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SUBJECTIVE ASSESSMENT OF DRIVER HEADROOM

FINAL REPORT

Matthew P. Reed
Lawrence W. Schneider

Biosciences Division
University of Michigan
Transportation Research Institute
2901 Baxter Road
Ann Arbor, MI 48109-2150

Submitted to:

Ford Motor Company
Advanced Engineering Center
20000 Rotunda Drive
Dearborn, MI 48121-2053

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16. Abstract

A study of driver headroom perception was conducted using a reconfigurable vehicle mockup and two subjective assessment techniques. In ratings testing, the positions of the vehicle interior components near the driver's head were varied over a 75-mm range on three perpendicular axes. Ninety-nine drivers rated each of 12 conditions on headroom sufficiency and acceptability scales. In method-of-limits testing, the roof was moved continuously along each of the three axes from specified starting points. The subjects indicated stop points, or limits, corresponding to boundaries between unacceptable, acceptable, and comfortable regions. Testing was conducted with men and women representing a wide range of statures. Body landmark data collected in each test condition were used together with detailed data on each subject's head and hair contours to calculate the actual head and hair clearances. Statistical models were created to relate roof positions and clearances to subjective assessments.

There is considerable intersubject variability in headroom perception, both in the ratings and method-of-limits trials. Two conventional measures of headroom, SAE W27 and H35, were found to be poor predictors of subjective headroom ratings over the range of conditions studied. Better prediction of headroom ratings was obtained using translations of the roof relative to the nominal condition, which was chosen to be representative of a typical midsize sedan. The vertical position of the roof had the strongest effect, followed by lateral position. Fore-aft roof position, over a 75-mm range, had only a small effect on headroom ratings.

Stature was a poor predictor of subjective headroom assessment. Short-statured drivers were as likely as tall drivers to give poor ratings to restrictive headroom conditions. The posture and head clearance analysis suggests that the seat positions chosen by short-statured drivers move their heads closer to the sun visor and header portion of the roof contour, so that the actual clearances to the interior surfaces in front of the forehead are similar for short and tall subjects.

The data analyses focused on prediction of the roof positions and headroom measurements that would likely result in a specified percentage of the population finding the headroom to be "sufficient" or "acceptable." For the conditions in this study, an overall minimum clearance relative to the SAE 95th-percentile headspace contour of 70 mm is a reasonable estimate of the headroom required to achieve subjective ratings of "sufficient" or "acceptable" from 95 percent of drivers.

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1.0 INTRODUCTION

Recent trends in vehicle occupant protection have led to 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. 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 (SAE 1997). 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 (Roe 1975). Recently, the implementation of these contours in computer software was simplified by adopting approximating ellipsoids (J1052, SAE 1997).

Figure 1 shows the SAE J1052 95th-percentile headspace 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 heads of 95% 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. There are several other head clearance measures defined in SAE J1100, but most do not provide useful comparative measures of headroom. H41, minimum sideview head clearance, is measured at the shortest distance between the roof and head-position contour, and hence can be a measure of clearance at any angle. Similar H41 values obtained at different locations on the contour are likely to represent different headroom conditions from the driver's perspective. H61 measures the height of the roof on the driver centerline above the depressed seat surface on a vector eight degrees rearward of vertical from the SgRP. L38 measures the minimum sideview distance from the head-position contour to the windshield molding, but because of varying roof, sun visor, and windshield geometry, this value is not a good comparative headroom measure.

The SAE procedures predict the distribution of driver head 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 can be used to predict the percentage of drivers that would rate a particular roof condition at a criterion level, or, alternatively, to specify the roof positions or clearances that would be required to achieve a desired percentage of subjective responses at or above a criterion level.

2.0 METHODS

2.1 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 approximately representative of 1997 Taurus package geometry. The interior structures near the driver's head, including the header, sun visor, and 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 5 and Table 1 show some important interior dimensions for the nominal configuration.

Figure 3. Reconfigurable vehicle mockup. Rear view (right) and driver-side view (left).

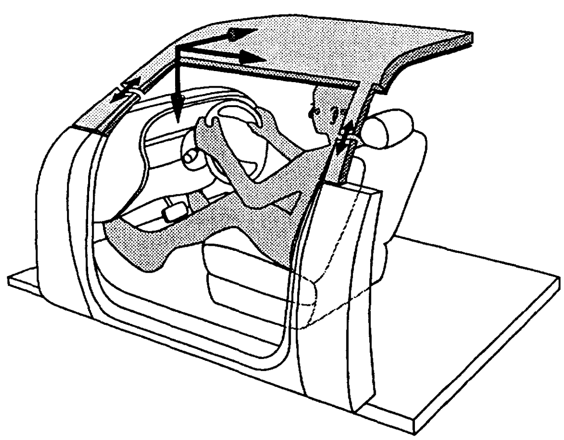


Figure 4. Roof adjustment axes. Arrows show directions of movement from nominal. A and B pillars telescope and pivot to allow roof translation.

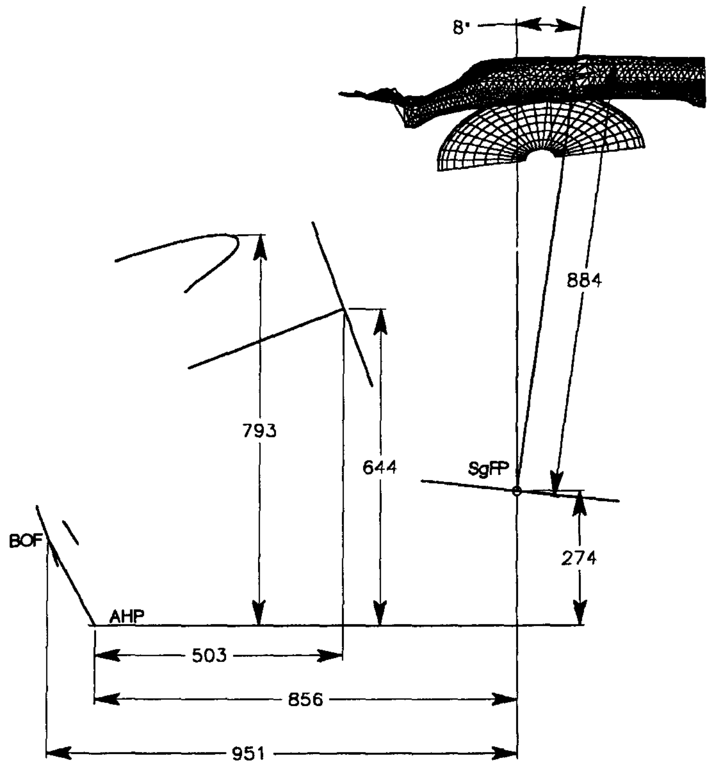


Figure 5. Package dimensions in test configuration.

Table 1
Package Dimensions

Dimension	SAE J1100 Designation	Value (mm)
Seat Height	H30	274
SW to AHP (X)	L11	503
SW to AHP (Z)	H17	644
SgRP to AHP (X)	L53	858
SgRP to BOF (X)	--	951
Design Seatback Angle	L40	22.5 *
Headroom Measures:†		
Vertical Head Clearance	H35	57.4
Minimum Head Clearance	H41	57.4
Effective Headroom	H61	986
Header Clearance	L38	187
Diagonal Clearance	W27	59.0

*Using J1517, 95th-percentile seat-position curve.
†All headroom measures obtained with the roof in the nominal condition (ratings condition 1).

FARO Arm Digitizer – Vehicle component and subject 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).

2.2 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 2 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.

Table 2
Subject Pool

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

*Percentiles of the U.S. adult population by gender (Abraham et al. 1979).

2.3 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.

* 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.

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 geometry were measured using the FARO arm and a specially designed head stabilization fixture, illustrated in Figure 6. A set of head and face anatomical landmarks, listed in Table 3, 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.

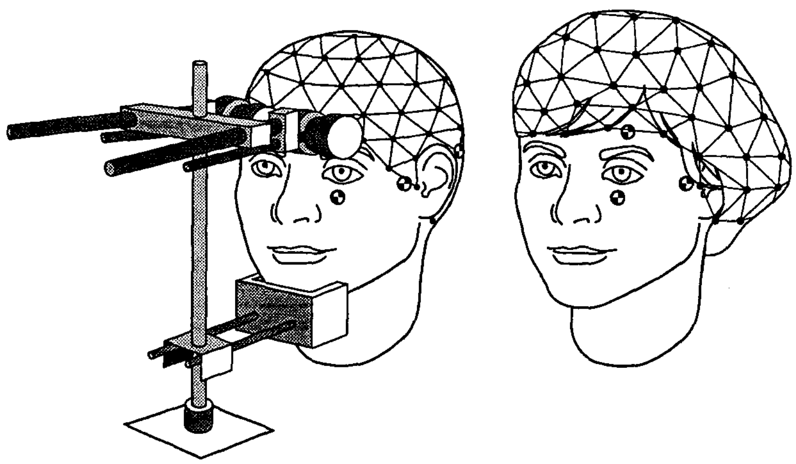


Figure 6. Schematic of head and hair contour digitization procedure, showing head stabilization fixture and points on the head and hair contour recorded using the FARO arm.

Table 3
Head Landmarks

Landmark	Definition
Glabella	Undepressed skin surface point obtained by palpating the most forward projection of the forehead in the midline at the level of the brow ridges.
Infraorbitale (right and left)	Undepressed skin surface point obtained by palpating the most inferior margin of the eye orbit (eye socket).
Tragion (right and left)	Undepressed skin surface point obtained by palpating the most anterior margin of the cartilaginous notch just superior to the tragus of the ear (located at the upper edge of the external auditory meatus).
Occiput	Undepressed skin surface point at the posterior inferior occipital prominence. Hair is lightly compressed.
Vertex (head)	Undepressed skin surface point at the most superior point on the head. Hair is lightly compressed.
Vertex (hair)	Undepressed point at the most superior point on the subject's hair.
Corner of Eye	Undepressed skin surface point at the lateral junction of the upper and lower eyelids.
Tip of Nose	Undepressed skin surface point at the tip of the nose.
Posterior Head	Undepressed skin surface at the most posterior point on the head. Hair is lightly compressed.

During analysis of the 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 7 shows typical head and hair contours from one subject, along with anatomical reference points.

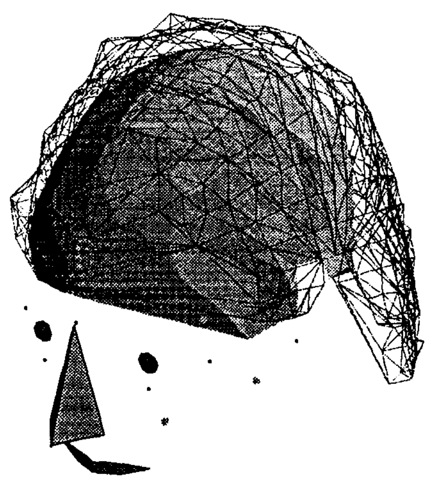


Figure 7. Head and hair surface data for a midsize-female subject. Head landmarks and reference points are shown as dots. The hair surface is shown as a wireframe so that the head surface may be seen. Facial features are generated synthetically based on measured face landmarks.

2.4 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 ($3^3 = 27$ 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 4 lists the test conditions. Condition 1 is the initial configuration (similar to Taurus 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 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 initial 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 4
Nominal 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 – In ratings testing, each subject answered ten questions for each of the test conditions. The complete questionnaire is reproduced in the Appendix. The analyses presented in this report are based on responses to questions 1, 2, 4, and 9. Figure 8 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." 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 8. 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 test time and to reduce the possibility that the subject's ratings would be influenced by 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, listed in Table 5. 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 9 shows a head reference point being measured using the FARO arm.

Table 5
Definitions of Body Landmarks

Landmark	Definition
Suprasternale (manubrium)	Undepressed skin surface point at the superior margin of the jugular notch of the manubrium on the midline of the sternum.
Substernale (xyphoid process)	Undepressed skin surface point at the inferior margin of the sternum on the midline.
Anterior-Superior Iliac Spine (ASIS)	Depressed skin surface point at the left anterior-superior iliac spine. Located by palpating proximally on the midline of the anterior thigh surface until the anterior prominence of the iliac spine is reached.
Acromion	Undepressed skin surface point obtained by palpating the most anterior portion of the lateral margin of the acromion process of the scapula.
Head Reference Points	Three reference points arbitrarily located on the forehead, left cheek, and left temple, used to locate the head in the vehicle space. The locations of these reference points relative to anatomical landmarks were determined during head digitization.

Figure 9. Subject's head posture recorded with the FARO arm.

2.5 Method-of-Limits Testing

Test Conditions – Method-of-limits testing (hereafter called limits testing) was conducted using eight different combinations of starting roof position and movement axis. Table 6 lists the eight limits conditions, relative to ratings condition 1. In each case, the roof position on the movement axis started 45 mm less restrictive than the corresponding axis position for ratings condition 1. For example, in limits condition 1, the roof started out 45 mm higher than in ratings condition 1, but with the same lateral and fore-aft positions.

Table 6
Method-of-Limits Test Conditions re Ratings Condition 1*
(Moving axis in **bold**)

Condition	Start X	Start Y	Start Z
1	0	0	**+45**
2	-75	0	**+45**
3	**+45**	0	0
4	**+45**	0	-37.5
5	**+45**	0	-75
6	0	**+45**	0
7	0	**+45**	-37.5
8	0	**+45**	-75

* Positive numbers indicate less restrictive headroom than ratings condition 1 (roof higher, further forward, or further outboard). Numbers in bold indicate starting position for moving axis. Values are nominal positions; actual average positions were within 5 mm of nominal.

