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ABSTRACT

Recent changes in impact protection requirements have led to increased padding on vehicle interior surfaces. In the areas near the driver's head, thicker padding can reduce the available headspace and may degrade the driver's perception of headroom. A laboratory study of driver headroom perception was conducted to investigate the effects of physical headroom on the subjective evaluation of headroom. Ninety-nine men and women rated a range of headroom conditions in a reconfigurable vehicle mockup. Unexpectedly, driver stature was not closely related to the perception of headroom. Short-statured drivers were as likely as tall drivers to rate a low roof condition as unacceptable. Statistical models were developed from the data to predict the effects of changes in headroom on the percentage of drivers rating the headroom at a specified criterion level.

INTRODUCTION

Trends in vehicle occupant protection have resulted in renewed interest in the perception of headroom. Federal Motor Vehicle Safety Standard (FMVSS) 201 was recently revised to require better energy absorbing performance for interior structures near the driver's head (1).* Thicker padding on the A pillar, headliner, and roof rail used to meet the new performance standards may reduce the space around the driver's head, potentially degrading the perception of headroom and restricting driver vision outside the vehicle. This study was conducted to investigate the relationships between physical headroom and subjective perception of space and vision.

Driver headroom in vehicles is currently measured using tools, procedures, and definitions described in Society of Automotive Engineers Recommended Practices J1052 and J1100 (2). Head position contours intended to describe the distribution of driver head positions were originally developed by manipulating a fixed-size head form around the perimeter of driver eyellipses (3). Recently, the implementation of these contours in computer software was simplified by adopting approximating ellipsoids, as described in Recommended Practice J1052 (2).

Figure 1 shows the SAE J1052 95th-percentile head-space contour in relation to the roof and A-pillar surfaces used in this study. Like the eyellipse, the head-space contour is intended to be a cut-off contour. By definition, the head surfaces of 95 percent of drivers should lie to one side (below or toward the driver centerline) of any plane tangent to the ellipsoid, for a 50-percent-male/50-percent-female U.S. driver population. To account for head turn, the ellipsoid is extended outboard by slicing the ellipsoid at the driver centerline and translating the outboard section 23 mm laterally. The head-space contours are positioned using procedures described in SAE J1052. The centroid is positioned in package space using equations based on the eyellipse locating procedures in SAE J941. The inputs to the equations are the seating reference point (SgRP) coordinates and the design seatback angle (defined as L40 in SAE J1100).

SAE J1100 defines several headroom measurements that are made with respect to the head-position contour. Figure 2 illustrates measurements made in rear view. The measurements of primary interest are H35, W27, and W35. Using a rearview section at the centroid, the head position contour is translated upward to the point of first interference to define H35. If an initial interference condition exists (roof and head contours intersecting), the head-position contour is moved in the opposite direction to define a negative clearance measurement. Similarly, outboard lateral translation of the contour defines W35, and translation laterally and upward at a 30-degree angle with respect to the horizontal defines W27.

The SAE procedures predict the distribution of driver head surface positions, but do not provide any information on how changes in the physical clearance dimensions affect the perception of headroom. The current study was conducted to examine the relationships between interior roof location and drivers' subjective evaluations of headroom. The primary objective was to develop design criteria by determining the relationships between roof positions and subjective assessments. The statistical analysis of the experimental data was used to predict the percentage of drivers that would rate a particular roof condition at a criterion level, or, alternatively, to

* Numbers in parentheses denote references at the end of the paper.

specify the roof positions or clearances that would be required to achieve a desired percentage of subjective responses at or above a criterion level.

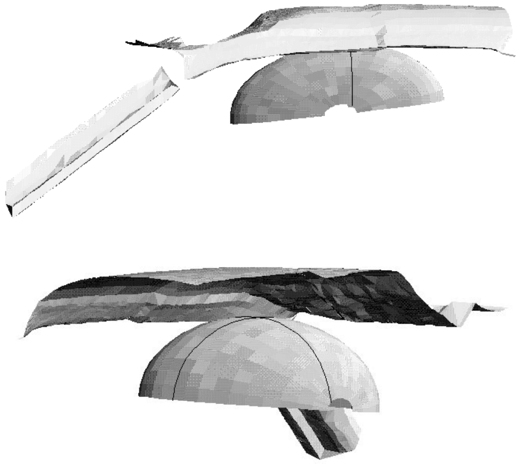

Figure 1. Roof and A-pillar surfaces with SAE 95th-percentile head contour in nominal condition.

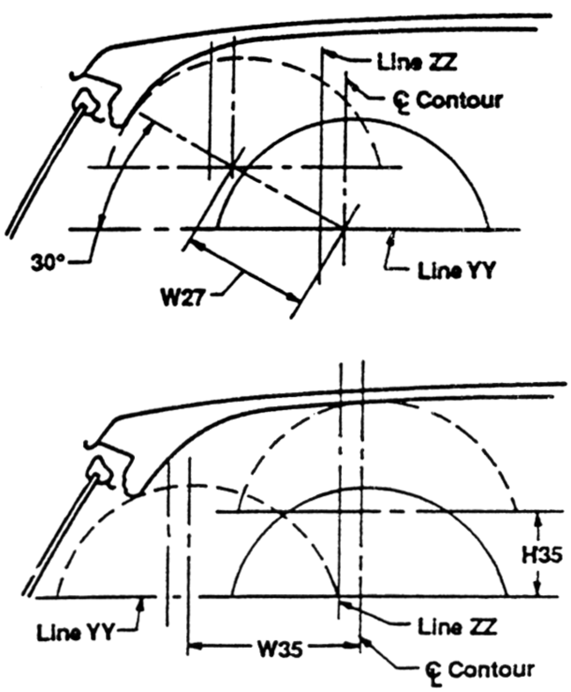

Figure 2. Rearview driver head clearance dimensions defined in SAE J1100.

