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IMPROVED HEAD RESTRAINT DESIGN FOR SAFETY AND COMPLIANCE

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ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) recently revised Federal Motor Vehicle Safety Standard (FMVSS) 202, which governs head restraints. The new standard, known as FMVSS 202a, establishes for the first time in the U.S. a requirement for the fore-aft position of the head restraint. The fore-aft distance between the head restraint and headform representing a midsize male occupant must not exceed 55 mm when measured with the seat back angle set to 25 degrees. The goal of the rule change is to reduce the incidence of whiplash-associated disorders caused by rear impacts. Moving the head restraint closer to the head prior to impact decreases the amount of relative motion between the occupants' heads and torsos and is believed to decrease the risk of soft-tissue neck injury. As manufacturers phase in seats that meet the new criterion, some vehicle models are producing complaints from drivers that the head restraint causes discomfort by interfering with their preferred head position, forcing them to select a more reclined seat back angle than they would prefer. To address this issue, an analysis of driver head locations relative to the seat was conducted using a new optimization-based framework for vehicle interior optimization. The approach uses simulations with thousands of virtual occupants to quantify distributions of postural variables of interest. In this case, the analysis showed that smaller-stature occupants are disproportionately likely to experience head-position interference from a head restraint that is rigidly affixed to the seat back. Using an analysis approach that considers both postural and anthropometric variability, design guidelines for the kinematics of an articulated head restraint are proposed. Such a

restraint would provide optimal head restraint positioning across occupant sizes while minimizing interference.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) recently revised Federal Motor Vehicle Safety Standard (FMVSS) 202, which governs head restraints. The new standard, known as FMVSS 202a, establishes for the first time in the U.S. a requirement for the fore-aft position of the head restraint. The head restraint position is measured using the Head Restraint Measurement Device (HRMD), shown in Figure 1. The HRMD headform is mounted on the H-point machine, a weighted manikin that is widely used for measuring automotive seats. With the seat adjusted so that the torso angle of the manikin is 25 degrees aft of vertical, the head of the HRMD is leveled and a probe is moved rearward from the head of the manikin to measure the head restraint position. FMVSS 202a requires that the distance between the back of the HRMD headform and the head restraint, a dimension termed "backset," be no more than 55 mm.

The purpose of the backset requirement is to reduce the distance between occupants' heads and the head restraint. Simulations and epidemiological studies both suggest that decreasing backset decreases the likelihood of whiplash-associated disorders (WAD) in rear-impact crashes. A backset of zero (i.e. back of the head is in contact with the head restraint) has been found to be "optimal" [1] and others suggest a maximum of 60 mm [2]. Reductions of the incidence of WAD are a high priority for vehi-

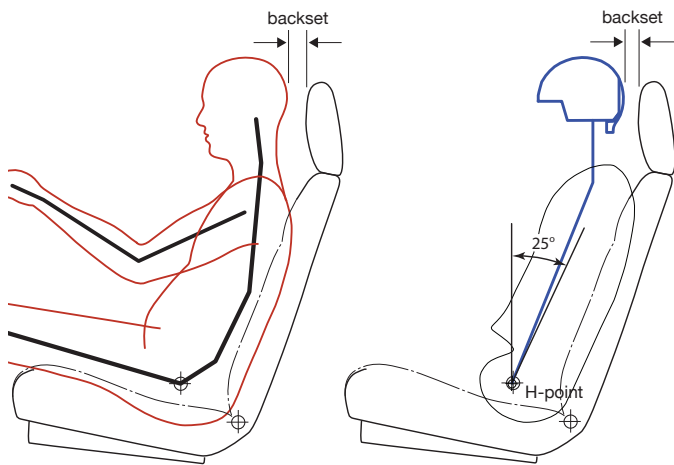


Figure 1. Backset measurement for a driver and for the HRMD headform mounted on the H-point machine.

cle safety regulators because of the high societal cost associated with these injuries—including approximately 27% of all costs to insurance companies for bodily injury claims [3].

As manufacturers have begun to phase in head restraints that comply with the FMVSS 202a backset requirement, they are receiving an increasing number of complaints from drivers who find that the head restraint is so close to their heads that it interferes with their preferred head posture. Prior to the adoption of the new rule, Reed et al. [4] analyzed data from driver posture studies conducted in vehicles and in laboratory conditions in which the head restraint did not affect driver posture. Based on the distribution of driver head locations with respect to the seat, Reed et al. estimated that the required HMRD-measured backset of 55 mm would interfere with the preferred head positions of more than 10 percent of drivers, if seat designs remained the same except for changes in the head restraint.

