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Rear Seat Occupant Protection: What Do We Know and What is the Future?

HU Jingwen

(1. *University of Michigan Transportation Research Institute,*
2. *Department of Mechanical Engineering, University of Michigan,* Ann Arbor, MI 418109, USA)

Abstract: Field data analyses have shown that the occupant protection in rear seats failed to keep pace with the advances in front seats likely due to their low occupancy and the lack of advanced safety technologies. This study provided a comprehensive literature review on rear seat occupant protection addressing the different needs for a diverse population, ranging from children in harness restraints to adults with a wide range of stature, age, and body shape. Based on the findings from field data analyses, experimental studies, and computational simulations, rear seat safety can be improved by properly using age-appropriate child restraints and introducing adjustable/advanced/adaptive features into the rear seat restraint systems. However, the lack of biofidelic injury assessment tools for children, older, and/or obese occupants will be one of the major challenges for further improving the rear seat safety. The increased proportion of older and obese populations, the growth of light-weight vehicles, the popularity of smart-phone-based ride service, and the advances in active safety technology and autonomous vehicles will likely increase the significance of rear seat safety but at the same time will pose additional challenges. All these trends suggested that more efforts on optimizing rear seat restraint systems adapting to a wide range of impact conditions, occupant characteristics and sitting postures are necessary in the future.

Key words: vehicle safety; rear seat occupant protection; diverse population; seatbelt; airbag; restraint system optimization; autonomous vehicle

汽车后排乘员保护——回顾与展望(英文)

胡敬文

(1. 密歇根大学 交通研究院; 2. 密歇根大学 机械工程系，安娜堡市，密歇根州，418109, 美国)

摘 要: 事故数据显示，汽车后排乘员保护未能跟上前排乘员安全进步的步伐，可能因为其使用率不高和没有使用先进的安全技术。该文综述了后排乘员保护，旨在解决后排乘员多样化(从需要儿童座椅的儿童到不同身高、年龄和体型的成年人)造成的不同安全需求。基于事故数据分析、实验研究和计算机模拟的结果，正确使用适龄儿童约束系统和引入可调节、高级、或自适应的约束系统可以改善后排乘员安全。然而，缺乏具有足够人体真实度的代表儿童、老年人、和肥胖者的损伤评估工具或将成为进一步改善后排乘员安全的主要挑战之一。老年人和肥胖人口的比例增加、轻型车辆的增长、智

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第一作者 / First author : HU Jingwen / 胡敬文(1977—)，天津，副研究员。E-mail: jwhu@umich.edu

能手机打车服务的普及、以及主动安全和无人驾驶车辆技术的进步将可能增加后座安全的重要性，同时也会对后排乘员保护带来额外的挑战。因而，未来需努力优化适应各种碰撞工况、乘员特性和坐姿的后排乘员约束系统。

关键词: 汽车安全; 后排乘员保护; 多样化人群; 安全带; 安全气囊; 乘员约束系统优化; 无人驾驶车辆

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Introduction

Despite the advances in vehicle safety designs in the recent years, motor vehicle crashes continued to be one of the leading causes of death among the younger age groups in many nations, and they caused over 1.2 million deaths worldwide in 2012 based on a recent report by World Health Organization [1]. The current design process for vehicle safety systems relies heavily on crash tests to ensure vehicle crashworthiness and occupant protection. In the U.S., crash test programs include those defined in Federal Motor Vehicle Safety Standards (FMVSS), the U.S. New Car Assessment Program (US-NCAP), and the safety rating system designed by Insurance Institute for Highway Safety (IIHS). In Europe, China and many other countries, similar crash test programs are available. Unfortunately, most regulation and consumer crash tests have focused on the protection for front seat occupants due to their high occupancy. Even for crash test programs that include rear seat occupants, their safety criteria are not as comprehensive and stringent as those used for front seat occupants. As a result, advanced safety technologies that are widely used in front seating positions are less frequently available in the rear seat environment. A direct consequence of the lack of technologies is that the safety advantage of sitting in the rear seats over the front seats has diminished significantly for newer vehicle models in the recent years. Many studies have even shown that front seats are safer than the rear seats in newer vehicles, especially for older occupants.

The safety designs for the rear seat occupants are made more challenging by the wide range of occupant sizes and ages. Unlike the front seats, which are occupied almost entirely by adults, the rear seat environment has to accommodate younger children in harness restraints and older children using boosters or directly sitting in the vehicle seats. In addition, the rear seats are more often used by older population who cannot or are not willing to drive. This diverse population in rear seats has posed different needs for safety designs, which may conflict to each other.

Moreover, there are also several trends in the demographics, energy policies, transportation modes, and vehicle technologies that may significantly affect the rear seat occupant protection. These trends include, but not limited to, the significant increase of older and obese populations worldwide, the increase of fuel-efficient small vehicles and the associated severe crash pulses, the rapid growth of smart-phone-based on-demand ride services in many countries, and the increased attention of autonomous vehicles, which would virtually put all occupants into "rear seats". Such trends will have significant impacts on who will be sitting in rear seats, the occupancy rate in rear seats, and the crash severity that has to be considered for rear seat occupant protection.

Given the complex problems and trends related to the rear seat occupant protection, the objective of this literature review is to better understand the crash injury problems associated with rear seat occupants, the designs and technologies that can help improve the rear seat occupant protection for the diverse population, and the challenges and directions for future rear seat safety research.

1 Crash Injury Data for Rear Seat Occupants

1.1 Rear Seat Safety is not Keeping Pace with Advances in the Front Seat

Although previous field data analyses have estimated that rear seat occupants are typically at lower risk of serious injury and fatality than front seat occupants in motor vehicle crashes [2-3], more recent studies have shown that the rear seat's safety advantage has been diminishing, especially for elderly occupants, in newer vehicle models [4-10].

Specifically, Kuppa et al. [5] conducted a double-paired comparison study using data from Fatality Analysis Reporting System (FARS), and found that occupants younger than 50 years of age benefit from sitting in rear seats, while the front seats can provide significantly better protection to belted occupants 50 years and older. Smith and Cummings [7] confirmed the findings from Kuppa's study by a matched-cohort analysis using FARS data and further found that the relative effectiveness of rear seats to mitigate fatality decreased with increase in occupant age. They also suggested that when front passenger air bags are present and occupants are belted, putting adults in front and children in back will enhance child safety without sacrificing adult safety.

Kent et al. [4] found similar injury trends to the above two studies, and further discovered that the protective effects of sitting in rear seats relative to front seats for belted adults in newer vehicle models is lower than that in older models. Similarly, Sahraei et al.[6] found that vehicle model year has a significant effect on the relative safety benefits of rear seats with respect to the right front seats based on the FARS data. Winston et al. [10] found that with drivers experiencing significant safety benefits with newer vehicle models, children restrained by safety belts alone derived less safety benefit from new vehicles. Bilston et al.[9] conducted a matched-cohort analysis of data from the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS), and concluded that the safety for front seat occupants has improved over the last decade, to the point where, for occupants over 15 years of age, the front seat is safer than the rear seat. While the benefit of rear-seated children aged 9-15 years has decreased over time, they are still at lower risk in the rear seat. A more recent study by Durbin et al. [8] further confirmed that, as compared with front seat occupants, rear seat occupants older than 55 years of age had increased risk of serious and fatal injuries in the newest vehicle models. These findings do not necessarily mean that the rear seat safety is getting worse over the years, but rather highlighted the fact that rear seat safety is not keeping pace with advances in the front seat.