METHODS

FACILITIES

Vehicle Mockup – Testing was conducted using a reconfigurable vehicle mockup manufactured by Prefix, Inc., known as the Programmable Vehicle Model (PVM). All of the components of the vehicle cab, shown in Figure 3, are mounted on motorized tracks under computer control. For this testing, only the roof component locations were manipulated. All other components, including the seat, floor, console, and steering wheel, remained in their initial positions, which were set for this study to be representative of a typical midsize sedan. The interior structures near the driver's head, including the roof liner, the header and sun visor, and the roof side rail, were moved as a unit on three independent axes parallel to the vehicle coordinate axes. Figure 4 shows the movement directions. The corner of the roof above and to the left of the driver can be adjusted fore-aft, laterally, and vertically. The A and B pillars articulate and telescope so that they remain connected to the roof and the frame.

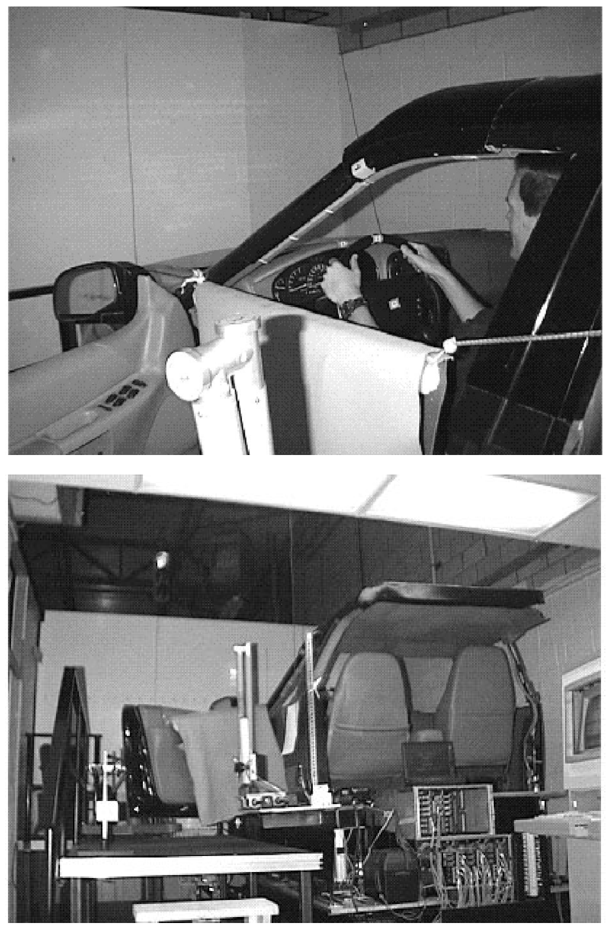

Figure 3. Reconfigurable vehicle mockup. Driver-side view (top) and rear view (bottom).

FARO Arm Digitizer – Vehicle component and body-landmark locations were recorded in three dimensions during subject testing using a FARO Arm, a portable coordinate measurement device. The FARO Arm was also used to record head and hair contour geometry (see below). To record the subject and roof positions during testing, the FARO arm was rigidly mounted to the PVM frame. Reference points on the roof and PVM frame were recorded during each posture measurement so that the data could be translated to a common package reference.

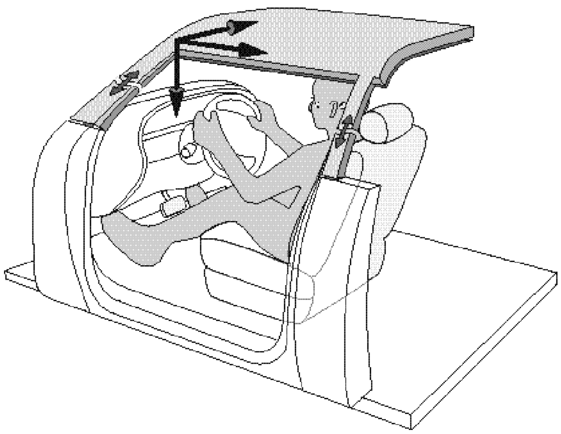

Figure 4. Roof adjustment axes. Arrows show directions of movement from nominal. A and B pillars telescope and pivot to allow roof translation.

SUBJECTS – Ninety-nine male and female drivers were recruited for testing.* Because taller drivers were expected to experience more restricted head clearances, tall drivers were oversampled relative to their representation in the U.S. driver population. The resulting data can be reweighted to represent many different populations. Table 1 lists the subject pool by gender/stature group. Subjects were recruited by word of mouth, previous subject lists, and newspaper advertisements. At the start of the test session, the nature of the testing was explained to the subject and written consent was obtained.

