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DEVELOPMENT OF A PREDICTIVE MODEL AND DESIGN GUIDELINES BASED ON SUBJECTIVE EVALUATION OF REAR SEAT PASSENGER HEADROOM

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by

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16. Abstract

A laboratory study of rear-seat passenger headroom perception was conducted with 102 men and women using a reconfigurable vehicle mockup. The subjects rated three different roof shapes at five different roof positions on numerical sufficiency and acceptability scales. The subjects' head and hair contours were digitized prior to testing and combined with measured head positions in the vehicle mockup to obtain actual head and hair clearance dimensions in each of the test conditions. Statistical analysis demonstrated that subject body dimension (stature), vertical roof position, lateral roof position, and vertical roof-to-rail offset all have important interactive effects on headroom perception. For example, the degradation in perceived headroom with an inboard lateral movement of the roof rail is dependent on the vertical offset of the rail relative to the roof. Logistic regression analysis was used to create statistical models that accurately predict the percentage of an occupant population who will rate the headroom at a desired criterion level as a function of roof geometry and position. Three new geometric measurements are introduced that are substantially better related to subjective headroom perception than the conventional SAE dimensions. In addition to the mathematical models, which can be applied to any desired population, an Appendix is provided with graphical plots that can be used as a design guide for one particular reference population.

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EXECUTIVE SUMMARY

A laboratory study of rear-seat passenger headroom perception was conducted with 102 men and women using a reconfigurable vehicle mockup. The subjects rated three different roof shapes at five different roof positions on numerical sufficiency and acceptability scales. The subjects' head and hair contours were digitized prior to testing and combined with measured head positions in the vehicle mockup to obtain actual head and hair clearance dimensions in each of the test conditions. Statistical analysis demonstrated that subject body dimension (stature), vertical roof position, lateral roof position, and vertical roof-to-rail offset all have important interactive effects on headroom perception. For example, the degradation in perceived headroom with an inboard lateral movement of the roof rail is dependent on the vertical offset of the rail relative to the roof. Logistic regression analysis was used to create statistical models that accurately predict the percentage of an occupant population who will rate the headroom at a desired criterion level as a function of roof geometry and position. Three new geometric measurements are introduced that are substantially better related to subjective headroom perception than the conventional SAE dimensions. In addition to the mathematical models, which can be applied to any desired population, an Appendix is provided with graphical plots that can be used as a design guide for one particular reference population.

INTRODUCTION

Recent trends in occupant protection have led to greater padding on interior vehicle surfaces, particularly those near the occupants' heads. Adding padding to existing vehicle designs tends to reduce the available space, potentially degrading the subjective perception of headroom. Styling trends may also result in restricted headroom. In each of these cases, design decisions are difficult without quantitative information about the tradeoffs between roof geometry and subjective headroom assessment.

In a previous study, the effects of changes in roof position on driver headroom perception were investigated using a reconfigurable vehicle mockup (Reed and Schneider 1998, 1999). The study quantified the relative importance of vertical and lateral roof position, and reached the unexpected conclusion that the more-forward seat position of small drivers made them approximately as sensitive to low roof heights as taller drivers for the roof shape used in the study. A predictive model based on logistic regression was developed to predict the percentage of drivers who would rate the headroom at a desired criterion level as a function of the roof position. The model was used to develop a set of guidelines for roof geometry based on the SAE J1052 headspace contour.

In the current study, the methods developed for the driver research were adapted to rear seat passengers. A reconfigurable vehicle mockup was used to create a range of roof positions spanning those typical of passenger cars, and inserts were used to change the interior roof shape. Subjective assessments of fifteen different position/shape combinations were obtained for 102 men and women. The data were analyzed to create models that predict the percentage of a target occupant population who will rate the headroom at each of five subjective criterion levels. This report describes the data-collection methods, analysis procedures, and model development. Procedures for applying statistical models and reference plots to vehicle design are provided.

METHODS

Equipment

Vehicle Mockup – Testing was conducted using a reconfigurable mockup of a midsized four-door sedan manufactured by Prefix, Inc., known as the Programmable Vehicle Model (PVM). The vehicle components, Figure 1, are mounted on motorized tracks under computer control. An initial configuration was set for this investigation that is approximately representative of 1998 Taurus package geometry. The interior structures near the rear passenger's head, including the header and side rail, were moved as a unit on two independent axes, parallel to the vehicle Y and Z coordinate axes. Figure 2 shows the movement directions. The corner of the roof above and to the left of the passenger's head was adjusted laterally and vertically.

Figure 1. Reconfigurable vehicle mockup. PVM and control unit in UMTRI laboratory (left) and left side view (right).

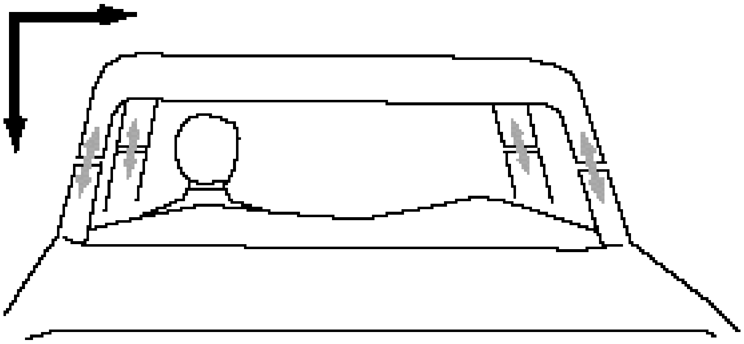


Figure 2. Roof adjustment Axes. The arrows show the lateral or vertical movement from nominal. The pillars articulate and telescope to allow roof translation.

FARO Arm Digitizer – Vehicle component and subject-body landmark locations were recorded in three dimensions using a FARO arm, a portable coordinate measurement device. The FARO arm was also used to record head and hair contours. Figure 3 shows the FARO arm being used to measure a subject's head contours.

Subjects

Subject recruitment methods consisting of word-of-mouth, previous subject lists, and newspaper advertisements were used to recruit 102 male and female drivers. The subject sample for this investigation had twice as many subjects in the taller stature groups than in the shorter stature groups, because the taller subjects were expected to be more sensitive to restrictive conditions. The resulting data can be reweighted to represent many different populations. Table 1 lists the subject pool by gender/stature group. At the start of the test session, the experimenter explained the nature of the testing and the subject signed a consent form.

Table 1
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	8
4	Female	1638 - 1681	60 - 85	8
5	Female	1681 - 1722	85 - 95	8
6	Male	1636 - 1679	5 - 15	8
7	Male	1679 - 1727	15 - 40	8
8	Male	1727 - 1775	40 - 60	8
9	Male	1775 - 1826	60 - 85	12
10	Male	1826 - 1869	85 - 95	12
11	Male	over 1869	> 95	12
Total				102

Preliminary Data Collection

Standard Anthropometry – Standard anthropometric measures were taken from each subject, including detailed measurements of head geometry (see Table 2). These measurements complement the head contour data collected later using the FARO arm.

Table 2
Head Geometry Measures

- Head breadth
- Head length
- Chin-to-top-of-head distance
- Head circumference
- Eye-to-eye lateral distance
- Glabella to Occiput

Head and Hair Geometry – A principal objective of this study was to quantify relationships between the rear passengers' actual head- and hair-to-roof clearances and the passengers' perception of the sufficiency and acceptability of the headroom. A method developed for a previous headroom study was used to accurately characterize the positions of the roof and head for each test condition. This method permits the calculation of any clearance measure of interest in post-test analysis. The key to this method is 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.

The locations of a set of head and face anatomical landmarks were recorded, followed by scans of the subject's head and hair contours. A specially designed head stabilization fixture, shown in Figure 3, assisted the subject in remaining still during data collection. A large number of points (150 to 400) were recorded over the left lateral and superior head and hair contours using the FARO arm probe. Colored labels were placed at three reference points on the subject's face. Two reference points were located arbitrarily on the forehead and cheek and the third was located on the temple at the same height as the subject's tragion. These three reference points were digitized along with each head and hair surface scan. This data collection method allowed the head landmarks and the head and hair surfaces to be aligned with the reference landmark locations when the latter were subsequently measured in the seating buck.

Figure 3. Head digitization with subject resting in stabilization fixture.

A three-dimensional triangulation method developed in a previous headroom study was used during analysis of the contour data. Polygonal surfaces were fit to the head and hair data and then complete head and hair contours were formed by reflecting the data collected from the left side to the right. Figure 4 depicts the head and hair contours of one subject.

Test Conditions

Roof Positions – Test conditions consisted of combinations of lateral and vertical roof positions. The fore-aft position maintained its rearmost setting. A rectangular array of five nominal conditions was chosen for this investigation. This array includes 80 mm of vertical travel and 106 mm of lateral travel. Table 3 describes this array. Figure 5 shows the test condition array from a rear view.

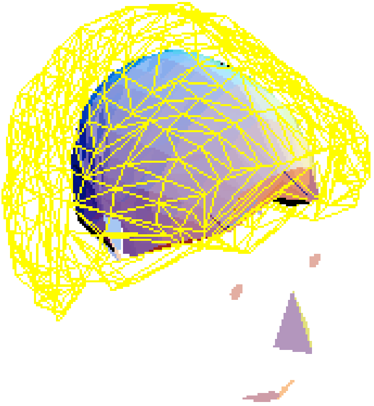


Figure 4. Typical head and hair contours from one subject.

Table 3
Roof Positions

Configuration Number	Vertical Position	Lateral Position
1	high	out
2	high	in
3	low	in
4	low	out
5	mid	mid

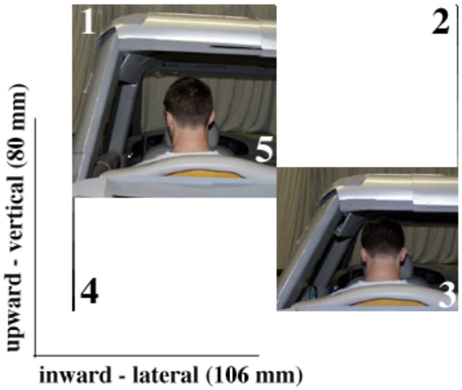


Figure 5. Five roof positions for testing with photos at two extreme positions.

Roof Shapes - The interior roof shape was varied to evaluate the relative importance of roof rail height and the height of the roof above the subject in determining subject responses. The three roof shapes are shown in Figure 6 as they appeared to the subject. A schematic of the shapes is shown in Figure 7. Roof shape was modified using two inserts that attached to the PVM roof. Changes were concentrated in the area directly above and to the left of the subject's head. The inserts created (1) a completely flat roof condition and (2) an extreme side rail condition. With the flat roof insert, the subject's seat was lowered 71 mm to maintain the H-point-to-roof distance. The rail insert created a side rail condition that doubled the vertical offset between the roof rail and the roof above the subject's head, producing a distance of 142 mm (rail-to-roof offset without insert is 71 mm). The insert shapes, as well as the PVM roof contour were scanned using the FARO arm and used in post-test analyses.

Figure 6. Three different roof contours. PVM shape (left), rail insert (middle), roof insert (right).

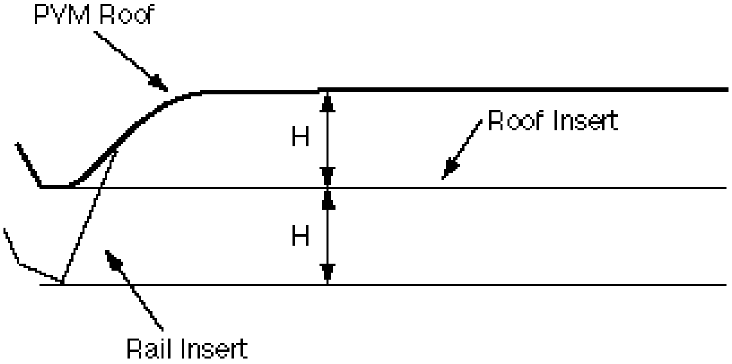


Figure 7. Representation of roof shapes in rear-view cross section. H = 71 mm.

Test Matrix - The test matrix was designed to investigate the effects on subjective evaluations of changes in roof positions and shapes. As previously described, three experimental variables made up the test matrix: vertical roof position, lateral roof (rail) position, and roof shape. The five nominal roof conditions were tested with each roof shape. Table 4 describes the test matrix.

Table 4
Test Matrix

Test Condition	Roof Position	Roof Shape
1	1	PVM
2	2	PVM
3	3	PVM
4	4	PVM
5	5	PVM
6	1	Roof Insert
7	2	Roof Insert
8	3	Roof Insert
9	4	Roof Insert
10	5	Roof Insert
11	1	Rail Insert
12	2	Rail Insert
13	3	Rail Insert
14	4	Rail Insert
15	5	Rail Insert

Subjective Rating– Each of the subjects rated the headroom for each of the test conditions by providing numerical responses to complete the following three sentences:

1. The space above my head is:

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

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

Responses were on two scales: sufficiency (1-5) and acceptability (1-4). The scales were defined using numbers as well as words. The response scales in Figure 8 were displayed on the back of the driver seat in front of the subject. Prior to the evaluations, the subject was encouraged to move his or her head as he or she would as a passenger in a vehicle, touching roof components as desired. Subjects responded verbally to each statement spoken by the experimenter with two numbers.

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. Subject ratings scales as displayed for the subject.

Position Measurement – At the end of each trial, subject posture and PVM location were recorded with the FARO arm. The location of the three head reference targets and the acromion, suprasternale, substernale, and left anterior-superior iliac spine landmarks were recorded to characterize the subject's posture (Figure 9). Reference points were digitized on each PVM component that may move independent of other components, including roof components and inserts.

Figure 9. Subject's head posture recorded with the FARO arm. PVM is shown with the rail insert.

