SAE TECHNICAL PAPER SERIES

2006-01-0961

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Reprinted From: Reliability and Robust Design in Automotive Engineering 2006 (SP-2032)

ISBN 0-7680-1634-7

9 780768 016345

2006 SAE World Congress
Detroit, Michigan
April 3-6, 2006

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ISSN 0148-7191

Printed in USA

2006-01-0961

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ABSTRACT

Occupant packaging practice relies on statistical models codified in SAE practices, such as the SAE J941 eyellipse, and virtual human figure models representing individual occupants. The current packaging approach provides good solutions when the problem is relatively unconstrained, but achieving good results when many constraints are active, such as restricted headroom and sightlines, requires a more rigorous approach. Modeling driver needs using continuous models that retain the residual variance associated with performance and preference allows use of optimization methodologies developed for robust design. Together, these models and methods facilitate the consideration of multiple factors simultaneously and tradeoff studies can be performed. A case study involving the layout of the interior of a passenger car is presented, focusing on simultaneous placement of the seat and steering wheel adjustment ranges. Tradeoffs between adjustability, driver accommodation, and exterior vision are explored under this paradigm. These results are contrasted with those obtained using boundary manikins.

INTRODUCTION

Vehicle occupant packaging is the process of laying out the interior of a vehicle to achieve the desired levels of accommodation, comfort, and safety for the occupants (Roe 1993). The primary focus in occupant packaging is the driver's workstation. The driver package usually refers to the locations and adjustment ranges of the steering wheel and seat with respect to the pedals, but also encompasses the physical locations of controls and displays with which the driver interacts. Analysis of interior and exterior driver vision zones, both direct and indirect (using mirrors), is also typically considered part of packaging practice. Packaging is begun early in the vehicle design process, although often after the body exterior contour and window openings have been designed, as the first step in the design of the interior. The package is iterated upon through the design process as constraints change.

The objectives of the packaging process are usually stated in terms of percentage accommodation on particular measures. Accommodation is quantified as the fraction of the driver population achieving some targeted level of fit or comfort (Roe 1993). For example, the seat track adjustment range is often selected so that 95% of drivers are able to sit with the seat position that they prefer. Another common goal is to ensure that 95% of drivers achieve a minimum upward vision (upvision) angle through the windshield.

Beginning in the late 1950s, the Society of Automotive Engineers began considering standardized tools and procedures for packaging. SAE Recommended Practice J826, first approved in 1962, defined a weighted three-dimensional manikin for measuring seats and a two-dimensional template with a similar profile for use on package drawings (SAE 2005). The manikin, known as the H-point machine, defines and measures the location of the H-point, a reference point that approximates the hip location of a person sitting in the seat (see Reed et al. 1999). The template creates a standardized, schematic visualization of a driver with long legs, originally for purposes of ensuring adequate legroom for tall men (Geoffrey 1961). A new H-point manikin was developed in the 1990s (Reed et al. 1999) and is now the basis for SAE J4002 (SAE 2005).

In addition to the measurement tools, the SAE Recommended Practices relating to packaging are focused on percentile accommodation models created by statistical analysis of data on driver behavior. SAE J941 introduced the first percentile accommodation model, the eyellipse, in the early 1960s (Meldrum 1965). The eyellipse is a graphical construction that describes the expected distribution of driver eye locations, approximated as a three-dimensional normal distribution. The eyellipse, which has been used extensively for performing vision analyses over the last four decades, was recently upgraded to represent contemporary driver populations and to take into account the effects of steering wheel position on eye location (Manary et al. 1998). Other important statistical models in SAE Recommended Practices include the seating accommodation model in SAE J1517 (now superceded by SAE J4004 for passenger cars and light trucks); the driver reach curves in SAE J287; and the driver head clearance contour in SAE J1052. In each case, the model provides a geometric design guide that represents a specified percentage of the relevant measure from a population of drivers.

