its spine by the force of a crash (Fuchs et al. 1989), the spinal cord can be severed (Hoy and Cole 1993) or the child may live but suffer paraplegia or quadriplegia due to the stretched and damaged cord (Langweider et al. 1990, Trosseille and Tarriere 1993, Weber et al. 1993). The risk of spinal cord injury in children increases with crash severity and decreases with age (Stalnaker 1993). Although serious cervical spine injuries are rare among properly restrained forward-facing children, because of the potentially severe consequences, best practice dictates the relatively simple countermeasure of restraining smaller children rear-facing as long as possible (figure 6).

Tethers and crash performance

Top tethers should always be used with forward-facing child restraints to anchor the top of the child restraint to the vehicle and reduce forward rotation of the child restraint in a frontal crash (Brown et al. 1995, Legault et al. 1997). Figure 14 shows a crash sequence comparing the performance of the same model of child restraint tethered (closer to camera) and untethered (farther from camera) in a 48 km/h crash test with a 3-year-old sized dummy. The dummy in the child restraint attached with a tether experiences about 150 mm (6 inches) less forward movement of the head.

Reduced head excursion means that in an actual crash, a child would be less likely to experience head contact with the interior. Among children injured in forward-facing child restraints, head and facial trauma predominate (Nance et al. 2010, Arbogast et al. 2002). Head contact while the neck is in tension 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 (Stalnaker 1993, McElhaney and Myers 1993). Reduction of head excursion and elimination of head contact are therefore as

Figure 14. Crash sequence showing reduced head excursion of 15 cm (6 inches) with tether use (near side) versus untethered (far side) child restraint.

important for avoiding neck injury as they are for reducing head and facial injury in children. Top tethers can also partially compensate for suboptimal installation tightness using the LATCH strap or seatbelt by improving coupling between the child restraint and vehicle. However, the tether must be tight, as the improvement offered by a top tether is also degraded by slack. Failure to use the tether is a common misuse of forward-facing child restraints, occurring in half of forward-facing installations (Jermakian and Wells 2010).

Forward-facing child restraints and side-impact protection

Although frontal impacts are the most common type of crash, side impacts are more likely to result in serious and fatal injuries (Viano and Parenteau, 2008). Rear-facing restraints are so much more effective in side impact than forward-facing restraints that the transition to forward-facing should be delayed as long as possible (Henary et al. 2007). Injuries to the head and face are most common in side impacts, so restraints with larger padded sidewings may offer some protection (Orzechowski et al. 2003, Arbogast et al. 2010, Maltese et al. 2007). Laboratory testing of child restraints with different types of LATCH hardware indicate that rigid LATCH offers improved protection by limiting motion towards the struck side of the vehicle (Klinich et al. 2005). Tests using a tether and forward-facing child restraints showed a negligible effect on lateral head excursion compared to those without a tether (Klinich et al. 2005). Testing with additional energy absorbing elements (side air cushion) showed a significant improvement over a baseline design (Bendjallal et al. 2011)

Forward-facing child restraints and airbags

Although all children are safer in the rear seat, if all of the rear seating positions are occupied, a child in a forward-facing harnessed child restraint would usually be the best candidate to ride in the right-front passenger position. A child well secured in a properly installed forward-facing child restraint should be at no greater risk of injury from airbag deployment than a belted adult in the same seating position. The use of a harness around the child reduces the likelihood of being out-of-position and thus close to an airbag than an older child in a booster seat or seatbelt. Of the children sustaining fatal injuries from deploying airbags, none was seated in a properly used forward-facing child restraint (NHTSA 2009). If a forward-facing child restraint needs to be installed in the right-front position, the vehicle seat should be positioned as far rearward as possible, while still allowing for accommodation of the rear seat occupant.

CHILD BOOSTERS AND BELTS

Boosters

Recommended use and effectiveness

When a child no longer fits in a harnessed restraint, the next step is a belt-positioning booster seat used with a vehicle lap-and-shoulder belt. As with the transition from a rearward-to forward-facing child restraint, this step to a booster actually decreases the level of occupant protection offered and should be delayed as long as possible. Boosters do not restrain children. Instead, they reposition the child and redirect vehicle belts (designed to fit adults) to be routed appropriately relative to the child's body. Both the NHTSA and the AAP recommend that children use booster seats until they fit in seat belts alone, which means most children should be using boosters through age 8–12 years (AAP 2011). Booster seat use among 4-to-8 year olds has risen to 63% in 2007 from 15% in 2000, largely as a result of state laws requiring their use, public education programs, and more available booster products (NHTSA 2009).

Children aged 4–8 using boosters are 45% less likely to sustain injury in a crash compared to children using seatbelts alone (Arbogast et al. 2009, Durbin et al. 2003). Boosters are particularly effective at reducing abdominal injury: children using belts alone are 8 times more likely to sustain abdomen injury than children using a belt-positioning booster with the vehicle seatbelt (Jermakian et al. 2007). Figure 15 illustrates consequences from simulated frontal crashes for a 6YO with and without a booster. With a booster, the lap belt loads and restrains the strong bones of the pelvis. Without a booster, the dummy slides under the lap belt, so the belt loads the abdomen, vulnerable internal organs, and spine instead of the pelvis. This event is often called "submarining" under the lap belt.