Procedures – The goal of the limits testing was to determine the roof positions that correspond to the boundaries between three theoretical headroom zones of driver acceptance. Figure 10 shows a slide that was projected on the screen in front of the subject during each limits testing session. In the outermost zone, roof positions are comfortable. In the intermediate zone, the roof position remains acceptable, but is uncomfortable. In the closest zone, the roof position is unacceptable. Each subject identified the locations of the two zone boundaries (edges of the acceptability-but-comfortable zone) by stopping the movement of the roof with a verbal cue.

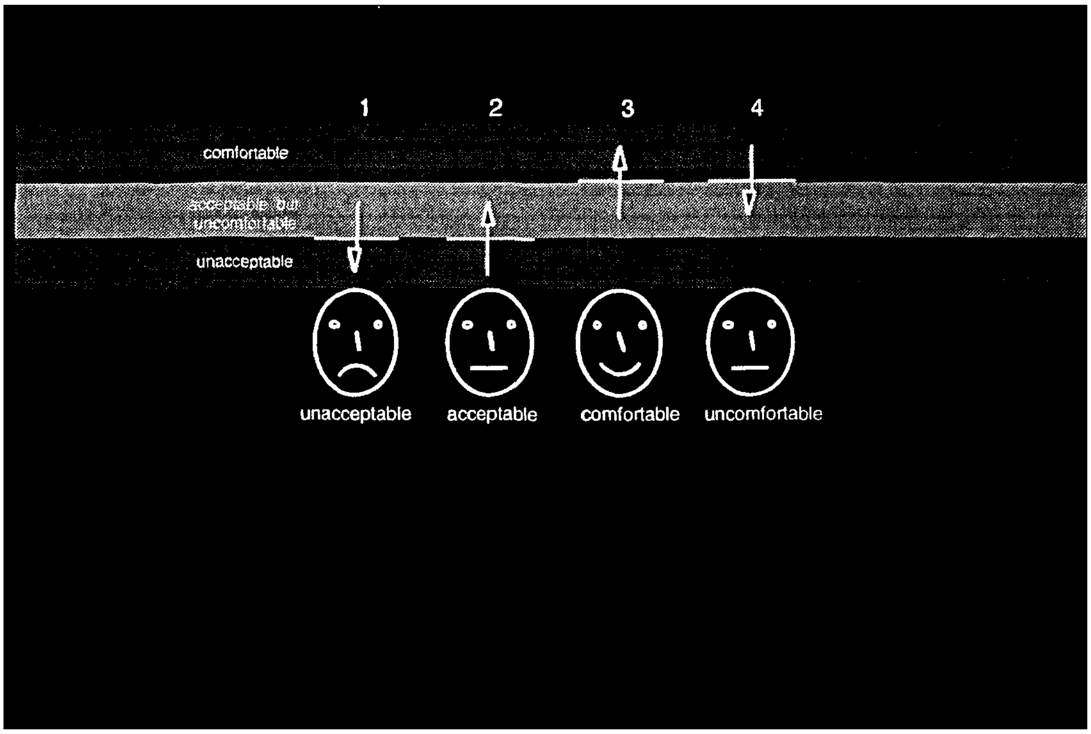


Figure 10. Method-of-limits slide, demonstrating regions of comfort and acceptability.

To begin each limits trial, the subject reclined the seat and closed his or her eyes, as in the ratings trials. After the starting roof position was set, the subject opened his or her eyes and adjusted the seat-track position and seatback angle to obtain a comfortable driving posture. The subject's posture and the starting position of the roof were recorded using the FARO arm. The roof was then set in motion on the tested axis (see Table 6), moving at approximately 10 mm per second.*

During each trial, the subject identified four stop points, corresponding to roof locations at the perceived boundaries depicted in Figure 10. The instructions to the subjects were phrased in terms of transitions. The subject was asked to identify the points as follows:

"When the roof position becomes unacceptable" (stop point 1, roof moving inward)
"When the roof position becomes acceptable again" (stop point 2, roof moving outward)
"When the roof position becomes comfortable" (stop point 3, roof moving outward)
"When the roof position becomes uncomfortable again" (stop point 4, roof moving inward)

The roof location was recorded using the FARO arm at each of four stop points. As the roof was moved inward, the subject was instructed to say "stop" when the roof position became unacceptable, at which time the experimenter halted the roof movement (stop point 1). The roof was then moved further toward the subject a small, varying amount (10 to 35 mm, or until it reached its limit of travel), and then moved steadily outward at the same speed. The subject again said "stop" when the roof position became acceptable again, ideally identifying the same boundary point (stop point 2). The roof was moved

* The original experiment design called for the roof axis position to be under the subject's direct or verbal control, so that the roof could be alternately moved in and out until the desired position was obtained (e.g., boundary of acceptability). However, the control circuitry of the PVM required a lengthy relay cycling process every time the roof was set in motion. This delay precluded using the PVM in this manner, and necessitated the adoption of the less-desirable experimental approach described here.

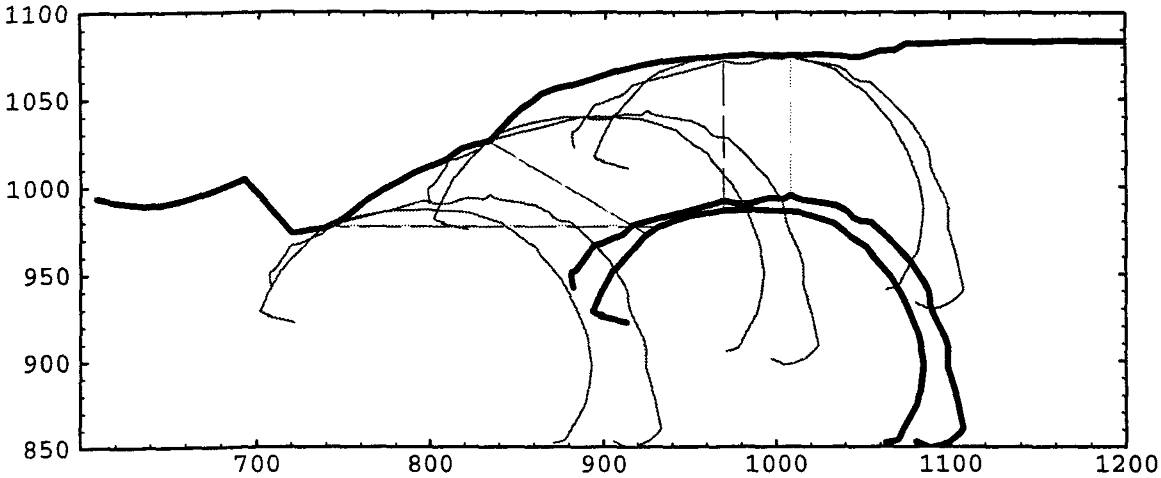


Figure 12. Schematic of sideview clearance calculations. Head, hair, and roof contours are shown with thick lines. Vertical, forward, and forward/up-30-degree clearance conditions are illustrated with dashed lines for both the head and hair contours. The gray lines show the translated positions of the head and hair contours at the maximum translations.

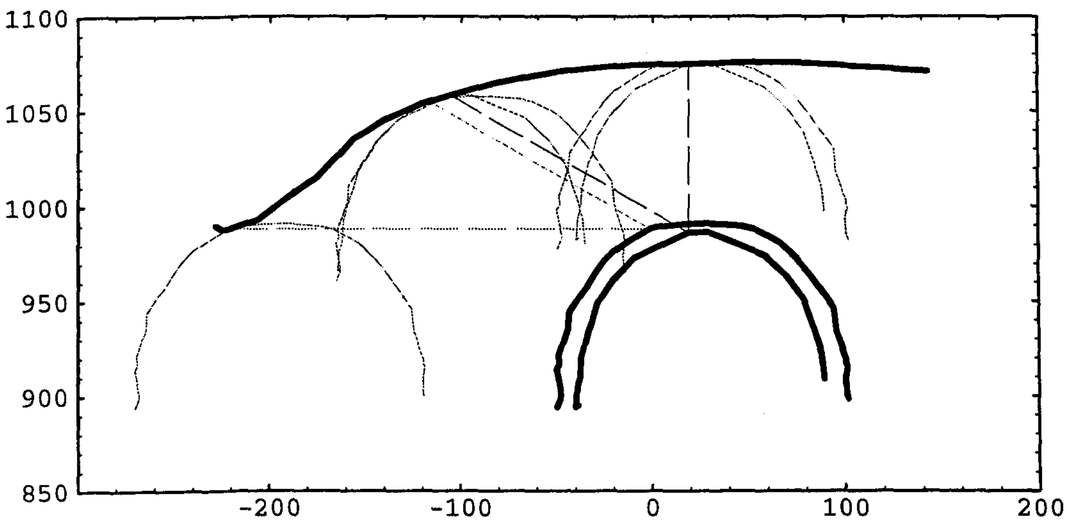


Figure 13. Schematic of rearview clearance calculations. Head, hair, and roof contours are shown with thick lines. Vertical, left, and left/up-30-degree clearance conditions are illustrated with dashed lines for both the head and hair contours. The gray lines show the translated positions of the head and hair contours at the maximum translations. For this subject and condition, there is no contact with lateral translation of the head contour.

3.0 RESULTS

3.1 Ratings Trials

PVM Performance – An important consideration in the analysis of the ratings data is the performance of the PVM. Unfortunately, the PVM did not consistently replicate the desired test conditions, although the average performance was fairly accurate. Because the actual roof location was measured for each trial, the data can be interpreted accurately in spite of the lack of precision, but the desired test conditions were often not achieved. Figure 14 shows the measured locations of one reference point by nominal roof condition. Figure 15 shows histograms of the same measures. Note that these plots show approximately 10 mm of range on the X axis and 30 mm on the other two axes. The Z axis is particularly inaccurate; there is overlap between the different nominal conditions in actual roof height. While this PVM performance was disappointing, the analysis was not substantially impeded because the actual roof locations were known with reasonable accuracy from direct measurement data for all trials.

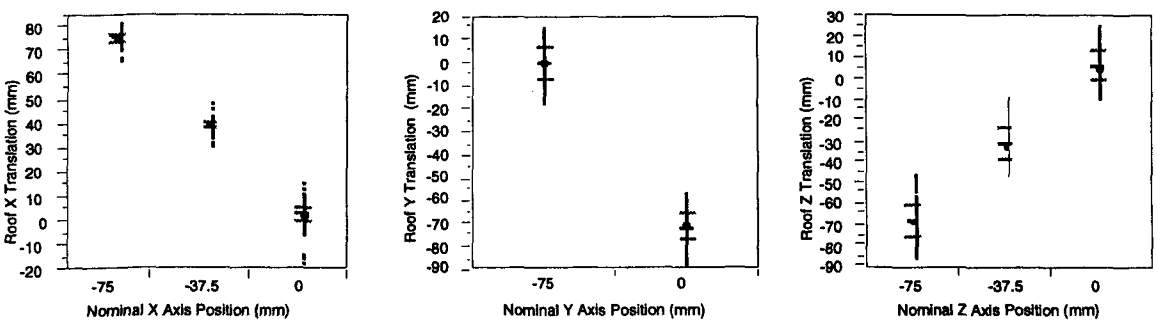


Figure 14. Roof reference point locations by nominal roof position on three axes (mm). Horizontal bars are ± 1 standard deviation.

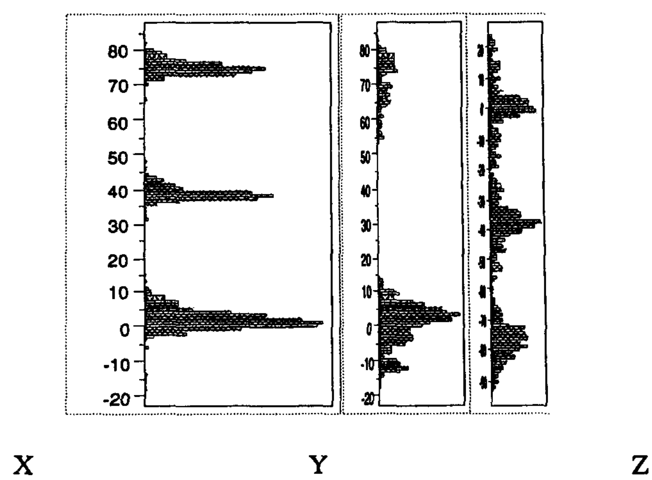


Figure 15. Roof reference point location histograms on fore-aft (X), lateral (Y), and vertical (Z) axes. Nominal values are 0, (-)37.5 and (-)75 mm.

Posture – A number of posture variables were calculated from the body and seat landmark data for each trial. Analysis of variance and linear regression were used to investigate the effects of the test conditions (roof translations) on posture variables. Fore-aft seat position and head orientation were not significantly affected by changes in roof position, but all of the available measures of torso recline showed effects of roof height. Mean selected seatback angle, referenced to the SAE J826 manikin back angle, increased from an average of 24.7 degrees in ratings condition 1 (the least restrictive roof position) to 26.8 degrees in ratings condition 12 (the most restrictive condition). There was also a large stature effect on seatback angle and a small interaction with vertical roof position. Average seatback angle was 29.3 degrees for the group 11 (tallest) subjects compared with 20.3 degrees for group 0 (shortest). Most of the roof height effect was observed in the tallest subject groups. The group 11 subjects increased their seatback angles an average of four degrees as the roof was lowered by 75 mm, while the seatback angles of group 0 subjects did not change significantly.

Stature Effects – The subjects responded to the 12 ratings test conditions with a wide range of ratings. Figure 16 shows mosaic plots of the responses to questions 1, 2, and 4. The vertical bars in each plot correspond to subject stature/gender groups (see Table 2). The divisions of each bar indicate the proportions of each response level when the ratings for all test conditions are combined.