An increasingly common approach to occupant packaging employs human figure models, rather than percentile accommodation models, to represent driver requirements. The use of kinematic linkage models of the human form (manikins) to represent the size, shape, and posture of vehicle occupants in design dates at least to the 1950s (cf. Dempster 1955). The use of three-dimensional computer graphics models of humans for vehicle interior design and assessment, as with many other engineering software applications, has followed the development of low-cost computers and the transition from paper to 3-D computer modeling for vehicle design. Early human modeling software programs such as SAMMIE (Porter et al. 1993) have been joined in the marketplace by Ramsis, Jack, and Safework, among others (Chaffin 2001). These digital human models (DHM) are now widely used for vehicle interior design and have replaced the SAE packaging tools in some companies, particularly in the commercial-vehicle industry (Loczi 2000).

Roe (1993) presents a useful overview of the relative strengths and weaknesses of the percentile-accommodation and manikin-based approaches. The models provide quantifiable accuracy and precision for the applicable variables (e.g., eye location in normal driving posture) and are fundamentally population models. That is, they describe percentiles of a population, not the behavior of any individual within the population. The primary disadvantage of the percentile accommodation models is their high level of abstraction. For example, communicating information about the need to improve visibility for people with low eye positions can be facilitated using a model that looks like a small woman, even if the eyellipse is needed for an accurate quantitative vision analysis.

An important limitation of the percentile accommodation models (e.g., the eyellipse in J941 and the seating accommodation model in J4004) is that they are essentially univariate, dealing with a single measure of interest (seat position, eye location). In addition, only a subset of the potential geometric factors influencing driver posture are included in the models. For example, the potential influence of a low roof on driver eye location, through restrictive headroom, is not taken into account in J941.

Figure models provide good face validity and also provide the capability of responding to kinematic constraints that are not represented in the population accommodation models. The effects of restricted headroom could be represented by requiring the figure models to maintain a gap between their heads and the roof. A large number of figure models would be needed to attain good estimates of population accommodation. In an attempt to reduce the number of figure model analyses that must be performed, analysts frequently select a small number of *boundary manikins* that span a large percentage of the range of body dimensions in the target population. Methods for selecting boundary manikins range from simplistic ”5th-percentile female and 95th-percentile male” approaches to sophisticated techniques using factor analysis (Bittner 2000).

However, the boundary manikin approach does not generally provide accurate assessments of accommodation. As typically used in software packages such as Jack and Ramsis, only the variance in posture attributable to body dimensions and vehicle geometry is included. Reed and Flannagan (2001) showed that variance in outcomes of interest (e.g., eye location and seat position) that is not associated with body dimensions and vehicle geometry must be included to obtain accurate assessments of population accommodation from figure model analyses. However, this requires a simulation method that allows this residual variance to be taken into account. Recently, Parkinson et al. (2005) introduced a new approach to driver packaging based on an advanced use of the figure-model approach in the context of an optimization framework. Using the example of truck cab packaging, drivers were sampled randomly from an anthropometric distribution. At each design evaluation, the drivers were postured in the vehicle using statistical posture prediction models. A random component was added to each predicted degree-of-freedom based on the findings from the driver-posture studies used to develop the posture-prediction models. The optimization framework was used to determine the optimal seat track locations under the influence of geometric constraints, including a short cab length and low roof height.

The present paper extends these methods to SAE Class-A vehicles (passenger cars and light trucks with design seat heights less than 405 mm) and compares the efficacy of the method to the boundary manikin approach for several vehicle design problems.

METHODS

PARAMETERIZING THE DRIVER PACKAGE Figure 1 shows the reference points and variables used to describe the driver package. All analyses were performed in two dimensions (side view). The steering wheel was described by a pivot location, range of telescope, and range of angle. The seat track adjustment range (H-point travel path) was defined by the location of the full-forward, full-down position relative to the accelerator heel point (AHP) and the horizontal and vertical adjustment ranges. The track was fixed at 6 degrees downward from horizontal, a typical value for passenger cars. The height of the floor and roof were defined with respect to the ground, and a roof thickness was assigned. Upward and downward vision restrictions were represented by three points: the upper daylight opening (DLO), the cowl point at the base of the windshield, and the hood point.

