Chapter 2
Epidemiology of Child Motor Vehicle Crash Injuries and Fatalities

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Introduction

Although children represent only 10–15% of the overall traffic fatality burden in the United States, motor vehicle crashes (MVCs) remain a leading cause of death and disability for children and young adults, accounting for nearly half of all unintentional injury deaths to children and adolescents (Centers for Disease Control and Prevention National Center for Injury Prevention and Control, Web-based Injury Statistics Query and Reporting System [CDC NCIPC WISQARS] 2010). Moreover, their exposure to motor vehicle risk is significant because they travel by motor vehicles nearly as much as adults. Prevention of the fatalities, injuries and disability associated with MVC must be a priority for ensuring our children's overall health.

Since the mid-1990s, the injury prevention and control community has achieved significant success in reducing this burden. For example, in 2009, 41% fewer children under 14 years of age died as a result of MVCs than in 1996 (National Highway Traffic Safety Administration [NHTSA] 2010a). These reductions have been achieved, in part, through a combination of increased attention to age-appropriate restraint use and rear seating. From 1999 to 2007 there was a nearly threefold increase in child restraint system (CRS) use among 3–8 year old children in crashes, with a specific emphasis on booster seats for those 5–8 years of age (Children's Hospital of Philadelphia [CHOP] 2008). Spurred by the child fatalities associated with passenger air bag deployment in the early 1990s, more children are also

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J.R. Crandall et al. (eds.), *Pediatric Injury Biomechanics: Archive & Textbook*,
DOI 10.1007/978-1-4614-4154-0_2, © Springer Science+Business Media New York 2013

being seated in the rear seats of vehicles. Specifically, by 2007, ~90% of children 0–7 years of age rode in the rear seat (CHOP 2008). Even with increases in age-appropriate restraint use and rear seating, the protection of children in motor vehicles can be further improved. As many as one-third of 8–12-year-olds were still routinely seated in the front row (CHOP 2008) and as recently as 2009, data indicate that 45% of 4–7-year-olds were not restrained in accordance with best practice recommendations for their age (Pickrell and Ye 2010).

As a first step towards reducing MVC injuries and fatalities, statistical analyses of surveillance and other epidemiologic data can be used to identify specific injury-producing circumstances and provide population-based estimates of the potential effectiveness of safety technologies and other interventions. Such analyses identify and help prioritize problems in motor vehicle safety and define the specific nature and magnitude of these problems by examining risk factors for and outcomes of crashes and injuries. Specifically, they can help put individual cases into a broader population-based context of specific crash injury scenarios. The translation between epidemiology and engineering is important. Ideally, epidemiologists will identify and define problems. Building on this new knowledge, engineers can pursue countermeasures to solve these problems. Subsequently, both disciplines can then work together to evaluate the real-world effectiveness of the countermeasure(s). To achieve this goal, it is important that motor vehicle injury epidemiology incorporates knowledge of the biomechanics and kinematics characterizing the injury event because this information is fundamental to the development, evaluation, and modification of safety technologies.

This chapter reviews and examines the current state of knowledge of the epidemiology of child MVC injuries and fatalities to provide context for the biomechanical focus of the remaining chapters of this textbook. It begins with a review of the magnitude of the child MVC injury and fatality problem, briefly summarizes existing data sources available for epidemiological analyses, and then describes the risks associated with the various pediatric restraint practices and other factors influencing crash injury and fatalities.

Magnitude of the Problem

With the exception of those under 1 year of age, unintentional injury is the leading cause of death, serious injury, and acquired disability for children and youth, up to 14 years of age (Table 2.1). For children and young adults aged 5–24 years, MVCs are the leading cause of death, representing 63% of unintentional injury deaths in 2007 (Fig. 2.1).

Fatalities represent only the tip of the MVC problem for children. For every 1 fatality, ~18 children are hospitalized and over 400 receive medical treatment for injuries sustained in a crash (CDC NCIPC WISQARS 2010). MVCs are among the top ten leading causes of non fatal injuries treated in hospital Emergency Departments for ages 5–24 years with 876,943 injuries sustained in 2008. Of interest, reductions

Table 2.1 Top five leading causes of death by age group, the United States—2007 (CDC NCIPC WISQARS 2010)

<1 year	1–4 years	5–9 years	10–14 years
Congenital anomalies (5,785)	Unintentional injury (1,588)	Unintentional injury (965)	Unintentional injury (1,229)
Short gestation (4,857)	Congenital anomalies (546)	Malignant neoplasms (480)	Malignant neoplasms (479)
SIDS (2,453)	Homicide (398)	Congenital anomalies (196)	Homicide (213)
Pregnancy complications (1,769)	Malignant neoplasms (364)	Homicide (133)	Suicide (180)
Unintentional injury (1,285)	Heart disease (173)	Heart disease (110)	Congenital anomalies (178)

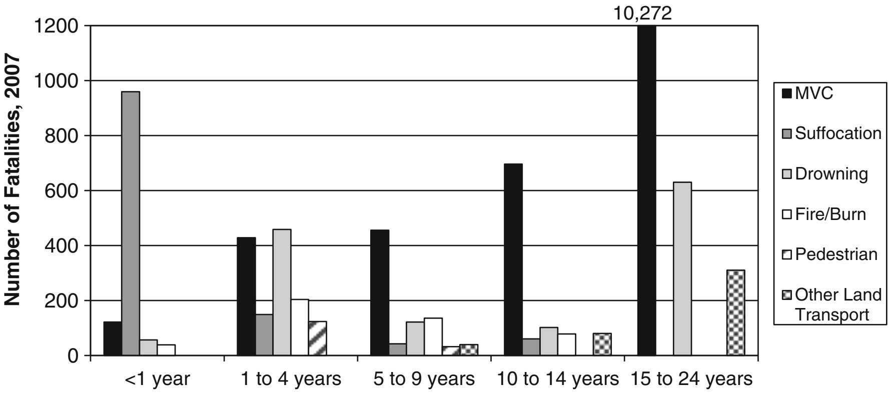

Fig. 2.1 Top five leading causes of unintentional injury death for children, the United States—2007 (CDC NCIPC WISQARS 2010)

in nonfatal injuries due to MVCs from 2007 to 2008 for those children 1–4 years have removed MVC from the top ten list for that age group (CDC NCIPC WISQARS 2010).

The potential exposure of children to MVCs is great. Children travel nearly as much as adults with an average of 3.2 trips per day for children 5–14 years (Santos et al. 2011) (Fig. 2.2).

Through the early 1990s child occupant fatality rates remained relatively stagnant at ~3.5 deaths per 100,000 children (NHTSA 1999b). However, the number of motor vehicle fatalities and serious injuries among children has declined recently. In 2009, 1,314 child occupants aged 0–14 years died in MVCs in the United States representing a 41% decrease from 1996 (NHTSA 1999b) (Fig. 2.3). This shift was more immediate among children ages 0–3 years than among children ages 4–12 years, although the older children also experienced a decline in deaths after 1999 (Nichols et al. 2005). Injuries have seen a similar decline; in 1996, 354,000

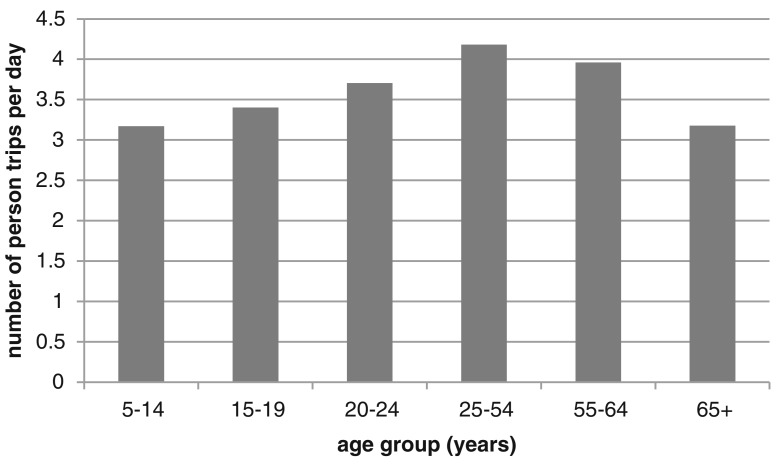

Fig. 2.2 Number of motor vehicle trips per day by age group (Santos et al. 2011)

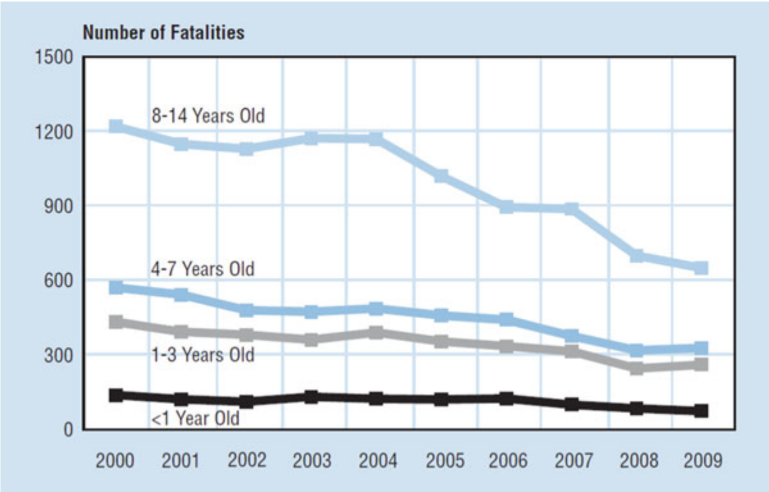

Fig. 2.3 Total traffic fatalities among children aged 14 and under by age group, 2000–2009 (NHTSA 2010b)

occupants aged 0–15 years were injured in MVCs, while in 2009, 179,000 were injured representing a 49% decline. It has been asserted that the mortality and morbidity reductions have been through a combination of increased attention to age-appropriate restraint use and seating position (Arbogast et al. 2004b; Braver et al. 1997; Durbin et al. 2003a, 2005; Elliott et al. 2006), and enhanced laws and enforcement of these laws (Segui-Gomez et al. 2001; Winston et al. 2007).

This burden extends beyond the United States and affects children globally. Worldwide, each year nearly 400,000 people under age 25 sustain fatal injuries on the world's roads—averaging more than 1,000 deaths per day, as noted by The World Health Organization (WHO) in its comprehensive report on Child Injury Prevention with an emphasis on Road Traffic Injuries (WHO 2008). Road traffic injuries are the second leading cause of death for 5–14-year-olds. Approximately one-third of these deaths are to pedestrians, while 65% are to vehicle occupants.

The portion of the text which follows reviews the epidemiologic literature on restraint effectiveness, injury causation scenarios and mechanisms for child occupants and is organized by restraint type. This review was primarily restricted to papers published during the past 10–15 years (i.e., since the mid-1990s) as the focus of this chapter was to establish specifics of the more recent trends and not to delineate the historical variations in pediatric injury patterns in MVCs. Moreover, we have focused our description on the more common injuries sustained by children. We begin with a review of the primary data sources that have been used and/or are available for study of motor vehicle injuries in children.

Primary Data Sources and Methodology

Several public and private databases exist upon which the findings presented throughout this chapter are based. A thorough description of their development, purposes, and content is contained in the Appendix. A brief description of the databases, their uses and limitations are described in Table 2.2.

While there are many sources of data providing information on children in MVCs, no single source provides the sufficient quantity and quality of data to address all issues requiring research in child passenger safety. Existing national surveillance systems such as NASS-GES, Fatality Analysis Reporting System (FARS), Cooperative Crash Injury Study (CCIS) and International Road Traffic and Accident Database (IRTAD), while capable of providing useful information on general trends of child occupant protection, do not collect the child-specific data required to conduct the most relevant analyses such as effectiveness of specific restraint systems or other best practice recommendations or to determine child specific injury mechanisms. Specialized data collection systems such as National Automotive Sampling System – Crashworthiness Data System (NASS-CDS), Special Crash Investigations (SCI), Crash Injury Research and Engineering Network (CIREN), and German In-Depth Accident Study (GIDAS) have the required specificity to identify the nature and body region of serious injuries to child occupants; however, they do not identify an adequate number of children to allow essential analyses to be conducted in a timely fashion. Child-specific data collection systems such as PCPS, CREST, and CHILD have attempted to provide both a sufficient number of cases and depth of child specific data but are difficult to sustain as part of ongoing data collection efforts as they have historically been funded by sole nongovernment sponsors or require consortiums of sponsors. Future progress in child passenger safety research will require better integration of these data sources, as well as the creation of a nationally representative child-focused crash surveillance system that combines the strengths of several existing data collection systems.