Unexpectedly, there are substantial percentages of short-statured subjects who gave some test conditions low ratings. For example, about 10% 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 17 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.

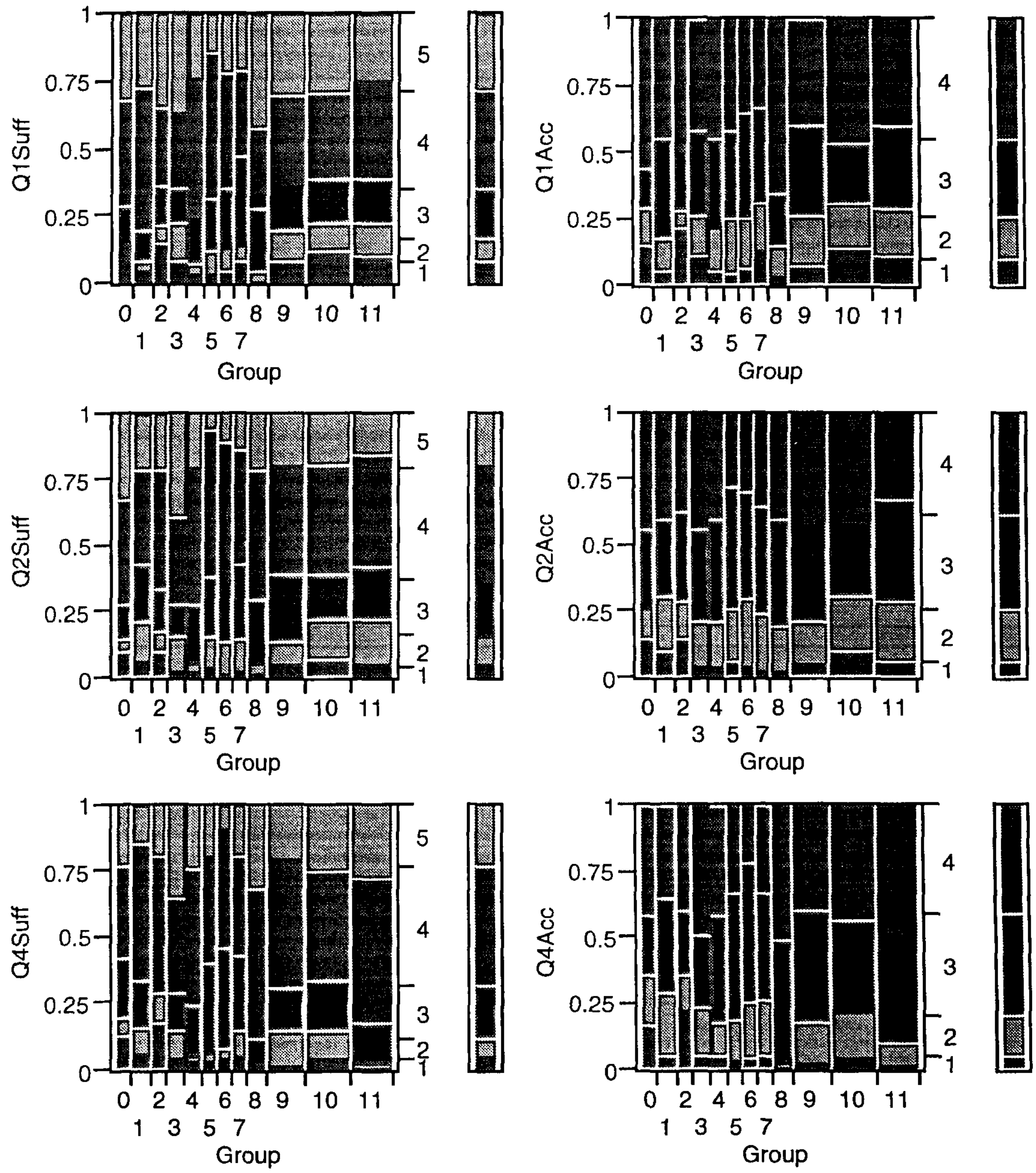


Figure 16. Mosaic plots of responses to questions 1, 2, and 4, by subject group, for all subjects and test conditions. Plots on the left show sufficiency ratings (1 to 5). Plots on the right show acceptability ratings (1 to 4). Each vertical bar is divided to show the proportion of each response level. The width of each bar is proportional to the number of subjects in the group.

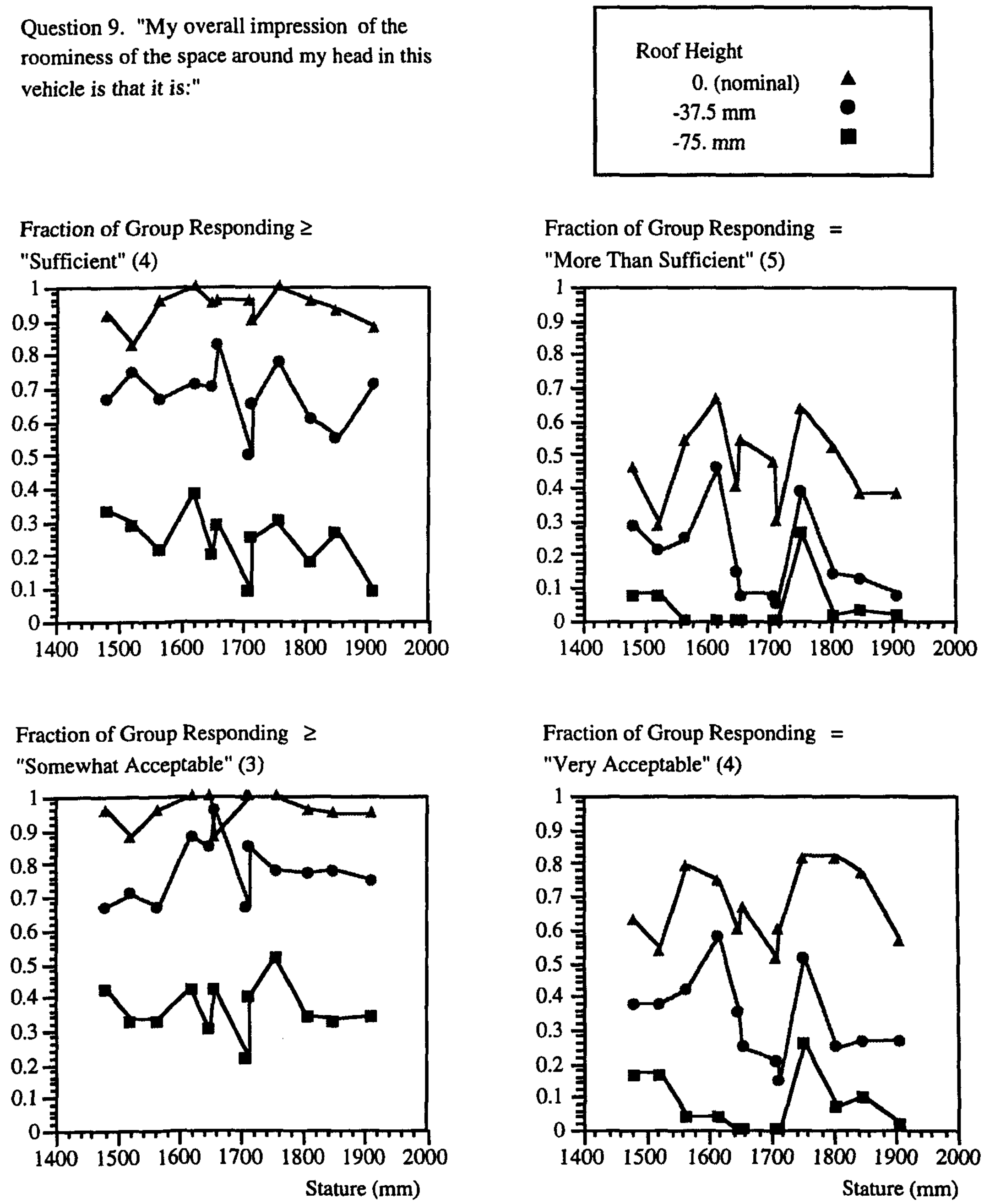


Figure 17. Fraction of each stature/gender group (plotted by group mean stature) at two sufficiency and acceptability levels for question 9 (overall headroom evaluation). Lines connect fractions at each of three roof heights (Z axis).

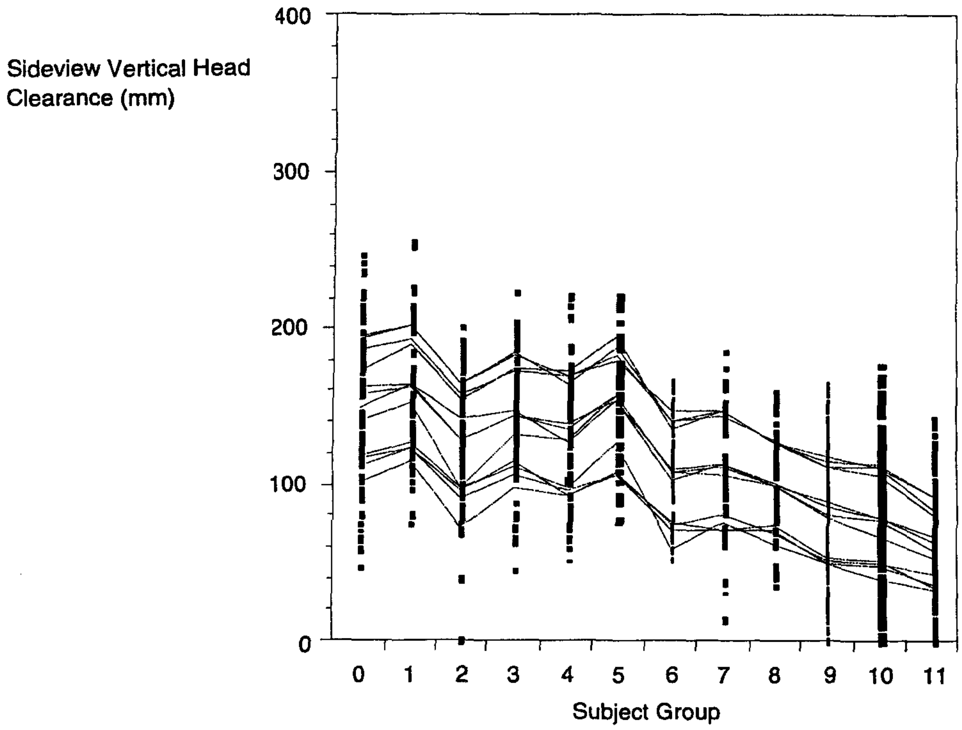
The unexpected and counterintuitive lack of a stature effect can be understood, in part, from examination of the actual roof-to-head clearances. In the bottom plot, Figure 18 shows the "sideview-30" head clearance measure, obtained by translating the sideview head section forward and upward 30 degrees to contact with the roof (analogous to W27). In the top plot, the actual vertical clearance above the subject's head is plotted. Each clearance measure is plotted versus subject group, so taller subjects are to the right in each plot. Lines connect means for each of the 12 ratings test conditions, each of which has a different nominal roof position.

The plot shows some interesting trends. Note that the ratings conditions affect both of these measures of actual head clearance. In the top plot (vertical clearance), there are three distinct bands of conditions, corresponding to the three vertical roof positions. Taking the top band, corresponding to the nominal-height roof conditions, the smallest subject group had an average of about 200 mm of vertical head clearance, while the tallest subjects had about 90 mm. At the lowest roof height, the vertical clearance is reduced by approximately the nominal change in roof height for the shortest subjects (75 mm), but not as much for the taller subjects. The difference in vertical clearance between the roof positions is smaller for the tallest subjects, probably because of more reclined postures induced by the low roof height.

The effects of test condition and subject stature on the sideview-30 measure is quite different. First, note that the roof height does not have the clean effect on the results that it has for the vertical measure. This is because both the fore-aft and vertical roof position affect the sideview-30 measure. For tall subjects, the contact point for the 30-degree forward translation is on the approximately flat portion of the roof, so fore-aft position changes do not affect sideview-30 much. For smaller subjects, who sit further forward, the contact point is in the visor area, and the fore-aft position affects the head clearance as much as the vertical position, producing the scatter in the lines at the left side of the sideview-30 plot.

It is instructive to compare these two clearance measures across subject groups for the most restrictive test conditions. Taking the lowest line across each plot (generally test condition 12), we see that the actual vertical clearance is about twice as much for the shortest subjects as for the tallest subjects. In fact, the shortest subjects have slightly more actual vertical headroom at the most restrictive condition than the tallest subjects have at the least restrictive condition (about 110 mm vs. about 90 mm).

In contrast, the sideview-30 measure shows that the clearances are more similar across subject groups in front of the subject's foreheads. In the most restrictive condition, the smallest subjects averaged about 110 mm of sideview-30 clearance, compared with about 80 mm for the tallest subjects, a difference of only about 30 mm. The differences between short and tall subjects in actual head clearance to the roof liner in the areas visible to the subject in a normal, straightahead head posture were much smaller than the differences in vertical head position (sitting height) would suggest. This may account for the fact that small subjects rated the roof conditions in a manner very similar to taller subjects. Note also that the relative change in sideview-30 clearance across the test conditions for the shortest subjects is much larger, about a 65% reduction, compared to a reduction of about 50% for the tallest subjects. Figure 19 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 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.