One of the reasons that head restraints meeting the new requirements are problematic for some drivers is that the backset measurement is performed at a seat back angle that is more reclined than the seat back angle most drivers choose. As the seat back is moved more upright, a fixed head restraint that moves with the seat back tends to move closer to the driver's head—potentially interfering with the driver's preferred head location. Mean driver-selected seat back angles, as measured by the SAE J826 manikin [5] average about 22 degrees across vehicles for the U.S. adult population [6] while the backset measurement for regulatory compliance in FMVSS 202a is performed at 25 degrees.

One approach to mitigating this problem would be to have the head restraint articulate with respect to the seat back so that it

would comply with the regulation but be less likely to cause interference with drivers' preferred head positions. To develop design guidelines for such a system, driver head locations were analyzed using a new vehicle package optimization system developed previously by the authors [7, 8]. Vehicle geometry is evaluated with respect to human requirements by posturing thousands of virtual drivers, taking into account the available component adjustment ranges, and calculating dependent measures of interest, such as clearances and vision angles.

In the current investigation, the locations of drivers' heads relative to the seat were analyzed to assess levels of interference and to determine how head restraints can be positioned to minimize both backset and interference. The results show that head restraints designed to a relatively simple geometric relationship will reduce interference while complying with the regulatory requirements.

METHODOLOGY

A generic vehicle interior layout was used for the current analysis, because the results are largely independent of the vehicle. The vehicle interior is characterized by the relative locations of the accelerator heel point (AHP), seat, and steering wheel. The center of the seat adjustment range was 800 mm rearward and 245 mm above AHP. The seat had 200 mm of fore-aft and 20 mm of vertical adjustability. A telescoping steering wheel with 50 mm of extension was modeled. The steering wheel had 30 degrees of adjustability, with a neutral angle of 25 degrees from vertical. The pivot of the steering wheel was located at 300 mm rearward and 570 mm above the AHP. The seat back pivot location was 135 mm rearward and 90 mm below the H-point for the seat [4].

A virtual population of 1000 drivers was generated to represent the U.S. adult driver population ages 18 to 65. The population was characterized by three anthropometric dimensions that are used in the posture-prediction models: stature (erect standing height), erect sitting height, and body mass index (BMI). BMI, a widely used measure of weight-for-stature, is calculated by dividing body mass in kilograms by the square of stature in meters. Driver anthropometry is created separately for men and women, exploiting the fact that many anthropometric variables can be modeled as normal distributions within gender. For the current analysis, BMI was transformed by taking the natural log, which improves the accuracy of the assumption of normality. The mean vectors and covariance matrices for men and women were calculated using data from the third National Health and Nutrition Examination Survey (NHANES III) for non-institutionalized civilians from 18 to 65 years of age (NCHS 2006). The sampling weights used for the analysis are designed to provide a representative analysis for the population as of the 1990 Census.

Normal driving posture for each of the drivers in the population was predicted using the Cascade Model posture-prediction

approach [9]. The posture models were developed using data from a laboratory study and validated using measurements of driver posture in vehicles driven on-road [10]. Among other variables, the posturing algorithm predicts drivers' seat position, seat back angle, steering wheel position and angle, and eye locations. The back of head location for each driver is calculated based on the driver's eye location [4]. The posturing methodology includes the random variance not associated with the predictors, which allows drivers with similar body dimensions to be postured differently. Because of the large number of drivers in the virtual population, the range of preferred initial postures is statistically similar to that observed in real populations.

Under FMVSS 202a, head restraint position is measured using the HRMD, which is mounted on the H-point manikin (see SAE J826 in [5]). The H-point manikin is named for the primary seat reference point it is used to measure, which is located approximately in the area of occupants' hips. The H-point is used as part of the definition for many vehicle interior dimensions (see SAE J1100 in [5]) and is used as the origin for the current seat-based analysis. Seat back angle is quantified by the torso angle of the H-point manikin on which the HRMD is mounted (see SAE J826 in [5]). In the procedure, the HRMD measures the backset at a point about 665 mm above H-point when the seat back angle is set to 25 degrees. Figure 1 shows the HRMD and seat geometry schematically.