1.2 Age Distribution for Rear Seat Occupants

The design of a vehicle rear seat compartment for protecting occupants is challenging because of the wide range of occupant age that must be considered and protected. As shown in Fig. 1, based on motor vehicle crash data in the U.S., more than half of the rear seat occupants are children younger than 12 years old (YO), about 40% of whom are older children between 6 and 12 YO [11]. Previous studies have shown that most U.S. children 6 to 12 YO are riding without boosters, even if 100% compliance with the current booster laws is assumed because booster laws generally only apply to ages 8 and younger in the U.S. Because most 6-12 YO children are smaller in body size than adults, the slouched posture that these children typically assume in vehicle seats would result in poor belt fit that may significantly increase the risk of submarining [12, 13]. Trowbridge and Kent [14] conducted an analysis to quantify the rear seat occupant exposure and found that the annual rear seat travel exposure is similar among children younger than 12 YO and teens/adults from 13 to 64 YO (18.9 vs 19.1 billion person-trips), suggesting that child protection, especially for older children age 6-12 who use vehicle restraints directly, should be considered in rear seat advanced restraint system designs. If we combined these results with the higher injury risk for the elderly population in rear seats than in front seats, in addition to protecting mid-size male occupants, rear seat advanced restraint system designs should also provide improved protection to occupants of all ages and sizes, such as school-age children and older occupants.

1.3 Injury Patterns for Rear Seat Occupants

Interestingly, the injury patterns for the rear-seated children and adult populations are different. As shown in Fig. 2, based on a study by Kuppa et al. [5], for belted children, the most frequently injured body region is the head, while for adults the most frequently injury body region is the chest. School-aged children sustained significantly more injuries to the abdomen compared with other age groups. The main source of head injuries for rear seated children is the back of the front seat or other vehicle interior [15], while the major source of chest injuries for rear seated adults is the seat belt [5], likely due to the lack of advanced seat belt features, such as pre-tensioner and

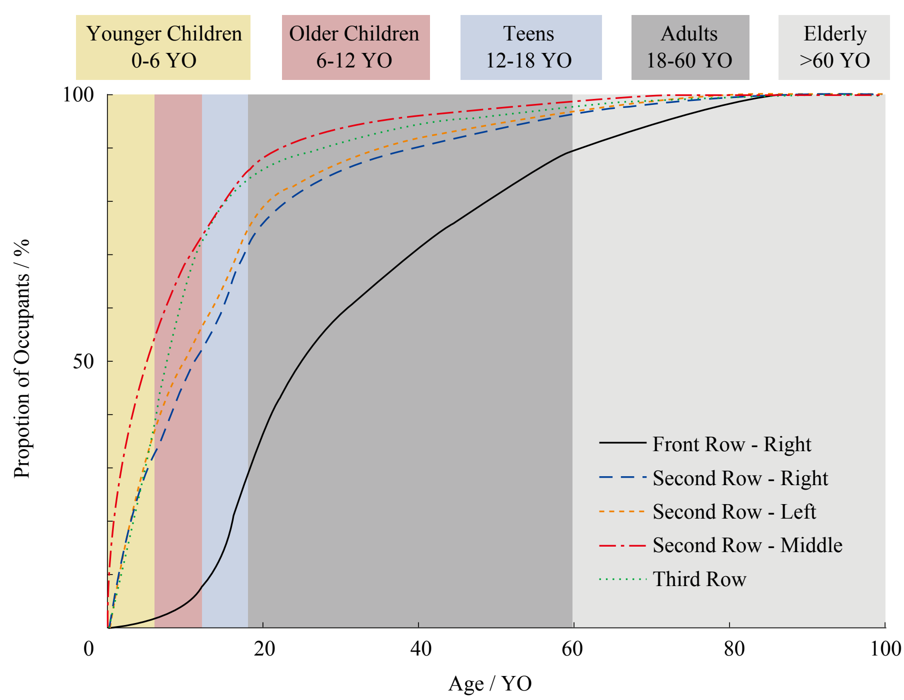

Fig. 1 Age Distribution of Rear Seat Occupants Involved in Motor Vehicle Crashes in U.S. [11]

load limiter. The abdomen injuries in school-aged children may often be referred to as "seat belt syndrome" [16-20], because they are frequently restrained by seat belts designed for adults while their immature pelvis [17, 21] can allow the belt to move up into the abdomen in frontal crashes, potentially producing serious abdominal injuries. These results suggested that the restraint system types and characteristics that provide optimal protection for children may be different from those for adults. An advanced restraint system capable of adapting to a range of occupant sizes and conditions and addressing different injury priorities and causations is necessary for systematically improving the rear seat occupant protection.

Fig. 2 Distribution of Injuries to Different Body Regions as a Function of Age for Belted Rear Seat Occupants (U.S. data based on Kuppa et al. [5])

2 Best Practice for Children in Rear Seats

Due to the large proportion of child occupants in rear seats, a good understanding of child passenger safety is an important step for improving rear seat occupant protection. Fortunately, based on the report by U.S. Centers for Disease Control and Prevention, over the past decade the number of death for children in motor vehicle crashes has reduced significantly to the point that it is no longer the leading cause of death for children aged 1-4 YO in the U.S. [22]. This reduction is, in part, due to the improvements in the child restraint designs and the increase in use of proper child restraints enforced by the state laws and promoted by education. The experiences gained in the U.S. and other developed countries can be applied to other countries for child passenger protection.

The safety benefit of using child restraints has been well documented in the literature. An early study by Kahane [23] reported that the effectiveness for reducing death and serious injury by correctly using rear-facing and forward-facing child restraints was 71% and 54%, respectively, while the average overall effectiveness of child restraints (correct users plus mis-users) was 46%. Later studies by Arbogast et al. [24] and Zaloshnja et al. [25] showed even more impressive safety benefit (78% to 82% injury reduction for children younger than 4) from forward-facing child restraints compared with 3-point belt, although lower safety benefit (28% reduction in fatality risk for children 2-6 years old) has also been reported [26]. For children aged 0-2, rear-facing child restraints were found to be more effective than forward-facing child restraints [27], while for children aged 4-8, booster seats reduced the injury risk by 45% compared with those in seat belts [28]. Given the fact that the 3-point belt alone can already reduce the fatalities of rear seat occupants by 44% [29], compared to children in age-appropriate child restraints, unrestrained children are >3 times more likely to sustain injury in crashes [30].

