MAPPING THE PATH FORWARD TOWARD EQUITY IN CRASH SAFETY: RECOMMENDATIONS FROM AN EXPERT WORKSHOP

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ABSTRACT

Crash testing historically has focused on the use of midsize male anthropomorphic test devices (ATDs). These tools and, more recently, ATDs representing a small female have been used to drive improvements for a diverse population with many differences that can affect injury risk. However, there are still gaps in protection for some population groups that may require different strategies to optimize their protection. To address this, 23 experts from industry, academia, and government convened in October 2022 for a 2-day workshop to reflect on opportunities and challenges in protecting both male and female occupants of different ages and sizes. Workshop participants included experts in biomechanics, behavioral science, human factors, communications, and policy. The discussion focused on how current tools and resources can be used to better protect a range of occupants and what future tools and data are needed to improve safety evaluations and incentivize robustness across the occupant protection design space. This paper reports on the workshop discussion and recommendations along the following key themes: the need to understand the current state of occupant protection to identify priority populations; the need for fundamental data on the populations of interest to improve ATDs and computational tools; computational modeling and human body models as critical tools for studying injury causation and evaluating countermeasures; currently available tools and strategies that can benefit a diverse population; and the importance of collaboration. The recommendations provide several paths to improve safety today and work toward improved protection in the future for a broader range of occupants with diverse needs.

INTRODUCTION

Crash testing historically has focused on the use of midsize male anthropomorphic test devices (ATDs) based on 50^{th} percentile values for stature and body weight for U.S. men in the 1970s. These tools and, more recently, small female ATDs based on 5^{th} percentile stature and body weight for U.S. women, have been used to drive improvements for a diverse population with many differences that can affect injury risk, such as age, sex, and size.

Improvements in vehicle crashworthiness ratings have been shown to have benefits for occupants in real-world crashes. Drivers in vehicles with a good-rating in the Insurance Institute for Highway Safety (IIHS) moderate overlap frontal crash test have a 46 percent lower fatality rate in frontal crashes than drivers in poor-rated vehicles [1]. A study by Teoh and Lund also found drivers in vehicles with a good side crash test rating were 70% less likely to die in a near-side crash compared with a driver of a vehicle rated poor [2]. Occupants in vehicles with a 5-star rating from the European New Car Assessment Programme have a 34% and 40% lower risk of serious injuries and fatalities, respectively, than occupants in 2-star-rated vehicles [3]. An analysis of head-on collisions of vehicles of similar weight from 1979-91 found fatality risk was 20%–25% lower for belted drivers of vehicles with good U.S. New Car Assessment Program composite scores than those in vehicles with poor scores [4]. Regulatory and consumer information crashworthiness evaluation programs have been important means of driving structural and restraint system improvements that have reduced injuries and saved lives.

Despite this progress, there is wide agreement that further improvements are possible. In recent years, there has been growing attention on equitable protection for all vehicle occupants, with a particular focus on narrowing the gap in protection for females relative to males. Studies garnering much of the attention have focused on the increased fatality risk [5] and injury risk [6] for females relative to males. A follow-up study by Noh et al. showed disparities in fatality risk between female and male front row occupants is lowest in the newest generation of vehicles (2.9%in 2015–2020 models) [7]. In 2021, Brumbelow and Jermakian showed that countermeasures have been effective at reducing risk for both males and females, with slightly greater reductions for females. Despite this, females still have a higher risk of moderate (2 on the Abbreviated Injury Scale [AIS]) lower extremity injuries [8].

Although most of the recent attention on inequity has focused on sex, other segments of the population could benefit from additional consideration during the vehicle design and evaluation process. This includes occupants of different sizes, shapes [9], ages [5], and seating positions [10,11]. In October 2022, a group of experts convened to discuss the current state of occupant protection and the necessary next steps to better protect all occupants. The purpose of this paper is to report on the group's findings.