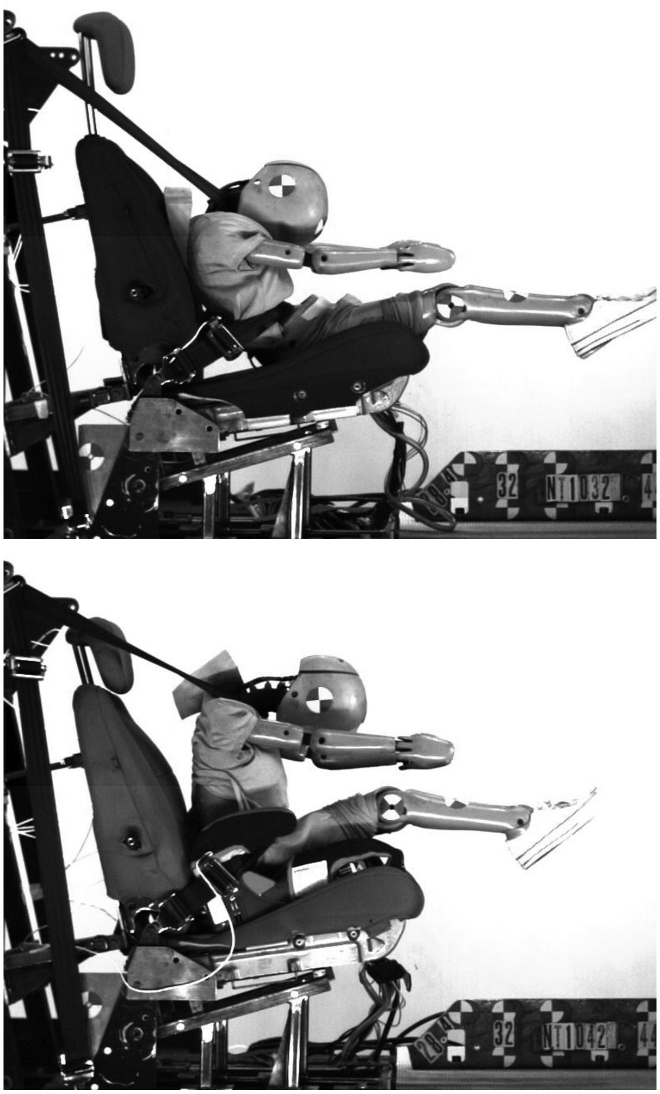

Figure 15. Without a booster (top), seatbelt loads the abdomen.

How boosters improve belt fit

Over the past decade, evaluations with child volunteers have examined how different booster seat designs improve belt fit using realistic vehicle and seat belt geometries (Reed et al. 2008, 2009, Bilston and Sagar 2007). This research has led to a better understanding of how booster seats improve belt fit.

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Figure 16. A 7YO child seated on the vehicle seat (top) has the shoulder belt against the neck and the lap belt over the abdomen. Use of a booster seat (bottom) shifts the child relative to the belts so they fit to provide better protection.

The first thing that any booster seat does is raise the child up relative to the vehicle belt as shown in figure 16. Even if the booster does not have a back, the elevation helps position the shoulder belt away from the neck so it is more comfortable and restrains the child through the shoulder structure in a crash. When considering the lap belt, shifting the child upwards relative to where the lap belt is anchored increases

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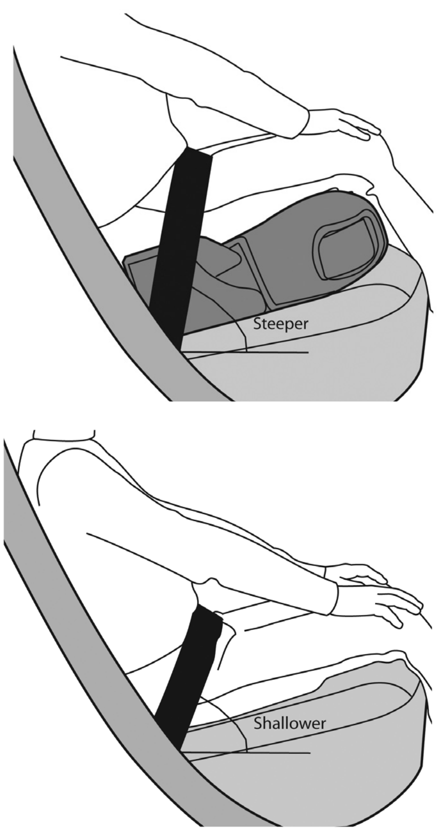

Figure 17. Lap belt angle increases with booster use (even without lap belt guides), allowing better engagement of the lap belt with the pelvis.

the lap belt angle, pictured in figure 17. The steeper lap belt angle is better because it makes it harder for the child to slide under the lap belt in a crash.

The second way boosters work is by improving occupant posture. Several studies have documented that the rear seats of most vehicles are too deep for children to sit upright with their knees bending over the edge of the seat and with their back fully supported for comfort (Huang and Reed 2006, Klinich et al. 1994, Bilston and Sagar 2007). Consequently, children scoot forward so their legs can bend over the front of the seat in a comfortable position, as shown in figure 18 (top). Using a booster seat provides them with a cushion length that is more compatible with their upper leg length (figure 18 center) and provides an upright posture similar to that of an older child (figure 18 bottom).