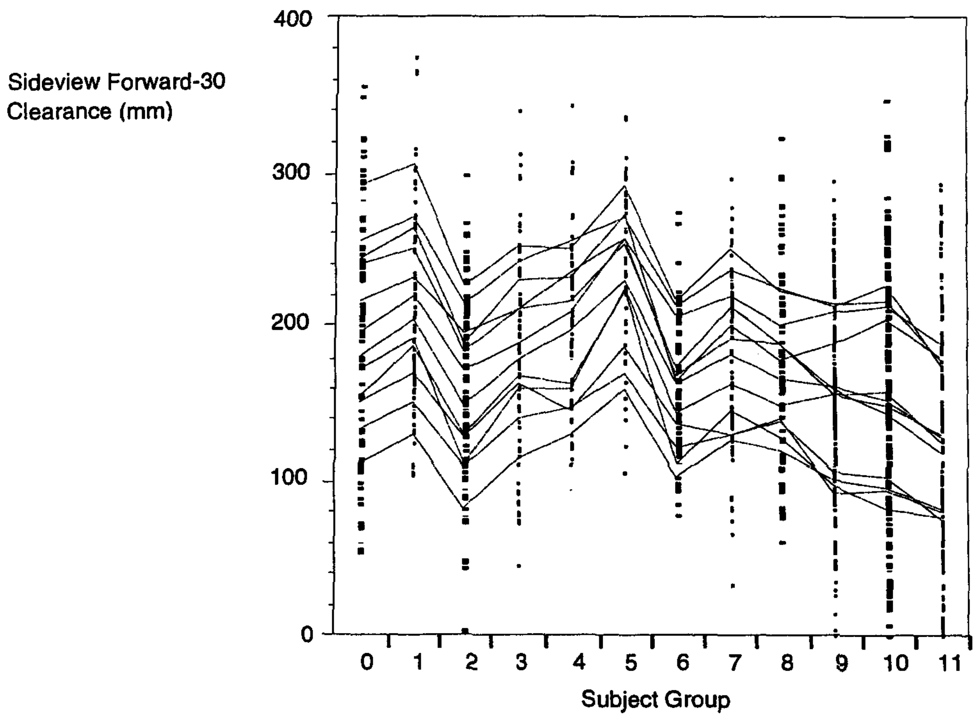


Figure 18. Actual vertical head clearance (top) and actual sideview-30 head clearance (bottom), calculated by translating the sideview head contour forward and upward 30 degrees to point of first contact. Plots show data from all subjects and ratings conditions. Lines connecting ratings condition means across subject groups.

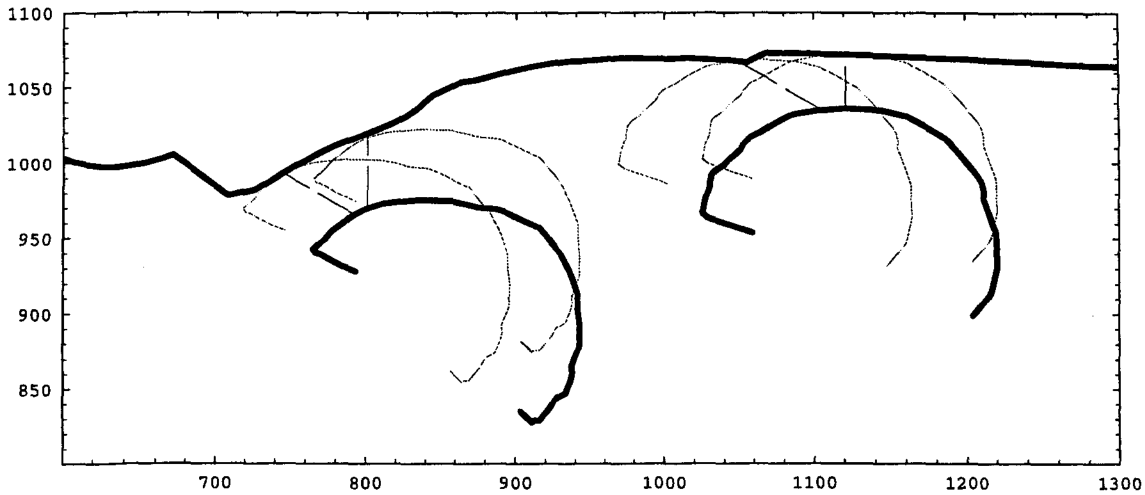


Figure 19. Sideview head and roof contours for two subjects in ratings condition 12. Light lines show the translations used to measure vertical and forward-30 clearances. The short-statured subject (group 0) sitting further forward has clearance in front of the forehead on the forward-30 measure that is similar to the clearance experienced by a tall subject (group 11).

Correlation Among Subjective Responses – The responses on the various headroom questions are correlated. Table 7 shows a cross tabulation of the response distributions on questions 1 and 9 (vertical headroom and overall headroom, respectively). Each cell in the table expresses the cell count as a percentage of the column total. For example, 69% of the time that a subject responded on question 1 with a 4 on the sufficiency scale, he or she also gave a 4 on the question-9 sufficiency scale. Since vertical headroom may be part of the perception of overall headroom, some association among the responses on these questions is expected. However, there is also strong association between responses on questions that were not expected to be as closely linked. Table 8 tabulates responses on question 1 (vertical space) and question 2 (lateral space). A response of 4 on question 1 was followed 65% of the time by a 4 on question 2.

Table 7
Cross Tabulation of Responses on Questions 1 and 9
(percent of responses by column)

	Q1 Sufficiency				
Q9 Sufficiency	1	2	3	4	5
1	**69.15**	11.46	3.33	0.00	0.00
2	22.34	**57.29**	18.10	2.17	0.00
3	4.26	29.17	**55.71**	21.01	2.13
4	4.26	1.04	21.43	**69.32**	31.00
5	0.00	1.04	1.43	7.49	**66.87**
Total	100%	100%	100%	100%	100%

Table 8
Cross Tabulation of Responses on Questions 1 and 2
(percent of responses by column)

	Q1 Sufficiency				
Q2 Sufficiency	1	2	3	4	5
1	**39.36**	6.25	1.90	0.48	0.00
2	35.11	**37.50**	15.24	6.52	1.82
3	18.09	41.67	**40.00**	18.36	6.08
4	7.45	14.58	41.90	**64.73**	34.65
5	0.00	0.00	0.95	9.90	**57.45**
Total	100%	100%	100%	100%	100%

Selection of Independent Variables – Since the primary purpose of this research was to develop design tools referenced to the current SAE headroom measures, analyses were begun using the SAE measures calculated for each test condition as the independent variables. However, a considerable problem emerged that necessitated a different approach. The ratings test matrix was intended to provide orthogonal variation of three characteristics of the available head space, so that the potential independent and interactive effects could be observed (Table 6). The roof structure near the driver's head was moved on three orthogonal axes to set each test condition. However, because of the nature of the contours of the roof and the SAE head-position contour, the SAE clearance measures of interest were highly correlated across the test conditions. Figure 20 shows the SAE rearview section and the roof contour at the highest roof position and two lateral positions. Note that when the head-position contour is translated vertically (measuring H35), the contact point changes substantially as the roof is moved laterally, reducing the translational measure of vertical headroom. A similar problem occurs in the rear view.

Table 9 lists the nominal test conditions along with the two rearview SAE measures (H35 and W27) and two analogous measures for side view. In condition 1 (the nominal condition), the vertical clearance measure obtained in rear view and side view is very similar, about 65 mm. When the contours are translated vertically, the uppermost part of the contour contacts the roof first in both views. However, when the fore-aft or lateral position of the roof is changed, the location of the first contact changes, altering the vertical clearance measure. For example, condition 2 is the same as condition 1 except that the roof has been moved 75 mm laterally (inboard). Because the rearview contact point changes, the vertical clearance measure (H35) is reduced by about 39 mm, even though the vertical position of the roof remained unchanged. A similar trend can be observed in the sideview vertical measure when the fore-aft roof position is changed.

One consequence of these observations is that the SAE and related measures are not well suited for use as independent variables. The correlation between the vertical and lateral clearance measures, for example, is about 0.8, making it difficult to discern any independent effects of lateral and vertical roof position using these measures. Instead, the analyses were conducted using the roof translations and the findings interpreted with respect to the SAE measures.

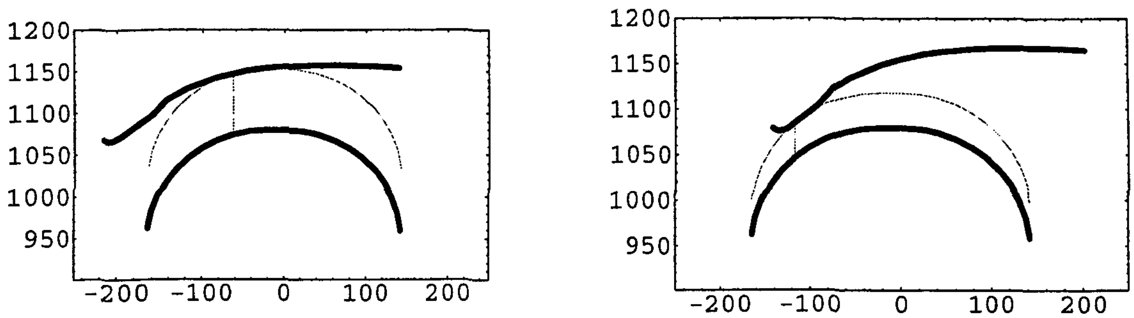


Figure 20. Illustration of interaction between SAE rearview head-position and roof contours. Plot on left is from ratings test condition 1. Plot on right is from test condition 2, in which the roof has been translated 75 mm to the right (inboard). Dotted lines show vertical translations of the head-position contour, showing the effect of lateral position on the SAE H35 clearance measurement.

Table 9
Average Values for Selected SAE Measures by Test Condition

Condition	X Fore-Aft Axis (mm)	Y Lateral Axis (mm)	Z Vertical Axis (mm)	Sideview Z (mm)	Sideview 30° (mm)	Rearview Z (H35) (mm)	Rearview 30° (W27) (mm)
1	0	0	0	64.5	89.0	62.7	65.6
2	0	-75	0	60.1	99.1	28.6	26.1
3	-37.5	0	0	60.7	68.9	62.0	65.7
4	-75	0	0	43.5	52.3	58.3	67.6
5	0	0	-37.5	28.2	45.5	26.4	35.1
6	0	-75	-37.5	22.9	46.7	-8.6	-7.7
7	-37.5	0	-37.5	23.1	24.0	25.1	35.4
8	-75	0	-37.5	4.4	6.4	20.4	32.4
9	0	0	-75	-9.8	-21.2	-11.7	-20.7
10	0	-75	-75	-14.3	-30.8	-45.6	-39.4
11	-37.5	0	-75	-16.3	-23.6	-13.2	-23.8
12	-75	0	-75	-35.3	-38.1	-17.7	-30.5

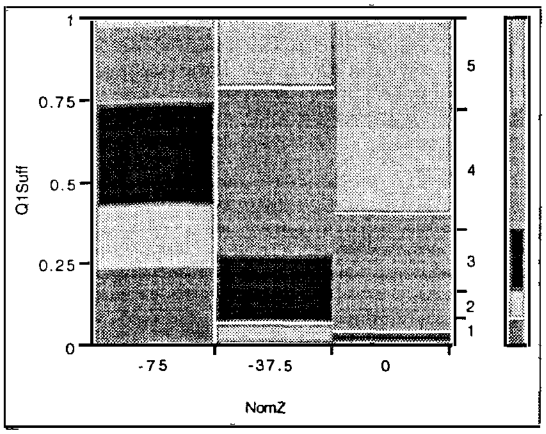
Factor Effects – The effects of vertical, fore-aft, and lateral roof movements on headroom ratings were examined initially by cross tabulation of responses by nominal condition level (i.e., the target roof translations were used, rather than the actual roof translations produced by the PVM). Figure 21 shows sufficiency ratings for questions 1, 2, and 4 plotted (space above, to the left, and forward of the driver's head) against the corresponding axis level. There is a fairly strong effect of the vertical position (NomZ) on sufficiency ratings, a moderate effect of lateral position (NomY), and only a minimal effect of fore-aft position (NomX). For example, about 23% of subjects reported that the vertical headroom was "very insufficient" when the roof was in its lowest position, while less than 1% rated the nominal condition as "very insufficient." Over 96% of the subjects gave the nominal roof height a 4 or a 5 with respect to vertical space, while only 26% gave the lowest roof position a 4 or 5.

The effects of lateral roof position are most apparent at the 3 versus 4 rating division (i.e., transition from "barely sufficient" to "sufficient"). At the outboard (nominal) roof position, 71% of subjects reported that the space to the left of their heads was "sufficient" or "very sufficient" (4 or 5), while only 39% gave a 4 or 5 rating with the roof at its inboard position. These totals reflect the responses at all levels of the other variables. Moving the roof rearward by 75 mm (NomX) had a smaller effect, reducing the 4 and 5 responses from 75% to 55%.

One might expect that the effects of lateral position or fore-aft position on the headroom perception would depend on the roof height. Figure 22 shows plots of the fraction of sufficiency responses greater than 3 for interactions between vertical position and the two other axes on four questions. Values for the interaction plots were calculated only at the nominal level of the other variable. For example, the interaction between vertical position and lateral position was investigated only for nominal fore-aft roof positions of zero.