Table 2.2 Summary of data sources used in studies of crash injuries to children

Database	Description	Used for	Limitations
Fatality Analysis Reporting System (FARS)	Census of all fatal crashes in the US	Characterizing crashes resulting in fatalities; estimates of restraint system effectiveness	Limited to crashes in which someone died
National Automotive Sampling System—General Estimates System (NASS-GES)	Probability sample of police reported crashes in the United States. Data limited to that contained on the Police Accident Report	Describing national trends in crash characteristics and injuries	Limited detail in data collected (e.g., relies on police report of injury)
National Automotive Sampling System—Crashworthiness Data System (NASS-CDS)	Probability sample of police reported crashes in the United States. Involves a detailed field investigation of the vehicle and scene and abstraction of the occupants' medical records	Describing national trends in crash characteristics and injuries; estimates of restraints system effectiveness; identification of injury sources	Limited number of child occupants identified
Special Crash Investigations (SCI)	Anecdotal dataset of in-depth crash investigations. Inclusion criteria are changed routinely to address emerging traffic safety needs	Identification of new or unique crash circumstances or injury-causing crash scenarios	Nonrepresentative selection of cases. Limited number of child occupant crashes
Crash Injury Research and Engineering Network (CIREN)	A network of trauma centers who collect highly detailed clinical and crash information to determine injury causation	Detailed descriptions of the sources and mechanisms of injury	Limited number of children included. Some bias in the selection of crashes due to hospital-based data collection system

Partners for Child Passenger Safety (PCPS)	Child-specific crash surveillance system that links insurance crash claims to detailed telephone survey data and in-depth crash investigations	Describing trends in crash characteristics and injuries; estimates of restraints system effectiveness	Not nationally representative; limited detail on nature of injuries; some selection bias due to insurance-based case identification. Data collected ended in 2007.
Child Restraint System in Cars (CREST) and Child Led Injury Design (CHILD) projects	In-depth crash investigations conducted by a consortium of European industry, government and academic entities	Case series analysis of in-depth investigations for injury causation	Not a representative sample of crashes
Cooperative Crash Injury Study (CCIS)	In-depth crash investigations of a sample of cases involving newer vehicles which are representative of crashes occurring in the UK	Describing trends in crash characteristics and injuries; estimates of restraint system effectiveness	Limited number of child occupants identified
International Road Traffic and Accident Database (IRTAD)	Traffic fatality data from many countries throughout the world	Comparing traffic fatality rates among countries	Limited crash or injury detail
German In Depth Accident Study (GIDAS)	In-depth crash investigations from two regions in Germany	Case series analysis of in-depth investigations for injury causation	Not a representative sample of crashes involving children

Restraint Use

Restraint Use Policy History and Trends in Restraint Usage

The first US state child occupant restraint law was passed in Tennessee in 1978 (Teret et al. 1986). By 1985, all 50 states and the District of Columbia had passed laws requiring use of child restraints by young children and consequently child restraint use increased dramatically. Beginning in 1995, when children killed by deploying passenger air bags were first reported clinically, attention began to be focused on the unique needs of children in automotive safety. Efforts to ensure appropriate restraint for children have emphasized such issues as improved access to CRS and booster seats, upgraded laws, and educational and media campaigns that recommended that all children under age 13 should ride in the rear seats of vehicles.

In response to evidence of injuries and fatalities to children from deploying passenger air bags, NHTSA initiated a two-pronged response of education and regulation. For a comprehensive summary of the nationwide effort to reduce air-bag-related deaths among children, see Nichols et al. (2005). First, NHTSA, joined by many national organizations, recommended that all child passengers younger than 13 years of age sit in the rear seats of vehicles. Second, in 1997, NHTSA enacted a substantial regulatory change to Federal Motor Vehicle Safety Standard 208, which provided automakers a choice between certifying frontal crash performance for unbelted adults by either rigid barrier tests or sled tests (NHTSA 1997). This change in the standard, in many cases, resulted in the redesign of frontal air bags to reduce the force with which they deploy. These new air bags are generally referred to as "second-generation air bags." The role of the air bag on risks to child occupants is further discussed later in this chapter.

NHTSA began a standardized child passenger safety training and certification program in 1998. Since then, over 35,000 individuals have been certified as child passenger safety technicians. These individuals have participated in thousands of community-based child safety seat clinics and have been a source of information on appropriate restraint guidelines, including the use of booster seats. In addition, several government and industry-sponsored initiatives have drawn significant media attention to the importance of age-appropriate restraint, including the use of booster seats by older children.

Recognizing the importance of laws in both changing restraint behavior and educating the public about recommended restraint practices, beginning in 2000, several states enhanced their child occupant restraint laws through the enactment of booster seat use provisions for older children. While the laws aim to ensure the appropriate use of all forms of child restraints (e.g., child safety seats, belt positioning booster seats, combination seats), the revised laws became generally known as "booster seat laws." Subsequent study of the association of a booster provision in a state child restraint law with changes in child restraint use in that state indicated that

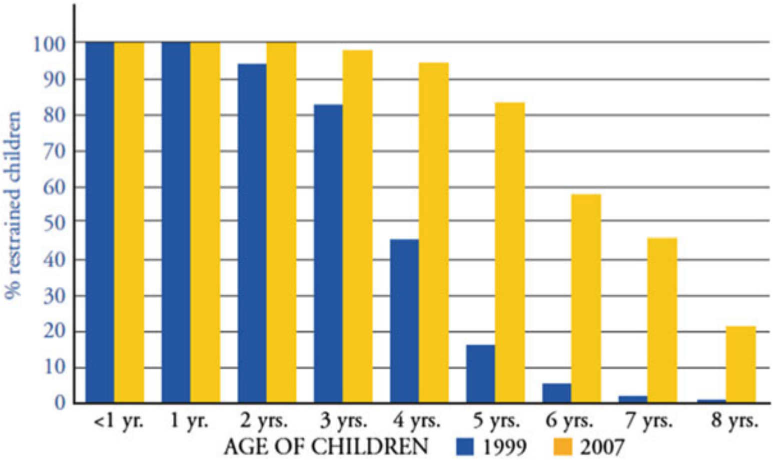

Fig. 2.4 Child restraint use by age: 1999 versus 2007 (CHOP 2008)

booster seat provisions covering children from 4 to 7 years have some effect on all children in this age range. Specifically, children aged 4–5 years in states with booster seat laws were 23% more likely to be reported as appropriately restrained than children in other states, while those aged 6–7 years were twice as likely to be reported as appropriately restrained. For 6–7-year-olds, the effect was much stronger when the law included those aged 4 through 7 years than when it included only those aged 4–5 years (Winston et al. 2007). Booster seat laws have been shown to be related to a decrease in child deaths as well (Farmer et al. 2009).

Due in large part to the increased attention paid to the needs of children in motor vehicle safety beginning in the mid-1990s, the period between 1999 and 2007 witnessed large increases in reported appropriate restraint use (including child safety seats, booster seats, and combination seats) by children ages 4 through 8 years. According to the PCPS data (an insured population), child restraint use for 4–8 year olds in crashes increased to 63% in 2007 from 15% in 1999 (Fig. 2.4). The largest relative increase in CRS use was for the oldest age group (6–8 years of age), yet 57% of these children continued to be inappropriately restrained in seat belts in 2007 (CHOP 2008). The youngest children, 3-year-olds, were primarily restrained by forward facing child restraint systems (FFCRS). Figure 2.5 shows the distribution of child restraint type over time. High back belt-positioning booster seats (BPB) were the most common restraints for the 4–5-year-old children, though the proportion of backless BPB continues to increase. Most appropriately restrained children over age 5 were in belt positioning booster seats, with somewhat more older children in backless, as opposed to high-back boosters (Jermakian et al. 2007b).

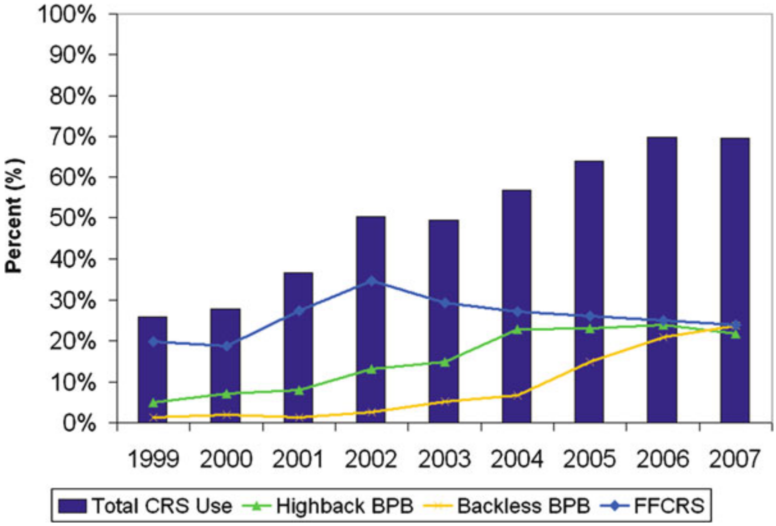

Fig. 2.5 Distribution of child restraint type for 3–8-year-olds: 1999–2007 (CHOP 2008)

NHTSA has conducted an observation study of child restraint use since 2006, the National Survey of the Use of Booster Seats (NSUBS). Survey data are obtained on children 12 years and under in passenger vehicles at a nationwide probability sample of gas stations, day care centers, recreation centers, and restaurants in five fast food chains. Restraint use is observed by trained data collectors prior to or just as the vehicle comes to a stop. Targeting a broader population than PCPS, NSUBS reported in 2009 that 41% of 4–7-year-olds were restrained in booster seats and 14% were in child safety seats (Pickrell and Ye 2010). These percentages have remained relatively flat since 2006. There is an age effect; 68% of 4–5-year-olds were in some form of child restraint; however, this was reduced to 39% for 6–7-year-olds. The variations in the laws and the effect of these differences as discussed above likely influences these percentages. In addition, restraint use for children driven by a belted driver is higher (over 90%) than for those driven by an unbelted driver (NHTSA NCSA 2008; Pickrell and Ye 2010).

Rear-Facing Child Restraints

The American Academy of Pediatrics (AAP) recommends that all infants and toddlers should ride in a rear-facing CRS until they are 2 years of age or until they reach the highest weight or height allowed by the manufacturer of their CRS (Durbin 2011). This recommendation results from the need to support the young child's posterior torso, neck, head, and pelvis and distribute crash forces over the entire body. Developmental considerations put young children at risk for spinal cord injury, including incomplete vertebral ossification and excessive ligamentous laxity (note that developmental anatomy will be discussed in detail in subsequent chapters). The rear-facing child restraint (RFCRS) addresses this risk by supporting the child's head, preventing the relatively large head from loading the proportionately smaller neck. Research on the effectiveness of RFCRS has found them to reduce fatal injury by 71% for infants <1 year of age in passenger cars and by 58% in light trucks (Hertz 1996).

In the US, few children remain rear facing past their first year of age, despite the fact that there are currently many RFCRS that have maximum weight limits beyond 9.2 kg. In fact, in a recent study of NASS data, over 40% of those 0–11 months were in a FFCRS (Henary et al. 2007). In Sweden, children remain rear facing up to the age of 4 years and transition directly from the RFCRS to a booster seat. Swedish researchers have studied the effectiveness of this behavior (Isaksson-Hellman et al. 1997; Jakobsson et al. 2005). They reported that RFCRS reduced the risk of Abbreviated Injury Scale (AIS) Score 2+ injuries by 90%, relative to unrestrained children, reinforcing their policy of children remaining in an RFCRS up to the age of 4 years. In contrast, Australian guidelines recommend rear facing only up to 6 months. In-depth crash research there has revealed no serious neck injuries, in the absence of head contact, among these forward facing children even in very severe frontal impacts (Paine et al. 2003). Of note, top tether use is mandatory in Australia, perhaps influencing these findings.

Recently, Henary et al. (2007) reviewed US crash data to calculate the relative effectiveness of RFCRS compared to FFCRS. These researchers extracted data on crash occupants 0–23 months restrained in a RFCRS or FFCRS from the NASS-CDS system from 1988 to 2003. Across all crash types, children in FFCRS were 76% more likely to be seriously injured than children restrained in RFCRS. When those 12–23 months were analyzed separately, these children were more than five times as likely to be seriously injured when restrained in FFCRS. Of interest, the largest benefits were realized by children in RFCRS involved in side crashes. These authors concluded that for children up to 23 months of age, the RFCRS provides the best protection. The lack of meaningful numbers of children 24 months or older in RFCRS in the US databases prevented extension of these analyses to age groups similar to the Swedish study.

Although the injury risk to children in RFCRS is significantly lower than those restrained in FFCRS (Henary et al. 2007), when injuries occur, they are primarily limited to head injuries. In a review of 31 cases of children restrained in RFCRS from the European CREST project, five sustained AIS3+ injury to the head and four sustained fractures to the extremities (upper and lower) (Lesire et al. 2001). It is important to realize that in European vehicles, it is more common to restrain a rear facing child in the front seat in the absence of a frontal passenger air bag or with the ability to turn the air bag off. As a result, some of the head injuries in this European study were related to the child being positioned in the front seat and having the area of the child restraint containing the child's head contact the dashboard. Of note was the absence of injuries to the neck or spine.

Forward-Facing Child Restraints

The recommendation for FFCRS has been based, in part, on an analysis by Kahane (1986) of laboratory sled tests, observational studies, and police reported crash data from the early 1980s that estimated correctly used CRS reduce the risk of death and injury by ~70% compared with unrestrained children. The engineering tests documented the biomechanical benefits of the CRS in spreading the crash forces over the shoulders and hips and by controlling the excursion of the head and face during a crash. The study further quantified the effectiveness of a partially misused CRS at a 45% reduction in risk of fatality and serious injury.