Based on the strong evidences of the safety benefit by using child restraints, both the American Academy of Pediatrics [31-32] and the National Highway Traffic Safety Administration (NHTSA) recommended four steps to keep children safe in the vehicles [33], which is shown Fig. 3. It was recommended that children should use rear-facing child restraints in the rear seat as long as possible to the rear-facing height and weight limits for the design, which could be up to age 2 or 3. Once the design limits for rear-facing are reached, children should use a forward-facing child restraint with a harness and tether in the rear seat as long as possible to the height or weight limit for the harness. Once children outgrow forward-facing child restraints, they should use booster seat in the rear seats until the seat belt fits. Good belt fits can be judged based on the following tests:

1) they can sit all the way back in the vehicle seat with knees bent at the edge of the seat cushion;

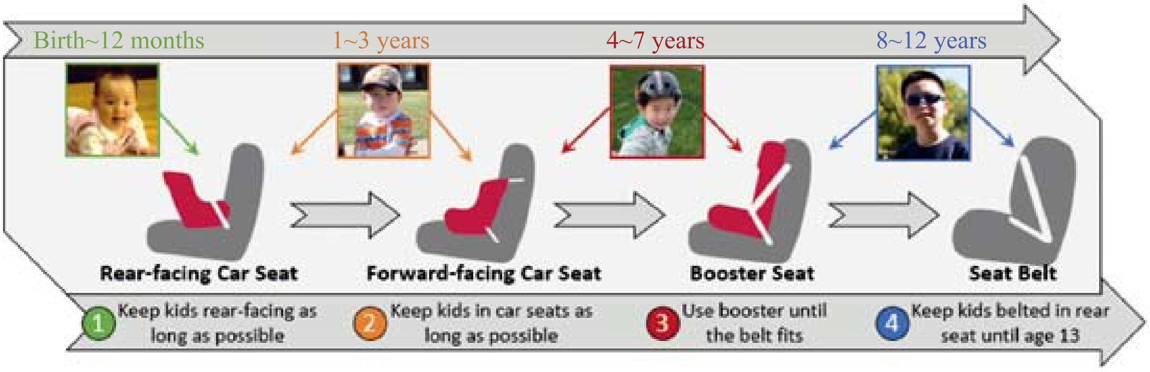

Fig. 3 NHTSA Recommended Four Steps to Properly Protect Child Passengers

2) the shoulder belt crosses the center of the chest and rests on the shoulder, not the neck; and

3) the lap belt fits low and snug on the upper thighs, not the abdomen. Teens should ride in a 3-point seat belt in the rear seats once they outgrow a booster seat.

Even though the NHTSA recommendations seem straight-forward, but they are not easy tasks. In the past decade a large number of studies have investigated interventions to increase the correct use of child restraints. However, misuse of child restraints continues to be a problem in the U.S. and many other developed countries. U.S. studies have shown that even though the usage rate of child restraints are high, especially for infants and toddlers, the misuse rate for child restraints was between 65% and 89% [34-38]. As for the developing countries, such as China, the public awareness of using age-appropriate child restraints is generally low, likely due to the lack of law enforcement and education [39-42]. Therefore, the improvement of child passenger safety in the developing countries may lie in stronger enforcement and better public education. Technical issues related to child restraints, including child seat installation [43], usability and vehicle/child restraint compatibility [44-45], child restraint designs [46-49], and quantitative method for evaluating the belt fit [50] have also been investigated extensively in the literature, all of which could be further improved.

3 Children from 6 to 12 YO

3.1 Belt Fit and Submarining

As mentioned earlier, it is recommended that 6 to 12 YO children should use boosters once they outgrow their harness restraint and before the seat belt fits properly. However, caregivers relying on age-based guidelines are likely to transition their children out of boosters at or before age 8. There is a need for rear seat environments to provide good crash protection for children ages 8 to 12 or even younger, who are not using boosters. The increased rate of injury when children transition from boosters to the vehicle seatbelt alone also supports the need for improved crash protection for young school-aged population [28, 51-52].

When 6 to 12 YO children use the vehicle seatbelt without a booster, the vehicle seat and seat belt geometry affect restraint performance. Most rear seats are too long for children between age 6 and 12 to sit without slouching [11], and these children generally obtain poor lap and shoulder belt fit when seated without boosters [53]. A poor lap belt fit (too high on the abdomen) allows the lap belt to deform the abdomen in frontal crashes through an occupant motion pattern known as "submarining", potentially producing serious abdomen and spine injuries [17, 19, 21, 54-55]. Shoulder belts that fit too close to the child's neck can lead to the child putting the shoulder belt behind the back or under the arm [56], and belts that are routed too far outboard can be ineffective in restraining the torso. Both of these types of misuse lead to poor torso restraint and an increased potential for head injuries due to contact with the vehicle interior.

3.2 Previous Studies on 6 to 12 YO Occupant Protection

Previous experimental studies have demonstrated the effects of restraint conditions on the occupant responses in frontal crashes using Hybrid III (HIII) 6 YO and 10 YO anthropomorphic test devices (ATDs) [57-58]. However, these tests were conducted using the FMVSS No. 213 test bench, which has been reported to be longer, flatter, and softer than real vehicle seats [59]. More recently, a series of 13 sled tests were performed to evaluate the effects of seat cushion length and lap belt angle on child ATD kinematics in real vehicle seats using the HIII 6 YO and 10 YO ATDs [60]. These test data also provided valuable information for understanding the kinematics of child passengers with a range of sizes under different restraint configurations. They suggested that shorter seat cushion and more vertically oriented lap belt can reduce the submarining risk for the HIII 6 and 10 YO ATDs.

Computer simulation plays an increasingly important role in automotive safety research due to its cost-effectiveness relative to physical testing and its versatility in addressing a wide range of crash conditions. Previous studies using child

ATD MADYMO models have demonstrated the feasibility and usefulness of improving pediatric restraint system designs using computational modeling [61-63]. Focusing on improving the ATD biofidelity for simulating submarining conditions, Hu et al. [64] developed a modified HIII 6 YO ATD model that incorporates more anatomically accurate ATD pelvis and abdomen designs. The modified ATD model correctly simulated ATD kinematics in cases with or without submarining under FMVSS No. 213 test conditions. However, because the physical versions of the modified pelvis and abdomen were under development, they do not represent the performance of the standard HIII 6 YO ATD used in regulatory testing. Furthermore, FMVSS No. 213 test bench was used to conduct the parametric study, which may not be representative to the real vehicle seats. To solve this problem, Wu et al. [65] developed a parametric MADYMO child ATD model representing children from 6 to 12 YO. This ATD model along with a real vehicle seat model were validated against 12 sled tests conducted by Klinich et al. [60] with the 6 YO and 10 YO HIII ATDs over a range of belt and seat conditions. This model provided a valuable tool for restraint system design optimization for 6 to 12 YO children. Using these models, Hu et al. [66] conducted a large-scale parametric study for optimizing the rear seat cushion length and stiffness as well as the seatbelt anchorage locations for 6 to 12 YO children without a booster (see Fig. 4). It was found that all the 6 to 12 YO children would benefit from a short and stiff seat cushion. Smaller (6YO) children would benefit more than the larger (12YO) children by moving the three seatbelt anchorages more forward, which will significantly reduce the submarining risk.