PRELIMINARY DATA COLLECTION

Standard Anthropometry – Standard anthropometric measures were taken from each subject, including stature, weight, and erect sitting height. Detailed measurements of head geometry were also obtained to complement the head contour data collected subsequently using the FARO arm.

Head and Hair Geometry – One of the objectives of this study was to relate drivers' actual head- and hair-to-roof clearances (proximities) to subjective responses. A method was developed that allowed complete, accurate characterization of the positions of the roof and head for each test condition, so that any clearance measure of interest could be calculated during post-test analysis. The key to this method was the accurate measurement of a large number of points defining the subject's head and hair contours relative to head anatomical landmarks and reference points.

Prior to testing in the PVM, the subject's head and hair surface contours were measured using the FARO arm and a specially designed head stabilization fixture, illustrated in Figure 5. A set of head and face anatomical landmarks was recorded, followed by scans of the subject's head and hair contours. The FARO arm probe was moved over the left lateral and superior head and hair surfaces, recording 100 to 300 points for each surface. Three reference points located arbitrarily on the forehead, cheek, and temple were marked with contrast targets and digitized, allowing the head landmarks and head and hair surfaces to be aligned with the reference landmark locations when the latter were subsequently measured in the seating buck.

Table 1. Subject Pool

Group	Gender	Stature Range (mm)	Percentile Range*	Number of Subjects
0	F	under 1511	< 5	6
1	F	1511 - 1549	5-15	6
2	F	1549 - 1595	15-40	6
3	F	1595 - 1638	40-60	6
4	F	1638 - 1681	60-85	6
5	F	1681 - 1722	85-95	6
6	M	1636 - 1679	5-15	6
7	M	1679 - 1727	15-40	6
8	M	1727 - 1775	40-60	6
9	M	1775 - 1826	60-85	15
10	M	1826 - 1869	85-95	15
11	M	over 1869	> 95	15
Total				99

*Percentiles of the U.S. adult population by gender (4).

During analysis of the head and hair contour data, a three-dimensional triangulation method was used to fit polygonal surfaces to the head and hair data. The data from the left side of the head were reflected to the right side to form complete head and hair contours. Figure 6 shows typical head and hair contours from one subject, along with anatomical reference points.

* The rights, welfare, and informed consent of the volunteer subjects who participated in this study were observed under guidelines established by the U.S. Department of Health, Education , and Welfare (now Health and Human Services) on Protection of Human Subjects and accomplished under medical research design protocol standards approved by the Committee to Review Grants for Clinical Research and Investigation Involving Human Beings, Medical School, The University of Michigan.

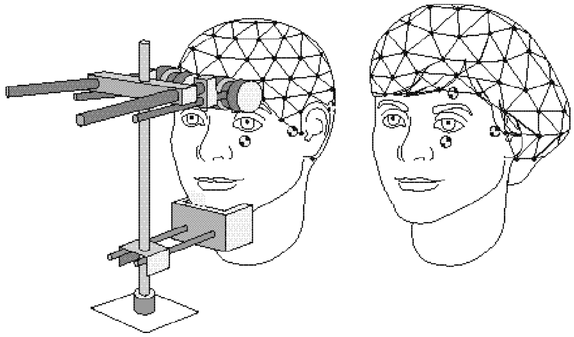

Figure 5. Schematic of head and hair contour digitization procedure, showing head stabilization fixture and points on the head and hair contour recorded using the FARO arm.

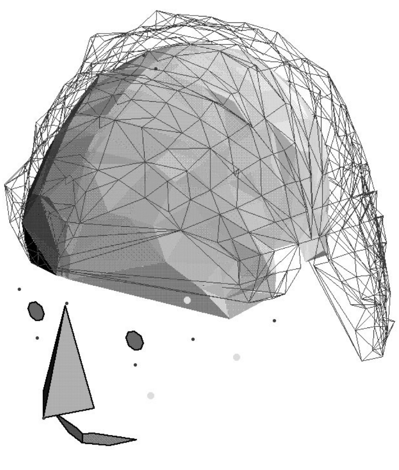

Figure 6. Head and hair surface data for a midsize-female subject. Head landmarks and reference points are shown as dots. The hair surface is shown as a wireframe so that the head surface may be seen. Facial features are generated synthetically based on measured face landmarks.

RATINGS TRIALS

Test Conditions – The test matrix was designed to investigate the effects on subjective evaluations of changes in roof position on each of the three movement axes, as well as the effects of interactions between the axes. For example, the rating of a particular vertical roof position might be dependent on the fore-aft position of the roof. An initial full-factorial matrix was developed with three levels on each of the three movement axes. The resulting matrix size (33 = 27 conditions) was prohibitively large for each subject to experience all conditions in a single test session, so the number of conditions was selectively reduced to preserve the ability to examine some two-way interactions while allowing every subject to be tested in every condition.