Estimates of effectiveness based on real-world crashes do vary based on which database was used, the years studied, and the analytical approach taken. Examining the preponderance of evidence, it is difficult to pinpoint a specific numerical value of effectiveness; however, universally, these studies indicated that FFCRS are highly effective at preventing fatal and nonfatal injuries. Two studies on FFCRS fatality effectiveness that are often quoted are Hertz (1996) and Elliott et al. (2006). Using FARS data from 1988 to 1994, Hertz found that, among children between 1 and 4 years of age in passenger cars, those in FFCRS experienced a 54% reduction in deaths compared with unrestrained children. Elliott and colleagues used a more recent dataset to compare the effectiveness of child restraints to seat belts and determined that FFCRS when not seriously misused (e.g., unattached restraint, CRS harness not used, two children restrained with one seat belt) were associated with a 28% reduction in risk for death in children aged 2 through 6 years after adjusting for key confounding variables. When including cases of serious misuse, the effectiveness estimate was slightly lower (21%). Rice and colleagues conducted a matched-cohort study, using FARS data to also estimate the effectiveness of child restraints at reducing the risk of death for children aged 3 and younger (Rice and Anderson 2009). The estimated death risk ratio, comparing children in child restraints to unrestrained children, was 0.33 (95% CI 0.29, 0.37). The authors found similar risk ratios for children in seat belts, suggesting that belts and child restraints were equally as effective at reducing the risk of death when compared to unrestrained children. There was evidence for the superior performance of child restraints for children under age 2 and the authors concluded that parents should be encouraged to use child safety seats instead of seat belts. Several studies have compared the effectiveness of FFCRS at preventing serious injury with effectiveness estimates ranging from a 71 to 82% reduction in serious injury risk in FFCRS compared to children of similar age in seat belts (Arbogast et al. 2004b; Winston et al. 2000; Zaloshnja et al. 2007). A summary table of these effectiveness studies is presented in section "Summary of Restraint Effectiveness Data for Child Occupants."

Historically, the harnesses in FFCRS have varied in design, including T-shields, tray shields and 5-point harnesses. For a thorough description of these differences, see Weber (2002). While sled tests typically show benefits of 5-point harnesses, no study has been able to identify benefits in real-world crash data among the harness types. Designs have evolved to be almost exclusively 5-point harnesses by the mid-2000s.

Although child restraints are very effective in preventing injuries, several authors have reviewed case series of children restrained in child restraints to gain insight into areas of focus for future optimization of these restraints. Sherwood et al. (2003) reviewed detailed police reports of crashes involving 92 fatally injured children (ages 5 and younger) in child restraints to obtain basic crash information and determine the factor most responsible for the fatality. These authors reported that half of the crashes were considered unsurvivable for the child, and 12% of fatalities were judged to result from gross misuse of the child restraint.

In a review of European data, the body regions of injury (defined as AIS3+ plus extremity fractures) for children in FFCRS in decreasing order of prevalence were the extremities, head, and neck (Lesire et al. 2001). Data from the US identified similar trends; the most common body regions of AIS2+ injury were the lower extremity, the face and the head (Arbogast et al. 2002a).

Individual studies have examined how these specific injuries occur. Head injuries sustained by child occupants restrained in child restraints include both contact-induced injuries as well as inertial injuries (Arbogast et al. 2005c; Jakobsson et al. 2005). Injuries such as skull fracture, epidural hematoma, and frontal lobe contusion are contact injuries (Gennarelli 1986, 1993) that are most likely due to excursion of the head and subsequent impact with the vehicle interior. Often, limited initial precrash space or intrusion reduces the space available for the child, thus increasing the likelihood for contact. Another contributing factor to head contact is looseness of both the vehicle seatbelt attaching the child restraint and the child restraint harness—both very common misuses (Bull et al. 1988; Decina and Knoebel 1997; Hummel et al. 1997; Lesire et al. 2001; Muszynski et al. 2005; National Safe Kids Campaign 1999). This laxity has been shown to increase head excursion (Henderson et al. 1994; Hummel et al. 1997). With loose vehicle belt attachment, the CRS is less tightly coupled to the vehicle and does not optimally benefit from the vehicle's energy management. With a loose CRS harness, there is relative movement between the torso of the child and the back of the child seat. While less common than contact-induced injuries to the brain and skull, children in FFCRS also sustain injuries to the brain where there is no evidence of contact to the head. Similar to head excursion, laxity of the child restraint harness and vehicle seat belt has been shown in a series of sled tests with child anthropomorphic test devices (ATDs) to increase resultant head acceleration (Hummel et al. 1997) suggesting contact may not be necessary to produce head injury metrics above suggested thresholds. In a review of over 150 cases of children 1–12 years with head injuries in MVCs, about 60% sustained intracranial injuries without accompanying skull fracture suggesting that at least a portion of these injuries may have occurred due to noncontact mechanisms (Arbogast et al. 2005c). Bohman et al. (2011) in a review of 27 in-depth crash investigations of head injuries sustained by restrained child occupants in frontal crashes have also identified nine cases in which these injuries occurred in the absence of evidence of head contact. The cases without evidence of head/face contact were characterized by high crash severity and accompanied by severe injuries to the thorax and spine. The circumstances under which these potential noncontact head injuries occur deserve further study.

Several researchers reviewed in-depth investigations of crashes from the CIREN database involving children seated in FFCRS with lower extremity injuries to determine the nature of the injuries and the circumstances under which they occurred (Bennett et al. 2006; Jermakian et al. 2007a). Injuries below the knee were the most common and they most often occurred due to interaction with the vehicle seatback in front of the child's seating position. This interaction with the seatback occurred in both frontal and lateral oblique crashes and was exacerbated by possible contributing factors such as intrusion of the front seatback into the child's occupant space or FFCRS misuse resulting in increased excursion of the child during impact.

Concerns have existed about the likelihood of cervical spine injuries in children restrained in FFCRS. Injuries to the cervical spine of young restrained children in MVCs are not common over the spectrum of crash severities. Pediatric cervical spine injuries, however, result in an increased fatality rate due to the fact they more commonly occur in the upper cervical spine compared to cervical spine injuries in adults which occur more often in the lower cervical spine (Brown et al. 2001; Dietrich et al. 1991; Fuchs et al. 1989; Huelke et al. 1991; Kelleher-Walsh et al. 1993; Kokoska et al. 2001; Myers and Winkelstein 1995; Patrick et al. 2000; Tingvall 1987; Vitale et al. 2006; Weber 2002). An analysis of fatal child cervical spine injuries in MVCs revealed an increased prevalence of females among those with these injuries (Stawicki et al. 2009). Many studies have identified a transition in cervical spine injury location that occurs at ~8 or 9 years of age (Elerkay et al. 2000; Finch and Barned 1998; Fuchs et al. 1989; Patrick et al. 2000; Platzer et al. 2007; Zuckerbraun et al. 2004). Children younger than this age demonstrate injuries of the upper cervical spine including "spinal cord injury without radiographic abnormalities" (SCIWORA), while older children sustain injuries to the lower cervical spine. SCIWORA has been documented to occur in about 15–25% of all pediatric cervical spine injuries (Platzer et al. 2007). These injuries are characterized by transient vertebral displacement of the spinal column with subsequent return to normal alignment resulting in a vertebral column that appears radiologically normal; however, injury has occurred to the spinal cord. This injury pattern occurs in the very young as the immature spinal column can stretch up to 5 cm before skeletal or ligamentous rupture (Kokoska et al. 2001). Odent et al. (1999) emphasized the increased frequency of upper cervical spine injuries in the youngest child occupants by reporting 15 cases of odontoid fractures in children less than 6 years—8 of which were children in FFCRS.

A current debate exists on whether severe cervical spine injuries in children in child restraints can occur in the absence of head contact. Huelke et al. (1991) reviewed the literature of case reports and NASS-CDS data from 1980 to 1989 to identify cervical injury without head contact. He concluded that although this injury is rare, the biomechanical characteristics of the immature spine discussed above predispose young children to a noncontact mechanism. Review of Swedish crash data also suggest that noncontact neck injuries with associated basilar skull fractures are possible

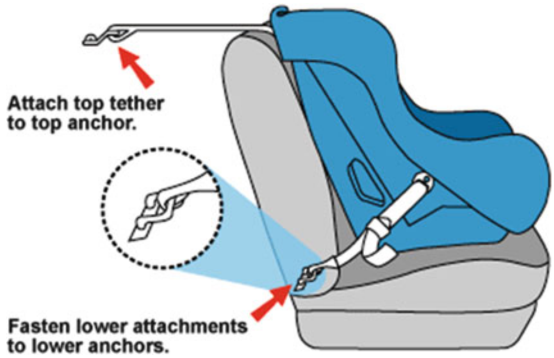

Fig. 2.6 Schematic of the LATCH system

in restrained young child occupants (Jakobssen et al. 2005). In contrast, Australian in-depth case reviews highlight the absence of cases of serious neck injury without head contact to a child in a FFCRS with top tether (Paine et al. 2003). The rare nature of this injury has prevented conclusive resolution to this debate.

Child Restraint Misuse and Novel Attachment Methods to Reduce Misuse

Several studies have highlighted the role misuse plays in how children in child restraints sustain injuries (Arbogast et al. 2004b; Czernowski and Muller 1993; Elliott et al. 2006; Sherwood et al. 2003). In light of this concern, researchers have sought to quantify the frequency and typical modes of CRS misuse (Bulger et al. 2008; Bull et al. 1988; Decina and Knoebel 1997; Decina and Lococo 2005; Eby and Kostyniuk 1999; Margolis et al. 1988, 1992; Morris et al. 2001). Most recently, Decina and Lococo conducted an observational study of over 5,000 children and measured the prevalence of CRS misuse to be 72.6% (Decina and Lococo 2005). In their study, the most common critical misuses were loose harness straps and loose attachment of the CRS to the vehicle by the seat belt.

In response to studies such as these, the method by which a CRS can be attached to the vehicle has been revised in the US. The Lower Anchors and Tethers for Children (LATCH) system was designed to reduce the difficulty associated with installing CRS. This system uses dedicated attachment points in the vehicle rather than using the adult seat belt for child safety seat installation. All vehicles and child restraints manufactured and sold in the United States in September 2002 or later were required to have this anchoring system (NHTSA 1999a). For RFCRS, there are two points of attachment at the base of the child safety seat. These lower anchors buckle into the vehicle at two dedicated attachment points. For FFCRS, a third dedicated attachment point is used for a top tether which is a length of webbing attached on one end near the top of the CRS and on the other end to hardware, such as a ring, bar, or bracket in the vehicle (Fig. 2.6). Most US-based CRS designs incorporate a flexible LATCH lower anchor attachment rather than a rigid lower anchor attachment mechanism (ISOFIX) that is common in Europe and Canada.

Previous research has studied the performance of LATCH (or its rigid lower attachment European counterpart ISOFIX) in laboratory sled test environments (Bilston et al. 2005; Charlton et al. 2004; Sherwood et al. 2004) and documented improved kinematics and reduced ATD injury metrics when compared to the existing seat belt attachment method. Arbogast and Jermakian reviewed cases of CRS attached using the LATCH attachment method and highlighted examples of LATCH misuse; however, to date, no study has evaluated the population-based benefits of this revised attachment system (Arbogast and Jermakian 2007).

At this time, LATCH, however, has not solved the misuse problem. In the first large-scale observation study examining LATCH use and misuse in the United States, data were collected at 66 sites across 7 states in 2005 (Decina and Lococo 2007). The study indicated that many parents purchasing newer vehicles do not update their CRS to take advantage of the available LATCH technology. Approximately one-fifth of the CRS in the vehicles equipped with LATCH did not have tether straps and one-sixth did not have lower attachments. Even when their CRS were LATCH equipped, approximately one-third of the drivers with LATCH-equipped vehicles stated that they could not use LATCH because there were no anchors in their vehicles. Much of the nonuse of lower anchors in this study was related to the fact that the vehicle safety belt was the only method available in the center rear position for installing a CRS. When parents had experience attaching CRS both using the safety belt or lower anchors, three-fourths reported a preference for LATCH, because they found it easier to use, obtained a tighter fit, and felt that the child was more secure.

Booster Seats

It is recommended that children who have outgrown FFCRS (based on the upper weight limit) be restrained in belt-positioning booster seats using the lap and shoulder belts in the rear seat of a vehicle until the vehicle seat belt fits properly—approximately at age 8–12 years. There are two types of belt positioning booster seats, high back and backless or low back. Booster seats raise the child up so that the lap and shoulder belts fit properly. The lap belt should fit low across the child's hips or upper thighs and the shoulder belt should cross the center of the child's shoulder and chest.

Durbin et al. (2003a) published the first real-world study to quantify the benefit of booster seats over seat belts for the young school age child. Using the PCPS dataset, these authors determined that the odds of injury after adjusting for child, crash, driver and vehicle characteristics was 59% lower for 4–7-year-olds in belt positioning booster seats than seat belts. This analysis, conducted on data from 1998 to 2002, was based primarily on children aged 4 and 5 years due to the usage practices during that time period. In the time since then, booster seat use among children 4–8 years of age has seen a threefold increase (CHOP 2008).

As more children, particularly older children, are appropriately restrained in booster seats, the performance of belt-positioning booster seats was revisited (Arbogast et al. 2009a). Arbogast et al. examined a greater percentage of older children; 37% of the study sample using booster seats was 6–8 years of age. After adjusting for potential confounders, children aged 4–8 using belt-positioning booster seats were 45% less likely to sustain AIS2+ injuries than similarly aged children using the vehicle seat belt when considering all crash directions and vehicle model years. Among children restrained in belt positioning booster seats, there was no detectable difference in the risk of injury between the children in backless versus high back boosters.