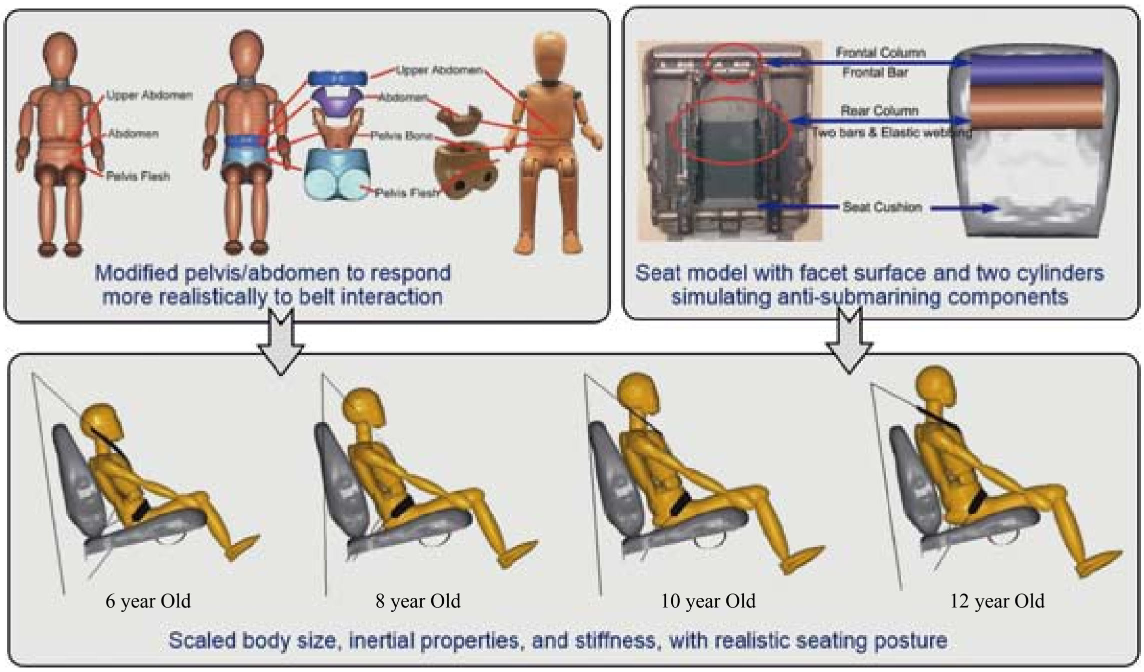

Fig. 4 MADYMO 6–12 YO Child Models Sitting in Vehicle Seats [66]

Furthermore, Hu et al. [67] conducted several series of sled tests and computational simulations focusing on optimizing the rear seat and belt geometries for 6 to 12 YO children, mid-size male adults, and infants in rear-facing child restrain system (CRS). It was found that the optimal belt anchorage locations and the seat cushion length for older children, adults, and rear-facing CRS-seated infants conflict with each other. In particular, as shown in Fig. 5, more-forward lap belt anchorage locations that prevent submarining for older children would reduce the protection to both adults and CRS-seated infants, although the protection is still acceptable based on regulated injury criteria. Shorter seat cushion could provide optimal protection to older children and adults, but would significantly increase the CRS rotation. These results suggested that adaptive/adjustable restraint systems may be necessary to simultaneously improve the rear seat occupant field performance for all age groups.

3.3 Challenges and Opportunities for Protecting Rear-Seated 6 to 12 YO Children

There are two major challenges in the research regarding 6 to 12 YO occupant protection. First, due to the lack of child cadaver tests, child ATDs are primarily the scaled versions of adult ATDs. Given the significant differences in both mechanical properties and anthropometry between adults and children, the scaling method poses many problems in the biofidelity of the current child ATDs. For example, the HIII child ATDs are often criticized for their stiffer spine compared to real children [68-69], which may result in unrealistic kinematics and high neck forces and moments in crashes, which might not be representative of their true injury potential [70]. Recent child volunteer [71-74] and cadaver tests [68, 75], as well as the computational modeling work [76-77] have provided much better understanding of child spine characteristics in

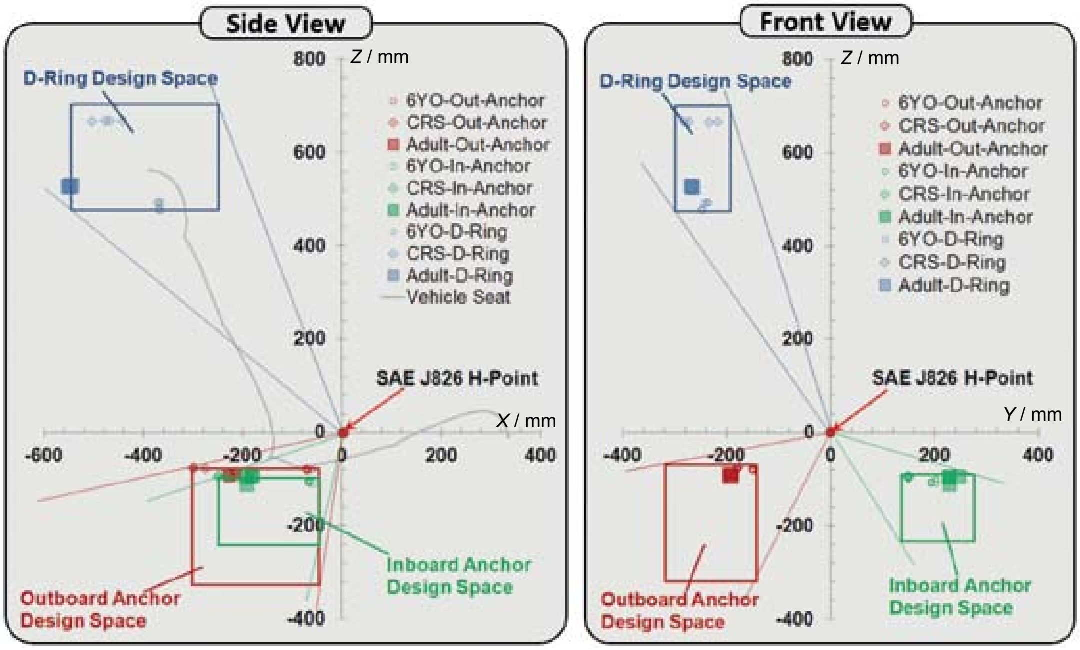

Fig. 5 Optimal Locations of Three Seatbelt Anchorages for 6 YO Children, Adults, and Infants in RF–CRS

impact conditions. However future work is critically needed for developing more biofidelic injury assessment tools for children. The advances in finite element (FE) human body models [78-86] may provide a good alternative to better predict the impact responses of children in the future. Second, field data have shown that the likelihood of head injury for 6 to 12 YO children is high, which are mainly due to the contact between the head and the back of the front seat or the B-pillar. However, previous experimental and simulation studies showed that the risk of the head contacting the vehicle interior is relatively low when a child ATD is properly restrained by the seatbelt. It is possible that the head injuries for 6 to 12 children were often associated with seatbelt misuse or occupant being out of normal sitting position, which has not been considered in the previous research. Unfortunately, such conditions are very difficult to be documented in crash injury data. In a recent study by Arbogast et al. [87], naturalistic driving data with a Kinect sensor monitoring the child occupant position were analyzed. The preliminary results showed more variability in children's head position in the booster seats than in forwarding-facing child restraints, and the role of activities, in particular interactions with electronic devices on head position was notable. Future studies on better protecting children with varied sitting posture and reducing the potential of seatbelt misuse are necessary.