RESULTS

Data Summary

A tabular data summary provides an excellent way to review the findings from the study. For each of the roof positions (five) and shapes (three), the percentage of subjects whose ratings exceeded a particular criterion level (e.g., acceptability ≥ 2) were tabulated. Figures 10, 11, and 12 show these percentages for sufficiency ≥4, for all subjects (Figure 10), subjects from the tallest four groups (Figure 11), and subjects from the shortest four groups (Figure 12). For each roof shape, the responses to all three questions are shown. Data from 12 subjects were excluded from these analyses because of missing data in one or more conditions; a total of 90 subjects were included.

In each figure, responses from each question (above, left, and overall headroom) and each roof shape (0, 71, and 142 mm roof-to-rail offset) are presented. Each column of boxes represents a roof shape (roof-to-rail offset level), and each row of boxes represents a question (above, left, or overall). Within each box, the percentages of subjects responding with sufficiency ≥ 4 (i.e., sufficient or better) are arranged graphically to correspond to the roof positions shown in Figure 5. For example, the graphic in the upper left corner of Figure 10 shows that 92 percent of subjects reported that the space above their heads was sufficient when the roof was flat and in position 5 (the center position). With the roof in its lowest, most inward position, only 41 percent of subjects rated the headroom as sufficient.

These figures illustrate most of the important observations from the analysis:

1. Vertical roof position has a strong effect on headroom perception. On average, the ratings for the lower roof positions are lower than for the upper roof positions. However, the effect is strongly non-linear. The center point ratings are much more similar to the upper position ratings than the lower position ratings.

2. Lateral position has an important effect, but the effect is strongest at lower roof positions and with a larger rail-to-roof offset.

2. Subject stature has a strong effect on ratings, with short subjects much more likely to rate the headroom as sufficient.

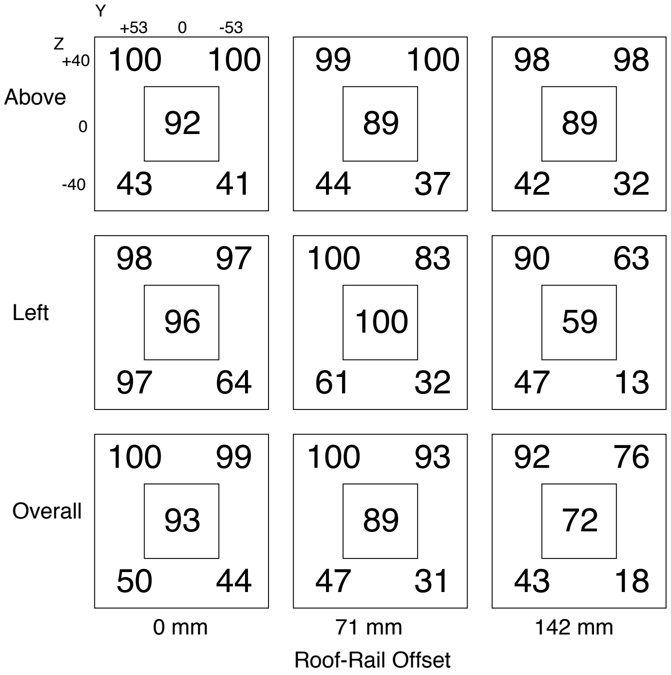


Figure 10. Percentage of subjects from ALL groups (N=90) rating sufficiency ≥ 4 (sufficient or better) by question, roof position, and roof shape.

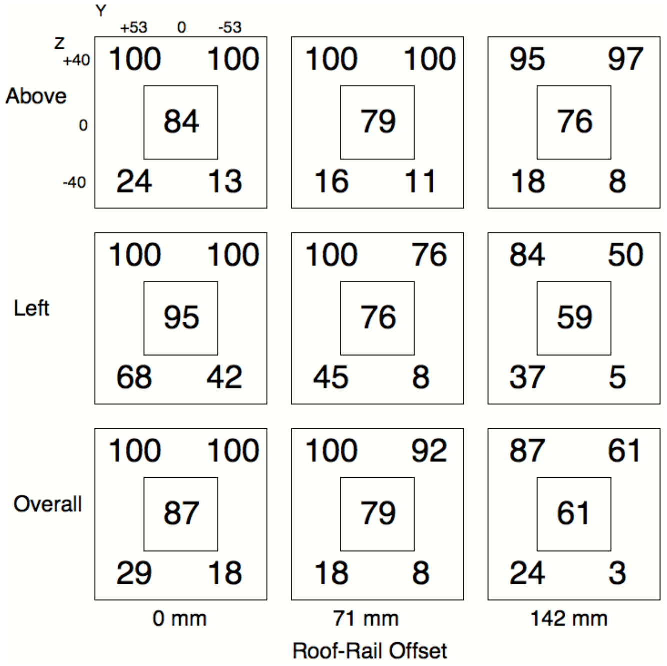


Figure 11. Percentage of TALL subjects (groups 8-11, N=38) rating sufficiency ≥ 4 (sufficient or better) by question, roof position, and roof shape.

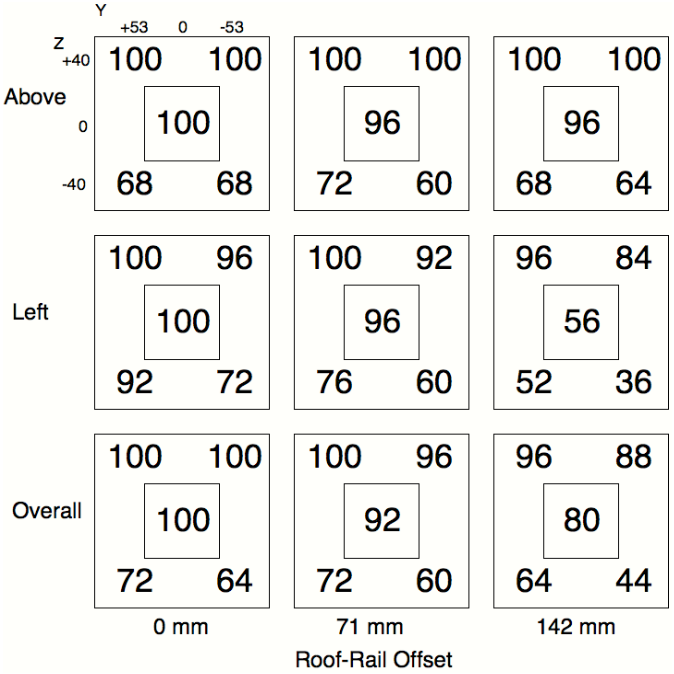


Figure 12. Percentage of SHORT subjects (groups 0-3, N=25) rating sufficiency ≥ 4 (sufficient or better) by question, roof position, and roof shape.

Logistic Regressions

Figures 10, 11, and 12 contain a wealth of information concerning the subjects' responses to changes in roof position and shape, but a more integrated statistical analysis is necessary to produce a useful design tool. Logistic regressions were performed, using a variety of criteria as the output variable.

A logistic regression fits the experimental data with a function of the form

$$P[x] = \frac{e^f}{1+e^f} = \frac{1}{1+e^{-f}}$$

where f is a function of the independent variables. The percentage of subjects rating at the selected criterion level is given by (1-P[x])*100%. A wide range of predictive models were assessed to determine the best way to model the data. Interactions were of primary importance because, for example, the effects of vertical roof position are strongly dependent on subject stature.

For logistic regression modeling, the test conditions were expressed using newly developed variables that express the roof geometry in ways that are associated with the test conditions. As demonstrated below, these variables are also strongly related to subjective assessments of headroom. Figure 13 illustrates three measures of headroom geometry. The Z value is the vertical distance from the SAE J1052 95th-percentile headspace contour centroid to the roof (headliner) surface. The Y value is the lateral distance from the occupant centerline to the roof rail reference point. The roof rail reference point is defined as the lowest point on the roof rail on a vertical plane oriented

30 degrees forward of the Y axis and passing through the head contour centroid. The roof-rail offset (RRO) is the vertical distance between the rail reference point and a point on the roof (headliner) directly above the head contour centroid. Table 5 lists these three dimensions (Y, Z, and RRO) for each of the five roof positions and shapes.

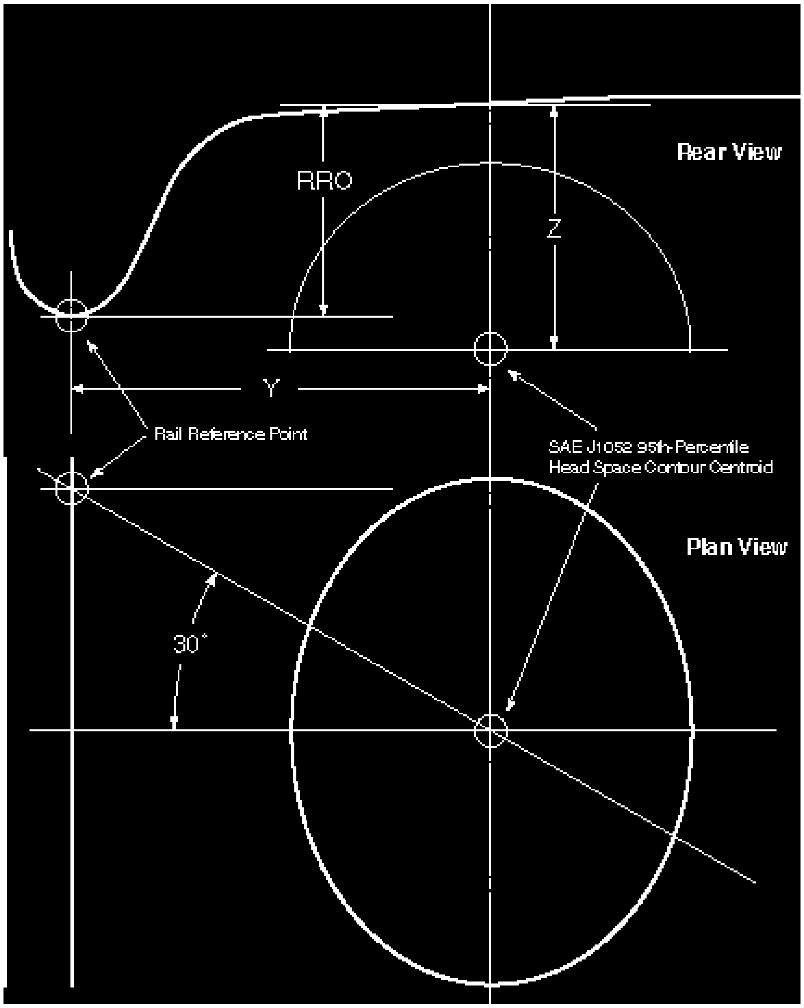


Figure 13. Measures used to characterize roof geometry in rear view (top) and top view (bottom).

Table 5
Test Conditions Expressed Using New Dimensions

Test Condition	Roof Position	Roof Shape	Y	Z	RRO
1	1	PVM	264	243	71
2	2	PVM	158	243	71
3	3	PVM	158	163	71
4	4	PVM	264	163	71
5	5	PVM	211	203	71
6	1	Flat*	264	243	0
7	2	Flat	158	243	0
8	3	Flat	158	163	0
9	4	Flat	264	163	0
10	5	Flat	211	203	0
11	1	Rail	264	243	142
12	2	Rail	158	243	142
13	3	Rail	158	163	142
14	4	Rail	264	163	142
15	5	Rail	211	203	142

* Flat roof insert condition

After considerable analysis, a predictive model was chosen using the following expression for f:

$$f = c_1 + c_2 \text{ Stature} + c_3 \text{ Z*Stature} + c_4 Z^2 + c_5 \text{ RRO*Y} + c_6 \text{ RRO*Z}$$

where

Stature is the subject stature,
RRO is the vertical roof-to-rail offset,
Z is the vertical position of the roof above the SAE 95th-percentile headspace contour centroid,
Y is the lateral position of the rail reference point relative to the occupant centerline, and
the c_n are constant coefficients obtained from the regression analysis.

The stature term reflects the fact that stature alone has a strong effect on headroom evaluations. The interaction between the vertical roof position and stature captures the fact that taller subjects' headroom ratings decrease more rapidly than short subjects' ratings as the roof is lowered. The Z^2 term provides for the nonlinear effect of roof position on headroom ratings, as illustrated in Figures 10, 11, and 12. The effect of the roof-rail offset (RRO) depends on both the lateral position of the roof (RRO*Y) and the vertical position (RRO*Z). Table 6 lists the coefficients for each term in the models for overall headroom evaluation at five different criterion levels. The coefficients have been multiplied by 1000 to simplify tabulation. All dimensions, including stature, are in millimeters.

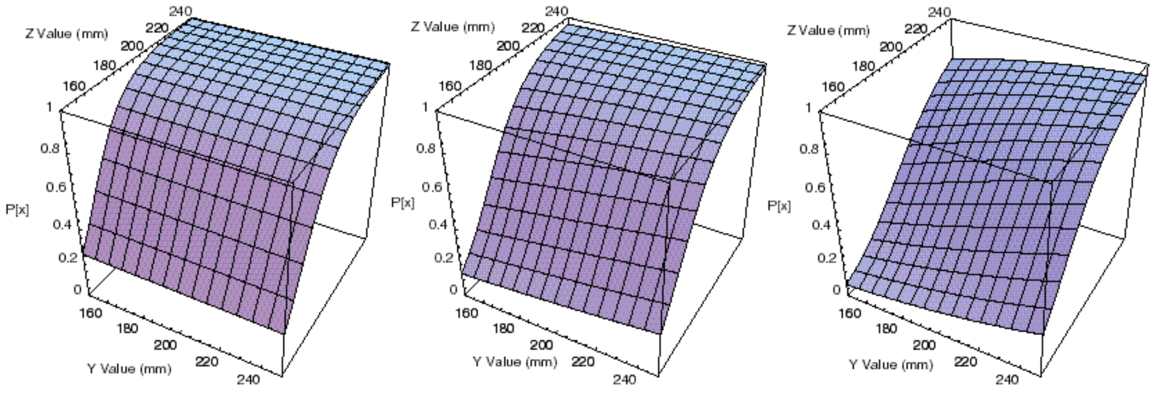
Table 6
Logistic Regression Model Coefficients (x 10^3) for Overall Headroom Evaluation*

Criterion	Intercept	Stature	Z*Stature	Z^2	RRO*Y	RRO*Z	R^2†
Suff = 5	-7538	12.9	-0.0515	0.0904	-0.1006	0.1341	0.30
Suff ≥ 4	-16984	20.0	-0.0780	0.1723	-0.1067	0.1786	0.37
Suff ≥ 3	-25020	27.3	-0.1128	0.2941	-0.1030	0.2106	0.39
Acc = 4	-13194	17.0	-0.0693	0.1943	-0.0831	0.1144	0.22
Acc ≥ 3	-16924	19.0	-0.0794	0.2256	-0.0688	0.1272	0.26

* The percentage of people of the specified stature who are predicted to rate the overall headroom at the specified criterion level.