NHTSA also evaluated the effectiveness of booster seats in preventing injury among 4–8-year-olds, using 1998–2008 data from NASS-CDS and 17 years of combined data from three US States that record the use of booster seats in their reported crash data as a distinct category separate from other types of child safety seats (NHTSA 2010b). NHTSA used a double-pair comparison method, in which each child in a selected vehicle is paired with the adult driver of the vehicle. The risk of injury to a child in a booster seat, relative to the driver, was then compared to the risk of injury to a child in a seat belt, also relative to the driver. The purpose of conducting the analysis this way was to estimate the effect on risk of injury of a single binary factor (in this case booster seats versus adult belts) without having to model the diverse confounding factors or exposure rates that may be affecting injury risk. Instead, the driver of the vehicle is used as a comparison "control" to account for exposure, severity and other confounding factors.

When analyzed collectively the data showed a 14% reduction in overall injuries (from mild to fatal) for children in booster seats relative to children in adult belts. When the analyses were restricted to more severe injuries, sample sizes were insufficient to make reliable inference about the effectiveness of booster seats, though results suggesting benefits of boosters were seen fairly consistently. Unweighted CDS analyses suggested that booster seats were associated with a 45% reduction in MAIS ≥ 2 injury risk when compared to seat belts for children aged 4–8. This injury reduction estimate was very similar to the results of Arbogast et al. (2009a) noted above, who used a similar definition of injury severity in their analyses.

Rice and colleagues examined the effectiveness of booster seats to reduce the risk of death for children aged 4–8 years, using a matched cohort study of 1996–2006 FARS data (Rice et al. 2009). Estimated death risk ratios for booster seats used with seatbelts, when compared to unrestrained children, were 0.33 (95% CI 0.28–0.40) for children aged 4–5 years and 0.45 (0.31–0.63) for children aged 6–8 years. The estimated risk ratios for seat belt use alone were similar, suggesting that booster seats and seat belts provided similar protection from death in crashes. Attempting to explain the seemingly inconsistent findings that booster seats are more effective than seat belts in reducing the risk of nonfatal injuries, but not fatal injuries, Rice noted that booster seats, which improve seatbelt fit, may not improve collision survivability because the effect of improving seatbelt fit is to lower the probability of injuries to the abdomen and lumbar spine, which can be severe but are much less often fatal than injuries to the head and thorax.

Corden (2005) took a slightly different approach in examining the protection afforded by belt-positioning booster seats by quantifying the decrease in deaths and hospitalizations if all 4–7-year-olds were in booster seats. Using Wisconsin state data from 1998 to 2002, there would be a 57 and 58% reduction in deaths and hospitalizations, respectively, compared to the numbers of deaths and hospitalizations based on restraint practices current at the time.

Of note, in the 1980s and 1990s shield booster seats were common restraints for children of booster seat age. Current recommendations do not advocate the use of shield booster seats in part due to several studies that have highlighted their injury and fatality risks (Edgerton et al. 2004; Whitman et al. 1997). Children in shield booster seats had eight times the risk of sustaining a serious injury than similar age children in FFCRS and four times the risk of sustaining a head injury (Edgerton et al. 2004). These researchers point to the lack of upper torso restraint as a key parameter that leads to suboptimal kinematics, increased head excursion and in several cases, ejection of the child from the shield booster (Whitman et al. 1997).

As stated above, belt-positioning booster seats are designed to better position the occupant such that the vehicle seat belt can provide optimal protection. In practice, this raises the child up and in the case of a high-back belt positioning booster seat moves them forward of the seat bight. The injury patterns in this restraint are related to this positioning. For example, in the Durbin study (2003a), the most common body regions of injury for children in belt positioning booster seats were the head and the face—many of them contact-related injuries. Of note, in this study, children in belt positioning booster seats had no injuries to the abdomen and spine—body regions characterized by the constellation of injuries known as “seat belt syndrome” (SBS) discussed in more detail below.

Review of 108 cases of children restrained in belt-positioning booster seats from the European CREST project shows a pattern of injuries that includes, in decreasing order, lower extremity fractures, AIS3+ injuries to the neck, chest, and abdomen (Lesire et al. 2001). The occurrence of abdominal injuries in children in booster seats in the European literature has been at odds with the US data, which has demonstrated a reduction in abdominal injury risk for booster-seated children (Jermakian et al. 2007b; Trosseille et al. 1997). This may be due, in part, to differences in data collection methodology. The US studies were based on a population-based sample of injured and noninjured children in crashes; however, the European study was based on a convenience sample of children in child restraints who were injured as a result of a crash. These differences in methodology might be responsible for the differences in injury distribution due to potential selection biases associated with convenience samples. Specifically, a convenience sample of injured children does not adequately estimate the appropriate population from which the injured children were drawn—i.e., the number of children in booster seats without abdominal injuries is unknown.

Seat Belts

According to NHTSA, vehicle safety belts are considered to fit correctly when the lap portion of the belt rides low over the hips or thighs and the shoulder portion crosses the sternum and shoulder (Fig. 2.7). Children are usually ready for the adult lap and shoulder belt when they can sit with their backs against the vehicle

Fig. 2.7 Proper positioning of a lap and shoulder belt

seat back with their knees bent over the vehicle seat edge (typically at ~4′9″) (Klinich et al. 1994).

Using FARS data, NHTSA has evaluated the effectiveness of lap and shoulder belts in the rear rows and found them to be effective in all crash modes for adult and pediatric occupants aged 5 years and older. The estimated fatality reduction was: 77% in rollovers, 42% in side impacts, 29% in frontals, and 31% in rear impacts and other crashes. These findings are applicable to occupants aged 5 years and older and are not specific estimates for children (Morgan 1999).

Two studies have evaluated seat belt effectiveness for children. Chipman et al. (1995) using a database of fatal crashes in Ontario estimated the effectiveness of seat belts for children aged 4–14 years and found that the odds ratio for serious injury or death was 0.60 compared to those without a seat belt. Wisconsin-specific data suggested that 100% seat belt use by children aged 8–15 years would result in 45 fewer deaths and 206 fewer hospitalizations compared to current restraint use rates of 72%. These estimates represent reductions of 45 and 32% for deaths and hospitalizations respectively (Corden 2005).

While seat belts may be recommended for children ages 8 and older, García-Espana and colleagues (2008) have identified an elevated injury risk for these age children compared to their younger counterparts in child restraints. The risk of injury for belted 8–12-year-olds in the rear seat was 1.3% with head and face injuries being most common followed by injuries to the upper extremity and the abdomen. These authors suggest that a systematic approach that includes research, public education, safety regulation, and legislative advocacy needs to be directed toward protection of this age child.

Note that the recommendation for seat belt restraint is a lap and shoulder belt rather than use of a lap belt alone. Lap and shoulder belts have been required in rear outboard positions since 1989. However, it was not until 2005 with a phase-in until 2007 that lap–shoulder belts were required in the center rear seat position. Many manufacturers introduced center rear lap–shoulder belts in advance of this requirement and by model year 2001 most vehicles were equipped as such (Kahane 2004). The benefits associated with this change were evaluated by Arbogast et al. (2004c). These researchers documented that for those children seated in the center rear in seat belts, the presence of a shoulder belt reduced the risk of injury by 81% with the primary benefit seen in reductions in abdominal injury. Parenteau and Viano (2003) previously documented a similar shift in the patterns of injury from lap only belt restraint to lap–shoulder belt. Their study, however, looked at the rear seat as a whole and did not separate out the rear seating positions. Of note, in the García-Espana study, one out of five 8–12-year-olds misused the shoulder portion of the vehicle seat belt suggesting that presence of a shoulder belt does not always lead to proper use (García-Espana and Durbin 2008).

Cases of serious cervical and lumbar spinal cord injury as well as intra-abdominal injuries to children restrained in lap and lap–shoulder belts have been described for many years, resulting in the identification of a so-called seat-belt syndrome (SBS) of injuries to children (Agran et al. 1989, 2007; Garrett and Braunstein 1962; Glassman et al. 1992; Gotschall et al. 1998; Hoy and Cole 1993; Khaewpong et al. 1995; Kulowski and Rost 1956; Lane 1994; Newman and Dalmotas 1993; Sturm et al. 1995; Stylianos and Harris 1990; Tso et al. 1993; Voss et al. 1996). First described by Kulowski and Rost (1956), the term "SBS" was coined by Garrett and Braunstein in 1962 to describe a distinctive pattern of injuries associated with lap belts primarily based on adult crash occupants (Garrett and Braunstein 1962). The first descriptions of SBS in children began appearing in the 1980s as restraint of children became more common with the introduction of rear seat belts (Agran et al. 1989).

The injuries associated with SBS include hip and abdominal contusions (now commonly referred to as the seat belt sign), pelvic (ileal and pubis) fractures, lumbar spine injuries including subluxations and compression fractures of the bodies of L2–L4, and intra-abdominal injuries to both solid organs and hollow viscera. Over the past four decades, a large number of case reports and case series have confirmed a characteristic pattern of injuries, which generally localize to the abdomen and lumbar spine (e.g., Anderson et al. 1991; Arajarvi et al. 1987; Blumenberg 1967; Chance 1948; Chandler et al. 1997; Ciftci et al. 1998; Doersch and Dozier 1968; Hampson et al. 1984; Hendey and Votey 1994; Hingston 1996; Huelke et al. 1995; McCarthy and Lemmon 1996; Moir and Ashcroft 1995; Porter and Zhao 1998; Rogers 1974; Steckler et al. 1969; Sube et al. 1967; Talton et al. 1995; Vandersluis and O'Connor 1987; Vellar et al. 1976; Wagner 1979; Wang et al. 1993; Yarbrough and Hendey 1990).

Intra-abdominal injuries include gastrointestinal tract perforation and small bowel mesenteric tears and perforations (Anderson et al. 1991; Arajarvi et al. 1987;

Blumenberg 1967; Chandler et al. 1997; Ciftci et al. 1998; Doersch and Dozier 1968; Glassman et al. 1992; Gotschall et al. 1998; Hendey and Votey 1994; Hingston 1996; Moir and Ashcroft 1995; Newman and Dalmotas 1993; Porter and Zhao 1998; Sube et al. 1967; Talton et al. 1995; Tso et al. 1993; Vandersluis and O'Connor 1987; Vellar et al. 1976; Wang et al. 1993). These injuries occur more often in children restrained by lap belts but can be sustained by children restrained by lap and shoulder belts as well (Gotschall et al. 1998). Occupants of all ages are at risk of developing SBS, though the poor fit of the belt in younger children likely places them at higher risk than older children. In a large case series of 98 children with SBS treated at Children's National Medical Center in Washington, DC between 1991 and 1997, the mean age of patients was 7.3 (±2.5) years, and 72% of cases were between the ages of 5 and 9 years (Gotschall et al. 1998). Arbogast and colleagues (2004d) further quantified the effect of age on the risk of seat belt related abdominal injuries and highlighted the increased risk for children 4–8 years of age. They were 24.5 times and 2.6 times more likely to sustain an AIS2+ abdominal injury than those 0–3 years and 9–15 years, respectively. Within a specific age group, appropriately restrained children (child restraints or booster seats for those up to 8 years and lap–shoulder belts for those >8 years) were one-third as likely as suboptimally restrained children to suffer an abdominal injury (Nance et al. 2004).

Age influences the abdominal injury pattern as well. Lutz et al. (2003) demonstrated that among restrained children with intra-abdominal injuries, those <8 years of age and restrained by a seat belt were four times more likely to have a hollow visceral than a solid visceral injury when compared with those who were following best practice recommendations for the choice of restraint for their age (in a child restraint or booster seat for those <8 and in a lap–shoulder belt for those 8 years and older).

In addition to abdominal organ injuries, children in seat belts sustain injury to the vessels of the abdominal cavity. Several researchers documented the occurrence of injuries to the abdominal aorta sustained by restrained occupants in MVCs (Anderson et al. 2008; Choit et al. 2006; Dajee et al. 1979; Roth et al. 1997; Swischuk et al. 2007). These injuries often occur in conjunction with bowel injuries and lumbosacral spinal fractures and are due to direct compression between the spine and the seat belt (Randhawa and Menzoian 1990).

In a review of 21 cases of abdominal injury sustained by children restrained in seat belts, researchers identified belt loading directly over the injured organ as the most common mechanism of injury (Arbogast et al. 2007). In these cases, injury occurred in several ways: (1) the child scooting forward prior to the crash on the soft, compressible seat cushion, creating a shallow lap belt angle exacerbated by the forward and downward occupant kinematics of the crash, (2) the child placing the shoulder belt behind his back resulting in a belt geometry that might move the lap belt higher on the abdomen during a crash, and (3) rear seat lap–shoulder systems that have belt geometry that places the lap belt high on the abdomen even when both parts of the seat belt are worn and the child remains seated back against the seat cushion. From these positions, during rapid deceleration, the immaturity of the pediatric pelvis prevents proper anchoring of the lap belt; the belt directly compresses the abdominal contents against the spinal column resulting in mesenteric tears and bowel wall contusions (Leung et al. 1982). Intestinal perforations are likely caused by a sudden increase in intra-luminal pressure, combined with compression of a short segment of bowel by the belt (Tso et al. 1993). Several studies demonstrated that the presence of an abdominal wall contusion significantly increased the likelihood of an intra-abdominal injury including bowel perforation and the need for operative intervention (Chandler et al. 1997; Lutz et al. 2004).

Two types of lumbar spine injuries—compression fractures and Chance fractures—have been described as part of SBS (e.g., Chance 1948; Durbin et al. 2001a; Garrett and Braunstein 1962; Gotschall et al. 1998; Hampson et al. 1984; Hingston 1996; Hoy and Cole 1993; Huelke et al. 1995; Khaewpong et al. 1995; Kulowski and Rost 1956; Moir and Ashcroft 1995; Mulpuri et al. 2007; Newman and Dalmotas 1993; Rogers 1974; Steckler et al. 1969; Sturm et al. 1995; Stylianos and Harris 1990; Subotic et al. 2007; Swischuk et al. 2007; Voss et al. 1996; Yarbrough and Hendey 1990). The mechanisms of these injuries are described in more detail elsewhere in this book.