Most vehicle seats have head restraints that move with the seat back. Under FMVSS 202a, head restraints can be adjustable both vertically and fore-aft, but they must comply with the regulations for height and backset in the full-down, full-rear position. The seats of interest for the current analysis have a seat back with a single pivot below and to the rear of the H-point and a head restraint that is "fixed" to the seat back, meaning that the head restraint moves one-to-one with changes in seat back (recline) angle.

For the analysis presented here, drivers were postured in the vehicle, including simulation of fore-aft and vertical seat position and seat back angle. Each driver's head location was expressed relative to the seat H-point location. The simulations assume that the driver's posture is not affected by the head restraint, so that the analysis can identify driver's preferred head locations.

The fixed head restraint was modeled as minimally compliant with FMVSS 202a, meaning that it presents an HRMD-measured backset of 55 mm with the seat back angle at 25 degrees. The headrest was assumed to be oriented vertically at 25 degrees and, to simplify the analysis, large enough to span the range of vertical head locations exhibited by the driver population.

The backset was calculated for each driver by differencing the horizontal location of the back of the head with the point on the restraint at the same height above H-point. Negative values indicate that the head restraint is interfering with the driver's preferred head location.

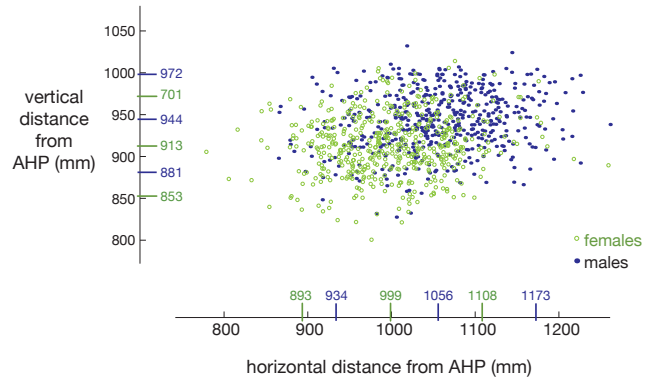


Figure 2. The preferred location of the back of head of the 1000 postured drivers. Measurements are relative to AHP. The 5th, 50th, and 95th percentile values are marked on each axis.

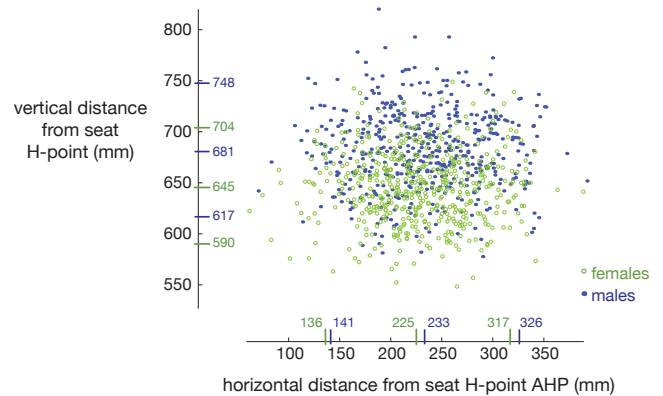


Figure 3. The preferred location of the back of head of the 1000 postured drivers, coded by gender. Measurements are relative to the seat H-point. The 5th, 50th, and 95th percentile values are marked on each axis.

RESULTS

As described previously, the driver posturing is done with respect to the AHP, a common reference point in vehicle design. The predicted back of head locations for the entire population are shown in Figure 2. The 5th, 50th, and 95th percentile values, by gender, are also shown.

Because the head restraint is rigidly attached to the seat, the data are easier to analyze when the seat is used as the reference point. The location of the seat H-point for each driver was subtracted from the corresponding back-of-head location to obtain the position with respect to the seat H-point. The data are replotted in Figure 3 and the new percentile values are shown.

Figure 2 shows that, on average, women sit further forward within the vehicle than men. The data in Figure 3, however, show

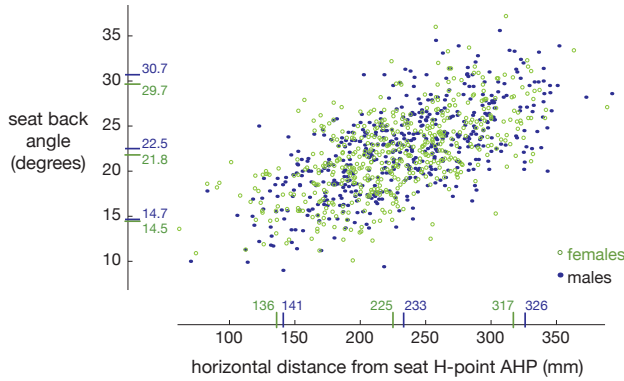


Figure 4. Plot of back of head location (relative to H-point) and seat back angle. The 5th, 50th, and 95th percentile values are marked on each axis.

that their heads are only slightly further forward than men with respect to the seat. The gender difference in vertical location is a reflection of the average difference in torso length.