† R^2 values at these levels (0.25 to 0.4) are indicative of a good fit for a logistic regression model.

Figure 14 illustrates the regression model for sufficiency ≥ 3 using the average subject stature (1708 mm). For each roof-rail offset used in testing, the probability of a subject rating the headroom as sufficient or better is plotted versus the Y and Z values for the roof geometry. The nonlinearity on the Z-value axis is particularly evident for the flat-roof condition (RRO = 0). The plots show that the effect of roof height (Z) is much stronger than the effect of lateral position over the respective ranges of interest, and that the lateral rail position effect grows with increasing roof-rail offset.



RRO = 0 mm

RRO = 71 mm

RRO = 142 mm

Figure 14. Illustration of logistic regression model for sufficiency ≥ 3 and the average subject stature. The vertical axes in the plots show the probability of the subjects rating the overall headroom as sufficient or better as a function of Y and Z at three RRO levels: 0, 71, and 142 mm. See Figure 13 for definitions of Y, Z, and RRO.

Model Predictions for Target Occupant Populations

The logistic regression models in Table 6 predict the percentage of people of a particular stature who will rate the headroom at the selected criterion level. In general, however, the ratings of a particular category of individual are of less interest than the aggregate ratings of a target population. A method has been developed to use the logistic regression models to obtain the percentage of a target population who would rate the headroom at the selected criterion level. The target population is represented by a normal stature distribution for each gender and the gender ratio. Individual predictions for each gender are combined using the gender ratio in the target population.

The concept is illustrated schematically in Figure 15 for a typical roof configuration. The figure shows three different normal stature distributions (dashed lines), representing different possible occupant populations. Each distribution is the same size, representing the same number of individuals. For each stature level, the percentage of people who are predicted to rate the headroom at the criterion level (e.g., sufficiency ≥ 3) is given by the logistic curve (heavy line). As expected, a higher percentage of short-statured people are predicted to rate any given roof geometry at the specified criterion. Multiplying each stature probability distribution by the logistic regression function gives the combined probability of selecting a person of a particular stature from the target population and of that individual rating the headroom at the criterion level (shown with thin, solid lines). The area under the resulting curve is equal to the fraction of the (single-gender) target population predicted to rate at the criterion level. The figure shows that a smaller percentage of a tall population would be expected to rate the headroom at a specified criterion level than would be the case for a short population.

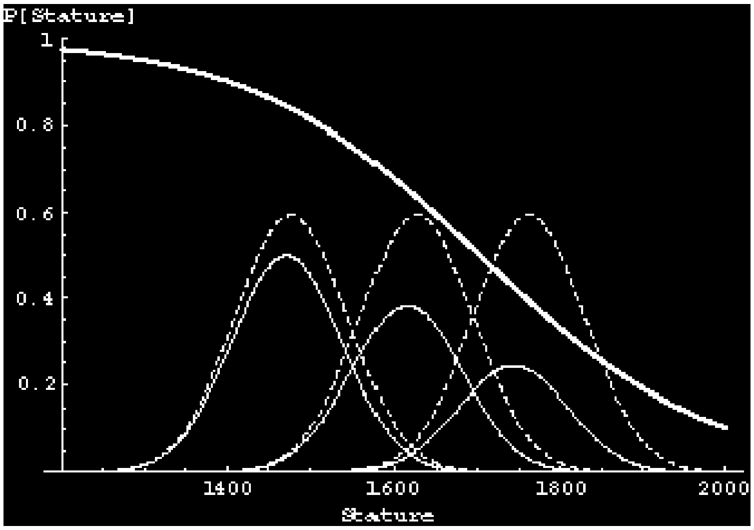


Figure 15. Illustration of method of combining stature distribution with a logistic regression function (see text). Bold line is a typical logistic regression function predicting the percentage of subjects of a given stature who will rate a particular headroom geometry at a specified criterion level. Three possible occupant stature distributions are shown with dashed lines (normal probability density functions multiplied by 100 for graphical presentation). The products of the stature distributions with the logistic regression curve are shown with solid lines. The percentage of people in each of the specified stature groups who would rate the headroom at the specified criterion level is proportional to the area under the product curves.

The concept is illustrated by three alternative stature distributions in Figure 15. For a short-statured population, almost all of the individuals will rate at the criterion level, so the product of the logistic function and the normal distribution will be close to the normal distribution (multiplying the normal probability density function by a probability near one). The area under the curve will be approximately equal to one. In contrast, for a sufficiently tall population, few of the subjects will be likely to rate the headroom at the criterion level. The normal distribution will be multiplied by values near zero, resulting in a smaller area under the curve.

Algebraically, the probability of obtaining a rating at the criterion level for a particular roof configuration is given by

$$Q[s] = 1 - P[s] = 1 - \frac{e^{a+bS}}{1 + e^{a+bS}} = \frac{1}{1 + e^{a+bS}}$$

where *S* is the probability of selecting a person of a particular stature from a normally distributed stature population. The distribution of *S* is given by the normal probability density function

$$N[\mu, \sigma] = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left[\frac{s-\mu}{\sigma}\right]^2}$$

where μ and σ are the mean and standard deviation of stature, respectively. The probability of selecting a person of a stature *S* and having that individual rate the headroom at the criterion level is given by the product

$$S[s] = Q[s]\, N[\mu, \sigma]$$

The fraction of the target population who are predicted to rate the headroom at the criterion level is the area under the curve S[s], given by

$$F = \int_{-\infty}^{+\infty} Q[s] N[\mu, \sigma]\, ds$$

Conveniently, for the models and stature distributions under consideration here, the true fraction F is closely approximated by the logistic regression model prediction for the mean population stature. Figure 16 compares the predictions given by the integral expression with the logistic regression evaluated using the average subject stature at the fifteen test conditions (five roof positions times three roof shapes) and five criterion levels. For predictions greater than 50%, the maximum error using the mean stature method is less than five percent of the integrated value.

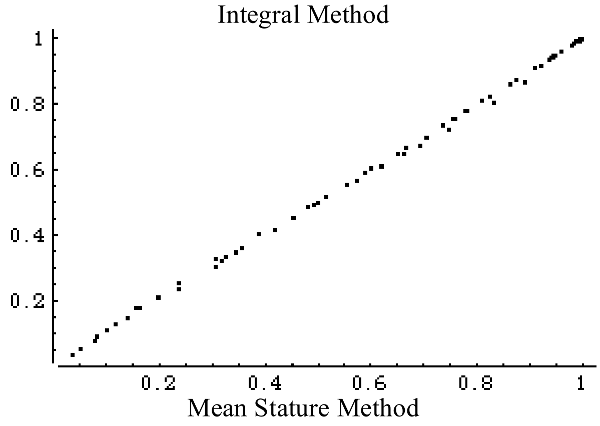


Figure 16. Comparison of integral method (vertical axis) with mean stature method (horizontal axis) for calculating population fraction rating at a specified criterion level. Axes show probability of rating overall headroom at the criterion level (five different levels are combined for this plot).

Model Evaluation

Using the mean stature method, the logistic regression prediction models can be compared to the subject data presented in Figures 10, 11, and 12. Figure 17 plots the predicted percentage of subjects rating overall headroom at the criterion level versus the observed value for fifteen test conditions (five roof positions times three roof shapes) and three subject groups (all subjects, tallest four subject groups, and shortest four subject groups). The model predictions are generally within five percent of the observed values. The greatest discrepancies occur in extreme roof configurations with the tallest subject groups. R^2 for a linear regression of predicted on observed is 0.98.

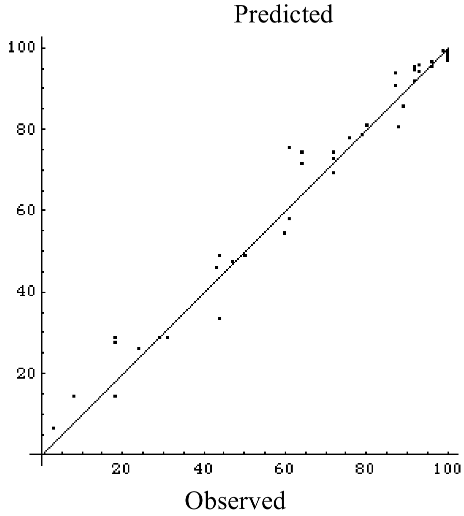


Figure 17. Predicted versus observed percentage of subjects rating the overall headroom with sufficiency ≥ 4 for fifteen test conditions and three subject groups (all subjects, tallest four subject groups, and shortest four subject groups).

MODEL APPLICATION

The statistical models developed in this study can be readily applied to candidate vehicle designs to predict the subjective responses of occupants. The models can also be used to create design guidelines for use in developing new designs. For the greatest flexibility, the regression models presented in Table 6 can be used to obtain predictions for a specific roof geometry , occupant stature distribution, and gender mix. For a simpler application of the model, the Appendix contains plots that show the tradeoffs between roof geometry and subjective ratings for one population.

Computational Approach

Several parameters must be defined for use in the models. Table 7 lists the parameters and typical values.

Table 7
Model Parameter Values

Parameter	Example Value
Population Definition:	
Mean Male Stature (MMS)	1762
Mean Female Stature (MFS)	1627
Fraction of Males in Population (FM)	0.25
Desired Subjective Response Level	
Criterion	Acceptability ≥ 3
Roof Geometry	
Z	200
Y	200
Roof-Rail Offset	60

The step-by-step process of using the model with the average stature method is outlined below.

1) Define the population average stature (PAS).

$$PAS = FM*MMS + (1-FM)*MFS$$

2) Select the appropriate model coefficients from Table 6 and construct the model.

$$P = 1 - \frac{1}{1 + e^{-f}}$$

$$f = (1/1000)*(-16924 + 19.0*PAS - 0.0794*Z*PAS + 0.2256*Z^2 - 0.0688*RRO*Y + 0.1272*RRO*Z$$

3) Substitute appropriate parameter values. For the example values in Table 7,

$$P = 0.883$$

meaning that 88.3 percent of the target population would be expected to rate the headroom as "somewhat acceptable" or better.

Graphical Approach

A graphical approach may be used as alternative to computation. Appendix A contains plots that show the tradeoffs between the three roof geometry parameters for five different criterion levels and four different population percentages. However, these plots were generated for a particular population having the characteristics of U.S. civilian adults and a 1:1 gender mix. If a different population is to be considered, the flexible computational method described previously should be used.

DISCUSSION

Summary

The experiment was successful in differentiating the effects of subject stature, roof shape, lateral rail position, and roof height on subjective headroom evaluation. Stature was an important determinant of headroom rating, apparently in proportion to the distance between the subject's head and the roof. That is, the decrement in headroom rating appears to be related to the percentage decrease in actual head clearance, so that a 50 mm decrease in headroom results in a larger decrease in headroom rating for a tall person than for a short person. No gender differences were noted that could not be attributed to differences in overall body dimensions.

As was found in the previous driver study, vertical roof position is the most important determinant of the headroom rating, followed by lateral position. However, the vertical offset between the rail and the roof, i.e., the rail prominence, has a strong effect that is dependent on the vertical and lateral position of the roof and rail. When the roof is approximately flat (no rail prominence) the lateral roof position becomes unimportant and only the vertical roof position affects the headroom ratings. In contrast, a prominent side rail makes the lateral rail position almost as important as the vertical roof position.

Roof Shape

As in the previous study, the typical SAE headroom dimensions (e.g., W27 and L35) were found to be poorly related to the headroom ratings. This is due to the fact that interactions between the roof contour and the SAE headspace contour do not measure the roof elements that people perceive. To create useful predictive models, new dimensions are needed that are closely related to the perception of headroom. Three new dimensions were developed that are measured relative to the SAE head space contour centroid. Using this centroid preserves continuity with current practice (for example, with respect to the effects of design seat back angle) while providing the needed geometric definitions.

The test conditions in this study were deliberately chosen to represent simplified roof geometry. The roof surface was approximately flat and level in the area extending from just behind the subject's head to well forward of the driver seat. The lateral (YZ-plane) section through the roof and rail was approximately constant in the area near the subject, so that the lower edge of the rail was horizontal and parallel to the vehicle X axis.

One consequence of this simplified roof shape is that a number of different methods for defining the geometry would result in an equivalent model. For example, the roof height could be defined directly above the H-point, or on an 8-degree-rearward vector from the H-point, rather than directly above the head contour centroid. Similarly, the roof-to-rail offset could be measured directly adjacent to the H-point or head contour centroid, rather than on a plane passing through the head contour centroid angled 30 degrees forward of the Y axis.

The vertical reference was chosen to be the head contour centroid because using the head contour centroid as a reference preserves the seatback angle effects in the current practice, since the seatback angle is an input to the J1052 head contour centroid locator equation. Variation in the Z value used in the models presented in this report (see Figure 13) is similar to variation in SAE H35 when the head contour used to measure H35 does not interact with the roof rail.