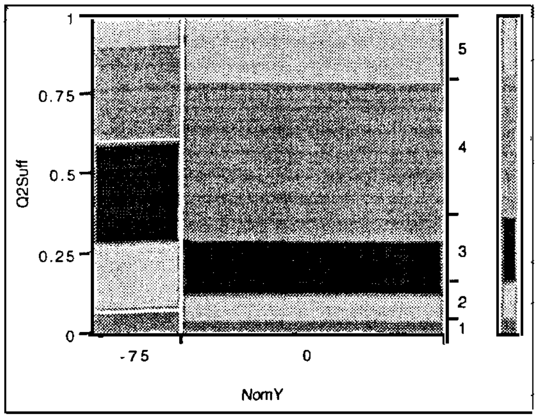
Figure 22A shows that the lateral roof position has a fairly strong effect on the perception of lateral space, but that this effect is approximately the same at different vertical roof positions. Lateral roof position has no effect on responses concerning vertical space (Figure 22B), but appears to affect the overall perception of headroom only at the less restrictive conditions. Figure 22C shows that the effect of vertical position on overall headroom perception is much larger than the effect of lateral position.

Fore-aft roof position decreases the perceived sufficiency of space in front of the head (Figure 22D) with the effect appearing to be larger at lower roof heights. The fore-aft roof position also has a small effect on the perception of vertical space (Figure 22E), about the same as the effect on overall headroom (Figure 22F). In general, lateral and fore-aft roof position have smaller effects on headroom perception than vertical position, and there do not appear to be any important interactions, meaning that the effects of headroom restriction on the three axes are approximately additive.



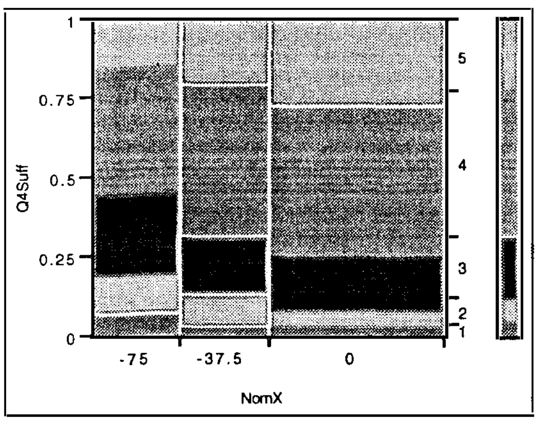
NomZ

Q1Suff Col %	-75	-37.5	0
1	23.40	1.33	0.26
2	19.41	5.31	0.53
3	31.65	21.22	2.91
4	22.07	50.66	36.51
5	3.46	21.49	59.79



NomY

Q2Suff Col %	-75	0
1	7.09	3.42
2	21.63	8.60
3	31.91	17.20
4	29.08	48.17
5	10.28	22.61



NomX

Q4Suff Col %	-75	-37.5	0
1	7.07	2.81	2.49
2	12.01	10.18	4.97
3	26.15	18.25	17.41
4	39.22	48.07	47.42
5	15.55	20.70	27.71

Figure 21. Effects of roof axis position on sufficiency rating distribution for X, Y, and Z axes and corresponding questions (1, 2, and 4, respectively).

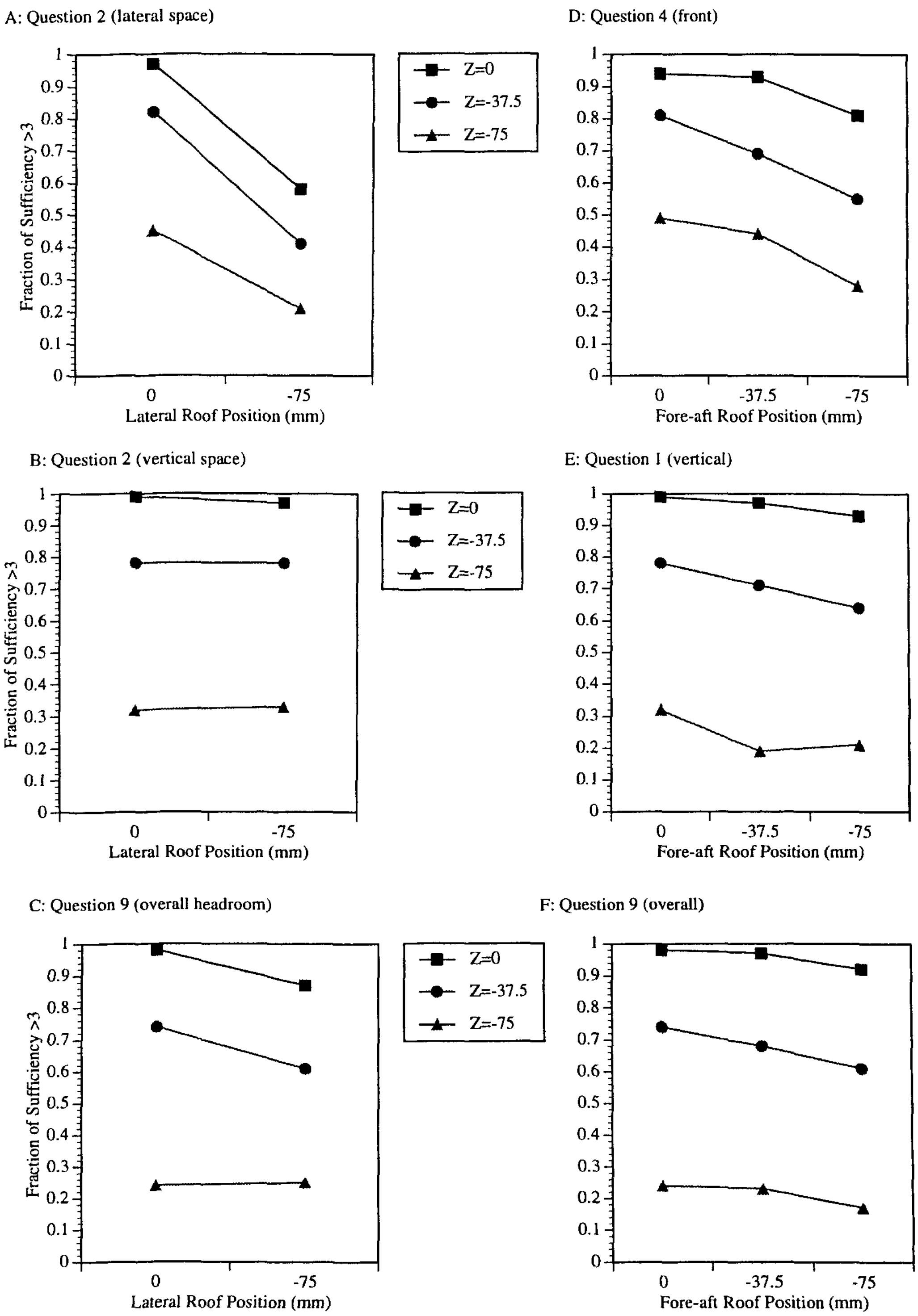


Figure 22. Factor effect interactions. Plots show fraction of sufficiency responses greater than 3. Data include only nominal levels of third factor. Lines in plots connect values from each of three vertical roof positions.

Logistic Regressions

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:

$$P(x) = \frac{e^f}{(1+e^f)} \quad [1]$$

where f is a linear function of the independent headroom measures and P(x) is the probability of the rating exceeding a particular criterion value. In these analyses, f is chosen to be

$$f = a\,x + b\,y + c\,z + d\,x\,z + e\,y\,z + f \quad [2]$$

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 23 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. 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 are weaker. For example, Figure 23A predicts that more than 95% 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% of subjects would rate the vertical space at 4 or 5. The figure shows that about 65% of subjects thought that the vertical head space in the nominal condition was "more than sufficient. "

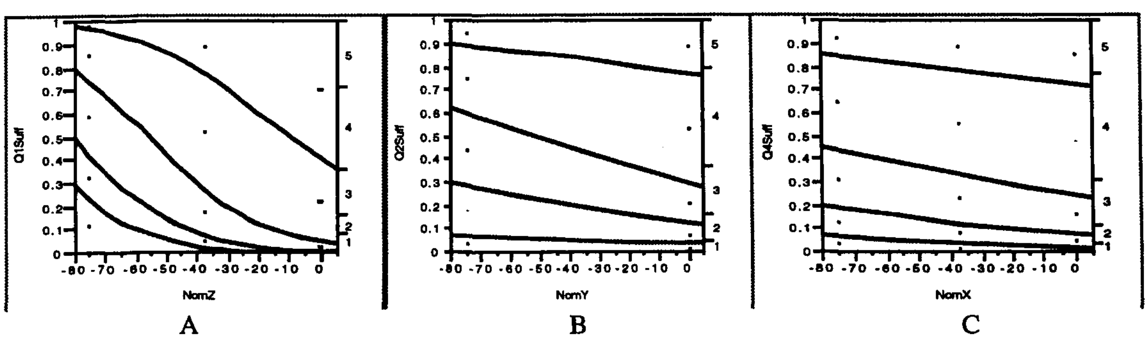


Figure 23. Logistic regressions predicting sufficiency response levels from roof axis positions. Each line in the plots shows the probability of responses less than or equal to levels 1 through 4. Right axis on each plot shows relative proportion of responses over all levels of the independent variable.

The plots in Figure 23 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. Table 10 shows model statistics for the probability that the overall evaluation is a 4 or 5 on the sufficiency scale. The model includes all three axis terms as well as the Z-by-Y interaction. The Chi-square column in the table provides a measure of the relative strength of each effect in the model. Note that although all parameter estimates are significantly different from zero, the Z-axis effect is by far the strongest.

Table 10
Model Fit Statistics for Combined Model Predicting Probability of Question 9
(Overall Evaluation, Sufficiency > 3)

Term	Estimate	Std Error	ChiSquare	Prob>ChiSq
Intercept	-3.3032389	0.2460518	180.23	<.0001
NomZ	-0.0583724	0.0038119	234.49	<.0001
NomX	-0.0085134	0.0030387	7.85	0.0051
NomY	-0.0187544	0.0047754	15.42	<.0001
NomZ*NomY	-0.0002482	0.000085	8.54	0.0035

The model described in Table 10 can be obtained by substituting

$$f = -3.303 - 0.0584\ \text{NomZ} - 0.0085\ \text{NomX} - 0.0187\ \text{NomY} - 0.0002482\ \text{NomZ*NomY}$$

into equation [1]. Table 11 shows output of the model over the test condition matrix, predicting the fraction of overall headroom sufficiency responses greater than 3 (overall headroom rated "sufficient" or "more than sufficient"). Examination of the values in Table 11 shows that the predicted percentage of people rating the headroom as sufficient or better declines from a high of 96% to 87% when the roof is moved inboard 75 mm. Moving the roof rearward 75 mm, however, only decreases the percentage who find the headroom sufficient to about 93%. Decreases in roof height have large effects, as demonstrated previously. Less than 25% of people are predicted to rate the headroom as sufficient when the roof is 75 mm lower than the nominal condition. To provide greater prediction generality, Table 12 gives model coefficients for three rating criterion levels on the sufficiency scale and two on the acceptability scale for overall headroom.

Table 11
Model Predictions for Overall Headroom Analysis
(Question 9, Sufficiency ≥ 4)

Condition	Fore-Aft (X) Axis (mm)	Lateral (Y) Axis (mm)	Vertical (Z) Axis (mm)	Predicted Population Fraction Rating Overall Headroom "Sufficient" or "More Than Sufficient"
1	0	0	0	96.4
2	0	-75	0	86.4
3	-37.5	0	0	95.1
4	-75	0	0	93.2
5	0	0	-37.5	75.1
6	0	-75	-37.5	59.6
7	-37.5	0	-37.5	68.2
8	-75	0	-37.5	60.3
9	0	0	-75	25.1
10	0	-75	-75	25.5
11	-37.5	0	-75	19.2
12	-75	0	-75	14.5

Table 12
Coefficients in Logistic Regression Models Predicting Overall Headroom Response Fractions*

Outcome	a (X)	b (Y)	c (Z)	d (XZ)	e (YZ)	f (const)
Suff. ≥ 3	-0.0081	-0.0203	-0.0682	0†	-0.000264	-5.49
Suff. ≥ 4	-0.0091	-0.0194	-0.0586	0	-0.000263	-3.3
Suff. = 5	0	-0.0069	-0.0423	0	0	0
Acc. ≥ 3	-0.0098	-0.0213	-0.0563	0	-0.000273	-3.85
Acc. = 4	0	-0.0095	-0.0454	0	0	-0.99

* To predict outcome percentage, use (1 - P(x))*100%, where P(x) is given by equations [1] and [2].
† Zero indicates that the model coefficient was not significantly different from zero with $p \leq 0.05$.

Tables 13 and 14 show the model predictions for the 12 ratings test conditions. In general, the logistic regression models accurately match the observed response percentages. For example, 86.7% of subjects rated condition 2 with a 4 or higher on the sufficiency scale. The logistic regression model predicts 86.4% Most errors are less than 2 percentage points, and the greatest discrepancies occur in the more extreme roof positions, which are of less practical interest than those near the nominal condition (condition 1).

Table 13
Predictions from Logistic Regression Models*
Overall Headroom **Sufficiency** Ratings

Condition	Suff. ≥ 3 (Obs)	Suff. ≥ 3 (Pred)	Error (O-P)	Suff. ≥ 4 (Obs)	Suff. ≥ 4 (Pred)	Error (O-P)	Suff. = 5 (Obs)	Suff. = 5 (Pred)	Error (O-P)
1	100.0	99.6	0.4	97.9	96.4	1.5	46.2	50.0	-3.8
2	98.9	98.1	0.8	86.7	86.4	0.3	36.7	37.3	-0.6
3	100.0	99.4	0.6	96.8	95.1	1.7	48.4	50.0	-1.6
4	98.9	99.2	-0.3	91.4	93.2	-1.8	49.5	50.0	-0.5
5	93.4	94.9	-1.5	74.7	75.1	-0.4	15.4	17.0	-1.6
6	88.2	89.6	-1.4	59.1	59.6	-0.5	11.8	10.9	0.9
7	94.5	93.3	1.2	67.0	68.2	-1.2	22.0	17.0	5.0
8	90.1	91.1	-1.0	59.3	60.3	-1.0	17.6	17.0	0.6
9	62.6	59.3	3.3	22.0	25.1	-3.1	4.4	4.0	0.4
10	59.1	58.4	0.7	25.8	25.5	0.3	2.2	2.4	-0.2
11	45.7	51.8	-6.1	22.8	19.2	3.6	3.3	4.0	-0.7
12	47.8	44.2	3.6	15.2	14.5	0.7	2.2	4.0	-1.8

* Predicted percentage of responses conforming to the criterion.