Table 2 lists the test conditions. Condition 1 is the initial configuration (typical midsize sedan geometry) and each of the other conditions represents a reduction in headroom on one or more axes. The maximum reduction in headroom available on each axis was about 75 mm, so the three conditions on each axis were selected to be 0, –37.5, and –75 mm. The lateral axis (lateral location of roof side rail) was tested at only two positions (0 and -75 mm), reducing the matrix from 27 to 18 conditions. Varying the fore-aft position with the lateral axis only at the nominal position further reduced the matrix to 12 conditions. The matrix allows examination of potential interactions between vertical and fore-aft position, and between vertical and lateral position. That is, the analyses can determine if the effect of a change in vertical roof position is influenced by the fore-aft position of the sun visor area or the lateral position of the roof rail.

Table 2. Test Conditions

Condition	Vertical Axis (mm)	Fore-Aft Axis (mm)	Lateral Axis (mm)
1	0	0	0
2	0	0	-75
3	0	-37.5	0
4	0	-75	0
5	-37.5	0	0
6	-37.5	0	-75
7	-37.5	-37.5	0
8	-37.5	-75	0
9	-75	0	0
10	-75	0	-75
11	-75	-37.5	0
12	-75	-75	0

Questionnaire – Each subject answered ten questions for each of the test conditions, evaluating the headroom and vision provided by the test condition. Figure 7 shows question 1 and the response scales as they were presented to the subject by projecting a color 35-mm slide on a large screen in front of the PVM. Question 1 asked the subject to rate the “space above my head;” question 2 asked the subject to rate the “space to the left side of my head;” question 4 asked the subject to rate the “distance forward from my head to the windshield header or sun visor;” and question 9 asked the subject to rate the “overall impression of the roominess of the space around my head.” Other questions dealt with related headroom and vision issues. Each of these questions required the subject to make two numerical responses. First, the subject evaluated the “sufficiency” of the headroom on a five-point scale, with the levels labeled “very insufficient,” “insufficient,” “barely sufficient,” “sufficient,” and “more than sufficient.” The subject also rated the “acceptability” of the headroom, with levels of “very unacceptable,” “somewhat unacceptable,” “somewhat acceptable,” and “very acceptable.”

1. The space above my head is:

very insufficient 1	insufficient 2	barely sufficient 3	sufficient 4	more than sufficient 5

very unacceptable 1	somewhat unacceptable 2	somewhat acceptable 3	very acceptable 4

Figure 7. Text from slide for question 1.

Procedures – With the PVM set to the nominal configuration, the subject sat in the vehicle mockup and adjusted the fore-aft seat track position and seatback angle to achieve a comfortable driving posture. A road scene was projected on the screen in front of the subject to provide visual cues. The operation of the reconfigurable mockup was explained and demonstrated to the subject. The ratings questionnaire was presented to the subject using slides presented on a large screen approximately 4 m in front of the driver. The first time through the questionnaire, each question and the range of appropriate responses was explained. The subject's verbal responses were recorded by an experimenter. Responses from the first trial at the nominal condition were recorded, but were not used in the analyses.

After completion of the questionnaire, the subject was asked to close his or her eyes and recline the seatback while the roof configuration was adjusted. When the roof was in the next test position, the subject opened his or her eyes and again adjusted the seatback angle and seat-track position to obtain a comfortable driving position while interacting with the steering wheel and pedals. The location of the roof components, the subject's selected seat position and seatback angle, and landmarks on the subject's body were recorded using the FARO arm. The questionnaire was then administered using the projected slides. The subject remained in the vehicle mockup between trials to save time and to reduce the possibility that the subject's ratings would be influenced by perceptions during ingress or egress. The procedure was repeated for each of the 12 test conditions, which were presented in random order.

Posture Measurement Procedures – At the start of each trial, the subject's selected "comfortable driving posture" was recorded by digitizing the locations of a number of body landmarks. Reference points on the door frame, seat cushion, seatback, and roof were also digitized to record the roof position and the subject's selected seat position and seatback angle. Figure 8 shows a head reference point being measured using the FARO arm.

Figure 8. Measuring a subject's head location

CLEARANCE CALCULATION METHODS – In each trial, the locations of reference points on the roof and the subject's head (three each) were recorded using the FARO arm. These data were used to calculate the relative positions and orientations of the roof and the subject's head so that clearance calculations could be performed. During the initial calibration of the PVM prior to the start of subject testing, the interior surface of the roof (headliner) near the driver was scanned with the FARO arm, along with the roof reference points. A triangulation method was used to create a polygonal surface approximating the interior roof geometry. Figure 9 shows the interior roof surface along with the head and hair contours from a midsize-female subject for one test condition.

Six clearance measures of interest were calculated for both the head and hair contours. Sideview and rearview sections were taken through the head origin, defined to be the midpoint between the left and right tragion landmarks. Clearance measures analogous to the SAE H35 and W27 measures were calculated by determining the distance that the head or hair contour could be translated prior to contacting the roof contour, as shown in Figures 10 and 11. In side view, clearances were calculated in this manner for upward, forward, and 30 degrees above horizontal. In rear view, clearances were calculated upward, leftward, and 30 degrees above horizontal. For each test condition, clearances were also calculated using the same translations with the sideview and rearview sections of the SAE headspace contour.