The third way boosters work is by routing the seatbelt using lap-and-shoulder belt guides. The lap belt should be positioned so it is completely below the top of the pelvis, which reduces the likelihood that it will slide up over the abdomen in a crash. Well-designed lap belt guides help position the belt so it touches the top of the child's thighs, and resists upward movement of the belt in a crash. Well-designed shoulder belt guides position the shoulder belt midway between the neck and arm, not at the edge of the shoulder or rubbing the neck (figure 19). Neck injury from the shoulder belt contacting the neck has not been identified as a problem in the field. The biggest danger from the shoulder belt touching the neck is that it could cause the child to put the shoulder belt under the arm or behind the back. Either misuse virtually eliminates upper-body restraint that the properly placed shoulder belt would provide. In one study of booster misuse, 20% of children improperly placed the shoulder belt behind the back or under the arm (O'Neil et al. 2009). Poorly designed shoulder belt guides can pull the shoulder belt too far off the child's shoulder, or allow slack to develop after a child leans forward because it interferes with easy retraction of the shoulder belt.

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Figure 18. When seated on the vehicle seat, a 7YO child tends to slouch forward (top). A booster seat (middle) lets the 7YO child sit upright more comfortably and obtain a posture similar to that achieved by a taller child on the vehicle seat (bottom).

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Figure 19. Shoulder belt guide positions the shoulder belt closer to the child.

BUILT-IN CHILD RESTRAINTS

Over the years, several vehicle manufacturers have offered the option of built-in or integrated child restraints in their vehicle seats. While harnessed, forward-facing, built-in restraints have been produced in the past, today only built-in booster seats that pop up from the vehicle seat cushion (Jakobssen et al. 2007) are currently available as an option on a few vehicle models (see below). The advantage of a built-in child restraint is that it links the child directly to the vehicle and eliminates errors in installing the child restraint to the vehicle. Arguments against built-in harnessed restraints are that rear-facing models have not been offered, a child could only use a harnessed forward-facing restraint for up to four years, and the restraint could not be transferred for use in other vehicles. A built-in booster may prove to be more popular, as a child could potentially use it for four-to-eight years, and recent commercial versions allow the children to enjoy the comfort and safety features of the vehicle seat back. In addition, older children who should use a booster may be less likely to resist extended use if it is part of the vehicle seat.

Built-in belt-positioning booster that stows in the vehicle seat cushion.

Changes in booster use and design

There are currently four styles of belt-positioning boosters: backless boosters, removable-back boosters, highback boosters, (figure 20) and built-in boosters. Backless boosters can be used when the vehicle seat and head restraint support the child's head to the tops of the ears. Some backless boosters have an optional shoulder belt guide on a strap to adjust the shoulder belt position if necessary. With removable-back boosters, the lower portion can be used alone or with a booster seat-back. Highback boosters are usually constructed as combination seats that can be converted from harnessed restraints. A few vehicle manufacturers provide integrated booster seats that fold out or pop up from the vehicle seat (Jakobssen et al. 2007).

Results from field data show that there was no difference in injury risk between boosters with and without backs (Arbogast et al. 2009). While boosters with backs have features that could improve protection in side impacts and may keep children in a better position laterally relative to the vehicle belt system particularly when sleeping, backless boosters allow children to sit further rearward, which effectively reduces head excursion. From a practical standpoint, backless boosters and built-in boosters allow children to enjoy the comfort features of a vehicle seatback, and since they are not as visible from outside the vehicle, they may be preferred by older children reluctant to use a booster. In addition, one study of children in boosters showed that children seated in products with large side wings for improved side-impact protection leaned forward 55% of the time compared to 25% of the time for children seated in boosters with less prominent side wings (Andersson et al. 2010).

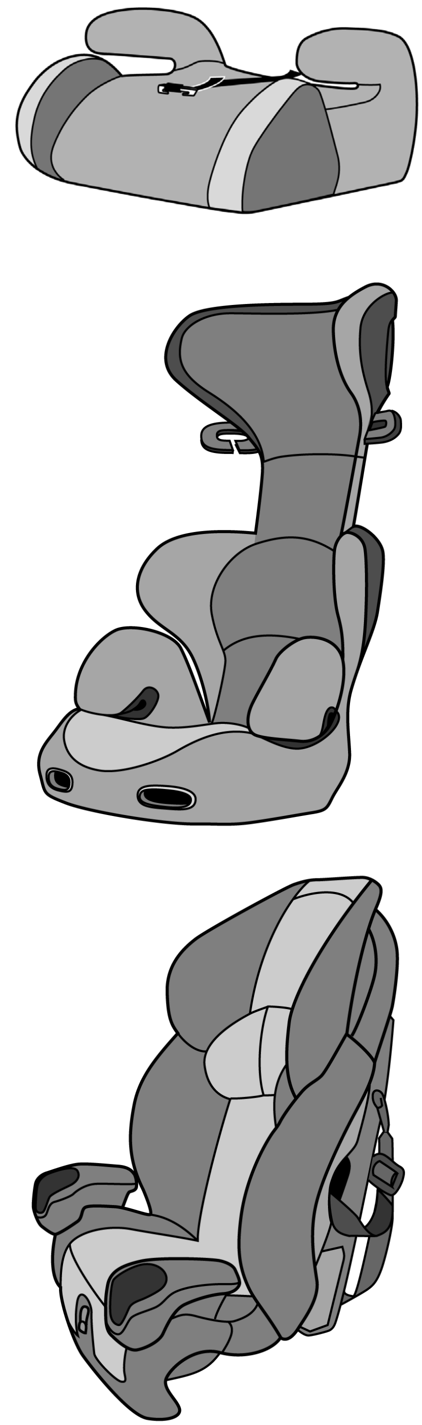

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Figure 20. Backless booster (top), removable back booster (center) and high-back booster (bottom).