PROCESS

Twenty-three experts from industry, academia, and government convened in October 2022 in Warrenton, Virginia, for a 2-day workshop to reflect on opportunities and challenges in protecting occupants of different ages, sizes, and sex. Workshop participants represented expertise in biomechanics, behavioral science, communications, and policy with experience in vehicle and restraint design, regulation, consumer information ratings programs, ATD development and evaluation, postmortem human subjects research, computational modeling, and behavioral research.

On the first day of the workshop, participants discussed individual perspectives on the theme *Achieving crash safety for all: how to protect our diverse population*. They shared their views on the current state of occupant protection and challenges and opportunities for improvements.

Based on the themes of Day 1, the following key scientific questions were developed and formed the basis for small group discussions on Day 2:

- Changes to regulation and consumer information programs aim to be rooted in real-world data. If we want to make relevant policy changes, what are the gaps in knowledge about real-world injuries and outcomes that will help us take the next leap forward in occupant protection? What are the most compelling research questions that need to be answered?

- We have made tremendous progress in protecting occupants with the tools we have available but there are still gaps in protection. How can we use the tools available today to optimize protection for a wider range of occupants? What tools hold the most promise for the future and what do we need to do today to make those tools viable?

- There is a need for additional human data on a wider range of subjects to improve our physical and computational tools. What are the priority populations for which we need these data? What types of data and how much more do we need? Are there opportunities to expand the avenues to get these data?

The discussion below reports on five key themes and recommendations of the workshop.

DISCUSSION

Theme No. 1: We need to understand the current state of occupant protection to identify priority populations.

Differences in injury risk to men and women have been the focus of many recent studies [6,8,12] and have captured the attention of policymakers and the media. A broader consideration of the literature suggests that while there have been large improvements in protecting all occupants [13,14], there are some populations that could benefit from more targeted occupant protection strategies [6]. To truly understand the significant sources of injury vulnerability requires looking beyond sex-related differences to also consider occupant age, stature, weight, body shape/weight distribution, body mass index (BMI), health comorbidities, posture, and different seating positions. Previous research has provided significant insight into some risk factors such as age [15,16,17], but less has been published about other risk factors such as posture. We need a more thorough understanding of the factors that make people more vulnerable in vehicles and adversely affect system performance, as well as the interdependence of these factors. This is required not only to design more effective countermeasures today, but also to plan for future needs as the population, vehicle fleet, and crashes change. For example, future designs should account for a population that is both older and has a higher BMI and for occupant compartments that allow different seating postures.

Recommendation: Focus research on injury risk differences due to occupant age, stature, weight, body shape/weight distribution, posture, and seating position in addition to sex.

Many studies aimed at identifying priority populations for improved protection continue to group vehicles across design generations. This can produce results that distract from opportunities with the greatest potential future impact. Analyses that include a wide range of model years do not account for the improved vehicle structures, energy management, and restraint systems that have resulted from the current suite of regulatory and consumer information tests [2,8,13]. Since only future vehicles can be improved, it is more informative to study outcomes in the most recent vehicles subject to current crashworthiness tests than to study outcomes in older vehicles that were produced under older, less rigorous safety norms. There are research questions that require grouping many years of data together to increase sample size or focusing on older models that remain on the road. However, needed improvements to regulatory or consumer information crash test programs will be identified most effectively by focusing on the modern vehicle fleet, thereby separating factors that have already been addressed from those that remain.

Recommendation: When analyzing crash data to identify occupant protection gaps, focus on issues that remain in the newest vehicles with the newest countermeasures.

Studies using real-world crash data are critical to developing relevant priorities but also have many limitations due to the nature of the data sources and study methods. Differences in injury risk among populations may present particular challenges, both for researchers and for those communicating the results of the research. For example, some occupants who are perceived as vulnerable may be more likely to have moderate or severe injuries coded than those who are perceived as less vulnerable. Some portions of the population may be more likely to refuse treatment for themselves or others. These types of data biases can influence the results in multiple ways, some of them more obvious, such as whether an occupant counts as injured in the data set, and others less so, such as how an individual crash is sampled and weighted. As another example, since crash injuries are rare compared with all crashes, small absolute differences between population groups may seem large when compared. Beyond data reliability, all analysis methods require assumptions and have strengths and weaknesses that affect the study outcomes. These challenges make it critical for authors to clearly convey study limitations to aid the reader in putting the study in perspective.