Figure 4 shows seat back angle as a function of back of head location. There is little difference in seat back angle preference across genders. Notice that the mean driver-selected seat back angle across genders is approximately 22 degrees, which is about one standard deviation less than the 25 degrees at which the FMVSS202a procedure is executed.

The backset was calculated for each driver using the minimally compliant head restraint fixed to the seat back. Those drivers with a negative backset would be unable to sit in their preferred driving posture due to head restraint interference and are said to be “disaccommodated.” With the fixed head restraint, 15.8% of drivers were disaccommodated.

The top row of Figure 5 shows head location and backset plotted with seat back angle. The drivers are plotted in three cohorts: those whose preferred posture was interfered with, those with backsets within the regulatory margin, and the rest. Notice the correlation between seat back angle and backset—as the driver’s preferred seat back angle decreases, the likelihood of being disaccommodated by the head restraint decreases. The 50th percentile backset distance is 48.9 mm. The 95th percentile distance is 135 mm.

The goal of an articulated head restraint, as discussed in the Introduction, is to improve accommodation (i.e., increase the number of people who are able to sit in their preferred posture) while still complying with the regulation (FMVSS202a). To accomplish this, the articulated restraint varies the position of the restraint with respect to the seat back as a function of seat back angle—away from the head as the seat comes forward and towards the head as seat back angle is increased. The ideal system would have the effect of decorrelating seat back angle and backset, so that drivers experience equal levels of accommodation,

and equivalent levels of protection, across the seat back angle range.

A linear regression analysis was performed on the backset and seat back angle data in the top row of Figure 5. The regression fit indicated that, with a fixed restraint, the mean backset increased 5.61 mm per degree of increase in seat back angle. An articulated restraint that rotated forward at that same rate would negate the effect. It requires careful implementation, however, since the restraint must still pass the FMVSS202a testing procedure. To ensure this, the restraint movement is implemented such that the restraint is vertical at 25 degrees and the head restraint movement relative to the seat back is calculated as a function of the seat-back-angle deviation from 25 degrees. The horizontal location of the articulated restraint for a single driver is then

$$X_{articulated} = X_{fixed} + 5.61(25 - SBA_{driver}) \quad (1)$$

where X_{fixed} is the horizontal location of the fixed restraint adjusted for the driver in question, 25 is the prescribed angle of the HRMD, and SBA_{driver} is the driver’s preferred seat back angle.

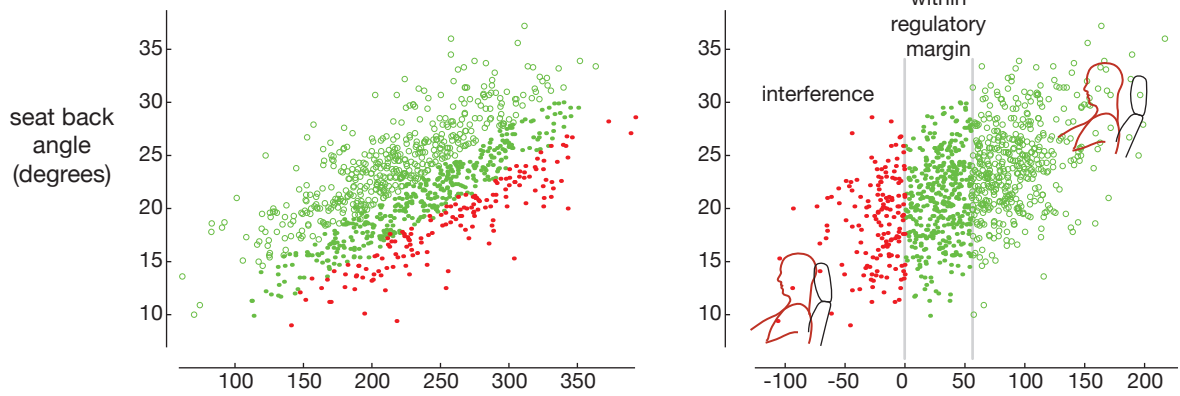
Horizontal and vertical head locations, relative to H-point, for the population of drivers using the articulated head restraint are shown in the bottom row of Figure 5. The backset vs. seat back angle plot in the same figure shows that the goal has been achieved and the two variables are now uncorrelated. The 50th percentile backset distance using the articulated restraint is 66.4 mm. The 95th is 135 mm. The percentage of disaccommodated drivers is 6.1%, which is an improvement of 10%.