While many boosters with backs have shoulder-belt positioning devices that improve static belt fit, research has indicated that the devices are not that effective at keeping the shoulder belt position in place during dynamic loading (Tylko and Dalmotas 2005, Klinich et al. 2008). Based on these results, it is best to choose a booster and vehicle seating position that achieves good shoulder belt fit with minimal redirection of the shoulder belt by the booster. As shown in figure 21, it would be better to have a straighter line path between the D-ring and shoulder (top) than one substantially rerouted by the booster (bottom).

Booster seats must meet dynamic FMVSS 213 requirements using a test bench equipped with only one defined lap-and-shoulder belt geometry. However, lap-and-shoulder belt geometry in the rear seats of vehicles can vary widely. Some boosters may not be able to route belts with a particular geometry so the belt will fit well on a particular size of child. In practice, the best approach is to evaluate the belt fit with the specific child, vehicle seating position and booster seat. Several studies have documented that the effectiveness of the booster seat routing features varies with vehicle belt geometry (McDougall 2011, Brown et al. 2009). The Insurance Institute for Highway Safety has developed a rating system for assessing the belt fit across a range of vehicle belt geometries (Reed et al. 2009). However, given the effectiveness of booster seats demonstrated in field data and the many factors that allow boosters to improve belt fit, any booster is likely to provide better seat belt fit for a child than the no booster condition.

Some children making a transition from a harnessed restraint to a belt-positioning booster often have trouble staying correctly positioned for the entire trip, as the shoulder belt's emergency locking retractor comfort features allow considerable movement unless activated and locked during a crash. If a child will not stay in position, some have suggested locking the shoulder belt with its switchable retractor (if available). However, this does not allow enough forward motion of the torso, which prevents submarining under the lap belt in the absence of a crotch strap. A child who is not developmentally ready to sit still in a booster would be better protected in a high-weight harness child restraint.

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Figure 21. A booster in a seating position with a relatively straight path between the D-ring and shoulder (top) is preferred to one requiring more redirection of the shoulder belt (bottom).

Securing a booster in a vehicle

When first introduced, belt-positioning booster seats were not secured to the vehicle, as their purpose is to position a child relative to the vehicle seat belt, but not to actually provide restraint. However, the lack of attachments sometimes allowed the boosters and child to shift during driving and caused instability during loading/unloading. Since many caregivers do not fasten the seatbelt around the booster when unoccupied as directed, a loose booster could be a projectile in a crash.

There are some booster products designed to allow the booster to be secured to the lower anchorages and/or tether anchorages with the LATCH hardware. This is most common among boosters that convert from a harnessed restraint to a belt-positioning booster and thus have LATCH attachments. Some boosters also have rigid or flexible LATCH attachments solely to hold them in place (SafeRideNews 2011). This practice has not been universally adopted, because there are lingering concerns among some manufacturers that if the booster and seatbelt but not the child are attached to the vehicle, the child could slide forward on the booster and have a greater risk of injury than if the booster moved with the child. Testing results with boosters attached to vehicles have been mixed, with some tests showing improved kinematics using a LATCH-secured booster, and others showing less desirable kinematics (Tylko et al. 2005, Transport Canada 2011).

SHIELD BOOSTERS

Shield boosters, originally designed for use in seating positions with only a lap belt, are no longer sold in the United States. The greater availability of harnessed restraints accommodating children of higher weights, add-on harness systems, and the requirement to have lap-and-shoulder belts in all rear seating positions, all provide better options with superior torso restraint than that of a shield booster (Stalnaker 1993, Whitman et al. 1997, Marriner et al. 1995, Shelness and Jewett 1983).

Boosters and Lap Belts

Belt-positioning booster seats are not designed to work with lap-only belts, as they cannot pass FMVSS 213 head excursion requirements when used this way. While using a booster seat with a lap belt may reduce the likelihood of abdomen injury (Kirley et al. 2009), it has the potential to increase the likelihood of head injury, which should be considered higher priority because of the greater potential for serious long-term consequences. A booster positions a child's head higher, and with a highback booster, more forward than a child sitting directly on a vehicle seat. Without torso restraint provided by a shoulder belt, the head position of a child using a booster increases the risk of head contact compared to a child on a vehicle seat. 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 belt positioning booster.

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Seatbelts for Children

The term seatbelt refers to either a lap-and-shoulder combination or a lap belt alone. Although lap-and-shoulder belts have become standard equipment in current vehicles and seating positions, there are still many vehicles 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. However, if a more appropriate restraint system is unavailable, seatbelts provide some protection even for small children, and effectiveness rates for seatbelts are calculated for occupants age 5 and up to be near 50% in terms of reducing fatal injuries (Wiacek et al. 2011). Seatbelts are part of the 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 (Louman-Gardiner 2008, Gotschall et al. 1998, Meissner et al. 1994), which degrades their performance and increases the likelihood of submarining and belt-induced injury.