Table 14
Predictions from Logistic Regression Models*
Overall Headroom **Acceptability** Ratings

Condition	Acc. ≥ 3 (Obs)	Acc. ≥ 3 (Pred)	Error (O-P)	Acc. = 4 (Obs)	Acc. = 4 (Pred)	Error (O-P)
1	97.9	97.9	0.0	71.0	72.9	-1.9
2	90.0	90.5	-0.5	54.4	56.9	-2.5
3	97.8	97.0	0.8	78.5	72.9	5.6
4	96.8	95.8	1.0	68.8	72.9	-4.1
5	85.7	85.1	0.6	38.5	32.9	5.6
6	72.0	71.3	0.7	19.4	19.4	0.0
7	81.3	79.8	1.5	35.2	32.9	2.3
8	67.0	73.2	-6.2	29.7	32.9	-3.2
9	37.4	40.8	-3.4	5.5	8.2	-2.7
10	38.7	39.3	-0.6	6.5	4.2	2.3
11	34.8	32.3	2.5	7.6	8.2	-0.6
12	27.2	24.8	2.4	6.5	8.2	-1.7

* Predicted percentage of responses conforming to the criterion.

The models presented in the previous tables quantify tradeoffs between translations on the three axes. Figure 24 illustrates this tradeoff using the model for Sufficiency ≥ 4. Contours representing 50%, 75%, 90%, and 95% of responses ≥ 4 are plotted against Y- and Z-axis translations. The figure shows that 95% sufficiency ≥ 4 can be achieved with the Z translation at zero and the Y translation at about -18 mm, or with the Z translation at about -8 mm and the Y translation at zero (nominal). Figure 25 shows a similar plot for acceptability ≥ 3.

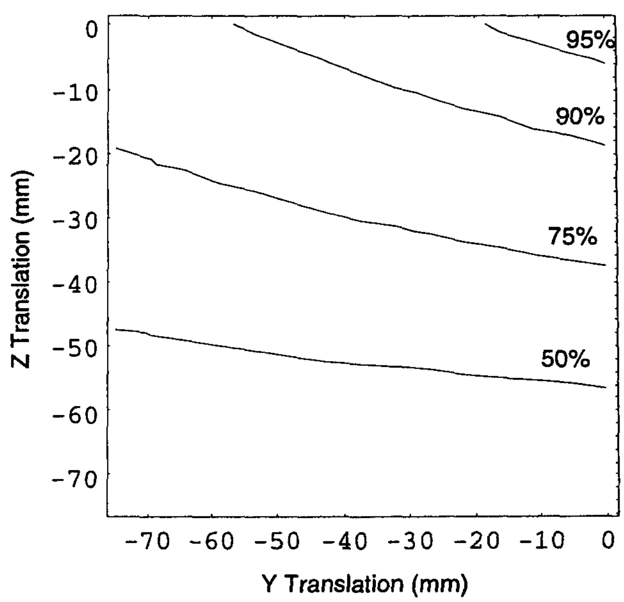


Figure 24. Contours for 50%, 75%, 90%, and 95% **sufficiency** ≥ 4 based on roof translations relative to nominal (95% contour is uppermost, 50% contour lowermost).

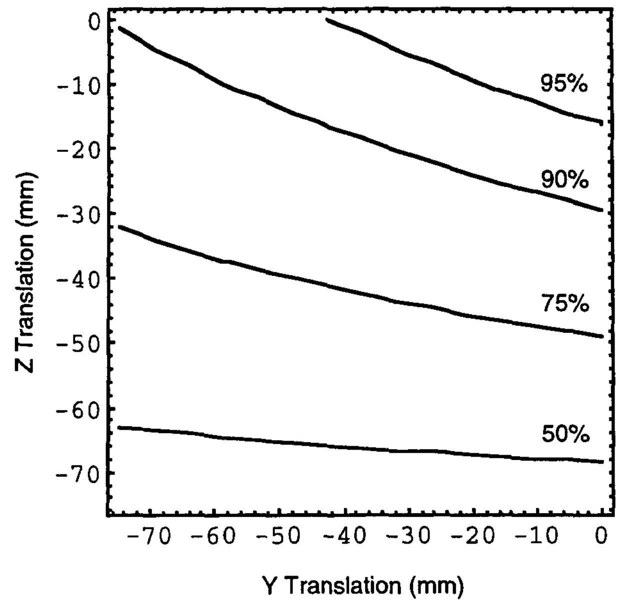


Figure 25. Contours for 50%, 75%, 90%, and 95% **acceptability** ≥ 3 based on roof translations relative to nominal (95% contour is uppermost, 50% contour lowermost).

The models in the preceding tables and figures were used to predict the percentage of drivers who would rate a particular roof design at a particular level. Solutions in the form of roof displacement vectors (X, Y, Z) were calculated for the 95th-percentile contours using the criteria Sufficiency ≥ 4 and Acceptability ≥ 3. Three alternative solutions were obtained for the former, and five for the latter. Tables 15 and 16 show these roof positions, each of which corresponds to the predicted 95th percentile on their respective rating criteria. Headroom measures for these positions were calculated with respect to the SAE headspace contour.

Tables 15 and 16 demonstrate that none of the measures are constant along the 95% contours, and indicate that none is a sole, independent predictor of subjective headroom evaluations. However, the mean values provide reasonable guidance for roof design. H35 values of about 63 mm and W27 values of about 71 mm should provide about 95% ratings of "sufficient" or better, assuming that the roof geometry is similar to that used in the study. Alternatively, preserving sideview and rearview clearances to the SAE headspace contour of at least 65 mm is predicted to provide about the same level of accommodation. Maintaining a minimum clearance of around 58 mm is predicted to result in 95% of drivers giving a lower rating of "somewhat acceptable" or better.

Table 15
SAE and Related Headroom Measures at Three Roof Positions
Predicted to Produce 95% of Sufficiency Responses ≥ 4

X	Y	Z	W27	H35	Forward-30[1]	MinSV[2]	MinRV[3]
0	0	-6.1	62.4	58.7	74.2	61.2	57.3
0	-9	-3.2	70.8	62.8	81.0	64.8	62.6
0	-18.3	0	79.7	67.1	85.1	67.9	66.8
		Mean:	71.0	62.9	80.1	64.6	62.3

Table 16
SAE and Related Headroom Measures at Five Roof Positions
Predicted to Produce 95% of Acceptability Responses ≥ 3

X	Y	Z	W27	H35	Forward-30[1]	MinSV[2]	MinRV[3]
0	0	-16.1	53.7	48.7	62.5	51.6	47.6
0	-10	-12.9	63.2	53.2	69.8	64.0	36.8
0	-20	-9.4	73.2	57.9	73.6	61.7	62.3
0	-30	-5.5	83.4	62.3	79.5	58.3	57.6
0	-42.5	0	39.8	46.9	77.8	55.1	53.8
		Mean:	62.7	53.8	72.7	58.1	51.6

[1] Forward-30 is a measure obtained by translating the sideview contour forward and upward at a 30-degree angle to the point of first interference, analogous to W27 in rear view.
[2] MinSV = Minimum Sideview Clearance: the minimum separation between the sideview contour and the corresponding roof section.
[3] MinRV = Minimum Rearview Clearance: the minimum separation between the rearview contour and the corresponding roof section.

To facilitate the use of these findings in design applications, a similar analysis was conducted for each of the criterion levels listed in Table 12. In general, the minimum sideview and rearview clearances at each of the roof positions on a contour varied considerably. This finding is consistent with earlier observations that suggest that the clearances measured with respect to the SAE headspace contour are generally not good predictors of subjective headroom assessment. However, in the interest of applying the results of the study to current design practice, Table 17 presents the average values obtained at the five roof positions on each contour, along with the range of values observed. Taking the first line of Table 17 as an example, 75% of the population is predicted to respond that the overall headroom is at least "barely sufficient" (sufficiency ≥ 3) when the minimum sideview clearance is 7 mm and the minimum rearview clearance is 24 mm. However, the range of rearview minimum clearances observed along the 50%/Suff≥3 contour is 69 mm, suggesting that these numbers are fairly imprecise. Reasonably good precision is obtained only at two levels: 95% sufficiency ≥ 4, and 75% acceptability = 4. In both cases, minimum clearances of 60 to 70 mm are associated with the specified criterion levels.

In spite of the lack of precision in measures obtained by this technique, the mean values show trends that could be exploited to make design decisions. For example, a minimum clearance of about 45 mm is predicted to result in about 95% of drivers rating the headroom as at least "barely sufficient". Alternatively, a slightly larger clearance of 51 mm is predicted to result in about 90% of drivers rating the overall headroom as "somewhat acceptable" or better. In general, the two criterion levels giving the most consistent estimates are sufficiency ≥ 4 and acceptability ≥ 3.

Table 17
Average Minimum Clearance Measures at a Range of Criterion Levels

Criterion	Population Percentage	Minimum Sideview Clearance	Minimum Rearview Clearance	Minimum Sideview Clearance Range	Minimum Rearview Clearance Range
Suff ≥ 3	75%	7	24	7	69
	90%	29	37	22	48
	95%	44	46	33	39
Suff ≥ 4	75%	44	45	34	40
	90%	57	57	17	24
	95%	65	62	7	9
Suff = 5	75%	61	34	74	79
	90%	83	35	71	102
	95%	81	61	115	105
Acc ≥ 3	75%	36	37	44	49
	90%	51	51	27	34
	95%	59	58	16	21
Acc = 4	75%	66	60	7	9
	90%	68	39	52	79
	95%	61	37	103	93

3.2 Limits Trials

In the limits trials, the primary data are the locations of the roof at the subject-selected stop points, corresponding to the boundaries between the unacceptable, acceptable, and comfortable zones (see Figure 10). The analyses focused on the effects of driver stature on stop point locations, the effects of the roof starting position, and the distribution of stop points.

Stature Effects – Figure 26 shows the location of the each stop point for limits condition 1, which involves downward movement of the roof with the fore-aft and lateral positions at the nominal level. The left plot shows a line connecting the four stop points for each subject group. Taller subjects have higher group numbers (see Table 2). The right plot shows the same information, except that lines connect stop points across subject groups. Figure 27 shows the downward roof movement at the first stop point, plotted against stature. There is little or no effect of stature on the lowest acceptable roof position.

The data points in the right plot of Figure 26 show the location of the first stop point for each subject. Note that there is considerable variability within all of the subject groups, with the short-statured subjects (low group numbers) having approximately the same variability as tall subjects (high group numbers). In general, this variability is not normally distributed, or distributed according to any other convenient function, so empirical percentiles must be calculated directly from the ranked data, rather than estimated from an assumed distribution.

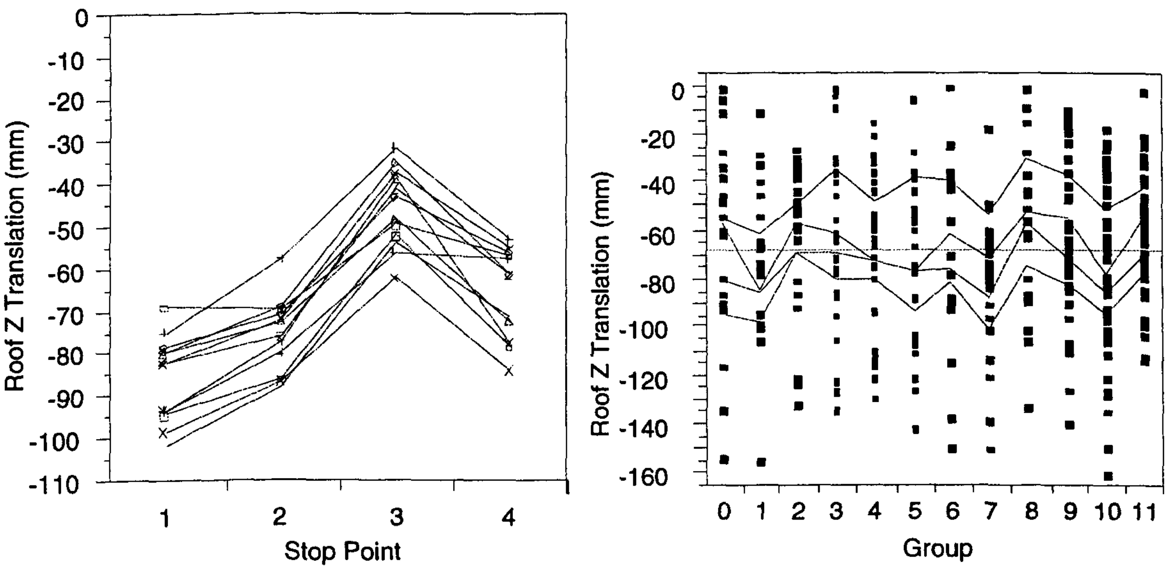


Figure 26. Stop points for limits condition 1 by subject group. Each line in the left plot connects mean values for a subject group. Each line in the right plot connects mean values for a stop point across subject groups.