4 Older and Obese Occupants

4.1 Increased Proportion of Older and Obese Population

Due to increasing life expectancy and decreasing birth rates, the growth rate of older population is much faster today than in the past and it is expected to be even faster in the next several decades in the US, Japan, China, and many other countries. By 2030, 20% of the US population will be age 65 or older (http://www.census.gov). Similarly, China will have 285 million people over the age of 60 by 2025, and the projected portion of China's population over age 65 will be more than 23% in 2050. The proportion of obese population has increased significantly worldwide since 1980s according to World Health Organization. In 2014, 39% of adults aged 18 years and over were overweight and 13% were obese around the world. In the U.S., the prevalence of overweight and obesity were 68.8% and 35.7% in 2009-2010, compared with 55.9% and 22.9% in 1988-1994 [88]. A study by Finkelstein et al. [89] predicted that the prevalence of obesity would be up to 42% in the U.S. in 2030. The projected increase of older and obese population motivates future efforts to develop safety designs in rear seats for mitigating injuries for these vulnerable populations.

4.2 Higher Injury Risk for Rear-Seated Older and Obese Occupants

Field data have also shown that in frontal crashes the most frequently injured body region for belted rear-seat adult occupants is the chest, and the major source of these chest injuries is the seatbelt [90-91]. Parenteau and Viano [92] found that in frontal crashes chest injuries accounted for 76% of the total AIS3+ injuries for belted rear-seat occupants older than 12 years old, while head and lower extremity injuries only accounted for 9% and 8%, respectively. Most of these head and lower extremity injuries were caused by the contacts to the back of the front seat.

While chest injury is the major concern for rear-seated adult occupants, obese occupants may sustain increased injury risks on different body regions, including the chest, than occupants with normal body mass index (BMI) levels. For example, by analyzing field data, Cormier [93] reported that obese occupants had 26% and 33% higher risk of AIS2+ and AIS3+ chest injuries, respectively, than lean occupants. By conducting cadaver tests, Forman et al. [94-95] found that obese occupants experienced greater head, torso, and knee excursions, higher chest deflections, and higher submarining tendencies than the lower BMI occupants. Computational studies by Turkovich et al. [96-97] and Shi et al.[98] also showed that increase in BMI may significantly increase the chest and lower extremity injury risks for front-seat occupants in frontal crashes. It was found that these increased injury risks are associated with greater mass and body-shape-induced poor belt fit for obese occupants.

4.3 Challenges and Opportunities for Rear-Seated Older and Obese Occupant Protection

One of the major challenges for improving the older and obese occupant protection in rear seats is the lack of injury assessment tools for those vulnerable populations. There are only three sizes (small female, midsize male, and large male) of ATDs available for the adult population. Unfortunately, FE human body models typically have the same size and shape specifications as adult ATDs because of the desire to compare predictions between human FE models and ATD models. As a result, current FE human body models are limited in the same way that adult ATDs are limited. They are not able to represent occupants with a wide range of body shape and age. The relative contributions of age and obesity related effects on injury risks in crashes can best be assessed using a parametric human FE model, which can be morphed automatically to account for age and BMI effects on geometries for the skeleton and external body shape. Several previous studies [99-101] in the literature have demonstrated that mesh morphing method can rapidly change a baseline human FE model into other geometries that are very different from the baseline model (see Fig. 6).

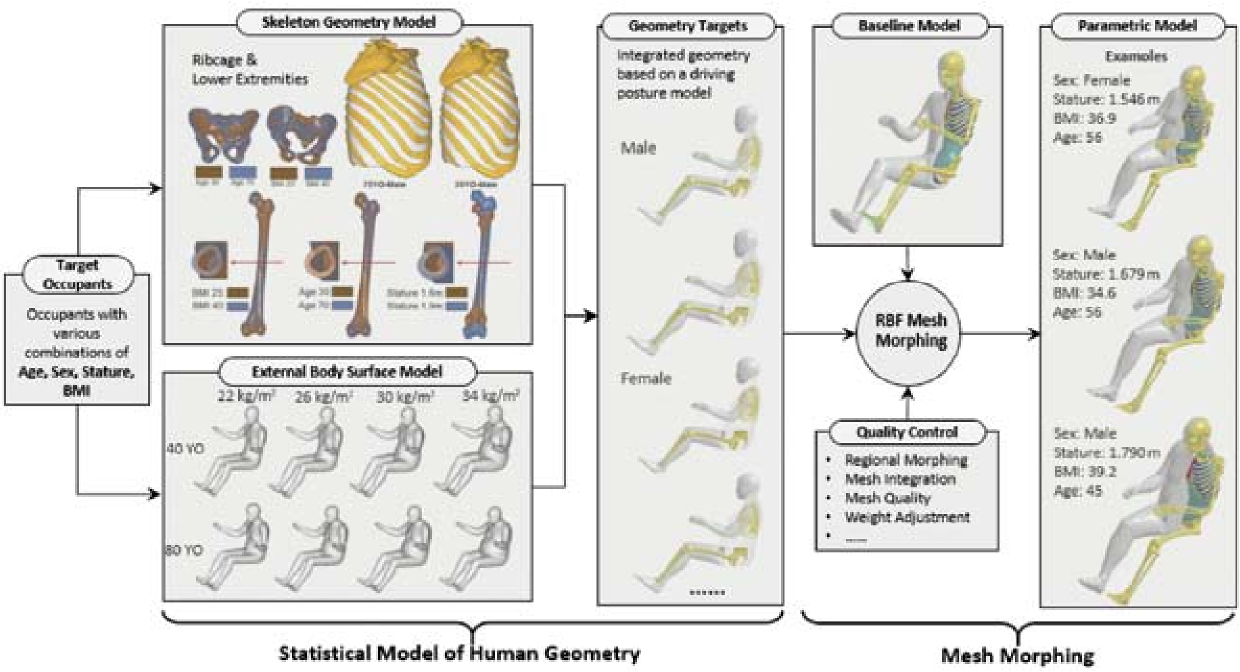

Fig. 6 Method for Developing a Parametric Human Model

A recent study by Wang et al. [102] used 4 morphed FE human models with different BMI levels to study the protection for rear-seated occupants considering the obesity effects. They found that optimizing load limiter and adding pretensioner(s) can reduce injury risks associated with obesity, but conflicting effects on head and chest injuries were observed. It was suggested that a seat belt system capable of adapting to occupant size and body shape should be used to improve protection for obese occupants in rear seats. Further enhancement for the rear-seated older and obese occupant protection could lie in adaptive restraint designs optimized by the parametric human FE models.