Child size and belt fit

Belt fit depends on the size and posture of the occupant, the size and shape of the vehicle seat, and the geometry and features of the belt system. A child who has good belt fit in one vehicle may not in another. Good fit of a lap belt is as low as possible on the pelvis, touching or flat across the tops of the thighs. A child can locate the top of his or her own pelvis by finding the bony points at the top front of the pelvis. A child's pelvis is generally shorter, less calcified and less prominent than that of an adult.

Therefore, it is critical that the lap belt should lie completely below these points to ensure that the lap belt can contact and restrain the pelvis during a crash (figure 22). The shoulder belt should lie flat on the shoulder about halfway between the neck and the arm and cross the chest at the middle of the sternum.

A common recommendation is that children should not use a seatbelt without a booster until they reach a standing height of 148 cm (58 in) and a clothed weight of 37 kg (81 lb) based on an early study of booster belt fit (Klinich et al. 1994). This size corresponds to a 90th percentile 9-year-old, a 50th percentile 11-year-old, and a 5th percentile 13-year-old. While a simple height, age or weight recommendation is convenient for educational or legislative purposes, several studies indicate that most children above this stature still experience better belt fit with a booster

To achieve the best seat belt fit, the child should be sitting fully upright with his/her pelvis as far back into the seat as possible, and preferably with his/her 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. Several studies have shown that children tend to move forward on the vehicle seat to allow their knees to bend comfortably over the front edge of the seat, causing the child to slouch. This rotates the pelvis rearward, making it more difficult for the lap belt to engage the pelvis, and can lead to the lap belt being positioned over the abdomen. If a child cannot achieve an upright, seated posture, or if the shoulder belt crosses the throat, the child needs to use a booster.

Shoulder belts that touch the side of the neck are not likely to cause injury unless they are very loose (Kortchinsky et al. 2008, Corben and Herbert 1981, Appleton 1983). However, discomfort from a shoulder belt against the neck tends to cause the child to put the shoulder belt under his or her outboard arm or behind the back. The shoulder belt should not be routed behind the child's back because it offers no torso restraint and tends to pull the lap portion of the belt upwards on the inboard side, both of which increase potential for injurious belt loading (Brown and Bilston 2007). Also, with most belt designs, routing behind the back eliminates the loading of the shoulder belt early in the crash sequence, which, on a properly worn belt, functions to snug the lap belt and, in some retractor designs, lock the belt. 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 (Gotschall et al. 1998, States et al. 1987).

It is possible for shoulder belt loading to cause thorax injury in severe crashes as it loads the child. To reduce likelihood of injury from belt loading, advanced seat belt features which have been implemented for front-row occupants are gradually being introduced in the rear seating positions. One of these features is a pretensioner, which removes slack from the seatbelt when a crash event is detected. Another feature is a belt load limiter, which allows the shoulder belt to spool out further once a particular load threshold is reached. An airbag mounted in the shoulder belt to provide better load distribution over the thorax has been introduced on rear-seat belts in some vehicles.

Vehicle manufacturers have also added seatbelt features to improve fit for various sizes of occupants. Many vehicles have an adjustable shoulder belt anchorage that can be raised or lowered to better route the belt over the occupant's shoulder. Some

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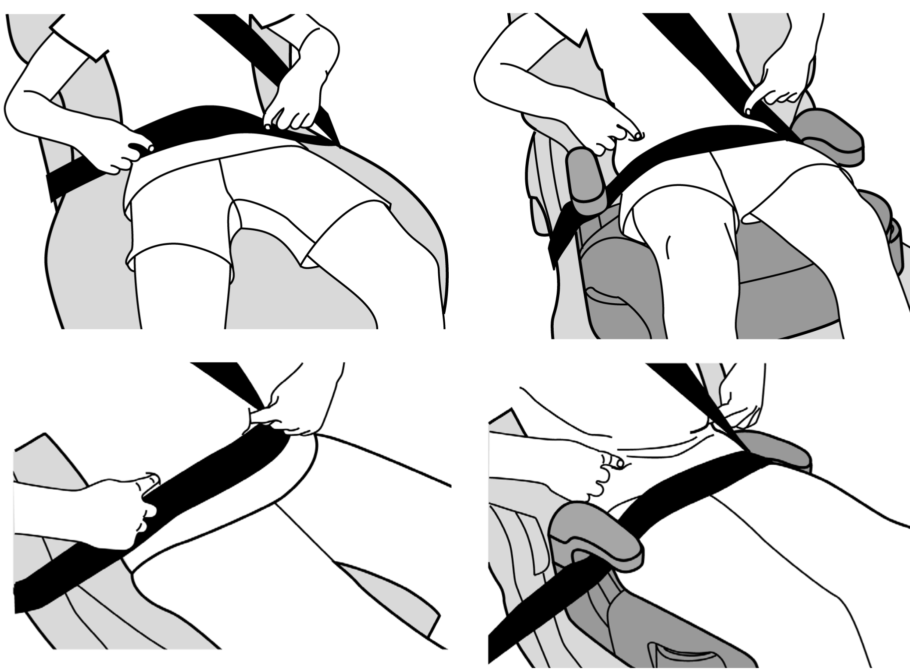


Figure 22. On a 7YO child seated on a vehicle seat (top left), the vehicle belt lies on the abdomen above the pelvis. When using a booster (top right), the lap belt lies below the top of the pelvis. For a 10YO child on the vehicle seat, the lap belt lies just below the pelvis (lower left), providing acceptable fit. Even so, the 10YO using the booster experiences much better fit over the hips (lower right).

have positioning guides or loops that can also help provide better fit for smaller occupants. However, these may not help fit problems with lap belts or vehicle seat cushions that are too long for a child to sit upright comfortably.