The FMVSS202a requirements state that the measured backset using the HRMD at 25 degrees must be 55 mm or less. To this point only this minimally compliant condition has been examined. A parametric study was conducted to examine the effect of designing seats that would measure different levels than this maximum (both less than—which would still meet the requirement—and greater than 55 mm). This was done for both the fixed and proposed articulated restraint. The 50th and 95th percentile backsets were calculated for each restraint at each of the HRMD-measured levels. The percent of disaccommodated drivers (with negative backset) was also calculated. All these results are shown in Figure 6.

For a given HRMD-measured backset, the 50th percentile backset for the driver population is always less with the fixed restraint, but this closeness translates into higher levels of disaccommodation. The 95th percentile backset does not change, for a given HRMD-measured backset, across the two restraint types.

Figure 6 illustrates two advantages of the articulated restraint. First, the fraction of drivers able to sit in their preferred driving posture is always higher than for the fixed restraint. Second, for a given level of disaccommodation, the articulated restraint will have a lower median and 95th percentile backset. For example, 15.8% of drivers are disaccommodated with a fixed re-

fixed head restraint



articulated head restraint

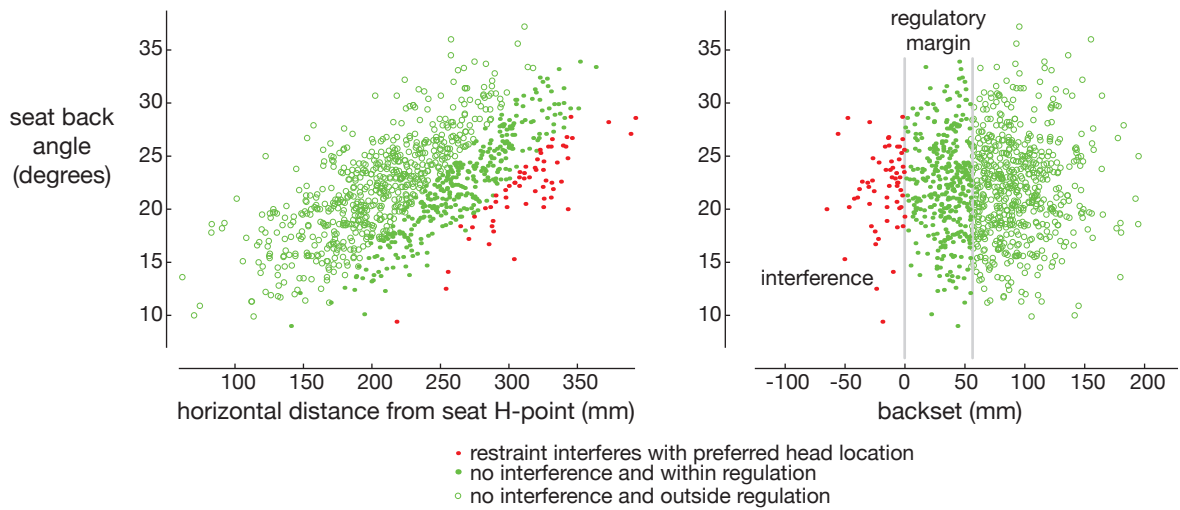


Figure 5. The two plots in the top row show horizontal head location and backset for each of the drivers plotted against seat back angle when using a fixed head restraint. Drivers whose preferred driving posture is interfered with are marked, as are those within and beyond the regulatory margin. The two plots in the bottom row are similar to those above, but for an articulated head restraint..

straint designed to an HRMD-measured backset of 55 mm (minimally compliant with the regulation). The 50th and 95th percentile backsets are 48.9 mm and 135 mm, respectively. When using an articulated restraint designed according to the guidelines presented above, 15.8% disaccommodation is achieved with an HRMD-measured backset of 30.1 mm. The 50th and 95th percentile backsets for the articulated restraint are 23.9 mm and 100 mm—a marked improvement. Thus, the articulated head restraint produces a more advantageous tradeoff between protection and disaccommodation.