5 Advanced Technology and Design Optimization

5.1 Advanced Restraint Systems Suitable for Rear Seat Occupants

Even though advanced safety technologies have become widely available in front seats, they are less frequently available in rear seats. Advanced seatbelt technologies suitable for rear seat occupant protection are shown in Fig. 7, including 3-point seatbelts with pre-tensioner(s) on the shoulder retractor, lap anchor, and/or buckle, constant load limiter (CLL), progressive load limiter (PLL), digressive load limiter (DLL), switchable

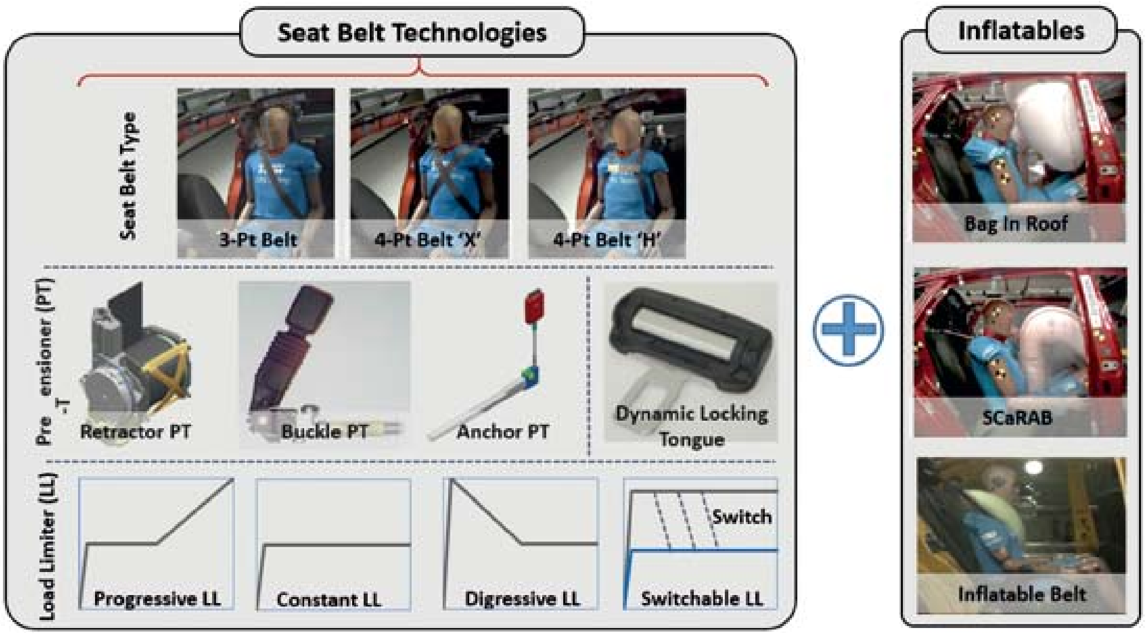

Fig. 7 Advanced Restraint Technologies for Rear Seat Occupant Protection

load limiter (SLL), and dynamic locking tongue (DLT). There are also special-designed seatbelts and airbags that may improve the rear seat occupant protection, including 4-point belt in X or H types, inflatable belt, Bag-in-Roof (BiR), and Self Conforming Rear-seat Air Bag (SCaRAB) (see Fig. 7).

Generally speaking, the advanced restraints are intended to engage the occupant early and allow the restraint systems to absorb the energy with a lower load without allowing contact to the vehicle interior. Pre-tensioners are used to engage the occupant early and begin to slow the occupant down relative to the vehicle. A retractor pre-tensioner is the most common form of pre-tensioner. It helps reduce the slack in the shoulder portion of the belt system. An anchor pre-tensioner helps reduce the slack in the lap portion, which may help reduce the pelvis excursion and prevent submarining. A buckle pre-tensioner is connected to both the lap and shoulder portions, therefore it adds pretension to both the lap and shoulder segments of the belt system.

Once the pre-tensioner fires, the load limiter in the retractor manages the load on the belt system to help reduce the occupant loads by allowing the occupant to travel further to absorb the energy. A CLL provides a constant load to the belt as the webbing is pulled out of the retractor, while PLL, DLL, and SLL provide different loading profiles to adapt to different size of the occupants or different crash conditions. For example, a PLL can progressively increase the load out of the retractor as the webbing is pulled out. As a result, smaller occupants will experience a lower load because not as much webbing is pulled out of the retractor, while larger occupants will pull more webbing resulting in higher loads.

The DLT is a lightweight and compact design consisting of a seatbelt tongue (the plate which fastens into the buckle) with a rotating cam and a concealed spring. The DLT allows webbing to pass freely through the tongue when buckling and in normal seatbelt use to ensure comfort and convenience for everyday use. However, in the event of hard braking or a crash resulting in greater than a set value (i.e. 45 N) of force on the belt, the DLT clamps the webbing and prevents the webbing transferring from the shoulder belt portion to the lap belt portion. It works with other seatbelt technologies helping to reduce loads on the occupant's chest.

There are limitations in the belt system when trying to balance low belt loads and excursion. One option to mitigate the excursion and allow low belt loads is to incorporate an airbag. Two airbag concepts have been investigated in the literature for rear seat occupants [103]. One is the BiR, which is a bag that deploys from the roof of the vehicle down between the rear seat occupant and front seat back. The second is the SCaRAB, a bag that deploys from the front seat back. Its shape and size allows it to conform to the space between the occupant and front seat back without adding bag volume.

A further option with a belt only system is the 4-point belt. It can be in X-type or H-type, but both configurations incorporate two retractor pre-tensioners with load limiters that position the belt over both shoulders and two tongues that anchor the lap portion. Since 4-poaint belts engage both shoulders, the load is more evenly distributed over the occupant. In addition, it helps balance the loading to the left and right sides of the body. Therefore, it can help even the loading in frontal oblique impacts.

An inflatable belt has a tubular inflatable bladder contained within an outer cover, generally on the shoulder belt only. During a crash, the bladder inflates with gas to increase the contact area between the occupant and restraint and also tighten the belt, both of which can potentially reduce the chest injury risk, especially for older occupants.

5.2 Previous Studies on Rear Seat Restraint Optimization Focusing on Advanced Seatbelt

Compared with the front seat, relatively few studies have focused advanced restraint systems for rear seats. However, some researchers have performed crash tests and computational simulations to evaluate the feasibility of introducing advanced seat belt features, such as load limiters and pre-tensioners, for enhancing rear seat occupant protection.

Zellmer et al. [104] used three sled tests to validate a MADYMO ATD model in rear seat environment. This model was further used to explore the protective effects of load limiters and pre-tensioners. They found that chest loading was significantly reduced with pre-tensioners and load limiters, but they also suggested that the optimal load limit level depends on occupant size and the space available for ride-down.

Kent et al. [4] conducted a parametric simulation study of rear seat restraint designs to assess chest deflection and head excursion trends for various seatbelt load limits, pre-tensioner locations and strokes, and impact severities with the H-III 50th and 5th ATD MADYMO models. The results showed that even though there is a tradeoff between chest deflection and head excursion, they can be reduced at the same time with seat belt load limiters and pre-tensioners even in the absence of an air bag and knee bolster for load sharing.