In addition to the classic abdominal and lumbar spine injuries, young children in seat belts are at increased risk of head and face injuries. These injuries occur more frequently when a child uses a poorly fitting shoulder belt, or the shoulder belt is misused (Arbogast et al. 2002b; Winston et al. 2000). In the extreme, children may place the shoulder belt behind the back or under the arm for comfort, but even young children wearing the shoulder portion may not have adequate torso restraint (Arbogast et al. 2007; Gotschall et al. 1998).

Other researchers have documented additional patterns of injury that, while rare, can occur in children restrained in seat belts. These include diaphragmatic injuries (Shehata and Shabaan 2006), upper cervical spine fractures (Deutsch and Badawy 2008), and iliac wing fractures (Emery 2002). Biomechanical characteristics of the child result in children being at increased risk of these rare injuries; this is discussed in more detail in subsequent chapters of this book.

Summary of Restraint Effectiveness Data for Child Occupants

The majority of the restraint effectiveness research for child occupants has been focused on frontal crashes. Table 2.3 summarizes both the effectiveness for reducing fatalities and that for reducing serious injuries for each restraint best practice recommendation for children as discussed in previous sections. Of note, there is limited research that examines similar analyses for other crash directions; the few studies that exist are summarized later in this chapter.

In order to provide guidance for further optimization of child occupant protection, Table 2.4 provides the distribution of injured body regions stratified by restraint type. In all cases, injuries to the head are the most common injury sustained by children. For children in FFCRS, injuries to the lower extremity, face, and upper extremity are also important. The distribution of body regions of injury between 4- and 7-year-olds in booster seats and 8–15-year-olds in seat belts—both age-appropriate

Table 2.3 Summary of restraint effectiveness data

Restraint	Effectiveness for reducing fatalities	Comparison group	Effectiveness at reducing serious injuries	Comparison group
RFCRS	71% reduction (Hertz 1996)	Unrestrained occupants up to 1 year of age	44% reduction (Henary et al. 2007)	Children aged 0–23 months in FFCRS
			90% reduction (Jakobsson et al. 2005)	Unrestrained occupants up to 4 years of age
FFCRS	71% reduction for correctly used seats (Kahane 1986)	Unrestrained occupants 0–4 years of age	72% reduction (Winston et al. 2000)	Seat belt restrained 2–5-year-olds
	54% reduction (Hertz 1996)	Unrestrained occupants 1–4 years of age	71% reduction (Arbogast et al. 2004b)	Seat belt restrained 1–4-year-olds
	28% reduction (Elliott et al. 2006)	Seat belt restrained 2–6-year-olds	82% reduction (Zaloshnja et al. 2007)	Seat belt restrained 2–3-year-olds
	67% reduction (Rice and Anderson 2009)	Unrestrained children aged 3 and under		
BPB			59% reduction (Durbin et al. 2003a)	Seat belt restrained 4–7-year-olds
			45% reduction (Arbogast et al. 2009a)	Seat belt restrained 4–8-year-olds
			45% reduction in MAIS≥2 injuries (NHTSA 2010)	Seat belt restrained 4–8-year-olds
	67% reduction for children aged 4- 5 years (Rice and Anderson 2009)	Unrestrained 4-5-year-olds		
	55% reduction for children aged 6–8 years (Rice and Anderson 2009)	Unrestrained 6–8-year-olds		
Seat belts	29% reduction in frontal impact crashes (Morgan 1999)	Unrestrained occupants aged 5 and older		

Table 2.4 Patterns of AIS2+ injury stratified by restraint type

	RFCRS, 0–11-month-olds	FFCRS, 12–47-month-olds	Belt-positioning booster seats, 4–7-year-olds	Seat belt (lap and lap–shoulder), 4–7-year-olds	Seat belt (lap and lap–shoulder), 8–15-year-olds
Overall AIS2+ injury risk (per 1,000 children in crashes)	2.3	3.0	4.9	16.6	13.6
Head (%)	83.3	56.9	61.1	67.3	62.5
Face (%)	0.0	8.3	7.0	5.8	6.5
Chest (%)	2.4	2.8	5.7	1.3	5.9
Abdomen (%)	2.4	3.3	8.9	17.8	7.1
Neck/spine (%)	0.0	1.7	1.3	0.7	1.6
Upper extremity (%)	7.1	8.3	7.0	4.5	11.0
Lower extremity (%)	4.8	18.8	8.9	2.5	5.4

Data from PCPS from 12/1/98-11/30/07. Limited to model year 1998 and newer vehicles. Differences between restraint types should not be interpreted as statistically significant differences restraint conditions—is very similar, although the overall injury risk in booster seats is substantially lower. For children between 4 and 7 years old in seat belts, the presence of SBS injuries to the abdomen is highlighted.

Other Factors Associated with Child Occupant Fatality and Injury Risk

Air Bags

Beginning in the 1990s, a portion of the deaths and injuries to children in MVCs were attributed to exposure to deploying passenger air bags. In November 1995, the Morbidity and Mortality Weekly Report issued by the US Centers for Disease Control and Prevention described eight deaths of child occupants involving air-bag deployment that were of special concern because they involved low-speed crashes in which the children otherwise might have survived (CDC 1995). The risk to small occupants from a deploying air bag had been a concern for the automotive industry for several years (Mertz 1988; Kent et al. 2005). As passenger air bags diffused into the market, numerous case reports began appearing in the medical literature describing brain and skull injuries sustained by children in RFCRS and brain and cervical spine injuries sustained by older children often unrestrained or restrained inappropriately in seat belts for their age (CDC 1996; Giguere et al. 1998; Hollands et al. 1996; Huff et al. 1998; Marshall et al. 1998; Willis et al. 1996).

Several researchers reviewed case series of children exposed to deploying passenger air bags to elucidate the mechanisms of injury (Augenstein et al. 1997; Huelke 1997; Kleinberger and Summers 1997; McKay and Jolly 1999; Quinones-Hinojosa et al. 2005; Shkrum et al. 2002; Winston and Reed 1996). For children killed in a RFCRS, the air bag typically deployed into the rear surface of the child restraint often fracturing the plastic shell of the restraint near the child's head causing fatal skull and brain injuries. Older children who were either unrestrained or inappropriately restrained in seat belts for their age were placed in proximity to the deploying air bag due to preimpact braking. In one typical scenario, upon deployment, the air bag causes the neck to go into combined tension and hyperextension loading resulting in a spectrum of injuries to the brain and cervical spine. These include atlanto-occipital fracture, brain stem injuries and diffuse axonal injury of the brain. The largest case series was from NHTSA's Special Crash Investigation program and is summarized in Winston and Reed (1996) and Kleinberger and Summers (1997). Case series of other injuries to child occupants associated with air bag deployment continue to appear in the literature including injuries to the eye (Ball and Bouchard 2001) and upper extremity (Arbogast et al. 2003a).

As a response to growing knowledge of the adverse effects of passenger air bags to child occupants, researchers began quantifying the population-based risks of air bag exposure and the benefits of rear seating. Early evaluations focused on the first generation air bag designs—defined as those designs in vehicles of model year earlier than 1998—and their effect on injuries and fatalities for children (Braver et al. 1997, 1998; Cummings et al. 2002; Kahane 1996; Smith and Cummings 2006. The presence of an air bag uniformly increased the risk to both restrained and unrestrained child occupants. A summary of the findings from the different studies, their age group of focus, and groups of comparison is contained in Table 2.5.

Kuppa et al. evaluated the influence of the air bag on the effectiveness of rear seating using a double-pair comparison study of FARS frontal crash data (Kuppa et al. 2005). Two pairs were analyzed: the first group consists of fatal crashes where a driver and front outboard seat passenger are present and at least one of them was killed; the second group consists of fatal crashes where a driver and a rear outboard seat passenger are present and at least one of them was killed. This analysis considered those vehicles with and without a passenger air bag separately. For restrained children 5 years of age or less, the presence of a passenger air bag increased the benefit, in terms of reduced fatalities, associated with rear seating. For restrained child occupants >8 years of age, the rear seat was still associated with a lower risk of death than the front, but its benefit was less in vehicles with a passenger air bag than in vehicles without. Specifically, the presence of a passenger air bag reduces the ratio of front row risk to rear row risk compared to vehicles without a passenger air bag.

Other researchers studied the impact of passenger air bags on injury risk as well. Based on the PCPS dataset, Durbin and colleagues determined the relative risk of nonfatal injuries to restrained children aged 3–15 years exposed to passenger air bags in frontal impacts compared to those in the front seat in similar crashes with no passenger air bag deployment and reported a 100% increase in injury risk. Exposure to passenger air bags increased the risk of both minor injuries, including facial and chest abrasions, and moderate and more serious injuries, particularly head injuries and upper extremity fractures (Durbin et al. 2003b). Using NASS-CDS data from 1995 to 2002, Newgard et al. reported a trend towards increased risk of serious injury from air bag deployment for children 0–14 years of age compared to those in the front seat with no air bag deployment, although these findings were not statistically significant (Newgard and Lewis 2005).

As described earlier in this chapter, as a result of the many injuries and fatalities to children from deploying passenger air bags, NHTSA revised Federal Motor Vehicle Safety Standard 208, in a way which, in many cases, resulted in the redesign of frontal air bags to reduce the force with which they deploy. These new air bags are generally referred to as “second-generation air bags.”

Several studies examined the effect of these design changes on child occupants in real-world crashes. Although the findings were nonsignificant, second-generation air bags reduced the risk of death among right front-seated children 6–12 years of age by 29% compared to no air bag (Olson et al. 2006). For children <6 years of age, both types of air bags increased the risk of death compared to no air bag; however, the increased risk of death associated with air bag deployment was less for second-generation air bags (10%) compared to first generation air bags (66%) adjusted for important crash and occupant parameters including the restraint status of the child and crash direction. Arbogast et al. (2003b, 2005a) quantified the risk of serious

Table 2.5 Summary of studies examining the role of the passenger air bag (PAB) and seat row in determining the risk of death and serious injury to child occupants

Study	Data source	Target group studied	Comparison group	Primary finding
Braver et al. (1997)	FARS 1992–1995	Children <10 years seated in the right front seat in vehicles with a PAB	Children <10 years seated in the right front seat in vehicles with only a driver AB	PAB increased the risk of death by 34%
Braver et al. (1998)	FARS 1988–1995	Children <13 years of age seated in the rear row	Children <13 years of age seated in the front row	In vehicles with a PAB, rear row seating reduced the risk of death by 46%; in vehicles without a PAB, by 35%
Cummings et al. (2002)	FARS 1992–1998 and NASS-GES 1992–1998	Children <13 years of age seated in the right front seat in vehicles in FARS	Children <13 years of age seated in the right front seat in vehicles in NASS-GES	PAB increased the risk of death by 5% for restrained occupants and 37% for unrestrained occupants
Smith and Cummings (2006)	FARS 1990–2001	Children <13 years of age, restrained and seated in the rear row in vehicles with a PAB	Children <13 years of age, restrained and seated in the right front seat in vehicles with a PAB	Rear row seating reduced the risk of death by 38%
Kuppa et al. (2005)	FARS 1993–2003	Children aged 0–12 years seated in the rear outboard seat position	Children aged 0–12 seated in the right front seat position	For restrained occupants in vehicles with a PAB, rear seating reduced the risk of death by 65, 35, and 20% for 0–5, 6–8 and 9–12-year-olds
Durbin et al. (2003b)	PCPS 1998–2001	Restrained children aged 3–15 years exposed to deploying PAB	Restrained children aged 3–15 years seated in the right front seat in vehicles in which there was only a driver AB and it deployed	Twofold increase in risk of AIS2+ injury with PAB exposure
Olson et al. (2006)	FARS 1990–2002	Right front seated children 6–12 years of age in vehicles with a second generation PAB	Right front seated children 6–12 years of age in vehicles with no PAB	Second generation PAB reduced the risk of death by 29% (nonsignificant finding)

(continued)

Table 2.5 (continued)

Study	Data source	Target group studied	Comparison group	Primary finding
Arbogast et al. (2003b), Arbogast (2005a)	PCPS 1998–2002	Restrained children aged 3–15 years exposed to deploying second-generation PAB	Restrained children aged 3–15 years exposed to deploying first-generation PAB	Second generation PAB reduced the risk of AIS2+ injury by 41%
Arbogast et al. (2009b)	PCPS 1998–2007, vehicle model year 1998+	Children aged 0–15 years seated in the front row of vehicles	Children aged 0–15 years seated in the rear row(s) of vehicles	Rear seating reduced the risk of injury by 64% for 0–8-year-olds and 31% for 9–12-year-olds

nonfatal injuries in frontal crashes among belted children in the front seat of vehicles in which second generation passenger air bags deployed, compared with that of belted children in the front seat of vehicles in which first-generation passenger air bags deployed. Serious injuries were reported in 14.9% in the first-generation group versus 9.9% in the second-generation group resulting in a 41% reduction in injury risk. Children in the second-generation group sustained fewer head injuries, including concussions and more serious brain injuries, than in the first-generation group.