DISCUSSION

Head locations relative to the seat are only weakly associated with overall body dimensions and show considerable variability, both with respect to the H-point and with respect to the seat back. One consequence of this variability is that drivers experience a wide range of head restraint backsets. With conventional head restraints that are fixed to the seat back, taller drivers on average experience larger backsets because they tend to select more-reclined seat back angles. Consequently, moving the head restraint forward relative to the seat back disproportionately interferes with the preferred head locations of smaller-stature drivers.

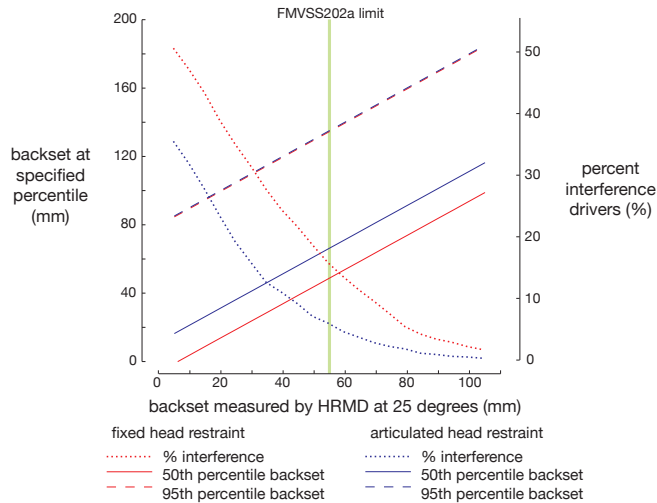


Figure 6. Tradeoff plot for both fixed and the proposed articulated head restraint. The 50th and 95th percentile backset levels are shown as a function of backset measured by the HRMD with a seat back angle of 25 degrees. The alternate vertical axis shows the percent of drivers that are interfered with.

The articulated head restraint concept presented in this paper equalizes the backset distribution across seat back angles, so that drivers who select more upright and more reclined seat back angles experience the same median backset and the level of disaccommodation. Application of this approach will allow manufacturers more flexibility to design seat backs by permitting smaller mean selected seat back angles without encountering unacceptable levels of driver complaints. The articulated head restraint also provides a better tradeoff between safety improvements due to backset reductions and customer dissatisfaction due to head restraint interference.

The analysis of head interference in this paper is conservative with respect to disaccommodation because we have not considered hair contact with the restraint. Occupants often respond negatively when their hair contacts any vehicle component, whether the roof liner or seat. This suggests that a head-to-head-restraint margin of at least 25 mm is necessary to avoid complaints about hair contact, although this will vary across individuals due to differences in hair styles.

In the FMVSS 202a final rule, NHTSA suggested that head interference is not a significant problem because drivers who experience interference will simply increase their seat back angles to eliminate the interference. These changes are not trivial, however, because the head restraint moves fore-aft only about 8 mm per degree of back angle change (depending on the seat back pivot location and head restraint geometry). To clear a 25-mm interference condition would require a change in seat back angle of up to 3 degrees, which is likely to substantially decrease

driver comfort. More importantly, it will move driver's eyes rearward and lower in the vehicle, disproportionately affecting small women whose eyes are already relatively low. To compensate for the extended distance to the steering wheel caused by the increased recline angle, drivers may move their seats further forward in the vehicle, potentially putting them at greater risk of injury in a frontal collision.

As noted above, one of the most important factors affecting the distribution of driver backsets is the mean selected seat back angle produced by the seat. The H-point manikin does not exactly replicate the interaction between drivers and the seat back and consequently the mean selected seat back angle varies substantially across vehicles [4, 6, 11] even though driver torso posture varies relatively little. The characteristics of seat back contour that result in large mean selected seat back angles have not been well characterized, but may involve relatively high lumbar prominences.

A number of manufacturers are equipping their seats with active head restraints that move up and forward as the occupant's torso loads the seat back during a rear collision [12]. The current analysis provides quantitative guidance for the design of these systems by describing the distribution of head locations with respect to the seat back. Using the articulating head restraint concept will reduce the amount of forward travel required in active head restraints and will ensure that the level of protection is equivalent across driver size.

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