Recommendation: Recognize, consider, and clearly communicate limitations of data sources and methods as well as the potential effect on conclusions drawn by the audience.

Theme No. 2: We need fundamental data on the populations of interest to improve our ATDs and computational tools to effectively evaluate safety for diverse populations.

Data supporting our understanding of how crashes occur, which loading conditions produce different injury types, and human injury tolerance have guided significant progress in occupant protection for decades, but there are still knowledge gaps that need to be filled to enable further progress.

Increasing the number of cases available in real-world crash investigation studies like the Crash Investigation Sampling System (CISS) conducted by the National Highway Traffic Safety Administration will help speed the rate of transmission of valuable data available to the research community. The possibility of adding new data sources from state and local municipalities also should be explored. The CISS sampling procedure emphasizes data collection from crashes involving the newest vehicles. Other data sources should follow this model to determine how the newest safety systems are performing. Information from Event Data Recorders (EDRs) provides the opportunity to obtain more accurate data for important crash variables such as impact velocity, occupant belt status, and precrash conditions that may affect an occupant’s position at the beginning of the crash (e.g., accelerator pedal position, braking, steering). Even though almost all (99%) of vehicles on U.S. roads have EDRs, only around one-third (36%) of vehicles in 2017–2020 CISS in which occupants sustained moderate to fatal injuries (AIS2+) also have EDR data available for the crash. Increasing the percentage of cases with EDR data should be a priority for administrators of crash investigation programs. Similarly, better collection of anthropometric data is essential for understanding the unique risks faced by segments of the population. Height and weight measurements do not exist for 34% of drivers in 2017–2020 CISS. Where it does exist, it may have been obtained from unreliable sources like driver’s license data.

Crash investigation studies also can be targeted toward crashes with injury types relevant to groups of specific interest. For example, because females have a higher risk of lower extremity injuries in frontal crashes, selection criteria used to determine which crashes are investigated can be refined to increase their representation in the sample. At the same time, inclusion of uninjured occupants provides data on how occupants are being protected and also is important for improving the accuracy of injury risk assessments. This can be hampered when detailed crash and occupant characteristics are not as well documented for cases without injury.

Some precrash variables are difficult to determine retrospectively. Additional naturalistic driving data and volunteer studies are needed to better quantify how seating posture, seat position, belt placement, and head restraint adjustment vary for occupants of different shapes and sizes. Studies of foot posture and footwear may also improve the understanding of lower extremity injury mechanisms. Understanding how occupants are seated or positioned before a crash is necessary to determine the factors that may affect restraint system performance. These efforts could be supported by the increasing number of vehicles with data loggers (not just EDRs) associated with driver assistance systems. Data and video from these systems could provide information on seat position, driver posture, belt fit, and other precrash conditions.

Recommendations: Expand existing crash investigation programs and push to obtain EDR data from a greater number of cases.

Oversample specific injury types where disparities exist for vulnerable groups.

Expand data collection beyond crash studies to better understand variability in occupant shape, size, posture, and seating position and the effects of these factors on restraint conditions such as belt placement and head restraint position.

Where crash investigation data indicate that certain populations are more likely to be injured or to sustain specific injury types, additional study is needed to understand whether these tendencies are due to physiological differences (e.g., vulnerability related to age or size), anatomical differences (e.g., certain body shapes/sizes that are less protected by restraint system designs), or a combination of both. Vulnerability related to sex, age, stature, shape, and BMI has studied to some extent, but there are still many opportunities for further research. In addition, there may be other indicators that factor into vulnerability and should be explored, such as preexisting conditions (comorbidities), socioeconomic status, and crash location, which can determine the availability of quality health care.

Additional funding is needed to expand post-mortem human subject (PMHS) testing. Groups underrepresented in available PMHS testing include females (including those of average size), larger body shapes (high BMI), and statures different from standard ATDs. Selection of PMHS also should take into consideration future population trends. Whole body testing is needed to better understand how subjects respond kinematically to varying test severity and loading conditions. Additional isolated segment testing also is needed to establish biomechanical corridors and improved injury thresholds for body regions of interest, like the female thorax and lower extremity. Edge cases where PMHS testing severity is close to human injury tolerance (cases with and without injury) are important for establishing good biomechanical reference data.