People appear to respond to the rail location in an area some distance forward of their heads, perceiving the shape by turning their heads to look out the side window and past the rail. The roof area directly adjacent to the subject's head was generally not the most important area, but neither was a position far forward of the subject. The 30-degree angle described in Figure 13 appears to be a reasonable choice, but other similar angles cannot be ruled out by the findings from this study.

For simple roof geometries, like the one used in this study, the definition does not affect the analysis much. However, for a roof/rail design that changes vertical position and offset with X-axis position, the choice of reference points could affect the analysis. People applying the models presented in this report are encouraged to consider the limitations of the models for roof shapes that diverge from those used in this study and interpret the model results accordingly.

Application

Two different ways of applying the study findings to vehicle design are presented in this report. The figures in the Appendix may be used to obtain a graphical prediction of the tradeoffs between roof geometry and the percentage of a particular target population who would rate the headroom at a particular level. However, the reference population (1:1 male:female, U.S. adults) is not representative of the rear seat occupant population for many vehicles. For most design and analysis purposes, the computational model should be used with the appropriate specification of the target population. For example, the population might be only 25 percent men, or include only shorter-statured men.

For a particular roof geometry, a range of evaluations is possible depending on the choice of population and subjective criterion. For example, 95 percent of a particular population might be predicted to rate the headroom as greater than 3 on the sufficiency scale, but only 90 percent rate the headroom as acceptable. The choice of population, criterion level, and population percentage are left to the discretion of the user.

Validation

The models developed in this study, and the previous driver study, have not been validated using independent data sets. A validation study using actual vehicles would be very useful in determining the effectiveness of these models in predicting headroom ratings for novel roof configurations. Similar studies comparing driver postures in laboratory mockups and actual vehicles have shown good correlation, but a specific study of headroom perception in actual vehicles will be necessary to ensure that the models presented in this report are accurate.

Further Work

In addition to a validation study, there is much more work that could be done to improve understanding of headroom perception. There is considerably more information in the available data that could be extracted with further analysis. For example, a set of trials were conducted in which the subject's vertical seat position was adjusted to place all of the subjects' heads in approximately the same position with respect to the roof. These data present an opportunity to examine the relationship between a subject's headroom perception and the actual clearances between the subject's head and the roof. Such an analysis might further illuminate the characteristics of the roof that most influence headroom perception. Other possible analyses include:

- analysis of comfortable head movement data (obtained for all subjects in this study) to describe the space necessary for head movements,
- modeling of head location for head restraint and side airbag design, and
- standardized hair contours (e.g., 95th-percentile hair) for use with human CAD models.

The data collected in this research program represent a valuable resource that can be exploited through additional analyses.

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Reed, M.P., and Schneider, L.W. (1999). *Investigating driver headroom perception: methods and models*. Technical Paper 990893. Warrendale, PA: Society of Automotive Engineers, Inc.

National Center for Health Statistics (1997). National Health and Nutrition Examination Survey, III 1988-94. CD-ROM Series 11, No. 1. Hyattsville, MD: U.S. Department of Health and Human Services.

APPENDIX

Plots for Design Guide

The following plots depict the percentage of a particular target population who are predicted to rate rear-seat headroom at a range of criterion levels as a function of three roof geometry variables.

The target population is U.S. adults, aged 18 to 65 years, with 50% males and 50% females. The population was defined on stature, using values obtained from NHANES III (National Center for Health Statistics 1997). Statures were assumed to be normally distributed within gender, and represented by the following parameter values:

Male Mean: 1762 mm
Male Standard Deviation: 72.4 mm
Female Mean: 1627 mm
Female Standard Deviation: 67.2 mm

These plots are not applicable to any other population. See the report text for methods of computing acceptability and sufficiency percentages for alternative populations. Figure A1 shows the subjective response levels for which predicts can be obtained.

The roof geometry is described using three parameters depicted in Figure A2. The Z value is the vertical distance from the SAE J1052 95th-percentile headspace contour centroid to the roof (headliner) surface. The Y value is the lateral distance from the occupant centerline to the roof rail reference point. The roof rail reference point is defined as the lowest point on the roof rail on a vertical plane oriented 30 degrees forward of the Y axis and passing through the head contour centroid. The roof-rail offset (RRO) is the vertical distance between the rail reference point and a point on the roof (headliner) directly above the head contour centroid. For more discussion of these measurements, see the report text.

Each plot shows the tradeoffs between Y, Z, and RRO for a particular subjective criterion level (e.g., Sufficiency ≥ 3) and a particular population percentage (e.g., 95 percent). For example, the plot for Sufficiency ≥ 3 at 95% gives combinations of Y, Z, and RRO that are predicted to result in 95% of the target population giving an overall headroom rating of “sufficient” or better.

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 A1. Subjective rating scales.

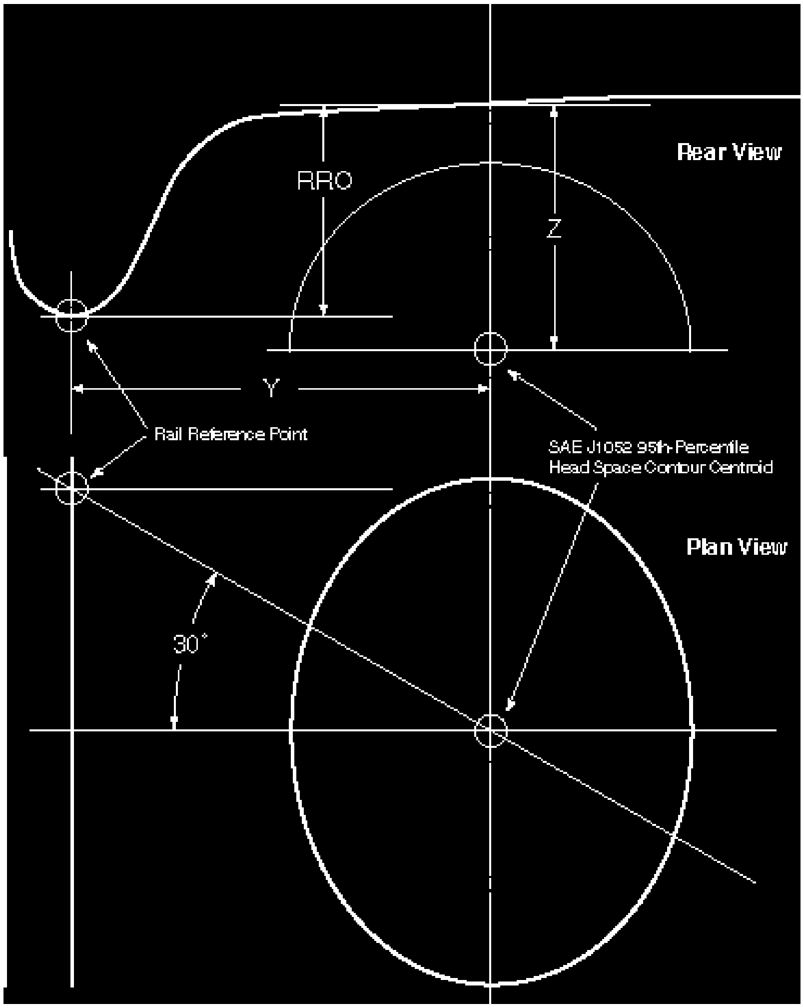
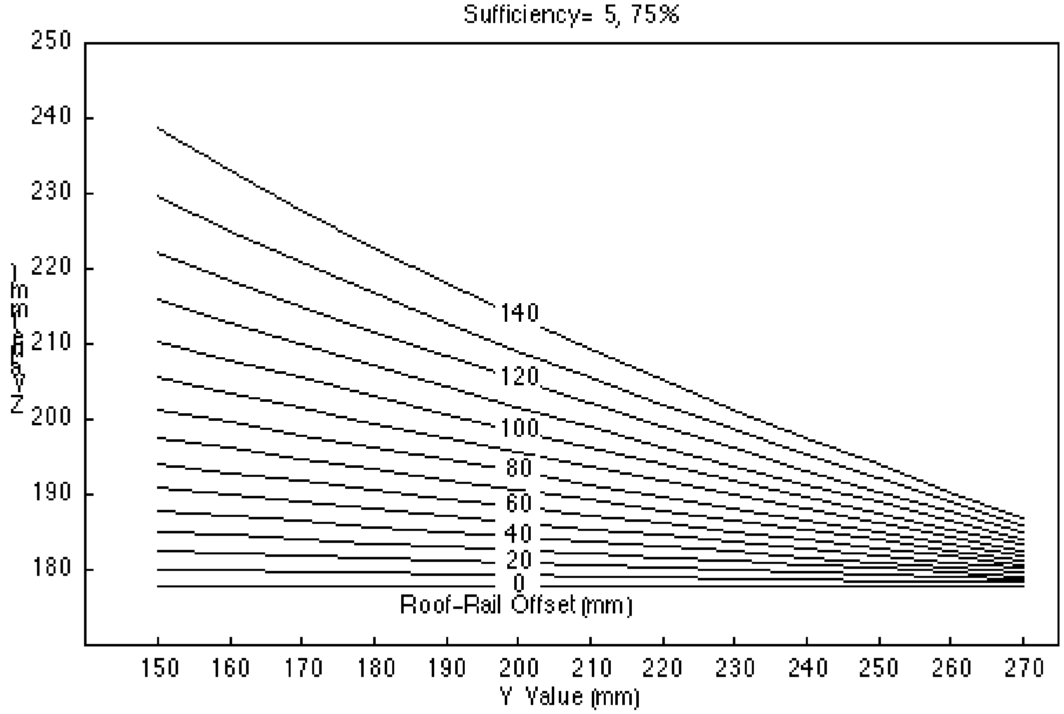
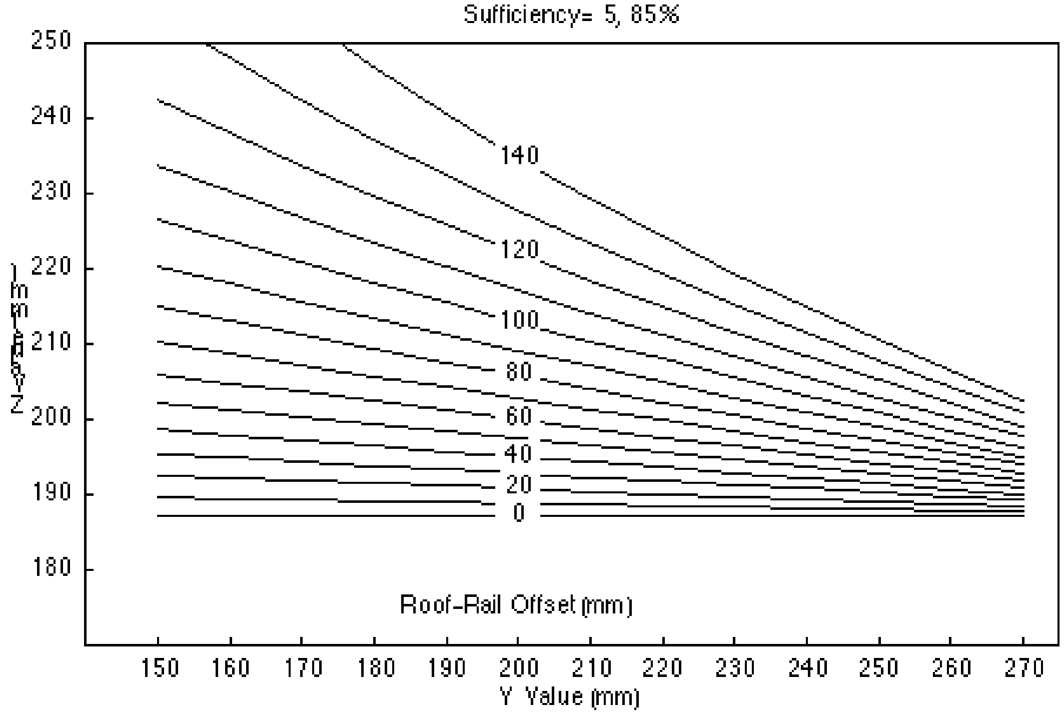
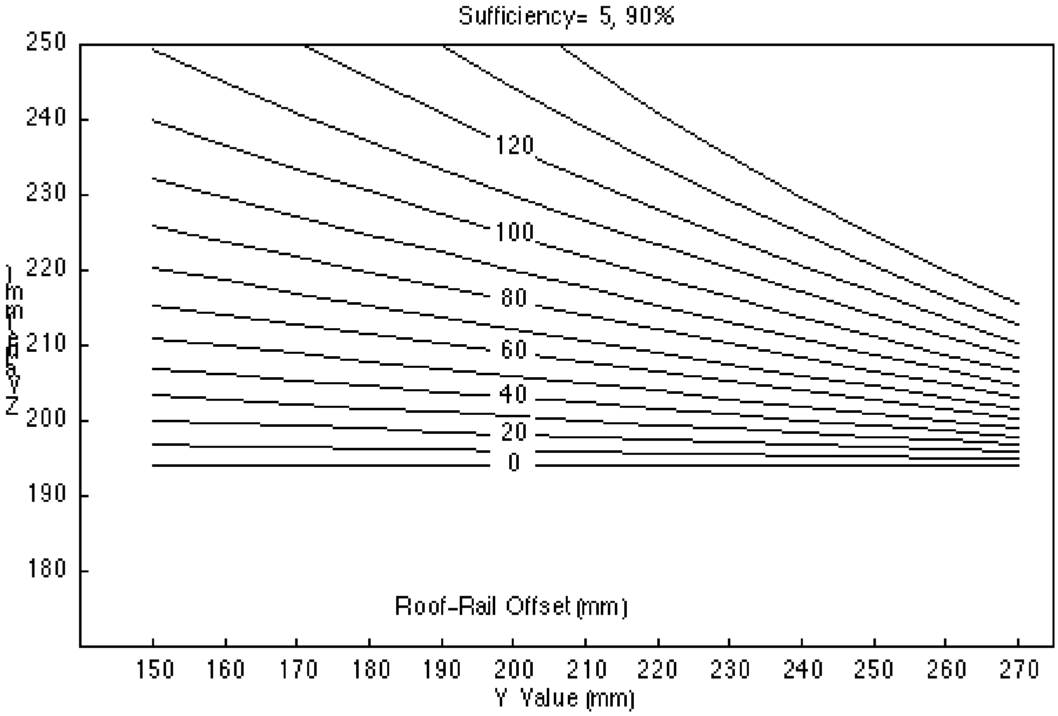


Figure A2. Measures used to characterize roof geometry in rear view (top) and top view (bottom).