STATISTICAL ANALYSIS AND MODELING

STATURE EFFECTS – The subjects responded to the twelve ratings test conditions with a wide range of ratings. Unexpectedly, there are substantial percentages of short-statured subjects who gave some test conditions low ratings. For example, about 10 percent of the responses from group 0 subjects (average stature 1481 mm) on question 1 were "very unacceptable" (rating level 1). In fact, there is no apparent relationship between stature and the relative proportion of ratings given to the test conditions.

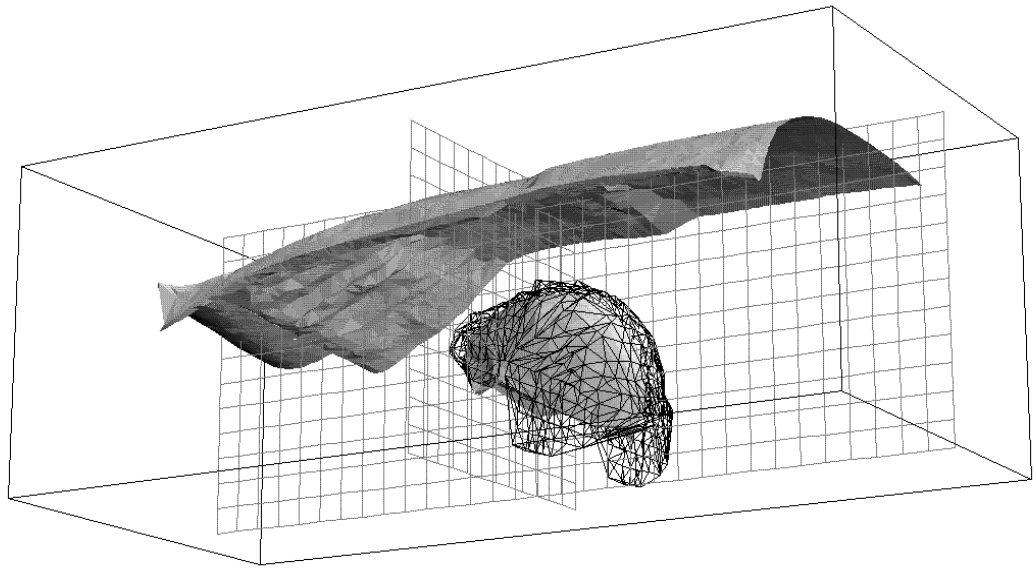

Figure 9. A female subject's head and hair contour data located in the measured position relative to the roof surface for ratings condition 12. The X and Y planes that generate the sections used in the clearance analysis are shown.

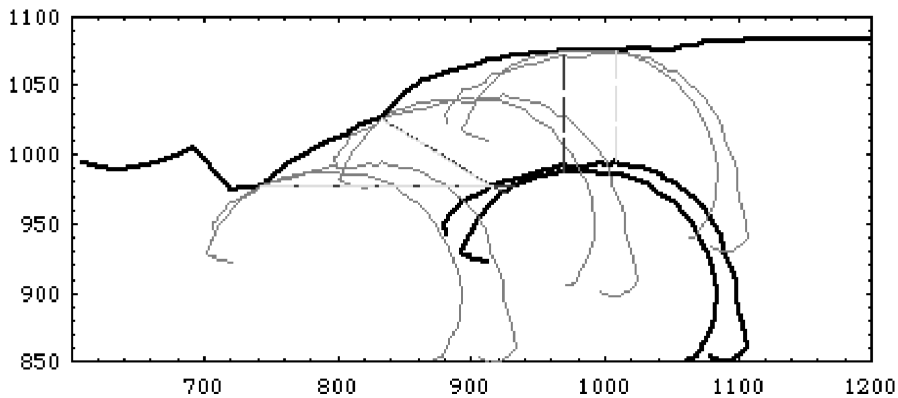

Figure 10. Schematic of sideview clearance calculations. Head, hair, and roof contours are shown with thick lines. Vertical, forward, and forward- up-30-degree clearance conditions are illustrated with dashed lines for both the head and hair contours. The gray lines show the translated positions of the head and hair contours at the maximum translations.

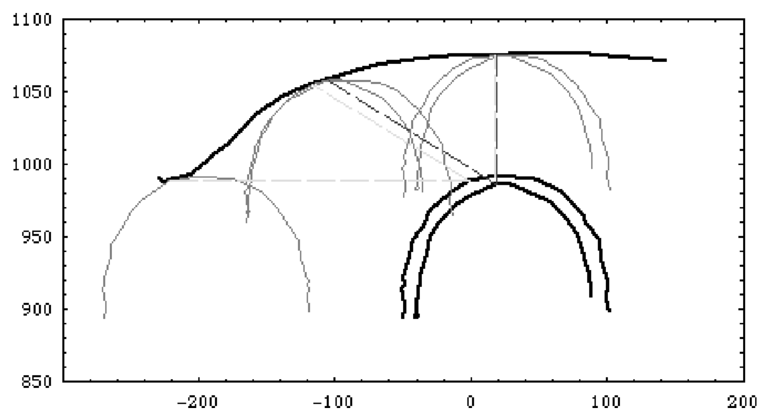

Figure 11. Schematic of rearview clearance calculations. Head, hair, and roof contours are shown with thick lines. Vertical, left, and left/up-30-degree clearance conditions are illustrated with dashed lines for both the head and hair contours. The gray lines show the translated positions of the head and hair contours at the maximum translations. For this subject and condition, there is no contact with lateral translation of the head contour.