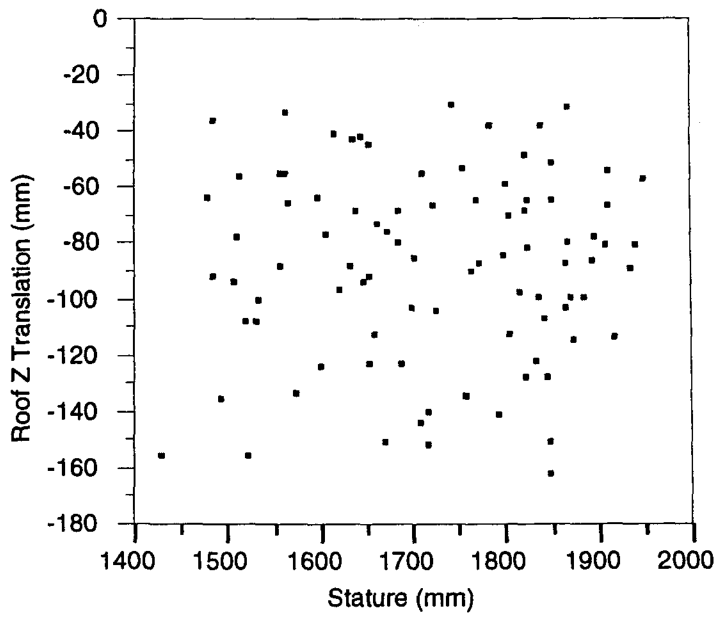


Figure 27. Downward movement of the roof at the unacceptable boundary (stop point 1, limits trial 1), plotted against subject stature. The vertical axis shows vertical roof movement relative to the starting point.

Average Stop Points by Limits Condition – Table 18 shows the average stop point locations relative to the starting point by condition. Negative numbers in the table refer to inward movement relative to the starting point (toward the subject), hence all stop point values are negative. Table 18 contains some interesting information. Note first that the pattern illustrated in Figure 26 is consistent across test conditions: the first stop point is the lowest, followed by the second, fourth, and third. In general, the direction of roof travel affects the location of the stop point. To facilitate the analysis, the first two stop points were averaged to estimate the location of the unacceptable/acceptable boundary, and the second two stop points were averaged to estimate the uncomfortable/comfortable boundary. Table 18 lists these boundary estimates expressed relative to the roof starting position for each trial and relative to ratings condition 1.

Table 18
Limits Test Conditions and Results
(Moving axis in **bold**)

Cond.	Start* X	Start Y	Start Z	Stop Point[1] 1	Stop Point 2	Stop Point 3	Stop Point 4	Un/ Acc.[2]	Un/ Comf	Un/ Acc.[3] re R01	Un/ Comf re R01
1	0	0	**+45**	-85	-75	-46	-65	-80	-56	-35	-11
2	-75	0	**+45**	-84	-74	-44	-65	-79	-55	-34	-10
3	**+45**	0	0	-94	-83	-54	-65	-89	-60	-44	-15
4	**+45**	0	-37.5	-79	-67	-37	-49	-73	-43	-28	2
5	**+45**	0	-75	-49	-38	-15	-22	-44	-19	2	27
6	0	**+45**	0	-79	-66	-36	-54	-73	-45	-28	0
7	0	**+45**	-37.5	-71	-58	-27	-40	-65	-34	-20	12
8	0	**+45**	-75	-54	-41	-14	-23	-48	-19	-3	27

* Positive numbers indicate less restrictive headroom than ratings condition 1 (roof higher, further forward, or further outboard). Numbers in bold indicate starting position for moving axis. Values are nominal start positions; actual average positions were within 5 mm of nominal.

[1] Stop points are inward translations on the moving axis relative to the starting position.

[2] Unacceptable/Acceptable boundary (average of stop points 1 and 2). Uncomfortable/Comfortable boundary is average of stop points 3 and 4.

[3] Boundary values expressed as inward translation relative to ratings condition 1. Positive numbers indicate that the boundary is further outward (less restrictive) than the ratings condition 1.

The results from limits condition 1 show that the roof would need to be moved down 35 mm from ratings condition 1 to reach the average threshold for unacceptability. The roof becomes uncomfortable, on average, when moved down only 11 mm from the nominal position. The PVM configuration for condition 2 was the same as condition 1, except that the starting lateral roof position was 75-mm inboard. However, the boundary locations for vertical roof translation did not change substantially, suggesting that preferences for vertical roof position are not dependent on lateral roof position.

In contrast, the stop points on the other axes (X and Y) are strongly influenced by the vertical roof position. For lateral movement, the average acceptability boundary moves outward from -44 mm to +2 mm as the roof height is lowered from nominal to -75 mm. Similarly, the acceptability boundary for fore-aft roof movement is moved forward from -28 mm to -3 mm as the roof is lowered from nominal to -75 mm.

Posture – A within-subjects analysis of variance (ANOVA) was conducted, comparing posture variables across the 8 limits conditions. No significant differences in translated H-point location or head angle were found, but seatback angles were affected by the starting roof position. In limits conditions 5 and 8, the vertical roof position was set 75 mm lower than the nominal condition at the start of the trial. The subject-selected seatback angles averaged 1.7 degrees more reclined in trials 5 and 8 than in the other trials. Interestingly, this behavior did not appear to be dependent on body size ($p>0.05$ for the subject-group-by-condition interaction). On average, male subjects chose a seatback angle of 27.5 degrees and female subjects selected 22.2 degrees. An overall average seatback angle, weighted to reflect a 50/50 gender mix, is 24.9 degrees. As a result of the more reclined seatback angles in conditions 5 and 8, head positions were an average of 7 mm lower and 8 mm more rearward than the average of the other trials.

Percentiles of the Unacceptable/Acceptable Boundary – For design purposes, the roof positions that correspond to the boundary between unacceptable and acceptable, defined by the average of the first two stop points, are of greatest interest. Table 19 shows the initial conditions and moving axes for the limits trials, along with selected percentiles of the acceptable/unacceptable boundary distribution. Roof translations are expressed relative to ratings condition 1.

Although the starting point for the moving axis was +45 mm (away from the subject) relative to the ratings condition 1 (the nominal roof position), extreme starting positions on the other axes (e.g., condition 5), resulted in many subjects finding the initial condition unacceptable. For example, the 90th percentile in condition 5 is +45 mm. Looking only at the 95th percentile, an increase in roof height (Z axis) of about 10 mm relative to ratings condition 1 would put the roof into the acceptable region for 95% of subjects. Switching to lateral movement of the roof, starting at the nominal height (condition 6), an outward lateral movement of about 11 mm would accommodate 95% of subjects, based on their acceptable/unacceptable boundary responses.

Clearance dimensions relative to the SAE headspace contour were calculated for each of the roof positions defined by the translations in Table 19. For example, the 50th-percentile clearances for condition 1 were calculated by translating the roof downward from the nominal position by 32 mm. Table 20 shows the W27 values calculated for each of the conditions in Table 19, and Table 21 shows H35 values. Table 22 lists values obtained by translating the sideview headspace contour forward and upward at a 30-degree angle, analogous to W27. Table 23 lists the minimum separation distance between the headspace contour and the roof in sideview, and Table 24 lists the same dimensions in rearview.

Although there are a large number of values in each table, only a few rows are useful to examine. In general, any condition that resulted in the 90th-percentile translation value being within 10 mm of the start point (i.e., +35 or greater in Table 19) should be disregarded, because the start point did not represent a condition that was acceptable to a large enough segment of the subject pool. These rows in each table (conditions 5 and 8) are shaded.

The findings from the remaining conditions can be examined in detail to determine the effects of roof position on acceptability. A comparison of conditions 1 and 2, which differ only in roof fore-aft starting position, shows that the vertical boundary for acceptability is essentially unaffected by fore-aft position in the range studied. We can then estimate that a roof position about 10 mm higher than the ratings condition 1 will result in about 95% of the population judging the roof position to be acceptable. Consulting Table 21, this condition corresponds to an H35 value of about 75 mm. (For the nominal lateral and fore-aft positions, H35 is a reasonable measure of vertical roof position.)

Lateral roof position for acceptability at the 95th percentile is not strongly dependent on vertical roof position up to -37.5 mm relative to ratings conditions 1 (limits conditions 6 and 7). An outward movement of the roof of about 21 mm is necessary to accommodate 95% of the subjects, with the roof height at either nominal or -37.5 mm. Comparing conditions 1 and 3 shows that a larger adjustment in fore-aft position is necessary to accommodate 95% of the population than in vertical position. Although raising the roof by 11 mm will suffice, a forward translation of 23 mm is required for the same level of accommodation at the nominal height.

Table 19
Empirical Acceptable Boundary Percentiles Relative to Ratings Condition 1
(mm of roof translation on moving axis)

Cond.	Start* X	Start Y	Start Z	50%ile	75%ile	90%ile	95%ile	97.5%ile
1	0	0	**+45***	-32	-12	3	11	14
2	-75	0	**+45**	-31	-14	4	9	21
3	**+45**	0	0	-43	-19	13	23	24
4	**+45**	0	-37.5	-28	8	23	32	45
5	**+45**	0	-75	9	44	45	45	45
6	0	**+45**	0	-23	-4	11	20	27
7	0	**+45**	-37.5	-19	5	20	22	26
8	0	**+45**	-75	-2	16	44	45	45

*Moving axis shown in **bold**.

Table 20
W27 Values Calculated at Roof Acceptability Boundary Percentiles

Cond.	Start* X	Start Y	Start Z	50%ile	75%ile	90%ile	95%ile	97.5%ile
1	0	0	**+45***	43	57	70	77	80
2	-75	0	**+45**	41	55	70	75	84
3	**+45**	0	0	67	67	68	69	69
4	**+45**	0	-37.5	38	36	37	38	38
5	**+45**	0	-75	-16	-16	-16	-16	-16
6	0	**+45**	0	53	65	75	81	85
7	0	**+45**	-37.5	25	39	46	47	48
8	0	**+45**	-75	-17	-14	-13	-13	-13

*Moving axis shown in **bold**.

Table 21
H35 Values Calculated at Roof Acceptability Boundary Percentiles

Cond.	Start* X	Start Y	Start Z	50%ile	75%ile	90%ile	95%ile	97.5%ile
1	0	0	**+45***	33	53	67	75	79
2	-75	0	**+45**	25	43	61	66	78
3	**+45**	0	0	62	64	65	65	65
4	**+45**	0	-37.5	26	28	27	28	28
5	**+45**	0	-75	-10	-10	-10	-10	-10
6	0	**+45**	0	59	64	66	67	68
7	0	**+45**	-37.5	23	28	30	30	30
8	0	**+45**	-75	-10	-8	-7	-7	-7

*Moving axis shown in **bold**.

Table 22
Forward-30 Values Calculated at Roof Acceptability Boundary Percentiles

Cond.	Start* X	Start Y	Start Z	50%ile	75%ile	90%ile	95%ile	97.5%ile
1	0	0	**+45***	48	68	84	93	98
2	-75	0	**+45**	8	29	49	55	67
3	**+45**	0	0	61	71	88	93	93
4	**+45**	0	-37.5	24	45	51	58	60
5	**+45**	0	-75	-15	-13	-12	-12	-12
6	0	**+45**	0	75	79	85	85	85
7	0	**+45**	-37.5	35	44	44	44	45
8	0	**+45**	-75	-14	-15	-16	-16	-16

*Moving axis shown in **bold**.

Table 23
Minimum Sideview Clearances Calculated at Roof Acceptability Boundary Percentiles

Cond.	Start* X	Start Y	Start Z	50%ile	75%ile	90%ile	95%ile	97.5%ile
1	0	0	**+45***	36	56	69	77	80
2	-75	0	**+45**	6	22	40	45	56
3	**+45**	0	0	48	57	68	68	68
4	**+45**	0	-37.5	22	31	30	30	30
5	**+45**	0	-75	2	1	0	0	0
6	0	**+45**	0	63	66	68	68	67
7	0	**+45**	-37.5	29	30	30	30	30
8	0	**+45**	-75	3	2	0	1	1

*Moving axis shown in **bold**.

Table 24
Minimum Rearview Clearances Calculated at Roof Acceptability Boundary Percentiles

Cond.	Start* X	Start Y	Start Z	50%ile	75%ile	90%ile	95%ile	97.5%ile
1	0	0	**+45***	33	52	65	71	74
2	-75	0	**+45**	26	43	61	66	78
3	**+45**	0	0	62	63	63	63	63
4	**+45**	0	-37.5	26	28	28	26	27
5	**+45**	0	-75	3	4	3	3	3
6	0	**+45**	0	49	61	66	67	68
7	0	**+45**	-37.5	23	29	30	30	30
8	0	**+45**	-75	2	1	2	1	1

*Moving axis shown in **bold**.

Summary – Summarizing the findings from the limits trials for use in design is difficult because of inconsistencies between different conditions and the limitations of the SAE headroom measures. However, reasonable estimates can be made for criterion values on several measures related to the 95th-percentile SAE headspace contour.

W27 – For roof heights close to the nominal value (H35 values approximately 60 mm), the W27 value for 95% acceptable is about 79 mm, based on results from conditions 1 and 6. However, smaller W27 values are tolerated when other dimensions are changed. For example, W27 values as low as 38 mm, produced by lowering the roof height, were acceptable at the 95% level when the roof was also moved forward by 32 mm (condition 4).

H35 – Values for the H35 measure are reasonable measures of vertical head clearance for lateral and fore-aft roof positions near the nominal position. In that situation, the point of first contact when translating the rearview contour upward is at the top of the contour, hence H35 is equivalent to the vertical contour clearance. From the results of condition 1, H35 or vertical clearance values are about 75 mm at the 95th percentile, when the roof is moved vertically. It should be noted, however, that the ratings analysis showed that H35 is not significantly related to overall headroom evaluations.