SUFFICIENCY = 5






Sufficiency= 5, 90%
Z Value (mm)
250
240
230
220
210
200
190
180
120
100
80
60
40
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Roof-Rail Offset (mm)
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200
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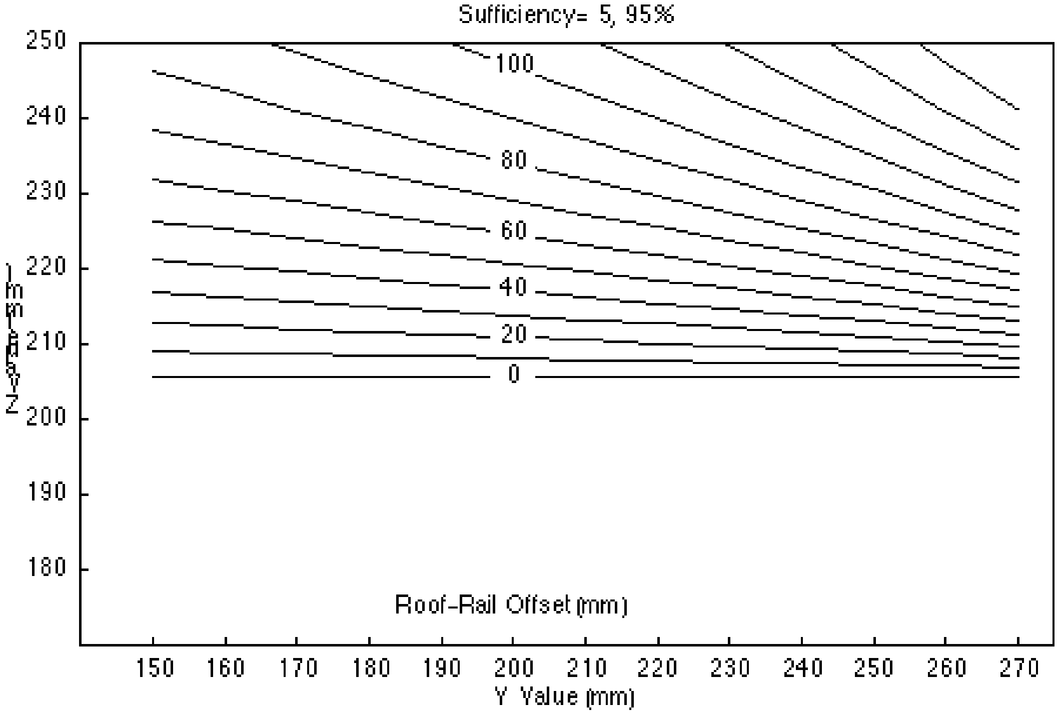
230
240
250
260
270
Y Value (mm)


Sufficiency= 5, 95%
Z Value (mm)
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Roof-Rail Offset (mm)
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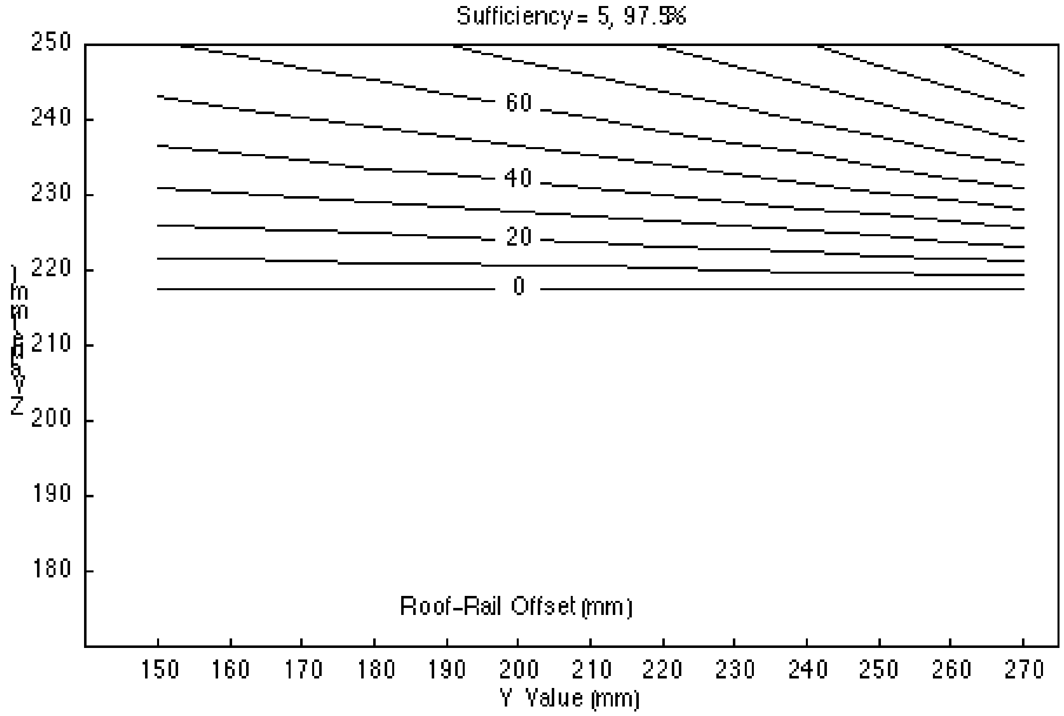
Y Value (mm)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Z Value (mm)
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Roof-Rail Offset (mm)
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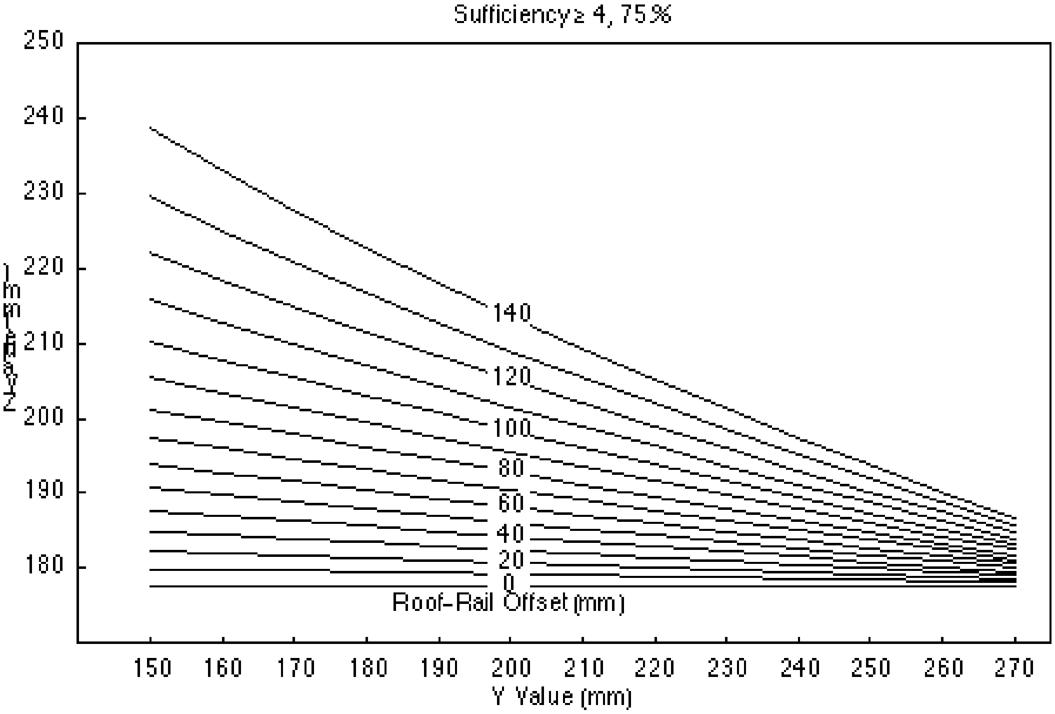
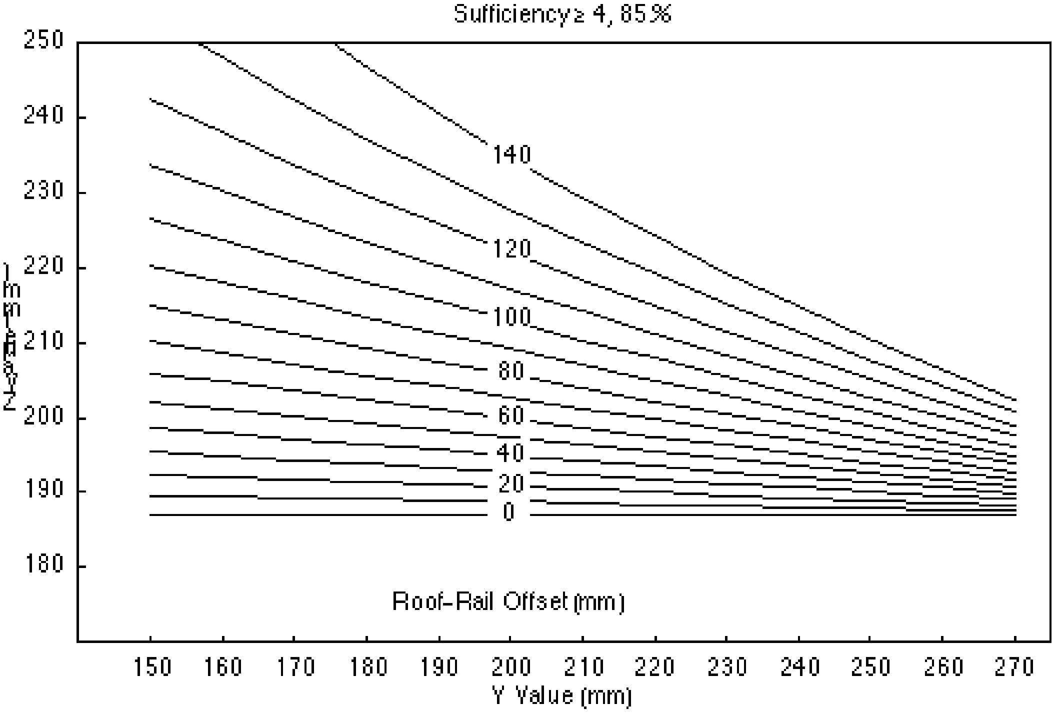
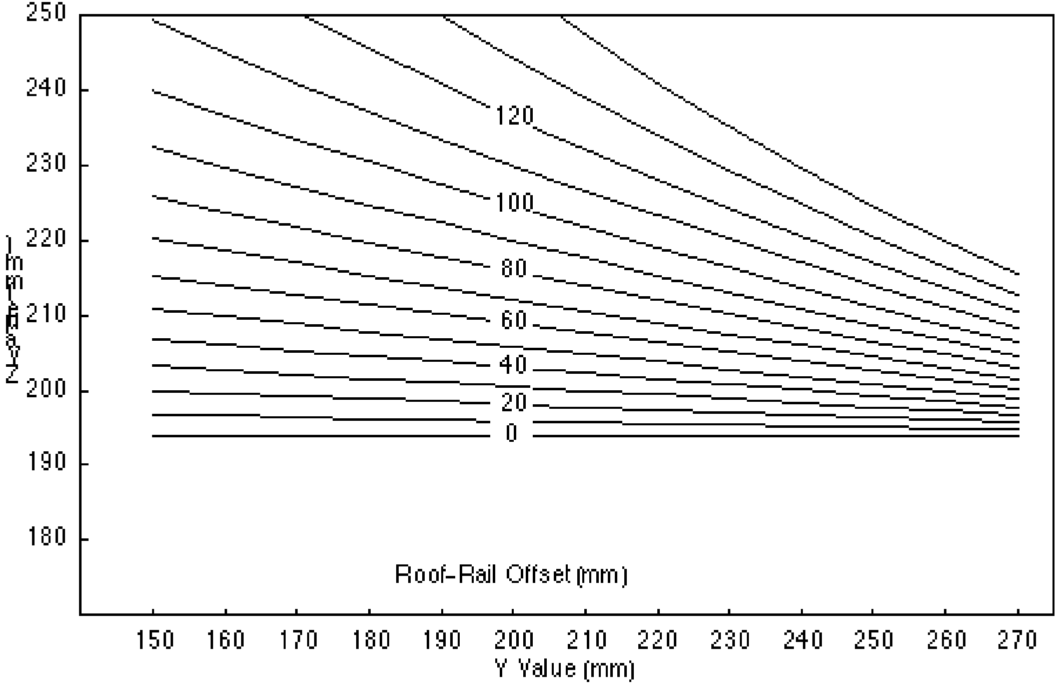
Y Value (mm)