Human subject testing needs to move beyond the norms established over the last 50 years. Boundary conditions for PMHS testing should reflect the load conditions a person would experience in a modern vehicle (belts, airbags, knee bolsters). ATDs and human body models (HBMs) used in computational modeling depend on realistic biofidelity and injury data for validation. HBMs have the potential to improve our understanding of how the range of physiological and anatomical differences in the population influence injury tolerance, but this depends on the availability of relevant PMHS tests to validate the models. For example, PMHS data investigating seat belt submarining for different body types is an important step toward developing models that can be used to design systems that protect a wide range of occupants in real-world crashes.

Recommendations: Increase collection of fundamental biomechanics data that capture the range of variability in the population.

Increase collection of fundamental biomechanics data with boundary conditions representing modern vehicles for improved validation of physical and computational modeling tools.

Theme No. 3: Computational modeling and human body models are critical tools for studying injury causation and evaluating countermeasures for diverse populations.

Physical testing traditionally has been the foundation of occupant protection system evaluation, but computational modeling already is prevalent during vehicle development and is poised to move into regulatory and consumer information evaluations. Crash tests are necessarily limited by available physical tools and resources such as lab time and monetary constraints. Computational modeling is a critical complement to physical testing because of the flexibility to evaluate additional test conditions in a more comprehensive and cost-effective manner. Creation of computational models is resource-intensive, but once created they can be exercised to evaluate a broader range of initial conditions such as crash severity or direction and occupant posture, size, or shape. These additional scenarios, even ones that represent relatively small changes from the physical test, will result in occupant protection systems that are more robust to variations in evaluated parameters. This flexibility to vary parameters makes computational modeling an ideal tool to evaluate protection for occupants not well represented by ATDs in standard crash test protocols.

Computational human body models have historically been developed with reference to the same body sizes as ATDs. However, the development of parametric human body modeling allows these baseline models to be morphed to represent a wide range of body sizes and shapes. These tools provide the best available means of assessing the effects of body size, shape, and posture on crash outcomes. Most importantly, using human models with a wide range of characteristics, rather than only 5th percentile female and 50th percentile male models, enables improved predictions of how changes in physical test procedures or injury criteria will affect the population of vehicle occupants.

While computational models already are used by automakers and suppliers during vehicle and restraint system development [18,19,20] and by researchers investigating the role of occupant factors on outcomes [21,22], they have not yet been fully embraced for regulatory or consumer information testing. This is due, in part, to the challenge of sharing proprietary data between organizations. Overcoming this requires collaboration to develop a data sharing framework that ensures confidence in the validity of the results while maintaining protection of intellectual property.

Perhaps an even greater obstacle to more widespread use of computational modeling is uncertainty that the models and associated simulation results represent what would be obtained from comparable physical tests. To encourage greater confidence, limits should be placed on the difference in the boundary conditions of the models relative to their underlying physical validation tests. It may be necessary to conduct more physical tests in the short term in order to provide more validation points for virtual testing. It also is important to understand the relative strengths and weaknesses of virtual testing with ATDs and HBMs, and to choose the tool most appropriate for a certain context. Simulations that replicate ATD response can be validated against physical tests with ATDs, but their ability to represent human response is more limited. HBMs are designed to better replicate human response but come with the added requirement to validate the models with limited available physical test data. In addition to better validation data (described above), we need better recommended practices and standardized protocols for use and validation of HBMs.

Recommendations: Expand and prioritize computational modeling as a complement to physical testing to ensure protection systems are robust enough to account for variation in occupant factors such as shape, size, and posture.

Accelerate development, validation and use of human body models to identify safety system advancements that would improve protection for diverse occupant populations.

Develop a framework for sharing simulation data among automakers, suppliers, and regulatory and consumer information programs.