Shoulder belt positioners

Various unregulated devices have been marketed to move a shoulder belt away from a smaller occupant's neck. Most of these products pull the shoulder belt into position by anchoring a device to the lap belt, thereby pulling that portion of the belt upward and gaining shoulder belt fit at the expense of proper lap belt fit (Brown et al. 2010, Sullivan and Chambers 1994). Unlike a belt-positioning booster, shoulder belt positioners typically pull the lap belt up onto the abdomen as they pull the shoulder belt down and away from the neck. In addition, they do nothing to improve the posture and slouching of a child too small to fit in the vehicle seat. Because pediatric dummies cannot currently measure loading to the abdomen, evaluation of the potential negative effects of shoulder belt positioners cannot be quantified. These products may be packaged with misleading claims that they "meet all relevant standards" when none apply. Shoulder belt positioners should not be used in place of belt-positioning boosters, which are proven in the field to reduce injury, particularly to the abdomen.

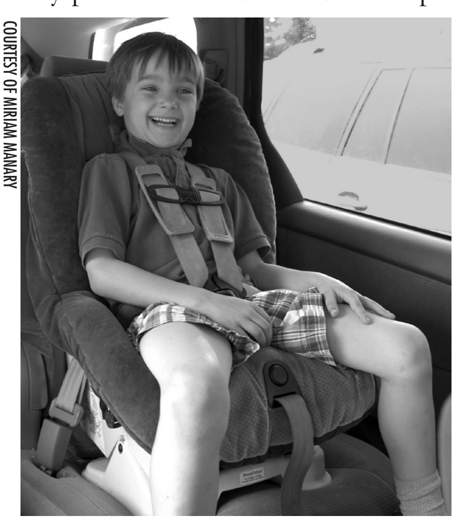
Lap versus lap-and-shoulder belts

Fortunately, the relatively recent requirement to provide lap-and-shoulder belts in all vehicle rear seating positions has reduced the need to use only lap belts to restrain occupants. The principles of restraint theory lead to the conclusion that lap-and-shoulder belts would be better for children, even if fit is not optimal, than a lap belt alone. Analysis of fatality data confirms that lap-and-shoulder belts are 15% more effective than lap belts alone. While lap-only belts reduce the risk of ejection and injury, they increase the risk of abdominal injuries; lap-and-shoulder belts reduce the risk of both head and abdominal injuries (Elliott et al. 2006, Mulpuri et al. 2007, Morgan 1999).

Lap-and-shoulder belts and airbags

Even with advanced airbags, which can sense and adjust deployment to the size and type of front passenger, parents are warned not to have children under age 13 ride in the front seat of a vehicle. Older vehicles such as small pickup trucks without advanced airbags may have on/off switches for frontal airbags.

In situations where a child must ride in the front seat with an active airbag, because no switch is available and the back seat is filled, a child in a seatbelt may be at greater risk of injury from the frontal airbag than a younger sibling restrained in a forward-facing child restraint. This is because the child using the lap-and-shoulder belt is able to lean forward in their shoulder belt or even put the belt behind the back. This behavior may place the child's head in the path of the deploying airbag or allow their upper body to be thrown forward during precrash braking.



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CHILD RESTRAINT TESTING

Test Procedures

FMVSS 213 Testing

Given the high level of occupant protection provided by current child restraints in all types of crashes, people are often surprised to find that the testing requirements as defined in the applicable federal rule, FMVSS 213, primarily focus on their performance in frontal crashes at one severity level (CFR, FMVSS 213). In addition, though vehicle seats, LATCH anchorage locations, and seatbelt geometry vary widely in vehicles, child restraints are tested on a generic, soft, flat, bench seat using either a single set of belt anchorages or LATCH anchorages. Child restraints are not crash tested in real vehicles, but tested using a sled that simulates the acceleration seen in a crash with a 30 mi/hr (48 km/hr) change in velocity. Sled tests are used because they are more repeatable and less expensive. At first glance, a 30-mi/hr (48 km/hr) test may not seem very severe, but 30 mi/hr (48 km/hr) refers to the change in velocity, not the velocity at the time of the crash, and the crash conditions used are more severe than 96% of actual frontal crashes in the United States.

When evaluating the dynamic safety performance of a child restraint, requirements vary with the type of restraint. For a car bed, the primary criterion is that the harness must keep the newborn size dummy in the restraint. For rear-facing restraints, a restraint will pass if the surface supporting the crash dummy's back does not rotate forward beyond an angle of 70°, the head and chest of the dummy stay in the restraint, and the acceleration characteristics for the dummy's head and chest do not exceed prescribed thresholds. For forward-facing restraints and booster seats, the dummy's head must not move forward past a point 720 mm (28.4 inches) from a seat reference point when tested with a tether or 813 mm (32 inches) when tested without a tether; in either condition, the knees must not pass a point 915 mm (36 inches) away. In addition, there are limits on head and chest acceleration-based measures. Unfortunately, better scores on the head injury criteria can usually be achieved by allowing more head excursion, although keeping the head from moving further forward corresponds to preventing the most common real-world head injury mechanism of the child's head striking something in the vehicle (Bohman et al. 2011). Other 213 requirements focus on webbing strength, width, and abrasion resistance, flammability of the components, buckle release characteristics, and padding requirements. Tests are also performed to determine whether the child would stay within the restraint when it is inverted.