SUFFICIENCY ≥ 4

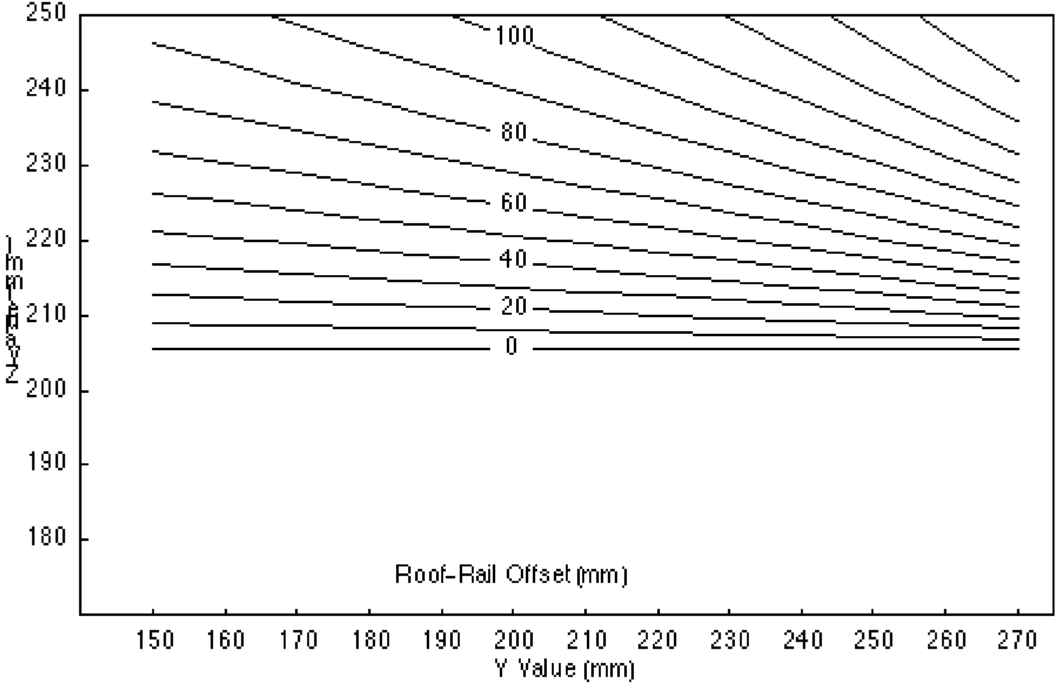


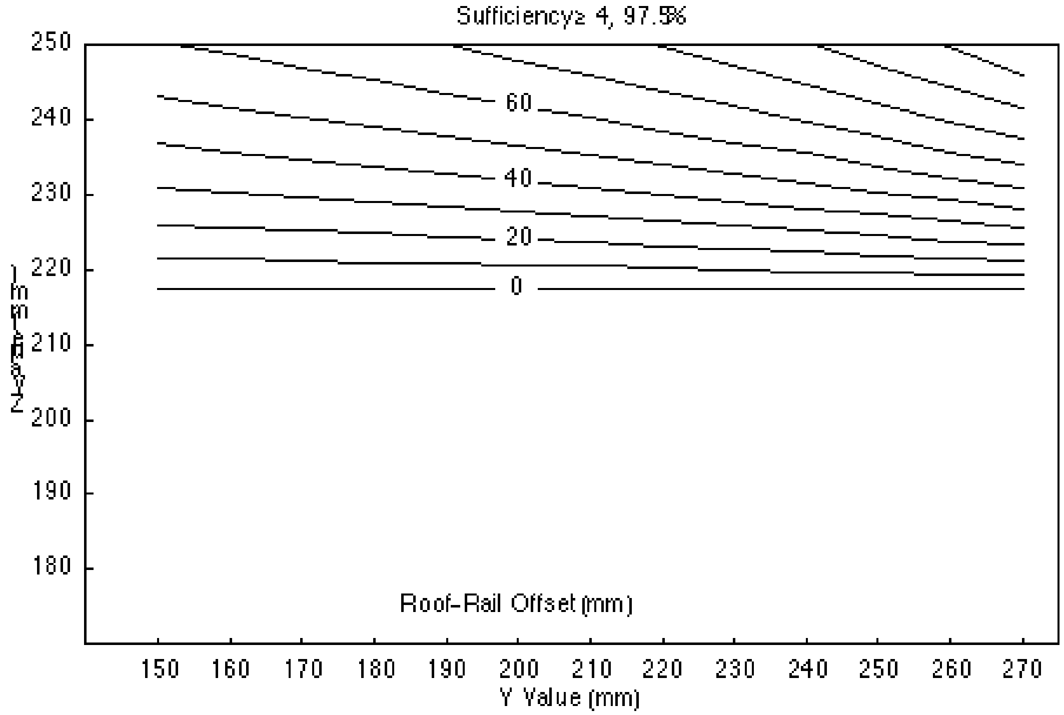


Sufficiency ≥ 4, 90%



Sufficiency ≥ 4, 95%




Sufficiency≥ 4, 97.5%
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Z Value (mm)
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Roof-Rail Offset (mm)
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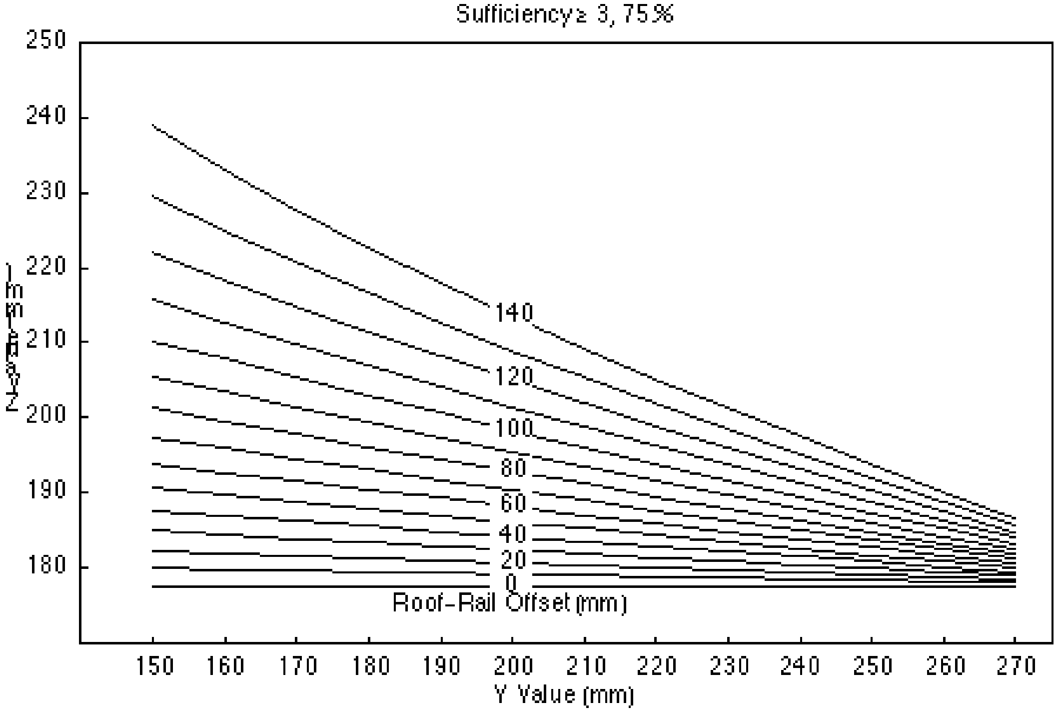
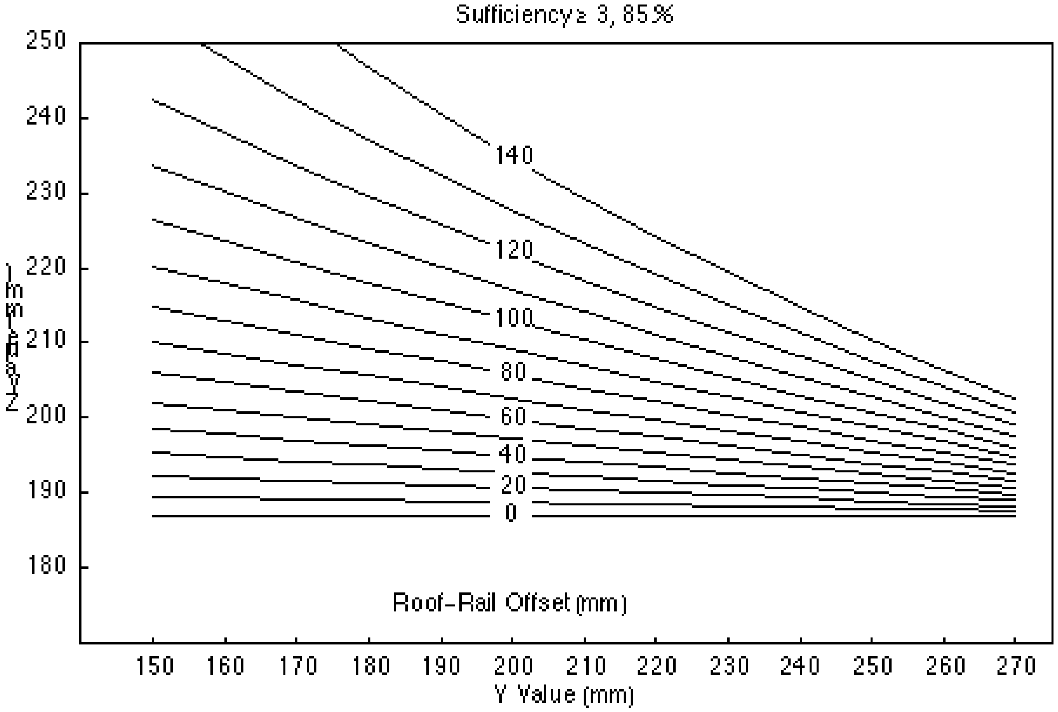
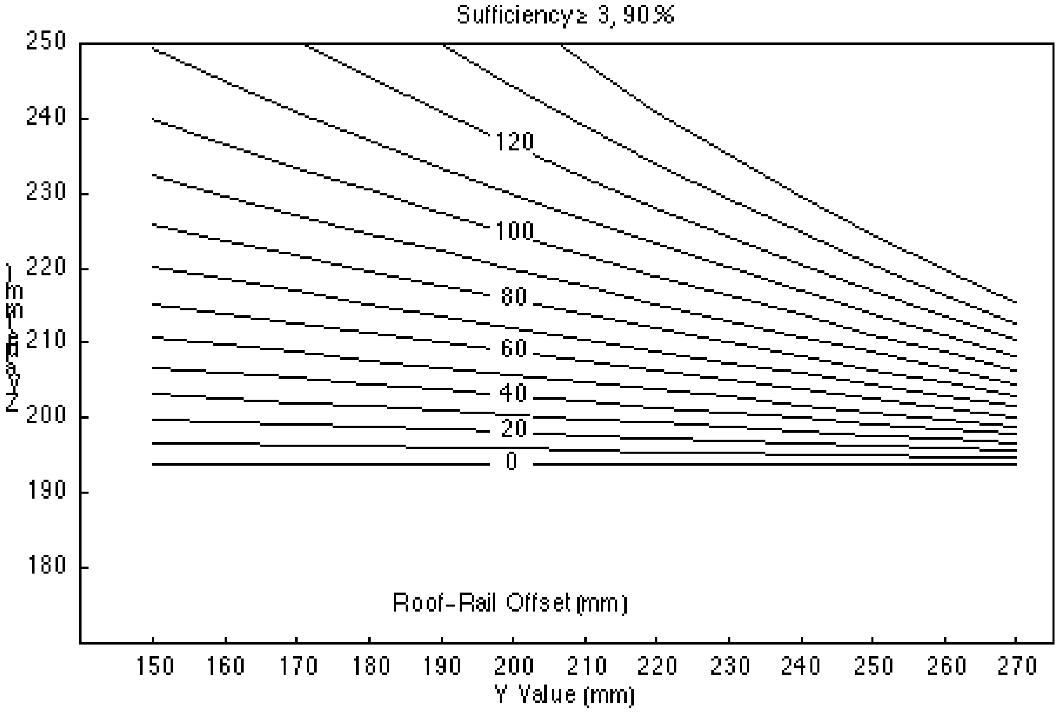
Y Value (mm)