Develop recommended practices for use of computational modeling tools, especially human body models.

Theme No. 4: There are tools and strategies available today that can be used to design for a diverse population.

There are a wide range of tools that can be used to further improve safety for all vehicle occupants. Recently, specific attention has been given to the perceived lack of representation of female ATDs in regulatory and consumer information testing. While ATD choice is one part of a crash test assessment, ATD development is a multidecade process, and there are other potential changes that could be made more quickly that may provide similar or greater benefits than would be achieved with an additional ATD. For example, higher female injury risk often is associated with vehicle selection differences between women and men [8], which is an issue better addressed by improving compatibility across vehicle types. In general, relatively quick progress could be made by improving how we interpret the data we get from current ATDs, evaluating additional occupant seat positions, varying test configurations, and incentivizing faster implementation of technologies known to prevent crashes or mitigate crash severity.

Analysis of real-world crashes has helped identify specific injury types for which improved test metrics are needed. These include chest injuries, especially rib fractures, and lower extremity fractures, especially in the foot and ankle. Potential solutions include adjustment of the maximum allowable ATD injury metrics, introduction of external sensors (e.g. seat belt load cells), metrics based on vehicle structure and/or qualitative measures of performance that can drive improvements in vehicle design. Updating injury assessment values requires additional research and should be done in a manner that aims to minimize harm across a wide range of occupants.

In addition to improving injury outcomes in high-severity crashes, more work is needed to reduce injuries in lower-severity frontal crashes where most rib fractures and lower extremity injuries occur. This would especially help improve outcomes for the most vulnerable occupants, such as the elderly. In high-speed frontal crash tests, modern vehicles tend to have minimal deformation of the occupant compartment, so it is reasonable to assume that injuries in low-severity crashes result from occupant interactions with the vehicle interior and/or restraint system components. Because full-vehicle crash tests can be very costly and time-consuming, improvements to restraint system performance in low-severity crashes can be achieved through sled tests focused on belt engagement and limiting belt loads to levels that are appropriate for older occupants. As with optimization of any system, there is potential for unintended consequences that may put occupants at greater risk in more severe crashes. If potential design changes result in safety trade-offs, optimization should target reduction of harm across a range of crash severities.

Using the existing family of ATDs in a wider range of seat positions is another example of a change that could be made today to improve occupant protection. Studies have shown that safety benefits for front-seat occupants have outpaced those of rear-seat occupants in frontal crashes [10,11]. Technologies that are standard equipment for all drivers and front passengers, like seat belt tensioners and force limiters, are commonly unavailable in rear seating positions. Beyond advances in seat belt technologies, novel airbags eventually may be needed to maximize safety benefits for rear-seat occupants, although care must be taken to ensure these are safe for all rear-seat occupants, including children in child restraints. Tests with existing ATDs may be sufficient for identifying appropriate restraint strategies.

The newest generation of frontal ATDs (THOR) is equipped with increased sensing capabilities and has improved biofidelity compared with the Hybrid-III family of ATDs for certain body regions. However, there is not yet established consensus that testing with these ATDs will result in significantly different test outcomes or drive changes that will benefit real-world occupants. If future test programs utilize new ATDs, they will only be effective at encouraging meaningful improvements when the new sensors have relevant injury criteria and limits.

Recommendations: Explore the use of modified injury criteria and supplemental assessment metrics to differentiate varying levels of occupant protection in existing crash modes.

Establish test methods and best practices for promoting restraint designs that mitigate injury risk in lower-severity crashes.

Establish test methods and best practices for promoting restraint designs that mitigate injury risk for occupants in rear seat positions.

Determine whether the newest generation of ATDs will enable improved crashworthiness and restraints for occupants in the broad spectrum of crashes in the field. If they do not, find ways to redesign these tools or modify how they are used.