Figure 12 illustrates the lack of a stature effect on headroom perception using responses to question 9 (overall headroom evaluation). Each line in the plots summarizes data from a single nominal roof height (Z-axis level). Although there is a strong effect of roof height on the overall headroom rating, short subjects are just as likely as tall subjects to find a low roof height insufficient or unacceptable. Further, there is no apparent interaction between stature and roof height. Average ratings are reduced equally for short and tall subjects when the roof is lowered.

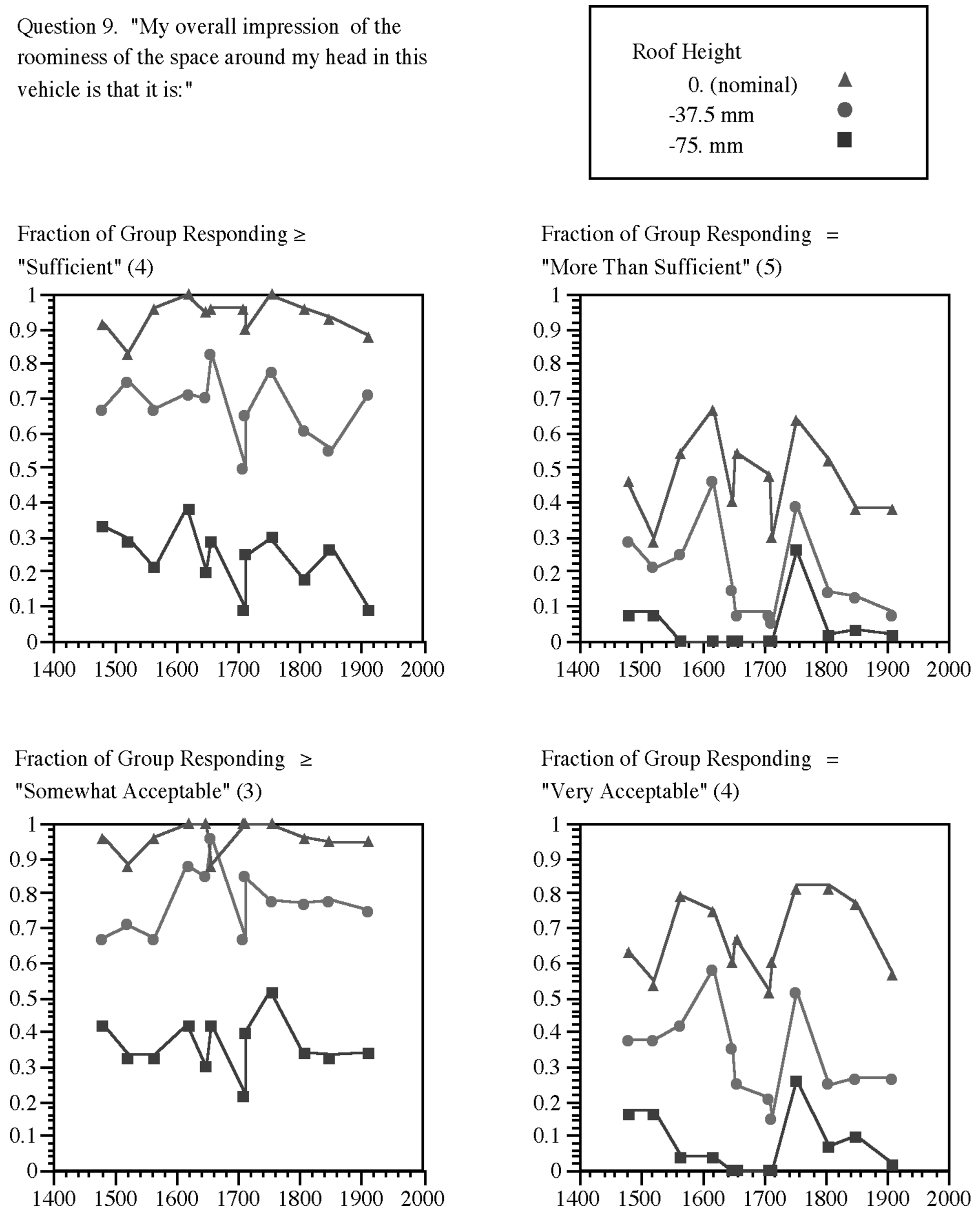

Figure 12. Fraction of each stature/gender group (plotted by group mean stature) at two sufficiency and acceptability levels for question 9 (overall headroom evaluation). Lines connect fractions at each of three roof heights (Z-axis).