Seating Position

In addition to the regulatory changes resulting in the redesign of air bags, a collaborative national response was directed towards encouraging rear seating for those children <13 years of age. In general, this effort has been effective. Data from the FARS from 1990 to 1998 indicated that the proportion of vehicles carrying children in the front declined from 42 to 31% over the 9-year period. By 2007, 95% of infants, 98% of children aged 1–3, and 88% of children aged 4–7 rode in the rear seat (NHTSA 2008). As the use of child restraints, particularly booster seats, by children aged 4–8 years has increased, the proportion of these children sitting in the front seat has declined from 18% in 1999 to 4% in 2007. However, in 2007 approximately one-third of 8- to 12-year-olds were still riding in the front seat (CHOP 2008). Factors associated with child front-seating include a single child occupant alone with the driver, older child age, male or nonparent driver, or lack of a passenger air bag (Agran et al. 1998; Durbin et al. 2004; Ramsey et al. 2000; Wittenberg et al. 1999).

Research on seating position has shown the rear seat to be protective for children regardless of restraint use. Several studies using the FARS dataset, described above in the section on air bags, documented a fatality reduction of 20–65% when the child occupant was seated in the rear rows rather than the front seat, depending on the age of the child and presence of a PAB (Braver et al. 1998; Kuppa et al. 2005; Smith and Cummings 2006). These benefits have been extended to serious injury as well with studies documenting a 40–60% greater risk of injury for children in the front seat compared with children in the rear, after adjusting for crash severity, depending on the restraint status of the child (Durbin et al. 2005; Lennon et al. 2008). Using Utah state-specific data, Berg et al. (2000) reported that children aged 0–14 years were 70% more likely to sustain a serious or fatal injury in the front seat compared to the rear row. An analysis of the CIREN dataset demonstrated that front seat child occupants sustained more severe injuries as measured by an ISS >16 than those seated in the rear rows (Erlich et al. 2006). A recent analysis of PCPS data examined the relative risk of front versus rear row seating in vehicles of model year 1998 and newer and found that rear seating reduced the risk of AIS2+ injury by 64% for those 0–8 years of age and 31% for those 9–12 years of age (Arbogast et al. 2009b). These authors further stratified their data by model year (1998–2002 and 2003+) and demonstrated a crude rear row injury risk that was lower than that of the

Table 2.6 Patterns of AIS2+ injury stratified by seat row

	Front row		Rear row(s)	
	Children 0–7 years in CRS	Children 8–15 years in seat belts	Children 0–7 years in CRS	Children 8–15 years in seat belts
Overall AIS2+ injury risk (per 1,000 children in crashes)	7.5	16.0	3.3	12.1
Head (%)	43.8	57.1	60.0	66.8
Face (%)	12.5	6.4	5.5	6.5
Chest (%)	6.3	7.7	4.2	4.4
Abdomen (%)	12.5	6.9	5.3	7.3
Neck/spine (%)	0.0	1.5	1.5	1.6
Upper extremity (%)	12.5	14.7	9.2	8.2
Lower extremity (%)	12.5	5.6	14.4	5.3

Data from PCPS from 12/1/98-11/30/07. Limited to model year 1998 and newer vehicles. Differences between seat rows should not be interpreted as statistically significant differences

front row for all model year, child age combinations. Durbin and colleagues (2005) examined the combined effect of rear seating and appropriate restraint and found a synergistic effect of the two parameters to provide the best protection for children in crashes. Of interest, the benefits of rear seating for child occupants appeared to extend to side impacts as well with children in the rear 62% less likely to sustain an injury (Durbin et al. 2001b).

Table 2.6 provides the body region specific injury risks stratified by seat row and age/restraint. For all children regardless of seat row or restraint, head injuries are the most common. For front seated children in CRS (including booster seats), other body regions of importance are the face, abdomen, and extremities. It is important to note that few children in CRS are seated in the front row so these body region distributions are based on small numbers. For CRS-restrained children in the rear row(s), except for the extremities, injuries to body regions other than the head are not common. For front seated children in seat belts, injuries are sustained by all body regions except for the neck and spine to which injuries are relatively rare. The body region distribution for seat belt restrained children is very similar between front seated children and rear seated children; however, the overall injury risk is elevated in the front row.

The center rear seat has been generally considered the safest rear seating location for children in child restraints. Lund (2005) used data from the NASS-GES system from 1992 to 2000 to evaluate the effect of seating position on the risk of injury for children in child restraints. They reported children seated in the center rear seat were not at a lower injury risk than children seated at either of the outboard rear seats. In contrast, Kallan et al. (2008) used PCPS data from 1998 to 2006 to evaluate this issue and demonstrated that child occupants restrained in child restraints and seated in the center had an injury risk 43% less than children in child restraints seated in either of the rear outboard positions. These contrasting findings are likely due to how injuries were defined in the two studies. Lund defined injury as any police-reported injury, which includes those of a relatively minor nature. The threshold for injury is higher in Kallan's analysis, resulting in more serious injuries, such as injuries involving internal organs and fractures of the extremity. This more stringent definition of injury facilitates differentiation between the protection afforded by the outboard seat positions and that of the center seat.

Crash Direction

Researchers have described variation in injury and fatality risk by crash direction. For historical data on this topic, the reader is referred to Agran et al. (1989), Henderson et al. (1994), Krafft et al. (1989), Kelleher-Walsh et al. (1993), Langwieder and Hummel (1989), Langwieder et al. (1996) and Tingvall 1987 as examples. A brief review of more recent data follows to set the context for a detailed review of injury causation scenarios and mechanisms by crash direction.

Similar to adult occupants, frontal crashes are the most common crashes experienced by child occupants. As a result, much of the research and restraint evaluation described earlier in this chapter has been focused on this impact direction. However, frontal impacts, side impacts, and rollovers account for similar numbers of child fatalities, and rollovers and side impacts have a greater case fatality rate (Starnes and Eigen 2002). In 2009, there were 164 fatalities for children aged 0–7 years in frontal crashes, compared to 101 in side impacts, and 165 in rollovers with only 50 in rear impacts. For rear-seated children aged 0–7 years, review of FARS data from 1996 to 2005 revealed that the crash mode with the highest fatality risk was rollover crashes (1.37%), followed by right-side (0.47%) and left-side impacts (0.34%) (Viano and Parenteau 2008a) (Fig. 2.8). In general, similar crash direction trends are found for serious injuries with slight variations among the studies due to different years and age groups of study (Erlich et al. 2006; Parenteau and Viano 2003; Viano and Parenteau 2008b).

Side Impacts

Side impact protection for child occupants has received much recent attention attributed to the high fatality and injury rate in this crash direction. Much of this research has focused on quantifying the relative risk among seating positions in side impact crashes. Howard et al. (2004) reported that the risk of fatality for children seated in the near-side position was twice as high as that for children in the center, while the center-seat position had a 40% higher fatality risk than the far-side position. Of interest, near-side crashes on the right side have twice as high fatality rate as near side crashes on the left side. Viano et al. attributed this difference to the dynamics of right side crashes, which often occur as the case vehicle is making a left turn across traffic and likely result in side crashes of increased severity (Viano and Parenteau 2008a).

Howard et al. (2004) extended this work to serious injuries and using the NASS-CDS dataset from 1995 to 2000, quantified that for restrained children 0–12 years

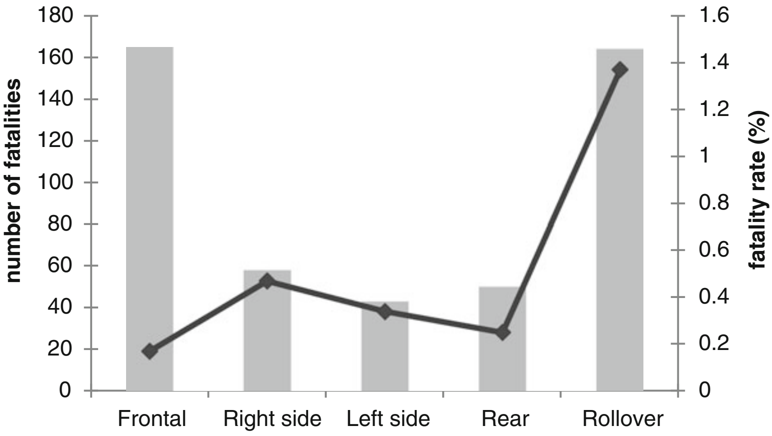

Fig. 2.8 Number of fatalities and fatality risk by crash direction for children aged 0–7. Number of fatalities from FARS 2009 and fatality risk from Viano and Parenteau (2008a)

of age, severe injury as measured by ISS > 16 was greater for children seated near-side (7 per 1,000 children) as compared to those seated in the center (2 per 1,000) or on the far side (1 per 1,000). Similar trends have been delineated for children in child restraints. Injury risk for children in FFCRS nearside to the crash was significantly higher (8.9 injured children per 1,000 crashes) than for children seated on the nonstruck side of the crash (2.1 injured children per 1,000 crashes) (Arbogast et al. 2004a).

Researchers quantified the relative effectiveness of belt-positioning booster seats as compared to seat belts in reducing the risk of injury among 4–8-year-olds in side impact crashes. Children in belt-positioning booster seats were at a 58% reduction in risk of injury than those in seat belts in side impact crashes. Benefits were obtained by reduction of injuries to the head and face as well as the pattern of injuries to the abdomen and spine known as SBS (Arbogast et al. 2005d). Using a broader, more recent sample from the same dataset, Arbogast et al. (2009a) documented that children in side impact crashes benefited the most from booster seats, showing a reduction in injury risk of 68% for near-side impacts and 82% for far-side impacts. In this study, among children restrained in belt positioning booster seats, no difference in side impact effectiveness could be detected between the children in backless versus high back boosters.

Maltese et al. (2005) reviewed cases of seat belt restrained child occupants 4–15 years of age in side impact crashes to explore the role additional occupants play on injury causation. These researchers identified that children who share the rear row with other occupants have a 58% reduced risk of injury in side impact crashes than occupants who sit alone on the rear row.

The limited diffusion of side air bags into the rear seat has prevented many studies of their effectiveness for child occupants. In a study of child occupants from the

PCPS study, Arbogast and Kallan (2007) measured a 10.6% AIS2+ injury rate of children exposed to a deploying side air bag. All injuries were of the AIS2 level and limited to concussions or fractures of the upper extremity. This study did not specifically compare the injury risk of those exposed to a deploying side air bag to those not exposed due to difficulties in identifying nondeployment crashes of similar magnitude to those crashes with deployment.

Many studies have reviewed in depth crash investigations of children restrained in child restraints in side-impact crashes to understand the mechanisms of injury. European studies from the early 1990s reviewed crash data and identified direct contact of the head with the intruding structure or B-pillar as the primary cause of injury or the bullet vehicle (Kamren et al. 1991; Langwieder and Hummel 1989; Langwieder et al. 1996). These researchers identified that most side-impact crashes were forward of direct lateral.

More recent studies confirmed these early findings. Sherwood et al. (2003) studied 14 fatal side-impact crashes involving children in child restraints, and of the six cases with sufficient injury information, head trauma was the cause of fatality. In all fatal side-impact crashes there was intrusion at the child's seating position. In a review of 32 cases of children restrained in FFCRS in 30 side-impact crashes, the most common injuries sustained were to the face, head, and lower extremity (Arbogast et al. 2005b). The absence of chest injuries in this study, a common injury sustained by adults in side impact crashes, and neck/back/spine injuries is of interest. The European-based CREST project reviewed 168 restrained children involved in severe side-impacts and confirmed the head as the most severely injured body region in 62% of the cases. Cervical spine injuries in children in child restraints in side-impact crashes were rare, but when they occurred, often lead to fatality (Lesire et al. 2001). McCray et al. analyzed NASS-CDS cases of 28 children aged 1–3 years in side-impact crashes and described a pattern of injuries that included in decreasing order of frequency: head, torso (including the thorax and the abdomen) and neck. The most common involved physical component associated with these injuries was vehicle interior structures—in particular head contact with the upper door in the area of the windowsill and the intruding seat back. Of interest, the thoracic injuries for children in CRS were primarily lung contusions rather than skeletal rib fractures typically seen in adults in side-impact crashes (McCray et al. 2007).

For children in FFCRS in side-impact crashes, key characteristics that were related to injury were intrusion that entered the child's occupant space or caused an interior part of the vehicle to enter the child's occupant space, forward component of the crash, and the rotation of the CRS, restrained by a seat belt, towards the side of the impact (Arbogast et al. 2005b). One recent study of NASS-CDS data confirmed the role of the longitudinal crash forces in these side-impacts and reported that the most common principal directions of force (PDOF) were 10 and 2 o'clock (McCray et al. 2007).

Several researchers have extended their review of children in side-impact crashes to children restrained in seat belts. In a case series of children treated at a level 1 trauma center that was part of the CIREN network, Orzechowski et al.

(2003) found that seat belt restrained child occupants were 2.8 and 4.8 times as likely to receive an AIS3+ head and chest injury, respectively, in side impacts as compared to frontal impacts. The lower seated height of children increases the risk of head and upper chest contact with the interior door panel or pillars in side-impact crashes. Howard et al. (2004) reported on a two-trauma center database of 28 children 0–12 years of age involved in side impacts and delineated between near-side and far-side injury patterns. Children seated near-side to the crash sustained severe head, trunk, and limb injuries which occurred both in the presence and absence of intrusion. In their study, center-seat and far-side occupants had severe injuries only when unrestrained. Lesire et al. reviewed European data from the CREST crash database, confirmed the significance of head injuries, and documented severe injuries to the chest and abdomen primarily when the child was restrained by a booster seat or was using the adult seat belt (Lesire et al. 2001). The increased frequency of serious head and thoracic injuries to belt restrained children in side impact crashes was reinforced in a review of the CIREN database by Brown et al. (2006). Maltese et al. (2007) in a review of 24 cases of children aged 4–15 restrained in seat belts in side impact crashes found that the majority of the head and face contact points were due to contacts with both interior vehicle structures and structures on the crash partners and were located horizontally within the rear half of the window and vertically from the window sill to the center of the window.