FMVSS 225

Requirements for LATCH hardware in vehicles are specified in FMVSS 225 (CFR FMVSS 225). Most vehicles have the minimum required LATCH hardware where top tether anchorages are provided in three seating positions and lower anchorages are provided in two seating positions. The regulation defines zones for locating the lower and tether anchorages, as well as quasi-static (or slow loading) testing procedures for evaluating the strength of the lower and top tether anchorages. Other requirements for lower anchorages include specifications for the size and spacing of the anchor bars that comprise the lower anchorages, and requirements for how a child restraint fixture must fit in the vehicle when attached to the lower anchorages. The lower anchorages must either be visible or labeled, but there are no labeling requirements for tethers.

Side impact testing

Vehicle-to-vehicle side impact events are often described based on the occupant's position relative to the striking vehicle. If the occupant is on the opposite side of the vehicle from the striking object it is called the "far-side" impact condition and a seat belt can play an important role in the outcome by limiting the possibility of occupant contact. When the occupant is positioned on the side of the vehicle closest to the striking vehicle it is called a "near-side" impact event and injuries are often caused by direct loading between the striking object and the occupant. In near-side events, use of the seat belt is less of a factor in the crash injury outcomes.

Near-side impacts are most injurious, and the occupant motions involve the child restraint moving toward the door as the door is intruding from the striking vehicle. US child restraint products currently do not have to be tested under side impact loading conditions. However, many child restraint manufacturers advertise that they have tested their products in side impact using internal test procedures. Side impact tests are generally conducted with dummies that are designed for side impact evaluation. In addition, the simulated side impact crash is run at a lower change in velocity than frontal impact testing to reflect the typical crash severity in the field.

Many different strategies have been proposed for testing child restraints in side impact to approximate the loading conditions seen in a vehicle. Child restraint manufacturers likely use some combination of these tests. Methods include:

- Repositioning the bench used for frontal impact testing and decelerating the child restraint laterally. This represents the loading that a child restraint would undergo in a far-side crash. This type of testing does not represent the most injurious side impact loading, but can demonstrate how well the attachment system keeps the child restraint from moving laterally and how well the dummy's head is contained within the restraint.
- Lateral loading into a fixed rigid wall. The main difference between this method and the previous one is that the test fixture includes a rigid plate mounted at the end of the seating bench. This testing method is used in Australian regulations (AS/NZS 1754). In addition to demonstrating the ability to prevent lateral movement and contain the dummy's head, this method allows a rough assessment of head injury potential from contacting a vehicle surface.
- Lateral loading into a rotating door. This approach, considered for European testing, was thought to provide a way of approximating intrusion. The characteristics of the door have a significant effect on the loading. It was difficult to achieve consensus on what the door characteristics should be as the design of vehicles has changed over time in response to vehicle side-impact requirements.
- Simulated door intrusion. This strategy propels a simulated door into the side of a fixed child

restraint. This approach captures most of the kinematics of a near-side crash except for the initial movement of the child restraint towards the intruding door. An example of this approach is the new European Union regulation that uses a moving sled to propel the child restraint into a padded fixed door and the side impact test fixture developed by Dorel and Kettering University.

- Simulated door intrusion including child restraint motion. Takata Corporation developed a side impact sled test method that simulates the door intrusion typical of a crash with a near-side occupant in a child restraint system. The method employs a base structure that simulates the vehicle door and a separate vehicle seat that slides on rails and moves into the door structure during the crash event. Honeycomb aluminum is positioned between the two elements to simulate the crush of the vehicle structure. The door structure is padded to simulate the compliance of a vehicle door. The method can be used to run a pure side impact or a side impact crash with a frontal deceleration component by adjusting the mounting angle of the entire buck relative to the primary direction of sled movement. (Sullivan and Louden 2009, Sullivan et al. 2011)

While the idea of testing child restraints in side impact has merit, design changes in response to side impact testing may have unintended consequences. If child restraints become wider to accommodate padding or larger sidewings, they may be more difficult to install with a child restraint in an adjacent seating position. Restraints may also become heavier and stiffer, possibly posing an injury risk to adjacent occupants. In addition, testing procedures evaluate injury risk by measuring lateral head excursion, and most rear-facing restraints have higher values than forward-facing seats even though they are demonstrated to be safer in crashes. Comparison of values may encourage caregivers to inappropriately shift to forward-facing restraints prematurely.

Vehicle testing

In addition to testing of child restraints, vehicles must meet regulatory requirements that pertain to protection of child occupants. Vehicle manufacturers perform a series of tests to ensure that frontal airbags do not deploy at injurious levels when a child occupant is in the right-front seating position, including when they are "out-of-position" and close to the airbag module (CFR FMVSS 208). Vehicle manufacturers also perform voluntary testing to check that side airbags do not pose a danger to children (Side Airbag OOP IT Working Group 2003). FMVSS 201 defines tests for evaluating the injury potential if occupants contact interior structures of the vehicle, such as the roof and B-pillars (CFR FMVSS 201). While children benefit from the interior padding and energy-absorbing structures that result from these requirements, the requirements do not apply to many of the structures in the rear seat that are commonly contacted by child occupants during crashes because the regulation primarily addresses interior points at or above the window sill (Arbogast et al. (in press), Jermakian et al. 2007). FMVSS 214, which evaluates the safety of vehicles in side impacts using adult-sized crash dummies, also benefits child occupants (CFR FMVSS 214).