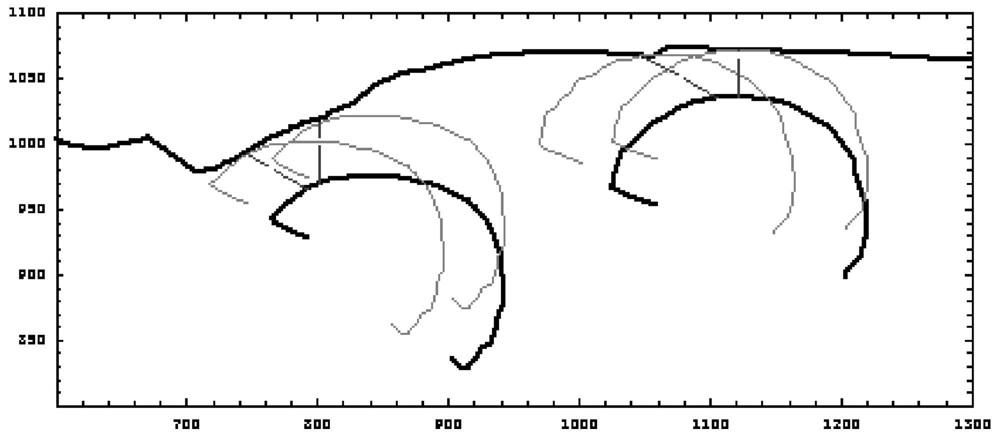

Figure 13. Sideview head and roof contours for two subjects in ratings condition 12. Light lines show the translations used to measure vertical and forward-30 clearances. The short-statured subject (group 0) sitting further forward has clearance in front of the forehead on the forward-30 measure that is similar to the clearance experienced by a tall subject (group 11).

The unexpected similarity between headroom ratings for short and tall drivers can be understood, in part, by considering the actual locations of the drivers' heads with respect to the roof. Figure 13 shows sideview head contours of a subject from group 0 (shortest group) and a subject from group 11 (tallest group), along with the roof profile in ratings condition 12 (the most restrictive condition). The figure demonstrates that the shape of the roof section results in actual head clearances in front of the forehead for small subjects being similar to those for tall subjects.

PREDICTIVE MODELS – Logistic regression provides a way to develop a smooth function to predict the fraction of drivers that would respond to a roof position with a particular rating level. The logistic regressions presented here have the form:

$$P(x, y, z, \alpha) = \frac{e^f}{(1+e^f)} \qquad (1)$$

where f is a linear function of the independent headroom measures and $P(x, y, z, \alpha)$ is the probability of the rating exceeding a particular criterion value α with the roof at position x, y, z. In these analyses, f is chosen to be

$$f = a\,x + b\,y + c\,z + d\,x\,z + e\,y\,z + f \qquad (2)$$

where x, y, and z are the nominal values on each roof movement axis and the remaining parameters are constants. Choosing a criterion level of 3 or 4 on the sufficiency scale transforms the ratings into a binary response appropriate for use with equations 1 and 2. The probability function in equation 1 is fit to the data using a least-squares procedure.

Figure 14 shows logistic regressions on sufficiency rating levels for each of the three roof-movement axes. Each axis value is plotted against ratings from the corresponding headroom ratings question (questions 4, 2, and 1 for the X, Y, and Z axes, respectively). As expected from the preceding analyses, the effect of Z-axis motion on the rating of vertical space is strong, while the effects of the other axes on the responses to the corresponding questions is weaker. For example, Figure 14A predicts that more than 95 percent of subjects would rate vertical head space with the nominal roof position at a 4 or 5 on the sufficiency scale. However, with the roof position set to -75 mm, only about 25 percent of subjects would rate the vertical space at 4 or 5. The figure shows that about 65 percent of subjects thought that the vertical head space in the nominal condition was "more than sufficient. "

The plots in Figure 14 are univariate analyses that average over levels of the other factors. To consider the effects jointly, a more complete model was created that takes into account all of the potential factors (three axis variables and the Z-by-X and Z-by-Y interactions; the X-by-Y interaction cannot be investigated with this test matrix). Since the model combines all of the factors, the ratings from question 9 (overall headroom evaluation) were used as the response variable. The logistic regression models developed in this manner predicted the percentage of subjects rating the headroom at a particular criterion level within about 2 percent.

DISCUSSION

This study examined the influence of roof position on the subjective perception of driver headroom. The most unexpected finding in the ratings analysis was the lack of influence of stature or sitting height on the headroom ratings. Three potential explanations for this surprising finding have been advanced:

1. Comparable Actual Clearances – The more-forward seat position of short-statured drivers brings their heads closer to the downward sloping header and visor area of the roof, resulting in greater similarity in actual head clearance between short and tall subjects than would be expected from their differences in sitting height. Analysis of actual head clearances showed that on the forward-30 measure of head clearance, which corresponds approximately to the amount of space in front of the forehead, large and small subjects had about the same amount of clearance in the more restrictive test conditions.

2. Different Expectations – Short-statured drivers may also have greater expectations for headroom than tall drivers, and may consequently find larger clearances to be unacceptable. Because of the correlation between seat position and stature, the roof geometry near the heads of the short subjects was different from the areas near the heads of the tall subjects, so it is difficult to isolate differences in tolerance or expectation. Further study is underway to separate these effects.
3. Response Expansion – Another possibility is that the subjects expanded their range of responses to fit the available range of stimuli. Since the test conditions were presented in random order, each subject would fairly quickly learn the range of roof conditions that could be expected. The subject might then try to use the full response range to characterize the range of roof positions. The analyses did not demonstrate this effect, however. The average rating of test conditions from subjects who experienced particular conditions as one of the first four presented did not differ from the ratings from subjects who experienced the same conditions as one of the last four.