SUFFICIENCY ≥ 3



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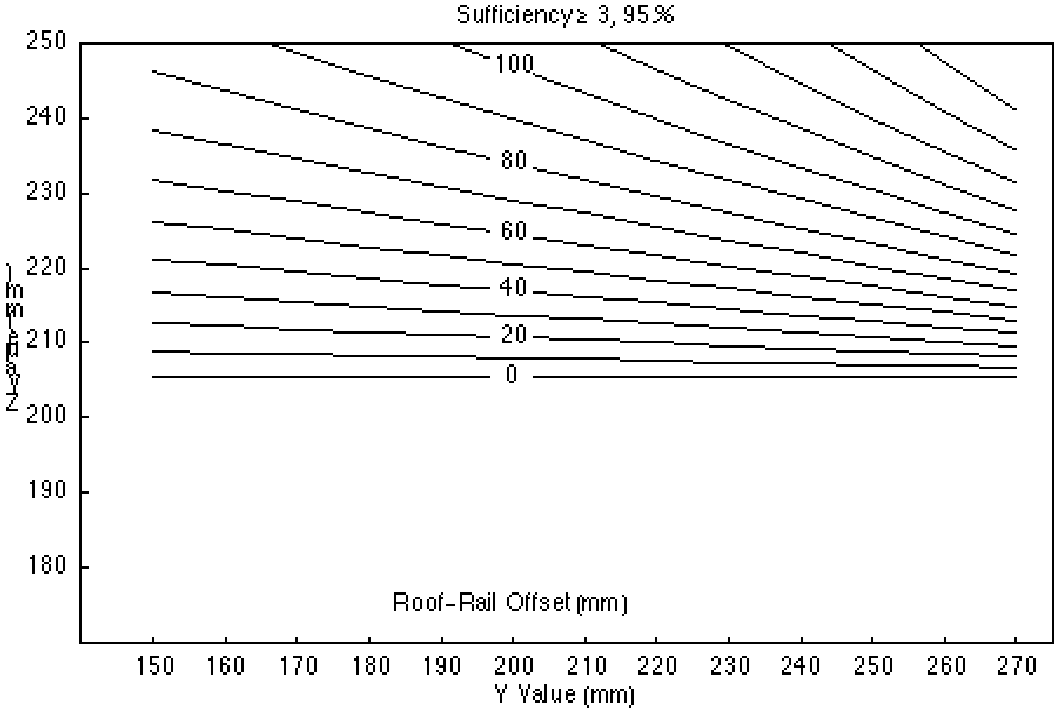
Y Value (mm)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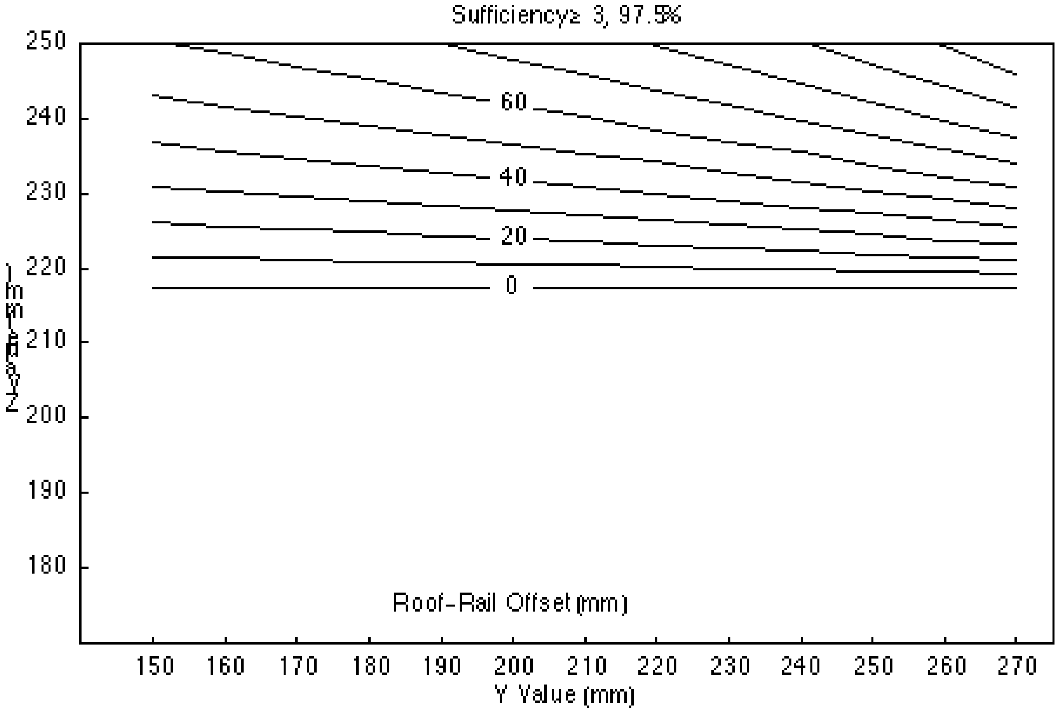
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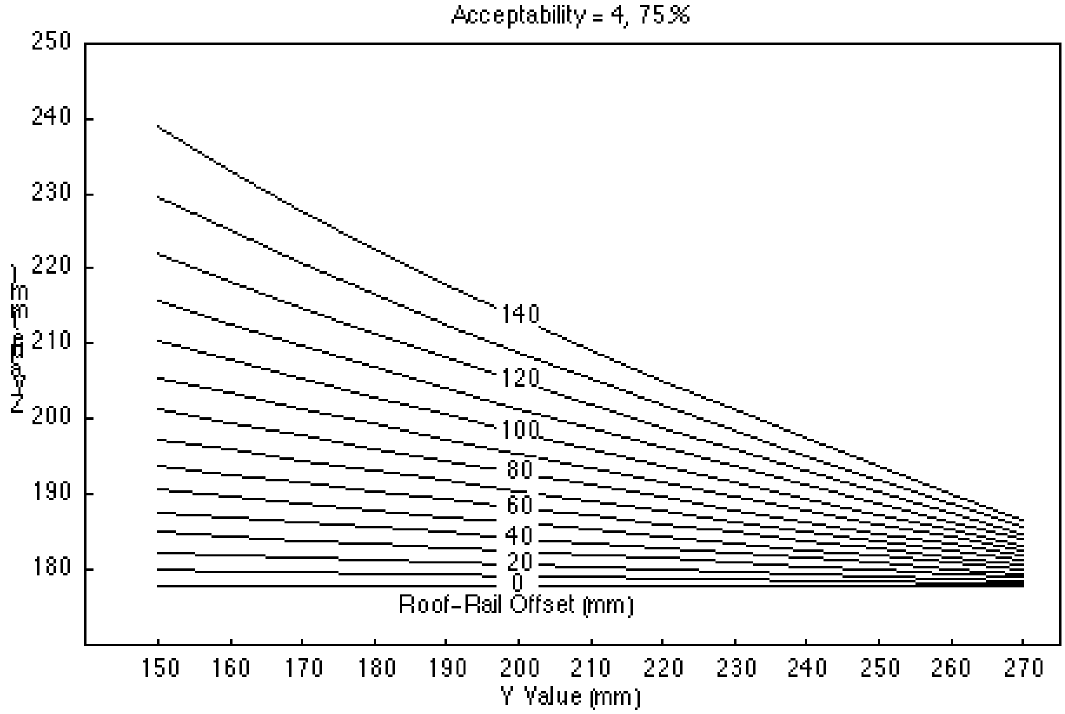
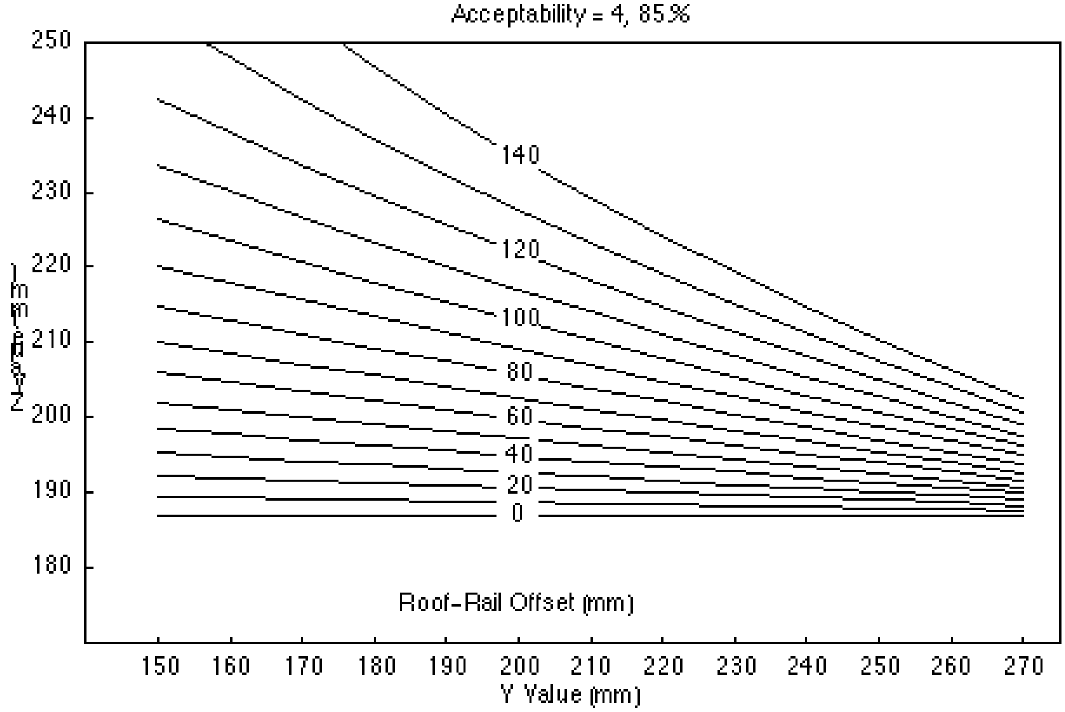
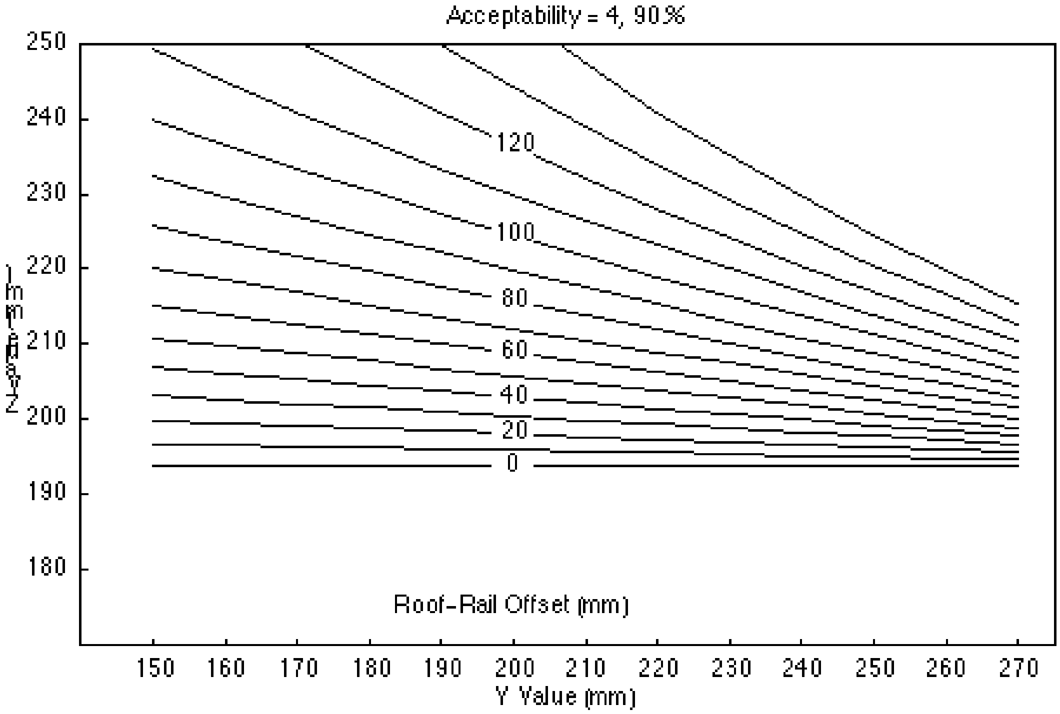
Y Value (mm)