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Child restraints are not currently tested in vehicle crash tests for regulatory purposes. However, vehicle designs developed to improve safety for adult occupants in regulatory and consumer testing may benefit child occupants as well. Research has been conducted using child restraints and pediatric dummies in a number of test programs that have identified possible issues with child restraint performance in severe crashes (Park et al. 2011, Tylko 2011). These results have led to additional research programs to identify methods of improving the safety of the rear seating compartment for the child occupants who primarily sit there (Hu et al. 2011, Klinich et al. 2008 and 2011, Reed et al. 2008).

Injury Criteria Limitations

The measure of head injury potential traditionally used in dummy testing is called HIC (head injury criteria). HIC involves integrating the measured head accelerations over a particular time period, and was originally developed to correspond with likelihood of skull fracture from direct loading (Versace 1971).

Injury threshold values for HIC were scaled for children from adult data (Irwin and Mertz 1997). While HIC seems to work reasonably to predict head injury from head strike, high HIC values can also arise from the dummy's head moving rapidly during deceleration without contacting anything.

Since the main pediatric head injury mechanism of direct contact with vehicle interior components is not simulated with the FMVSS 213 test fixture, the use of HIC as a measure during FMVSS 213 testing may be somewhat flawed. Head excursion, which is also evaluated during FMVSS 213 testing, is likely a better predictor of head injury potential, in that the further forward the head travels during loading, the more likely it will strike a vehicle interior component (even if that vehicle interior is not represented on the FMVSS 213 test buck.) Head injury from vehicle interior contact is the most common mechanism of pediatric head injury in crashes (Bohman et al. 2011). Nance et al. (2010) studied factors associated with clinically significant head injury and their findings for impact type and vehicle size suggest head contact as a mechanism. FMVSS 213 also places limits on the allowable thoracic loading based on the measured chest acceleration. However, serious chest injuries in the absence of significant intrusion are also relatively rare in field data.

Dummy Limitations

Pediatric crash dummies are designed to have the dimensions of an average child of the age they represent, primarily based on a 1977 study of child anthropometry (Snyder et al. 1977). Their overall weight matches the average child weight from this study as well, but the distribution of weight among body segments is scaled from the distribution found in adults. The response to loading of child dummies is also scaled down from adult dummies with limited adjustment made for changes in mass and stiffness (Irwin and Mertz 1997). The responses of adult dummies are primarily based on testing of elderly cadavers under dynamic loading conditions. Most pediatric dummies are designed for frontal impact loading, although some versions are designed for side impact testing.

Results from testing using crash dummies must be viewed within the limitations of the data from which they were developed. On the one hand, child crash dummies have been used to develop the safest restraints available. On the other hand, child dummies do not sit the way children do, have limited amounts of sensors/instrumentation, and have idiosyncrasies that can affect test results (Ash et al. 2009). When neck loads have been measured in child dummies seated in restraint systems, they often reach alarming levels relative to estimates of neck injury thresholds based on scaling adult values (Park et al. 2011, Menon et al. 2005). Given that serious neck injury to properly restrained children is rare, neck injury-related measurements need to be reviewed with caution. The

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design of the child dummy's spine only has flexible components in the neck and lumbar, not the thoracic region, which may be leading to more bending and higher loading in the neck than a real child with a fully flexible spine would experience (Seacrist et al. 2010).

Another example is that standard child dummies cannot currently measure abdominal loading, which is one of the more common body regions injured in older children not using boosters. The movement of the dummy during dynamic testing must be reviewed as well as the values from instrumentation, and both must consider the limitations of the dummy and instrumentation. Design of good child restraints must balance test results with field data and judgment.

CONCLUSION

The consistent and proper use of restraint systems by infants and children in passenger vehicles prevents hundreds of deaths and thousands of injuries each year. Misuse or improper selection of child restraints as well as nonuse by a small minority of children leads to many of the fatalities that do occur. Infants require the highest level of special treatment, with restraint systems designed to apply crash forces along the full length of their bodies. Toddlers can also benefit from rear-facing restraints. All children are best protected by harnessed restraints that snugly conform to their small body shape and are tightly installed in the vehicle. Belt-positioning boosters improve posture and belt fit so the vehicle seat belts can effectively protect older children in crashes. Seatbelts can provide good protection for children approaching the size of adults if the lap belt fits so it loads the pelvis and the shoulder belt fits so it loads the clavicle. Understanding both the theory behind the design of restraint systems and its application to child restraints is needed to develop improved restraint systems, and to provide informed guidance concerning child restraint selection and use.

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Kathleen B. Weber is an emeritus researcher from the University of Michigan who authored the original document, "Crash Protection for Child Passengers: A Review of Best Practice" (2000) ***www.umtri.umich.edu/content/rr31_3.pdf***. She was a pioneering researcher in the field of child occupant protection, published numerous papers on her research, and served on SAE, ISO, and advisory panels that provided the foundation for current best practices in child passenger safety.

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