The strategies described above involve tools aimed at reducing occupant injuries when a crash occurs, and this reflects the background and expertise of most of the workshop participants. However, strategies that avoid crashes altogether, reduce crash severity, or encourage restraint use will play a crucial role in improving safety for everyone. Many crash avoidance technologies available today already have proven benefits. Studies have shown that:

- Lane departure warning systems have lower rates of involvement in targeted crash types of all severities (18%), those with injuries (18%), and those with fatalities (86%) [23].
- Blind spot monitoring systems reduce lane change crashes of all severities (14%) and those with injuries (23%) [24].
- Automatic emergency braking (AEB) systems reduce all rear-end crashes involving passenger vehicles (50%) and those with injuries (56%); they also reduce rear-end crashes involving large trucks (41%) [25,26,27,28,29].
- Seat belts reduce injuries by 50%–65% and fatalities by 45%–60% [30], but unbelted occupants make up almost half of annual crash fatalities in the U.S. Incorporating fleet-wide persistent audible seat belt reminder systems could increase belt use by about a third [31].
- Speed affects crash frequency and injury severity [32]. Technologies that can help limit speeds (intelligent speed assistance systems) have the potential to prevent speed-related crashes or reduce the energy that needs to be absorbed by vehicle structures and restraint systems when they do occur.

While the diversity of the population presents unique challenges for crashworthiness technologies, active technologies can benefit all occupants in equipped vehicles, occupants in other involved vehicles, and vulnerable roadway users.

Recommendations: Increase adoption of technologies that prevent crashes or mitigate their severity, such as crash avoidance technology, intelligent speed assistance, and alcohol detection technology.

Incentivize persistent seat belt reminder systems in all new vehicles.

Theme No. 5: Collaboration will be the key to success.

The remaining areas for improved occupant protection are diverse. Optimizing protection for a small, young adult female may require different solutions than optimizing for a high-BMI, older occupant. As a result, our efforts in protecting a diverse population are likely to require multiple, potentially divergent paths that will divide a pool of limited resources. To maximize the effectiveness of our efforts, we need to rely on collaboration at all levels: across borders, organizations, and disciplines. This will allow our industry to take advantage of the strengths of different entities and expedite data sharing while limiting project overlap. Some specific needs include:

- Joint collection or development of data (see data needs above)
- Increased data sharing, especially for modeling purposes
- Round robin testing to identify issues with physical and/or computational tools more thoroughly and quickly
- Recommended practices or standards for use of computational modeling tools, especially human body models

In addition, our community should actively consider potential end users at all stages of research. This means considering other researchers and disciplines, policymakers, and designers, beginning with the research and design phase through the ultimate communication of research findings and their proper application.

Recommendation: Explore new formal or informal working groups and new mechanisms for funding and/or distributing research.

CONCLUSIONS

Large strides have been made in improving occupant protection for everyone. Although significantly reduced in newer vehicle designs, injury risk disparities remain, due to diversity in the occupant population and crash exposure differences. These factors must be better understood to keep making progress toward the goal of zero injuries and fatalities. Understanding the state of vehicle crashworthiness and the benefits of occupant protection countermeasures is a continual feedback process. To move beyond countermeasures that already are working, targets for improvement should be based on studies of the newest vehicles, which require up-to-date crash investigation databases. Additional human subject and PMHS data also are needed to augment our understanding of human kinematics and injury tolerance across a broader range of occupant sizes and shapes. This will allow us to improve our physical and virtual tools (ATDs and HBMs) as well as the injury metrics required to use those tools to protect a diverse range of occupant types.

Virtual testing holds much promise as an area that could enable future occupant protection improvements. To realize this promise, we need to develop a framework and best practices for model validation and data sharing that will allow simulations to supplement traditional crash test programs. This will allow industry to quickly develop robust structures, interior compartments, and restraint systems.

Many of the findings listed above require additional research and/or development time. The push to improve crash outcomes for specific groups of occupants should not overlook things we can do now to benefit everyone. Increasing belt use and accelerating the adoption of existing crash avoidance technologies will have an immediate effect on rates of crashes and injuries.

Studies consistently have shown that advances in vehicle crashworthiness have benefited the entire population. While future improvements will likely be smaller in magnitude, substantial gains can still be achieved as we collaborate to identify the risks faced by specific groups within the diverse occupant population and the countermeasures that are most effective at reducing those risks.

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