Forman et al. [105] performed sled tests with H-III 6 YO, 5th percentile female and 50th percentile male ATDs as well as THOR 50th to investigate the protective effects from load limiters and pre-tensioners for rear seat occupants. They found that load limiters and pre-tensioners can effectively reduce the chest deflections for all the ATDs without increasing their head excursions. Tests using cadavers have also been conducted by the same group [106], and the results suggested that 3-point seat belts with progressive load-limiters and pre-tensioners can improve the kinematics (increase forward torso rotation) of rear seat occupants with reduced belt load and chest acceleration.

5.3 A Comprehensive Study on Rear Seat Restraint Optimization

Recently, Hu et al. [103, 107] conducted a comprehensive study on rear seat restraint optimization for a diverse population. In their study, three series of sled tests (baseline tests, advanced restraint trial tests, and a final series of tests), two series of model validations (against each of the first two series of sled tests), and design optimizations using the validated computational models were conducted to investigate rear seat occupant protection with 4 ATDs (H-III 6 YO/H-III 5th percentile female/THOR 50th percentile male/H-III 95th percentile male), 2 crash pulses (soft and severe), 2 impact angles (0° and 15°), and 2 front seat locations (driver and passenger).

In the baseline tests [103], in which seatbelts without pretensioner and load limiter were used, crash pulse and occupant size were found to be the two dominating parameters affecting occupant injury risks, while impact angle and front seat location did not have statistically significant effects. Although no head-to-front-seat contact occurred in any of the baseline tests, in general, a severe crash pulse would result in head, neck, and check injury measures over the injury criteria for adult ATDs with higher ATD excursions than for the soft crash pulse. The HIII 6YO ATD sustained the potential for submarining kinematics in all the tests conducted without a booster seat due to the slouching pre-crash posture. No head-to-front-seat contact occurred in any of the tests with 6YO ATD, which is contradictory to the field data where head is the most commonly injured body region for children. It is possible that, in the field, head injuries in children are generally associated with poor shoulder belt fit or certain level of belt misuse. However, further investigations are needed. Submarining also occurred for 5th HIII and THOR 50th in all the tests under a severe crash pulse in the baseline tests. These results suggested that due to the lack of anti-submarining features in rear seats, submarining may be a common kinematics in severe frontal crashes.

Because field data show that chest is the most commonly injured body region for rear-seated adult occupants, in an attempt to reduce the chest loading while managing head excursion, a second series of sled tests was conducted in Hu's study using prototype countermeasures including 3-point belts with pre-tensioner and load limiter, X-type 4-point belts, inflatable belts, BiR concept, and SCaRAB concept. In this series, only the most severe testing condition (0° and severe pulse) in the baseline sled series was used to focus on the most extreme cases. Compared to the baseline rear-seat belt, advanced restraints generally helped reduce the injury measures for rear seat occupants. Fig. 8 shows examples of injury measure reductions by using different advanced restraints for the 5th HIII ATD. Pre-tensioners were very effective in helping seatbelt engage the occupant earlier and in turn reduce the chest deflection and head excursion, but lower load limit has to be chosen in caution. Submarining can be effectively prevented by the advanced restraints. For 6YO ATD, it might be due to the use of a booster seat, while for the adult ATDs, it is mainly a result of using anchor/buckle pre-tensioner, DLT, and load limiter. The limited results showed that inflatable belt provided similar, but not better restraint to the ATDs than that achieved with the 3-point belt with pre-tensioner(s) and load limiter. The 4-point belt generally reduced the head and neck injury responses for the adult ATDs below the injury assessment reference values (IARVs). Because of their cushion ability, airbag concepts, including BiR and SCaRAB, have the potential to allow further reduction of the torsion bar diameter in the retractor (equivalent to a reduction in load limit) in the seat belts without resulting in a hard head contact to the front seat, with the likely outcome that both shoulder belt load and chest deflection can be reduced

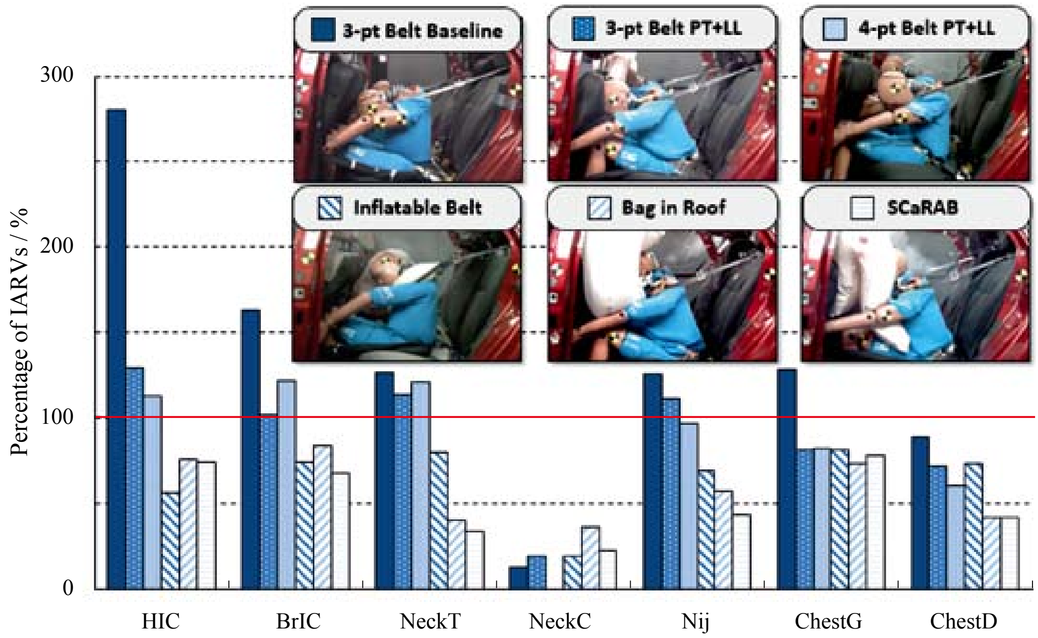

Fig. 8 5th ATD Injury Measures and Kinematics with Different Restraint Systems

with additional system optimization when compared to 3-point seatbelt only designs.

In Hu's study, the results of the above two sled series were used to develop and validate a set of MADYMO models for use in further refinement of countermeasure design. Good correlations between the tests and simulations were achieved through a combination of optimization and manual fine-tuning, as determined by a correlation method. The validated models were then used to perform design optimizations. It was found that advanced belt-only designs (3-point belt with pre-tensioner and load limiter) met all of the IARV constraints under the soft crash pulse but not the severe crash pulse, while the advanced belt and SCaRAB provided the best performance and met all the IARV constraints under both the soft and severe crash pulses.