Forward-30 – The forward-30 measure is analogous to W27 and is obtained by translating the sideview headspace contour forward and upward at a 30-degree angle to the point of first contact. The best limits conditions in which to evaluate this measure are conditions 3 and 4, in which the roof is moved fore-aft at two different heights. Taking the average of the values at the two roof heights, a limiting value for the forward-30 measure at the 95th-percentile level is 76 mm.

Minimum Clearance -- Sideview – The sideview minimum clearance (minimum clearance between the sideview headspace contour section and the corresponding roof section) is affected by both vertical and fore-aft translation of the roof. Considering conditions 1 and 3, in which the nonmoving axes were set to their nominal positions, a reasonable estimate for the 95th-percentile value for sideview clearance is 73 mm (average of 68 and 77 mm).

Minimum Clearance -- Rearview – Similarly, in rearview, examining conditions 1 and 6, a minimum clearance dimension at the 95th percentile is approximately 69 mm.

Based on the above analyses of the limits data, Table 25 presents recommended values for headroom measures that are predicted to result in "acceptable" evaluations from 95% of a driving population. Noting the considerable ambiguity in the findings, these recommendations should be considered preliminary, subject to further analysis and study. The values in Table 25 cover a 10-mm range, suggesting that a single clearance value relative to the SAE headspace contour might be suitable as a design guideline. Such a value could be conservative at around 80 mm, or more pragmatic at around 70 mm.

Table 25
Recommended Headroom Measures for 95-Percent Population Acceptability in Limits Data

Measure	Value (mm)
W27	79
H35*	75
Forward-30	76
Minimum Sideview Clearance	73
Minimum Rearview Clearance	69

*When point of first contact is at the top of the contour, that is, when H35 is equal to the vertical clearance at the top of the contour.

4.0 DISCUSSION

This report presents findings from a study of driver responses to changes in roof position affecting headroom. Each of 99 subjects participated in ratings and method-of-limits trials. Data from subjective responses to the ratings conditions and subject-selected stop points from the limits trials were analyzed to determine the effects of roof position and stature on subject ratings and preferences. Logistic regression modeling of the ratings results provided a means of predicting the percentage of subjects who would rate a particular roof position at a specified criterion level. The empirical distribution of the subject-selected acceptability boundaries in the limits data was used to predict the roof positions that would be acceptable to specified percentages of the driving population.

4.1 Ratings

Effects of Test Factors on Subjective Ratings – Responses on the various questions concerning headroom were well correlated. For example, ratings of the "space above my head" were similar to ratings of overall headroom. There was also a strong association within each question between the sufficiency and acceptability responses. Because of these correlations among responses, the analyses in this report were performed primarily with the overall headroom evaluation data (question 9). From a design perspective, these data are most applicable.

The vertical position of the roof (translation on the Z axis) has the greatest effect on the headroom ratings. Lateral position has a moderate effect, and fore-aft position has a minimal effect. In general, the effects are additive, although there is a small interaction between vertical and lateral positions. When the roof is in the middle height position, the effect of changes in lateral position is 50% greater than with the roof in the highest position. However, with the roof in the lowest ratings position, there is little change in the already poor ratings when the lateral position is changed.

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.

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 the conditions as one of the first four presented did not differ from the ratings from subjects who experienced the 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, 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.

Posture Effects – Tall subjects tended to sit more reclined than short subjects, evidenced by both larger seatback angles and more reclined torso angles. Taller subjects also showed effects of roof height on seatback angle, with lower roof heights tending to produce more reclined seatback angles. Small subjects did not change their seatback angles significantly as the roof was lowered. The importance of roof height for predicting a population average seatback angle or angle distribution depends on the population definition. Since only the tallest drivers are affected, the proportion of tall drivers in the population of interest would influence the effect on the population distribution of seatback angle.

Prediction of Headroom Ratings – Logistic regression equations were calculated to predict headroom 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.

To determine the characteristics of roof positions that would be judged to be "acceptable" or "sufficient" by the desired percentage of drivers, the logistic regression models were solved to calculate XY contours representing the family of roof positions that correspond to the desired criterion level. Several roof translation vectors were calculated along the 95th-percentile contours. The SAE and related clearance measures were calculated for these positions, and averaged to predict levels on the SAE measures that are likely to produce the desired rating levels.

Limitations of Ratings Testing – 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% 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.

Other limitations of the study include the lack of an actual driving task and the ranges of adjustability provided to the subjects. Without the driving task, taller subjects may have been able to adjust their seatback angles to accommodate reduced headroom in ways that would be unacceptable in actual driving. The lack of realistic vision requirements also may have influenced the ratings. Because subjects were free to choose their seat position and seatback angle, as drivers typically would, the subject's head locations relative to the roof geometry varied, effectively exposing each subject to a different set of actual headroom conditions. While this is useful for developing design guidelines for a diverse driver population, it makes it more difficult to determine which characteristics of the roof position or head clearance are most important in determining headroom ratings or to assess anthropometric effects.

4.2 Limits

Effects of Test Factors on Acceptable and Comfortable Boundaries – The design of the limits trials allows the effects of roof position on two axes to be considered simultaneously. Lateral roof position did not affect the acceptability boundary for vertical roof position, but vertical position strongly affected the boundary locations for both fore-aft and lateral position. When the roof was lower, the acceptability boundaries on the other axes moved further forward and outward. No explanation is apparent for why vertical position affected the lateral stop points, but lateral position did not affect the vertical stop points. A better understanding of the factors that influence the perception of headroom will be necessary to make this determination.

As in the ratings trials, no significant effect of stature on the stop point locations was found. In general, the stop points were highly variable, with subjects' acceptability boundaries located throughout the roof-axis travel range. The wide variability, together with observations by the experimenters during testing, suggests that subjects find it difficult to identify precisely the boundaries for acceptability and comfort, particularly when the roof is moving continuously. Comments from the subjects also suggested that headroom acceptability may be context dependent, determined in part by the driver's expectations for a vehicle. Reduced headroom might be more acceptable in a sporty car than in a luxury car, for example.

Prediction of Roof Position at Boundary Percentiles – For design purposes, it is useful to determine the minimum clearances necessary to provide acceptable headroom to specified percentages of the population. Unfortunately, the boundaries obtained from the stop points in the limits data were widely distributed, and did not conform to a convenient distribution (such as normal). This finding necessitated the use of empirical percentiles to estimate the roof positions that would be acceptable to specified percentiles of the driving population. Because of ambiguities in the results from different conditions, the findings are amenable to a number of different interpretations. In formulating design recommendations from these data, an averaging approach was taken, in which clearance measures obtained from a number of different roof positions, each appearing to meet the acceptability criteria, were combined.

Limitations of Limits Testing – Limits testing was complicated by the fact that the use of the PVM was substantially constrained. Ideally, the movement of the roof or roof components could be placed directly under the subject's control. Instead, the roof was moved slowly on an axis by the experimenters, with the subject verbally indicating a stop point when the desired boundary was reached. To accommodate this approach, the roof movements were very slow, typically about 10 mm per second. The average stop point locations were biased in the direction of travel, suggesting that latency in the perception and reporting of the boundary crossings may have added variability to the data.

Time constraints in testing necessitated a reduction in the test matrix so that only eight of the possible combinations of starting position and movement axis were tested. While this provided useful information, more detailed analyses concerning interactions between axes could not be performed. At a basic level, many of the subjects did not seem to be able to estimate the boundary locations of interest with a high degree of precision. The instructions to the subjects indicated that they were to report two different boundaries, but these boundary definitions were fairly abstract and may not have had much meaning to some subjects. In particular, the "comfortable" boundary did not have a precise location for many subjects, who found it easier to determine the boundary for "unacceptable" than for "comfortable."

The lack of a parameterized distribution for characterizing the population acceptability boundaries also complicates interpretation of the findings. If the boundary locations were, for example, normally distributed across the population, then all of the subjects' data could be used to compute estimates of the mean and variance of the normal distribution. Instead, empirical percentiles are used, which, in the tails of the distribution, can be inordinately affected by the responses of one or two subjects with the current sample size. Alternative techniques for estimating robust percentile values should be investigated in future work.

4.3 Limitations of SAE Headroom Measures

There are a number of important limitations to the methods defined in SAE Recommended Practices J1100 and J1052 for measuring driver headroom. First, the headspace contour is located using procedures analogous to those used to locate the SAE J941 eyellipses. Unfortunately, these locating procedures are based on the SgRP location and the designer's selection of the "design" seatback angle. The combination of these two reference dimensions does not generally result in a good prediction of driver position and posture in the vehicle. SgRP, located using the procedures in SAE J1517, is often not a good predictor of the 95th percentile of the seat position distribution for the U.S. driver population (Flannagan et al. 1998). More importantly, design seatback angle is often a poor predictor of mean driver-selected seatback angle (Manary et al. 1998). If the designer chooses a seatback angle that differs substantially from drivers' actual mean seatback angle, the headspace contour will not adequately represent the head locations of drivers.

The standardized measurements made relative to the SAE headspace contour, such as H35 and W27, are not good predictors of headroom ratings. Most of the problem is produced by the interaction between the shapes of the roof and the contour. When the roof is located a considerable distance from the contour (e.g., no closer than 100 mm), the SAE measures provide reasonable, fairly independent measures of vertical and lateral headroom. However, when the headroom is reduced, such as in the current study, the two measures become correlated, and neither is a good indicator of how the headroom is restricted from the driver's perspective. The overall minimum sideview and rearview clearance dimensions may provide a better way of using SAE-contour-based measurements in design, but consideration should be given to the relative importance of lateral and vertical clearance. Based on the findings from this study, actual vertical clearance is probably of lesser importance than the clearance in front of the forehead and to the side of the head. For modern vehicles with restrictive headroom, new measures of headroom that address the limitations of the current techniques should be developed. This effort would be facilitated by further study of the roof characteristics that affect subjective perception of headroom.

5.0 DIRECTIONS FOR FUTURE RESEARCH AND ANALYSES

This report presents analyses of the study data aimed at informing the development of design guidelines based around current SAE practices. However, there is considerably more information available in the study data that might be examined in future analyses. For every trial and condition, the actual location of the subject's head and hair in relation to the roof and other interior components is known. This information could be used to examine a number of different issues, including:

- relationship between actual head and hair clearances and headroom ratings,
- relationship between headroom ratings and vision restriction,
- relative importance of clearances above, forward of, and to the side of the head,
- spatial distribution of head locations on a population basis, and the influence of restrictive headroom on this distribution,
- location of heads with respect to head restraints, with consideration of the effects of restrictive headroom,
- motion patterns associated with looking at a traffic light: effects of body size and roof position, along with subjective assessments of motion acceptability, and
- models of acceptability boundaries based on actual head clearances.

Future studies of headroom perception should attempt to quantify the effects of changes in various parts of the roof geometry. As noted above, one of the more important limitations of the current study is that the roof geometry remained constant during the testing. In future work, the relative importance of vertical clearance, clearance in the visual field near the head, and vision restriction to the exterior environment should be quantified. Findings from such a study might indicate to designers how the perception of headroom can be improved without substantial changes in actual space.

6.0 APPLICATION TO DESIGN GUIDELINES

This concluding report section summarizes the findings from both ratings and limits trials for application to the development of design guidelines. Straightforward comparisons between the findings from the two trial types are complicated by the differences in methodology, but there is commonality in the findings that should be considered in developing design guidelines. Table 26 compares the criterion measurement values obtained from the two trial types.

The values obtained from the limits analysis are generally more conservative (larger) than those obtained using both of the ratings criteria. This may reflect the wider range of conditions experienced in the limits trials compared with the ratings trials. **Combining the two analyses suggests that clearances to the SAE headspace contour of around 70 mm, however measured, are likely to result in about 95% of drivers indicating that they have "sufficient" or "acceptable" headroom.**

Table 26
Comparison of 95th-Percentile Criterion Values Between Ratings and Limits (mm)

Measure	Ratings: Sufficiency ≥ 4	Ratings: Acceptability ≥ 3	Limits: Boundary Acceptable
W27	71	63	79
H35	63	54	75
Forward-30	80	73	76
Minimum Sideview Clearance	65	58	73
Minimum Rearview Clearance	62	52	69

7.0 REFERENCES

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APPENDIX

SUBJECT QUESTIONNAIRE

These questions are presented to the subject on color slides displayed on a screen in front of the test buck. The subject answers each question verbally.

First Slide (text): For the current set of vehicle conditions and your selected seat and seatback positions, please verbally indicate your numerical responses to the questions that will appear on the following slides.

1. The **space above my head** is:

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

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

2. The **space to the left side of my head** is:

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

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

3. The **space** to the **upper portion of the left windshield pillar** is:

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

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

4. The **distance forward** from my **head** to the **windshield header** or **sun visor** is:

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

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

5. The **upward visibility through the top of the windshield is:**

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

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

6. Do you have to move your head to see the **red traffic light**?

If your answer is **Yes**, is this movement:

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

7. The **visibility to the outside** in the area of the **left windshield pillar** is:

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

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

8. With regard to the left windshield pillar and your view outside, please indicate:

   a. the letter of the first mark **to the right** of the pillar that you can see without leaning is: ____________. This occurs at the __________ level mark on the pillar.

   b. The letter of the first mark **to the left** of the pillar that you can see without leaning is: ____________. This occurs at the __________ level mark on the pillar.

9. My **overall impression** of the roominess of the space around **my head** in this vehicle is that it is:

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

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

10. My **overall impression of my driving posture and position** with respect to the distance to the **accelerator pedal** and **steering wheel**, and the angle of the **seatback** is:

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