A common injury to adults in side-impact crashes is fracture of the pelvis. In pediatrics, these injuries occur infrequently due to the cartilaginous linkage of the pelvic bones and the increased elasticity of the symphysis pubis and sacroiliac joints. As a result, it has been hypothesized that it takes more force to cause a pediatric pelvic fracture compared to adults (Silber and Flynn 2002). These biomechanical characteristics were evident in a review of pelvic fractures of children in side-impact crashes (Arbogast et al. 2002c). In this study, prepubescent children experienced isolated pubic rami fractures, whereas postpubescent children experienced the more adult-like multiple fractures of the pelvic ring. This distinct injury pattern is directly related to the ossification during puberty of the cartilage connecting the three bones of the pelvis. This will be discussed in more detail in a subsequent chapter.

Other Directions of Impact

Rollover and ejection. Very little research has examined real-world crash data in other crash modes beyond frontal and side impact crashes. Rollover injury and fatality risk in children has received limited attention. Rivara and colleagues (2003) examined the NASS-CDS and FARS datasets from 1993 to 1998 to evaluate the risk associated with rollovers for child occupants 0–15 years of age. They reported about 10% of all children involved in crashes are in a rollover crash with an 11 times increased likelihood of being in a rollover crash in an SUV versus a passenger car. The risk of fatality and injury for children in rollovers was approximately twice that of nonrollover crashes. Using NASS-GES and FARS from a similar time period, other researchers estimated 2.2% of crash-involved children ages 0–12 years were in rollover crashes; however, these crashes represented 28% of the child fatalities. NASS-GES represents a broader dataset than NASS-CDS, which has the requirement of the vehicle being towed as an inclusion criterion; thus the lower estimate of rollover incidence (Howard et al. 2003). Data analyses from the PCPS dataset identified that rollover crashes increased the risk of injury to child occupants 0–15 years of age over three times compared to nonrollover crashes (Daly et al. 2006). More recently, Viano and Parenteau studied NASS and FARS data and found that rollovers accounted for ~60% of the fatalities of children seated in the second row of SUVs. They highlighted the lower belt use and higher likelihood of rollover in SUVs as primary causes of this high percentage (Viano and Parenteau 2008a). Howard et al. (2003) pointed to the role of ejection as a key component of the injury causation scenario for children injured in rollover crashes. Ejection from cargo areas of pickup trucks has also been highlighted as an issue particular to pediatrics (German et al. 2007; Woodward and Bolte 1990).

Rear impacts. Recent interest in child occupant protection in rear-impact crashes has focused on the likelihood of injury to children seated in the rear rows from deforming front seat backs. Jermakian et al. (2008) examined a population-based sample of restrained child occupants, 0–12 years of age, seated in a second row outboard position in rear impact tow-away crashes. For those children with seatback deformation occurring directly in front of them, there was a doubling of the injury risk (4.8 versus 2.1%). The nature of this dataset, however, does not allow the determination of injury causation scenarios. To this end, Viano and Parenteau (2008b) identified 19 cases of children 0–7 years of age involved in rear impact crashes with AIS3+ injuries from the NASS-CDS database from 1997 to 2005. Two-thirds of these cases experienced substantial intrusion into their seating location that caused them to move towards the front seats. The authors identified contact with the front seat back as the source of injury in 10 of the 19 cases; however, they specified that only one of the 19 was injured due to rearward rotation of the front seatback toward the child.

Summary of Injured Body Regions by Direction of Impact

In order to provide guidance for further optimization of child occupant protection, Table 2.7 provides the body region specific injury risks stratified by crash direction and age/restraint. The head is the most common body region injured regardless of crash direction or age/restraint. This is particularly true for near side and rear crashes. The importance of injuries to the extremities in children in CRS is highlighted in frontal and side crashes.

Table 2.7 Patterns of AIS2+ injury stratified by crash direction

	Frontal crashes		Near side crashes		Far side crashes		Rear crashes	
	Children 0–7 years in CRS	Children 8–15 years in seat belts	Children 0–7 years in CRS	Children 8–15 years in seat belts	Children 0–7 years in CRS	Children 8–15 years in seat belts	Children 0–7 years in CRS	Children 8–15 years in seat belts
Overall AIS2+ injury risk (per 1,000 children in crashes)	3.0	12.7	6.7	29.3	3.6	14.6	2.9	8.8
Head (%)	55.7	49.3	60.5	69.6	46.8	59.3	73.0	82.1
Face (%)	8.2	10.4	1.2	4.6	3.2	6.7	5.8	1.0
Chest (%)	4.4	9.0	4.9	4.6	4.8	5.9	3.6	1.8
Abdomen (%)	4.4	8.3	1.2	6.3	3.2	6.7	8.8	6.3
Neck/spine (%)	2.2	1.5	2.5	1.5	1.6	2.2	0.0	1.0
Upper extremity (%)	7.1	14.4	8.6	8.9	27.4	14.4	2.9	3.8
Lower extremity (%)	18.0	7.0	21.0	4.6	12.9	4.8	5.8	4.0

Data from PCPS from 12/1/98-11/30/07. Limited to model year 1998 and newer vehicles. Differences between crash directions should not be interpreted as statistically significant differences

Pedestrians

In 2009, 244 children under 15 years of age died as a pedestrian in the United States, representing one-fifth of the traffic fatalities to this age group. This number represents a 49% decrease in the number of pedestrian fatalities for children since 2000 which is in part attributed to increased attention to improved playing and walking environments for urban children. Incidence rates of pedestrian fatality peak in the young school age child—approximately 6–9 years of age (Dimaggio and Durkin 2002; Miller et al. 2004). Dissection of these numbers reveals a burden dominated by the urban environment with distinct seasonality and time of day effects (Dimaggio and Durkin 2002; Posner et al. 2002, NHTSA 2010a).

The global burden of child pedestrian fatalities is large. Approximately 760,000 pedestrians die each year worldwide with children making up 35% of those fatalities (World Bank 2001). In low and middle income countries, the percentage of pediatric traffic fatalities that are pedestrians outweighs those that are motor vehicle occupants (WHO 2008).

The fatality rates of pedestrians have been documented to vary with vehicle type. NHTSA examined their FARS database from 1997 to 2001 and identified that sport utility vehicles, pickup trucks and large vans have a higher pedestrian fatality rate than passenger cars. These differences were particularly amplified for those <8 years of age in part related to sight lines from these large vehicle types to the younger children (Starnes and Longthorne 2003). This effect has been confirmed by several other researchers (DiMaggio et al. 2006; Henary et al. 2003; Roudsari et al. 2004, 2005; Starnes and Longthorne 2003; Yao et al. 2007).

Child pedestrians have a lower mortality rate than adults and sustain a pattern of injuries that results in a lower ISS and shorter lengths of stay than either young adults or elderly pedestrians (Demetriades et al. 2004; Henary et al. 2003; Peng and Bongard 1999). Understanding the body regions of pedestrian injury requires an understanding of the kinematics of a pedestrian-vehicle impact. Initial impact with the bumper is followed by vehicular hood or windshield impact and then impact with the ground. Injuries associated with each of these three impacts are directly related to pedestrian stature (van Rooij et al. 2004) and thus the injury patterns vary across the pediatric age range. For the smallest children, the hood impact does not necessarily occur and they may be thrown forward or knocked down by the impacting vehicle (Roudsari et al. 2005).

Of note, half of pediatric pedestrian crashes are due to the child darting out between vehicles (Fildes et al. 2004)—rather than at an intersection. As a result, 23% of child pedestrian-vehicle impacts were to the right or left side of the vehicle rather than the front illustrating the importance of considering pedestrian protection when designing the side planes of the vehicle.

Overall for children, at both an AIS2+ and AIS3+ level, the most frequently injured regions in all pediatric age groups were the head/face and the lower extremities (Fig. 2.9). Approximately 15% of child pedestrians with an AIS3+ injury had an injury to the head or face. This percentage was fairly consistent across the pediatric age range. In contrast, the incidence of thoracic injury went down with child age,

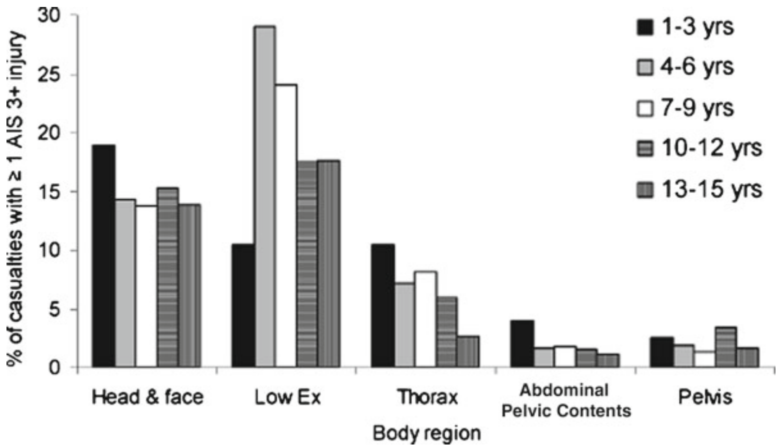

Fig. 2.9 Percentage distribution of pedestrian casualties with at least one AIS3+ injury by body region and age group. The percentages of casualties with ≥1 AIS3+ injury to the upper extremities, spine (lumber or thoracic), or neck (including cervical spine) did not exceed 0.7% in any of the five age groups (reproduced with permission from Ivarsson et al. 2006)

Table 2.8 Top ten priorities for child pedestrian injury mitigation and the associated harm per Fildes et al. (2004)

Top ten priorities for child pedestrian injury mitigation	Harm associated with child pedestrian injury (%)	Harm associated with adult pedestrian injury (%)
Head to hood	16	8
Head to ground	11	8
Leg above the knee to bumper	9	[b]
Head to front area of vehicle[a]	9	[b]
Leg below the knee to bumper	8	12
Head to A-pillar	6	7
Pelvis to front area of vehicle[a]	5	4
Head to windshield	4	21
Leg above the knee to front area of vehicle[a]	3	2
Chest to hood	3	4

[a] Front area refers to the grill, lights, and leading edge of the hood
[b] Not in the top ten priorities for adult pedestrian injury mitigation

while lower extremity injury increased with child age; again pointing to the influence of stature in the injury patterns. Of note, when lower extremity injuries occurred, 85% of the injuries were to the femur and most lower extremity fractures are mid-shaft (Woods et al. 2003).

Fildes et al. (2004) in a review of Australian and German fatal child pedestrian data calculated the HARM or total societal cost for pedestrian events. In this analysis, they identified the top ten body region–vehicle/environment structure impacts that deserve countermeasure development for child pedestrians (Table 2.8).

These areas of emphasis are similar to those highlighted by Roudsari et al. (2005). The harm associated with adult pedestrian injury for these pediatric priorities are also shown in the table for comparison.

Conclusions and Recommendations

While children represent only about 10–15% of the overall traffic fatality burden in the US, MVC remain the leading cause of death and disability for children and young adults and represent close to half of all unintentional injury deaths to children and adolescents. Prevention of the fatalities and disabling injuries associated with MVC is thus a priority for ensuring our children's overall health.

Since the middle 1990s, the safety community has achieved moderate success in reducing this burden. In 2009, 41% fewer children aged 0–14 years died as a result of MVCs than in 1996. These reductions have been achieved, in part, through a combination of increased attention to age-appropriate restraint use and rear seating. These successes should not lead to complacency, however. In 2009, for example, 45% of 4–8-year-olds were not restrained according to best practice recommendations for their age, and one-third of 8–12-year-olds were still seated in the front row.

Even with increases in age-appropriate restraint use and rear seating, the protection of children in motor vehicles must be further optimized. Achieving optimal protection will require knowledge of the unique biomechanical needs of children and youth described in the remaining chapters of this book. Future priorities in child occupant protection must focus on the following issues:

1. *Monitoring trends in child occupant protection through rigorous, child-focused crash surveillance.* Priorities will continue to evolve as child restraint design, restraint use practices, the vehicle fleet, vehicle safety technologies, legislative priorities and regulatory focus continue to evolve. Accurate, timely data are crucial for setting evidence-based priorities. Current crash databases have neither sufficient depth nor breadth of child-specific data to measure important trends, determine effectiveness of occupant protection systems, and identify emerging safety hazards for child occupants.
2. *Optimize the rear seating environment for children and youth.* Children who are too large for current add-on child restraints have an increased injury and fatality risk compared to their younger counterparts. The design and evaluation of a rear row restraint and seating environment that is intrinsic to the vehicle for these children deserves attention.
3. *Develop protection principles for child occupants in side impacts crashes.* Continue to explore the mechanism and causation of injuries sustained by children and youth in side impacts and increase understanding of the timing and nature of a child's interaction with vehicle and restraint components during a typical side impact crash.