Further research will be necessary to determine which of these or other factors accounts for the counterintuitive findings concerning stature. The matter is of considerable importance, because the subject selection and data weighting schemes that are appropriate for developing design guidelines are dependent on the anthropometric definition of the population, particularly with regard to the distribution of statures. In this report, the sampled subjects have been assumed to be representative of the population, since no stature-related effects on headroom ratings were noted. However, the subject sample was definitely not representative with respect to stature, instead being biased toward taller drivers. The effects of this sample bias on the findings are uncertain, because the potential effects of body size have not yet been demonstrated.

PREDICTION OF HEADROOM RATINGS – Logistic regression equations were calculated to predict head-room ratings as a function of roof translations on three axes relative to the nominal condition. The predictions from these equations matched the distribution of subjects' ratings quite accurately, with typical errors of less than 2 percentage points. While functions based on roof translation were effective, models based on the SAE measures of headroom, notably H35 and W27, were considerably less effective. In fact, H35 was not significantly related to the headroom ratings, and a model based on W27 was considerably less accurate than the model based on roof translations.

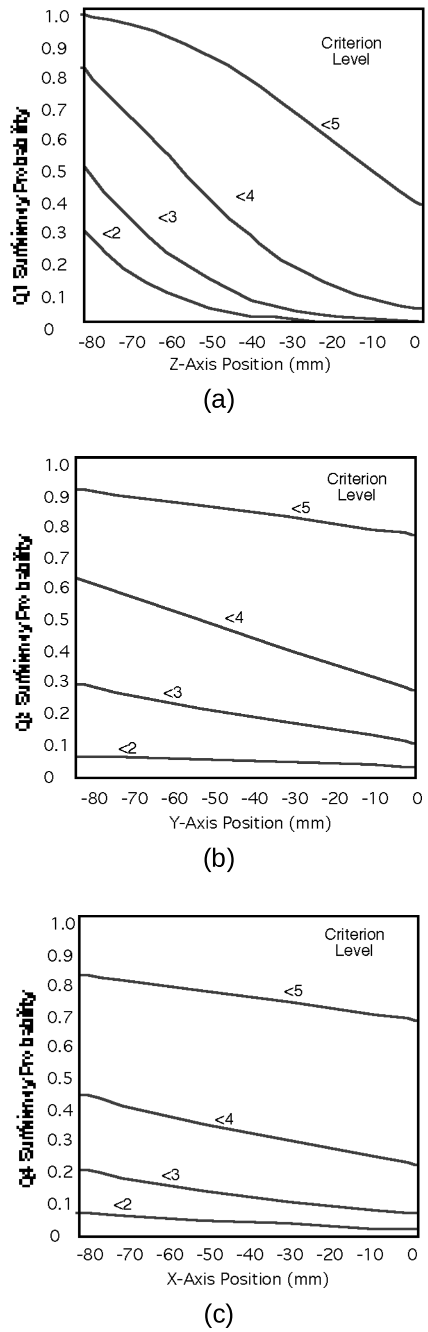

Figure 14. Logistic regressions predicting sufficiency response levels from roof axis positions. The vertical axis shows probabilities. Each line in the plots shows the probability of responses less than criterion levels 2 through 5.

LIMITATIONS OF TESTING METHODS – The most important limitation of the ratings testing was that the interior shape of the roof was not varied during testing. Instead, each test condition was obtained by translating the roof vertically, laterally, or fore-aft. This design, while the only practical approach using the PVM, did not allow independent exploration of the effects of, for example, vertical clearance and lateral clearance. When the roof height was changed in the PVM, both the vertical and lateral clearances changed simultaneously. Future experimentation should manipulate the roof geometry to determine how various characteristics of the roof geometry affect the perception of headroom. Such experiments would provide considerable guidance to designers trying to obtain high ratings with minimal clearances.

Another important limitation of the ratings trials was that only the least restrictive condition produced ratings above the important criterion levels (sufficiency = 4 or acceptability = 4) at the 95th percentile. Effectively, this meant that the region of the experimental design space of greatest interest was in one corner of the design. This test condition matrix reflected, in part, the limitations of the PVM. A better design for exploring the upper percentiles of acceptability (e.g., determining roof positions judged to be acceptable by 95 percent of drivers) would put roof positions that are likely to meet the criterion values near the center of the experimental design. Data from such an experiment would provide more robust estimates of these roof positions. Compared with data from the present experiment, the findings would help to determine if subjects tend to expand their responses to match the range of stimuli.

This research is believed to be the first systematic study to examine driver headroom perception. The new methods developed to quantify and evaluate driver headroom have resulted in an improved understanding of driver headroom perception. The observation of a counterintuitive influence of stature on headroom perception demonstrates the need for detailed study in this area. The modeling techniques developed in this study offer the ability to evaluate design changes with respect to the percentage of the population who will be accommodated at a selected subjective criterion level. Further research will expand the models to passengers and to include the effects of changing roof interior geometry.

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