Two physical prototype restraint systems, namely "belt only" design and "belt and SCaRAB" design, were tested in the final sled series (Table 1). As shown in Table 1, both advanced restraint systems effectively reduced almost all the injury measures for the 6 YO, 5th, and 95th ATDs under the severe crash pulse. The design with the belt and SCaRAB generally provided lower injury measures than those using the belt-only design. However, neither of the advanced restraints reduced the chest deflections for the THOR 50th, because the THOR kinematics is different to the HIII ATDs and the maximal chest deflection of THOR 50th always occurred at the lower chest location close to the buckle, which is not sensitive to the load limiter on the shoulder in the tested crash condition. Further studies are needed to confirm these findings, but this study demonstrated that advanced restraints, including pre-tensioner, load limiter, and airbags can reduce the head, neck, and chest injury risks for a diverse rear-seated population.

Table 1 Design Targets and Injury Risk Reductions for four ATDs by Using two Types of Advanced Restraints [107]

Restraint Configuration	Anchor PT	DLT	Retractor PT	Load Limiter	Air bag
Belt Only	Yes	Yes	Yes	10.5 mm torsion bar	None
Belt & Bag	Yes	Yes	Yes	9 mm torsion bar	SCaRAB

Design Target	Head			Neck			Chest
	Excursion / mm	HIC_{15}	BrIC	F_{tens} / kN	F_{comp} / kN	N_{ij}	D / mm
H-III 6 YO	<480	<700	<0.87	<1.49	<1.82	<1.0	<40 mm
H-III 5th	<500	<700	<0.87	<2.62	<2.52	<1.0	Minimize
THOR 50th	<580	<700	<0.87	<4.17	<4.00	<1.0	Minimize
H-III 95th	<600	<700	<0.87	<5.44	<5.44	<1.0	Minimize

Average Reduction	Restraints	HIC_{15} / %	BrIC / %	Neck T_{tens} / %	Neck F_{comp} / %	N_{ij} / %	Chest D / %
HIII 6YO	Belt Only	−24.1	−46.9	−33.3	−0.5	−43.3	−20.5
	Belt & Bag	−24.1	−56.1	−99.5	−0.5	−46.5	−32.2
HIII 5th	Belt Only	−31.2	−52.5	−67.2	−0.1	−13.1	−24.5
	Belt & Bag	−34.3	−62.0	−73.2	0.0	−18.4	−29.5
THOR 50th	Belt Only	9.6	−18.6	−25.7	0.0	20.2	0.8
	Belt & Bag	−18.4	−46.4	−94.4	0.0	9.1	1.0
HIII 95th	Belt Only	−26.6	−31.8	−34.5	0.0	−10.3	−40.3
	Belt & Bag	−34.4	−58.8	−35.3	0.0	−11.9	−39.6

6 Future Trends and Considerations

Several trends associated with the demographics, energy policies, transportation modes, and vehicle technologies may significantly affect the rear seat occupant protection in the next few decades. For example, the aging population and the increased use of light-weight vehicles may adversely affect traffic safety [108-110]. Over the next 20 years, the aging of population worldwide will result in a growing number of vulnerable occupants who may be more likely to sit in rear seats, and the increase in light-weight vehicles driven by fleet fuel economy requirements may result in stiffer crash pulses due to a smaller crushing zone in front of a small vehicle. Unfortunately, both of these trends tend to increase injury and fatality risks for rear seat occupants.

On the other hand, there is a rapid growth of smart-phone-based on-demand ride services in many countries, which might significantly increase the number of occupants in rear seats, especially in large cities. For example, in the U.S. alone, the Uber app was downloaded 3.8 million times in July 2016, and there are 15.8 million monthly active users for Uber on July 31, 2016 [111]. A similar mobile app in China "Didi Chuxing" serves 300 million users across over 400 Chinese cities, and it was reported that 1.43 billion rides were completed on Didi's platform in 2015 [112]. In the future, the smart-phone-based on-demand transportation may have significant impacts on the proportion of occupants who sit in rear seats, which may increase the significance of research on rear seat occupant protection.

Furthermore, the increased attention of different levels of vehicle automation may increase the importance of rear seat occupant protection as well. For lower levels of vehicle automation, the rear seat occupants may experience certain level of autonomous emergency braking before crashes. Such braking event will likely reduce the impact speed (if a crash cannot be avoided) and change the occupant postures right before the crash, both of which need to be considered when designing restraint systems. A computational study by Hu et al. [113] demonstrated that by considering the driver pre-crash posture and impact velocity, the injury risks for the drivers can be reduced by about 20% to 50% using the adaptive restraint systems. It is expected that similar injury reduction can be achieved for rear seat occupants as well. Looking further ahead, fully automated vehicles will likely be designed with different seating arrangements to enable better functions for business meetings, movie watching, laptop reading, napping, and/or other activities. With the dedicated driver's seat being eliminated, new seating arrangements, such as the face-to-face configuration often used in trains, may become available. The new seating configuration will open up new possibilities for passenger activities and interaction, but it will also have put all the occupants in a rear seat type of environment, which will have a profound impact on occupant protection and restraint system designs.

With the aforementioned trends that may increase the number of occupants in rear seats and provide more complicated environments for a diverse population, further efforts on optimizing rear seat restraint systems adapting to a wide range of impact conditions, occupant characteristics, and sitting postures will be necessary.

7 Summary

This study aimed at providing a comprehensive literature review on rear seat occupant protection and identifying the challenges and opportunities for future rear seat safety research. Field data analyses have shown that the occupant protection in rear seats failed to keep pace with that in front seats likely due to the low occupancy and the lack of advanced restraint technologies. The wide range of occupant age and size that the rear seats have to accommodate made the occupant protection a very challenging work. However, previous studies using experiments and computational simulations have demonstrated that better protection for a diverse population, including small children in child harness restraints, older children in boosters or vehicle seats, adult occupants in different sizes, and obese occupants, can be achieved by using age-appropriate child restraints and adjustable/adaptive restraint systems. The lack of biofidelic injury assessment tools for children, older, and/or obese occupants is one of the major challenges for rear seat occupant protection research. Technologies that can detect the occupant postures before the crashes or keep the occupants in normal sitting posture may be needed to further enhance the rear seat occupant protection, especially for children. With the rapid growth of smartphone-based on-demand ride services and different levels of automated vehicles, it is expected that the proportion of rear seat occupants will increase, especially in large cities; but the increase of older and obese occupants, the stiffer crash pulses associated with light-weight vehicles, and the changed crash conditions and occupant pre-crash postures by the active safety features may pose significant difficulties in designing rear seat restraint systems in the future. All these trends suggested that more efforts on optimizing rear seat restraint systems adapting to a wide range of impact conditions, occupant characteristics and sitting postures are necessary in the future.

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胡敬文　副研究员

密歇根大学交通研究院和机械工程系副研究员。研究兴趣主要集中在通过实验、模拟计算和流行病学多学科相结合的方法进行汽车碰撞中损伤生物力学的研究。最近的课题集中在各种碰撞工况下不同人群的的自适应安全设计。

Dr. Jingwen HU

An Associate Research Scientist at the University of Michigan Transportation Research Institute and the Department of Mechanical Engineering at University of Michigan. His research interests primarily focus on injury biomechanics in motor-vehicle crashes by a multidisciplinary approach using combination of experimental, numerical, and epidemiological procedures. His recent research focuses on adaptive safety designs under various crash scenarios for a diverse population.