4. *Focus epidemiological and injury causation analyses on injuries to the pediatric head and cervical spine.* Head injuries are the most common serious injury sustained by children in MVCs across most age, restraint, and crash direction strata. The exact burden of cervical spine injuries remains unclear in part due to inadequacies of current data collection systems highlighted above. Determination of the prevalence and nature of these injuries, the circumstances under which they occur and the importance of head contact in the causation scenario needs further study.
5. *Assess and evaluate the real-world impact on children and youth of new vehicle safety technologies.* These should include side-impact air bags, advanced frontal air bags, advanced vehicle belt systems such as pretensioners and load limiters, LATCH systems for child restraints, and advanced crash avoidance technologies.
6. *Develop appropriate traffic safety surveillance and intervention programs in the developing world with a particular focus on pedestrians.* Child pedestrian safety outweighs the burden of child occupant safety in many low and middle income countries.

While the safety of children in motor vehicles has improved since the introduction of the first child restraint law in 1978, further advances in child occupant protection will require rigorous collaborative research by epidemiologists and engineers that thoughtfully considers the unique needs of children. Evidence resulting from this research will provide an intellectually sound underpinning to the eventual introduction and adoption of appropriate public policies, improvements in vehicle and restraint design, and adaptation of consumer attitudes and behavior to further increase the protection of children.

Appendix-Data Sources and Methodology

NHTSA Field Crash Databases

To help the traffic safety community identify traffic safety problems, develop and implement vehicle and driver countermeasures, and evaluate motor vehicle safety standards and highway safety initiatives, the National Highway Traffic Safety Administration (NHTSA) developed a variety of field crash databases. Each has a specific purpose and role in the identification of vehicle safety issues and the assessment of countermeasures with the optimal cost/benefit. Many of the analyses described elsewhere in this chapter use these databases as their source of data and thus this description provides context for those studies. In addition, these databases represent resources for researchers to explore topics of motor crash injury for child occupants.

Fatality Analysis Reporting System

The Fatality Analysis Reporting System (FARS) was developed by NHTSA's National Center for Statistics and Analysis (NCSA) in 1975 to assist the traffic safety community in identifying traffic safety problems and evaluating both motor vehicle safety standards and highway safety initiatives. FARS contains data on all fatal traffic crashes within the 50 states, the District of Columbia, and Puerto Rico. To be included in FARS, a crash must involve a motor vehicle traveling on a traffic way customarily open to the public, and result in the death of a person (either an occupant of a vehicle or a nonmotorist such as a pedestrian) within 30 days of the crash event.

FARS case files contain descriptions of each fatal crash reported. Each case has more than 100 coded data elements that characterize the crash, the vehicles, and the people involved. All data elements are reported on the following forms:

- The Accident Form collects information such as the time and location of the crash, the first harmful event, and the numbers of vehicles and people involved.
- The Vehicle and Driver Forms record data on each crash-involved vehicle and driver. Data include the vehicle type, initial and principal impact points, most harmful event, and drivers' license status.
- The Person Form contains data on each person involved in the crash, including age, gender, role in the crash (driver, passenger, nonmotorist), injury severity, and restraint use.

Data are available for every year since FARS was established in 1975 and can be easily queried using a Web-based query system (http://www-fars.nhtsa.dot.gov/Main/index.aspx). To protect individual privacy, no personal information, such as names, addresses, or specific crash locations, is coded. It is important to realize that analyses using the FARS dataset are based on fatal crashes, which may differ in meaningful ways from the general spectrum of crashes on the roads.

National Automotive Sampling System

Established in 1979, the National Automotive Sampling System (NASS) was created as part of a nationwide effort to reduce MVCs, injuries, and deaths on our nation's highways. It is composed of two systems—the Crashworthiness Data System (CDS) and the General Estimates System (GES). Both systems are based on cases selected from a sample of police crash reports. CDS data focus on passenger vehicle crashes, and are used to investigate injury mechanisms to identify potential improvements in vehicle design. GES data focus on the broader overall crash picture, and are used for assessments of the magnitude of a specific traffic safety problem and tracking trends. NASS-CDS and NASS-GES select cases from police crash reports [also known as Police Accident Reports (PARs)] at police agencies within randomly selected areas of the country. Data from GES and CDS are weighted in such a manner that statistical analyses using these weighted data can result in national estimates of the traffic safety topic being studied.

For NASS-CDS, field research teams located at Primary Sampling Units (PSU's) across the country study ~5,000 crashes involving passenger cars, light trucks, vans, and utility vehicles each year. About 200 of these crashes involve a child occupant. Trained crash investigators obtain data from crash sites, studying evidence such as skid marks, fluid spills, broken glass, and bent guard rails. They locate the vehicles involved, photograph them, document the crash damage using sophisticated measuring procedures, and identify interior locations struck by the occupants. These researchers follow up on their on-site investigations by interviewing crash occupants and reviewing medical records to determine the nature and severity of injuries. The data collected by the PSU's are quality controlled by one of two NASS Zone Centers which have the responsibility for coordinating and supervising the activities of the field offices, keeping field offices informed regarding changes in functional and administrative procedures, sharing ideas and concepts throughout the system regarding new techniques, procedures, and components found on vehicles and updating field offices regarding changes in system hardware and software.

NASS-GES data comes from a nationally representative sample of police reported MVCs of all types, from minor to fatal. For a crash to be eligible for the GES sample it must involve at least one motor vehicle traveling on a traffic way, the result must be property damage, injury, or death and a PAR must be completed. These accident reports are chosen from 60 areas that reflect the geography, roadway mileage, population, and traffic density of the US GES data collectors make weekly visits to ~400 police jurisdictions in the 60 areas across the United States, where they randomly sample about 50,000 PARs each year. About 10,000 of these crashes involve a child occupant. The data collectors obtain copies of the PARs and send them to a central contractor for coding. No other data are collected beyond the selected PARs. Trained data entry personnel interpret and code ~90 data elements data directly from the PARs into an electronic data file. An annual publication, Traffic Safety Facts, is produced with GES data for nonfatal crashes, combined with information on fatal crashes from FARS. NASS-GES provides broad estimates of child crash exposures but with little data specific to children, especially on important parameters such as injury and restraint use. NASS datasets can be downloaded for analyses from NHTSA's Web site (http://www.nhtsa.gov/NCSA).

Special Crash Investigations

Since 1972, NCSA's Special Crash Investigations (SCI) Program has provided NHTSA with an in depth and detailed level of crash investigation data. The data collected ranges from data maintained in routine police and insurance crash reports to data from special reports by professional crash investigation teams. Hundreds of data elements relevant to the vehicle, occupants, injury mechanisms, roadway, and safety systems involved are collected for each of the more than 200 crashes designated for study annually.

SCI cases are intended to serve as an anecdotal dataset useful for examining special crash circumstances or outcomes from an engineering perspective. To this end, the inclusion criteria are changed routinely to address emerging traffic safety needs. The benefit of this program lies in its ability to locate unique real-world crashes anywhere in the country, and conduct in depth clinical investigations in a timely manner, which can be used by the automotive safety community to improve the performance of its state-of-the-art safety systems. Individual and select groups of cases have triggered both individual companies and the industry as a whole to improve the safety performance of motor vehicles, including passenger cars, light trucks, or school buses.

The SCI program's flexibility allows for detailed investigation of any newly emerging technologies related to automotive safety. A number of incidents involving alternative fuel vehicles, passenger side air bag deployments, vehicle-to-pedestrian impacts, and child restraints have been investigated. A focus of the SCI program in the 1990s was investigation of cases of serious injuries and fatalities to children exposed to deploying air bags. Summary tables of these cases as well as any other cases the SCI program has investigated are available on NHTSA's Web site (http://www-nass.nhtsa.dot.gov/BIN/logon.exe/airmislogon), as are copies of completed SCI reports.

Crash Injury Research and Engineering Network

In order to maximize the integration of crash data collected by engineers and crash reconstructionists with detailed injury and radiological information collected by clinical teams at hospitals, NHTSA has funded hospital-related studies since the 1980s. In 1991, NHTSA initiated the Highway Traffic Injuries Studies. Over the next several years, research projects were funded at four Level One Trauma Centers to collect detailed injury information on motor vehicle occupants involved in crashes. In 1996, the Crash Injury Research and Engineering Network (CIREN) was developed in response to the need for a uniform centralized data system when three additional Level I Trauma Hospitals were added to the network as part of a settlement agreement with General Motors.

CIREN is a sponsor-led multicenter research program involving a collaboration of clinicians and engineers in academia, industry, and government pursuing in-depth studies of crashes, injuries, and treatments to improve processes and outcomes. Its mission is to improve the prevention, treatment, and rehabilitation of MVC injuries to reduce deaths, disabilities, and human and economic costs.

There are not any CIREN centers focused specifically on children; however, all sites enroll children who present to their trauma centers. These child occupants are screened using criteria pertaining to specific vehicle and crash characteristics as well as the injury and restraint status of the child. Once a subject meets the criteria for enrollment and consents to participation in the study, an in-depth investigation is initiated to collect detailed crash and injury information. Traumatology experts review the occupant's radiology and clinical data for the location and type of the injury. Crash investigators investigate the crash vehicles and the crash scene to determine the severity of the impact and the physical evidence of occupant's interaction within the crash environment. Mechanical and biomechanical engineers experienced in the field of crash testing and biomechanics research evaluate each case to determine the role of the vehicle's design and the level of interaction with the occupant. Together, these multidisciplinary teams of engineers and clinicians review the cases to assess injury causation scenarios and injury mechanisms. These data are publicly available and can be accessed by http://nhtsa-nrdapps.nhtsa.dot.gov/bin/cirenfilter.dll.

Partners for Child Passenger Safety

In 1998, researchers at Children's Hospital of Philadelphia and State Farm Insurance Companies responded to a need for a crash surveillance system focused exclusively on children and created the Partners for Child Passenger Safety (PCPS) Study. Based on many of the design specifications of the NHTSA databases, PCPS data have been used to conduct many of the child-focused analyses that are discussed in this chapter. In place from 1998 to 2007, PCPS consisted of a large-scale, child-specific crash surveillance system: insurance claims from State Farm functioned as the source of subjects, with telephone survey and on-site crash investigations serving as the primary sources of data. Durbin et al. (2001c) described the study methods in detail.

Briefly, passenger vehicles qualifying for inclusion were State Farm-insured, model year 1990 or newer, and involved in a crash with ≥1 child occupant <16 years of age. Qualifying crashes were limited to those that occurred in 16 states and the District of Columbia, representing three large regions of the United States. A stratified cluster sample was designed to select passenger vehicles (the unit of sampling) for the conduct of a telephone survey with the driver. Probability sampling was based on two criteria: whether the vehicle was towed from the scene and the level of medical treatment received by the child passenger(s). For a subset of crashes of specific interest, in-depth crash investigations were conducted using a similar methodology to the SCI program.

International Data Sources

Several countries outside the United States have championed in-depth crash investigation programs to understand child occupant injuries. Examples of these programs are featured in several studies highlighted elsewhere in this chapter. A partial list of these programs includes the following:

- Child Restraint System in Cars (CREST) and Child Led Injury Design (CHILD)—European collaborative research projects (http://www.childincarsafety.org)
  - The CREST project (1999–2000) and the CHILD project (2002–2006) were European Union funded research efforts focused on child safety that involved a consortium of European industry, government and academic entities. As part of these projects, over 800 in-depth crash investigations involving child motor vehicle occupants were conducted. A subset of these in-depth investigations was reconstructed as full-scale vehicle to vehicle crash tests. A third project in this series, Child Advanced Safety Project for European Roads (CASPER) was started in 2009.
- Cooperative Crash Injury Study (CCIS)—United Kingdom (http://www.lboro.ac.uk/research/esri/vehicle-road-safety/projects/ccis.htm)
  - Based at Loughborough University, the CCIS study started in 1983 and investigates more than 1,200 crashes annually. The study selects a sample of cases involving newer vehicles which are representative of crashes occurring in the UK. Both adult and pediatric motor vehicle occupants are studied.
- German In Depth Accident Study (GIDAS)—Germany (http://www.gidas.org/en/home)
  - Officially started in 1999, GIDAS collects crash and medical data through in-depth investigation from ~2,000 cases annually in two cities in Germany—Hanover and Dresden. Cases are chosen based on a statistical sampling plan from crashes reported to police, rescue services and fire departments in the targeted areas. Both adult and pediatric motor vehicle occupants are studied.
- International Road Traffic and Accident Database (IRTAD) (http://www.irtad.net)
  - IRTAD, started in 1988, is a database that houses traffic fatality data from many countries throughout the world. It is maintained by the International Traffic Forum and the Organization for Economic Co-operation and Development. At present the following countries are included: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Korea (South Korea), Luxembourg, the Netherlands, New Zealand, Norway, Poland, Portugal, Sweden, Switzerland, Spain, Slovakia, Slovenia, Turkey, Hungary, the United States, the UK. It serves as an important resource in comparing road safety metrics between various developed countries.
- Volvo's statistical crash database—Sweden—(Jakobssen et al. 2005)
  - Volvo has compiled a crash database from crashes involving their vehicles identified through a Swedish Insurance company. Vehicle damage information is sent to Volvo's in-depth crash investigation team and injury data is gathered from medical records. Several publications have focused on the child occupants that are in this privately held database.

Each of these research efforts has varied objectives and data collection methods, which make it difficult to merge the data for analysis. They do however represent rich sources of detailed data on child occupant injury.

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Pediatric Injury Biomechanics
Archive & Textbook
Crandall, J.R.; Myers, B.S.; Meaney, D.F.; Zellers
Schmidtke, S. (Eds.)
2013, XVIII, 342 p., Hardcover
ISBN: 978-1-4614-4153-3