ACCEPTABILITY = 4



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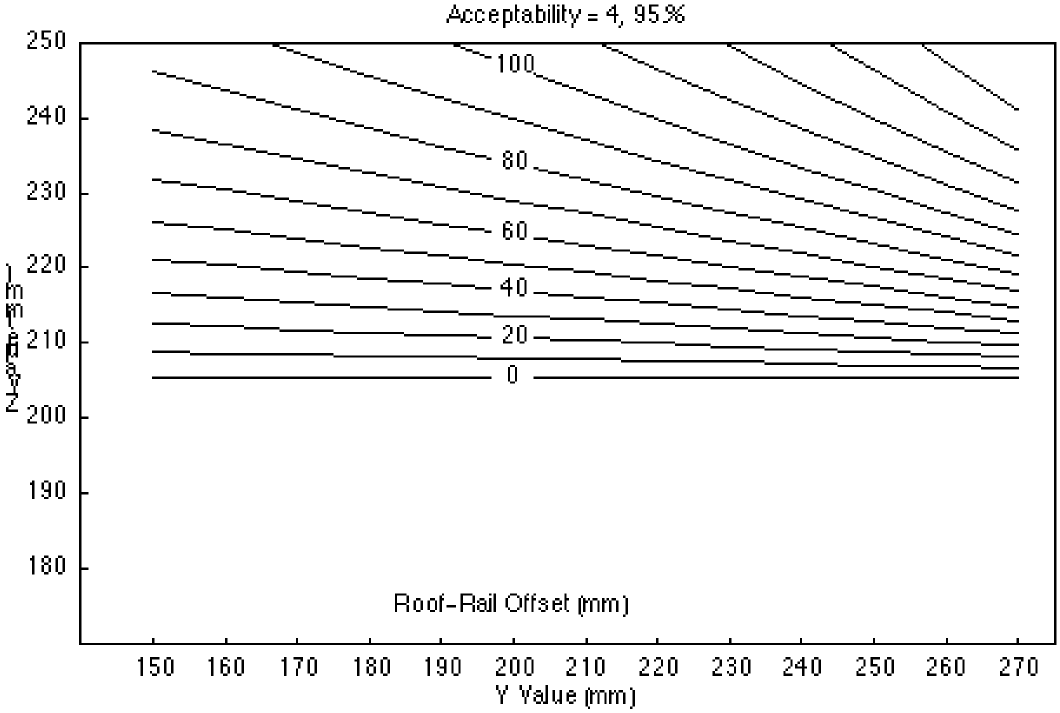
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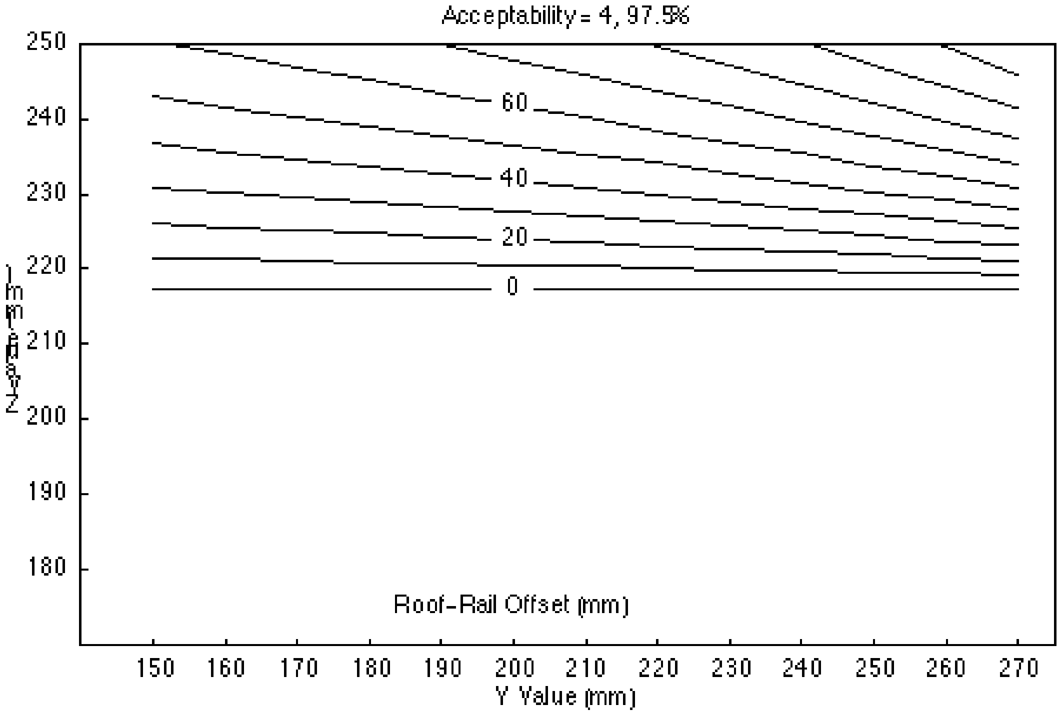
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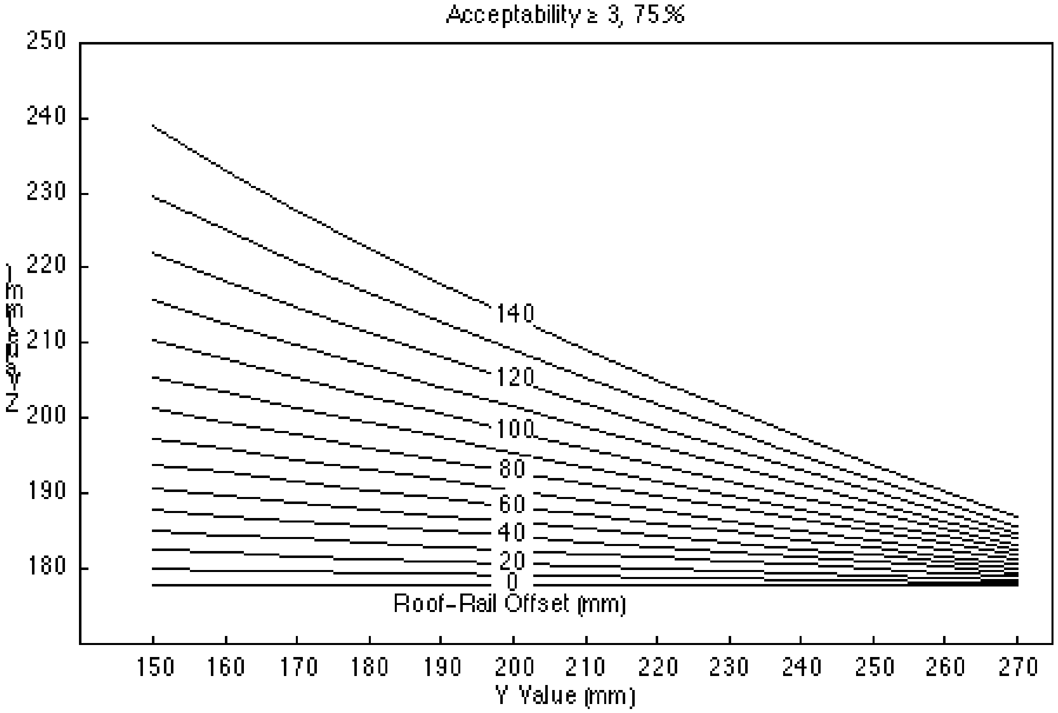
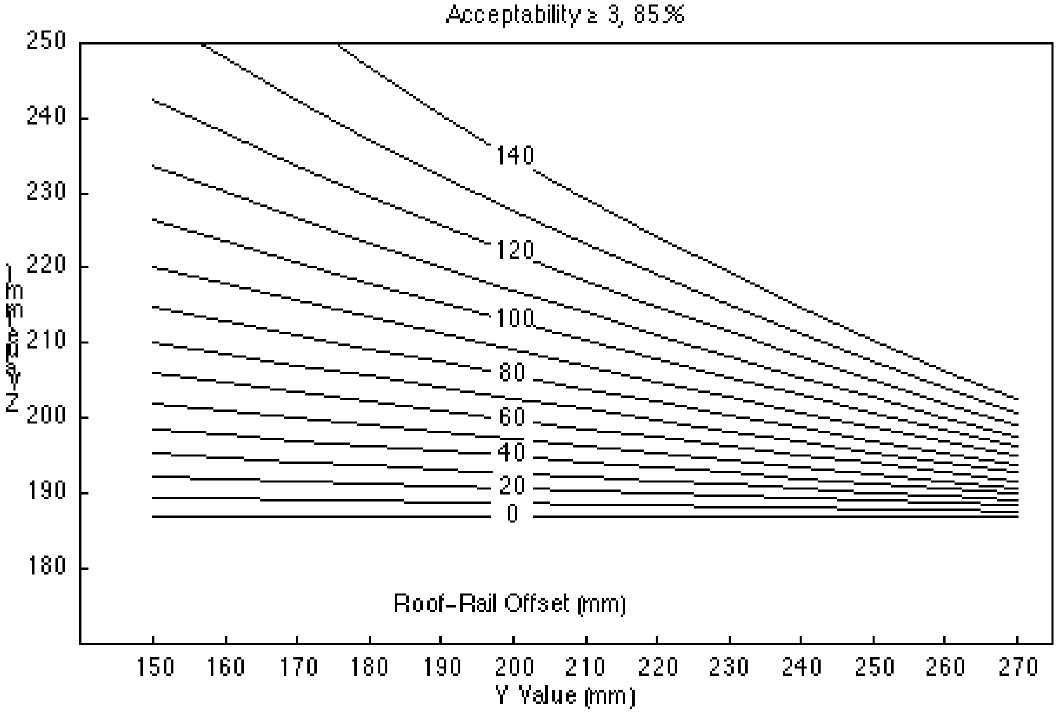
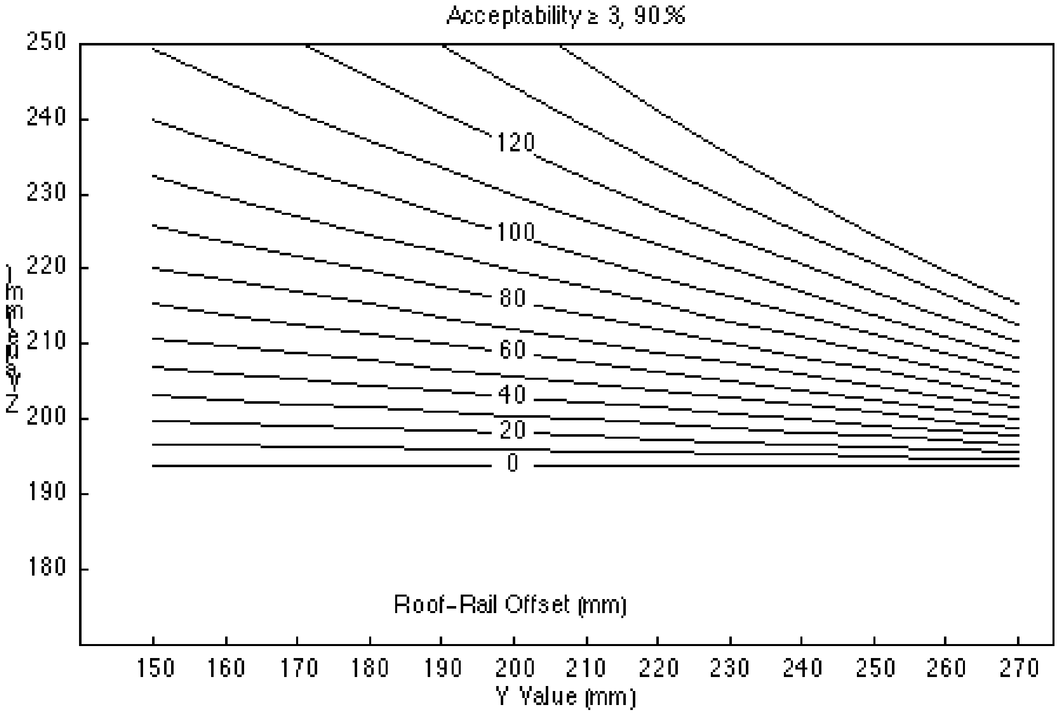
ACCEPTABILITY ≥ 3



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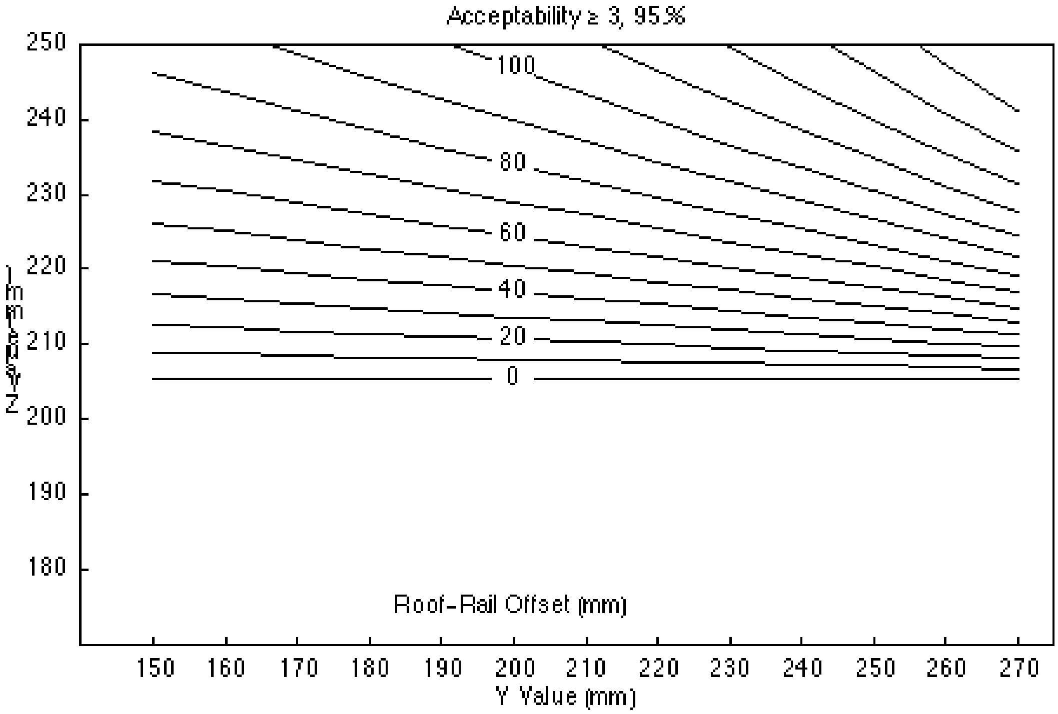
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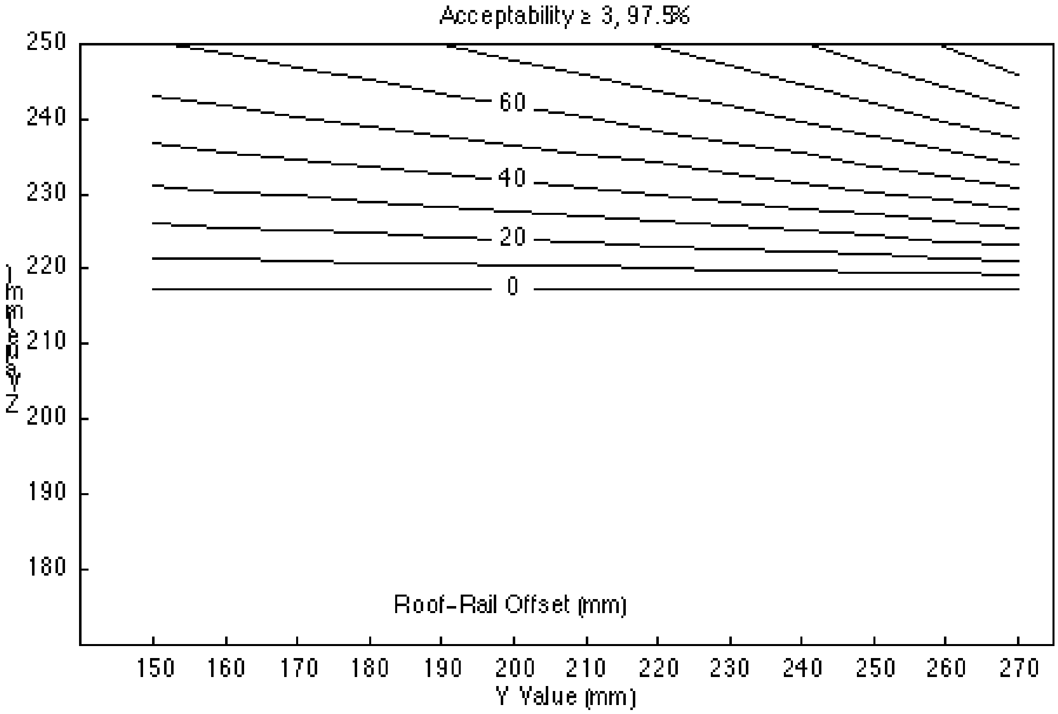
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Y Value (mm)