Among the dependent measures of interest were two vision angles calculated as shown in Figure 1. Upvision angle was calculated as the angle with respect to horizontal of the vector from the drivers eye location passing through the upper daylight opening point. Downvision angle was calculated using the vector through either the cowl point or hood point, whichever was most restrictive. Many other design variables and accommodation measures are important for packaging, but the set in Figure 1 represents the core of the driver packaging issues.

DRIVER POPULATION For the current analysis, the driver population was based on an analysis of data from a 1988 anthropometric survey of U.S. Army personnel (Gordon et al. 1989). The ANSUR data are widely used for anthropometric analyses because the data are publicly available and there are a large number measures in the data set. Table 1 lists the body dimensions of interest for the current study along with summary statistics. Drivers were represented by gender, stature (erect standing height), erect sitting height, and body mass index (BMI). BMI is calculated as the body mass in kilograms divided by the stature in meters, squared. The result is a measure of weight-for-stature that is less correlated with stature than is body weight.

A population of 500 men and 500 women was generated by sampling randomly from a multivariate normal distribution for each gender characterized by the means and standard deviations of stature, sitting height, and the natural log of BMI. BMI was transformed to achieve better representation by the normal-distribution approximation. To reduce correlation among the variables, the ratio of erect sitting height to stature was used in place of erect sitting height. Table 2 lists the covariance matrices for the male and female distributions.

Table 1: Means (standard deviations) of Anthropometric Variables for the Target Population.

	Males	Females
Stature (mm)	1755 (66.8)	1629 (63.6)
Erect Sitting Height (mm)	914 (35.6)	852 (34.9)
Erect Sitting Height / Stature	0.521 (0.0144)	0.523 (0.0147)
log(BMI)	3.23 (0.118)	3.14 (0.113)

BOUNDARY MANIKINS For comparison with the randomly-sampled population, a set of 14 male and 14 female boundary manikins was generated. A typical approach to using boundary manikins in anthropometric analyses follows these steps (HFES 300 Committee 2004):

1. identify anthropometric dimensions that are related to the accommodation measures of interest;
2. represent the anthropometric variance in these dimensions using a multivariate normal distribution;
3. construct an ellipsoid in this multi-dimensional space that encloses the same percentage of the anthropometric space as the target accommodation level for the design (e.g., 95 percent); and
4. sample individual cases (boundary manikins) from the surface of this ellipsoid, usually a minimum of two per anthropometric dimension (six or more for a three-dimensional anthropometric space).

The underlying assumption of the boundary manikin method is that accommodating individuals whose body dimensions collectively span a particular percentage of the anthropometric space will accommodate at least that percentage of actual users. Because the number of body dimensions of interest is often higher than three, principal component analysis (PCA) is often used to reduce the dimensionality, often to three components (cf. Bittner 2000). For the vehicle driver accommodation problem, people might choose leg length, buttock-popliteal length, functional arm reach, sitting height, seated eye height, and abdomen depth, among others. Manary et al. (1999) showed that most of the variance in anthropometric measures potentially related to driver accommodation were accounted for by just three variables: stature, sitting height, and body weight. Seidl (1994) identified three similar measures as accounting for most of the variance in anthropometric measures relevant to driver accommodation, substituting waist circumference for body weight.

Table 2: Covariance Matrices for Multinormal Approximations to Male and Female Anthropometric Distributions.

Males

	Stature	SH/S*	log(BMI)
Stature	4463	-0.3190	0.1008
SH/S	-0.3190	1266	0.00011
log(BMI)	0.1008	0.00011	0.0138

Females

	Stature	SH/S*	log(BMI)
Stature	4045	-0.2692	-0.4531
SH/S	-0.2692	0.00022	0.00010
log(BMI)	-0.4531	0.00010	0.0127

*ratio of erect sitting height to stature

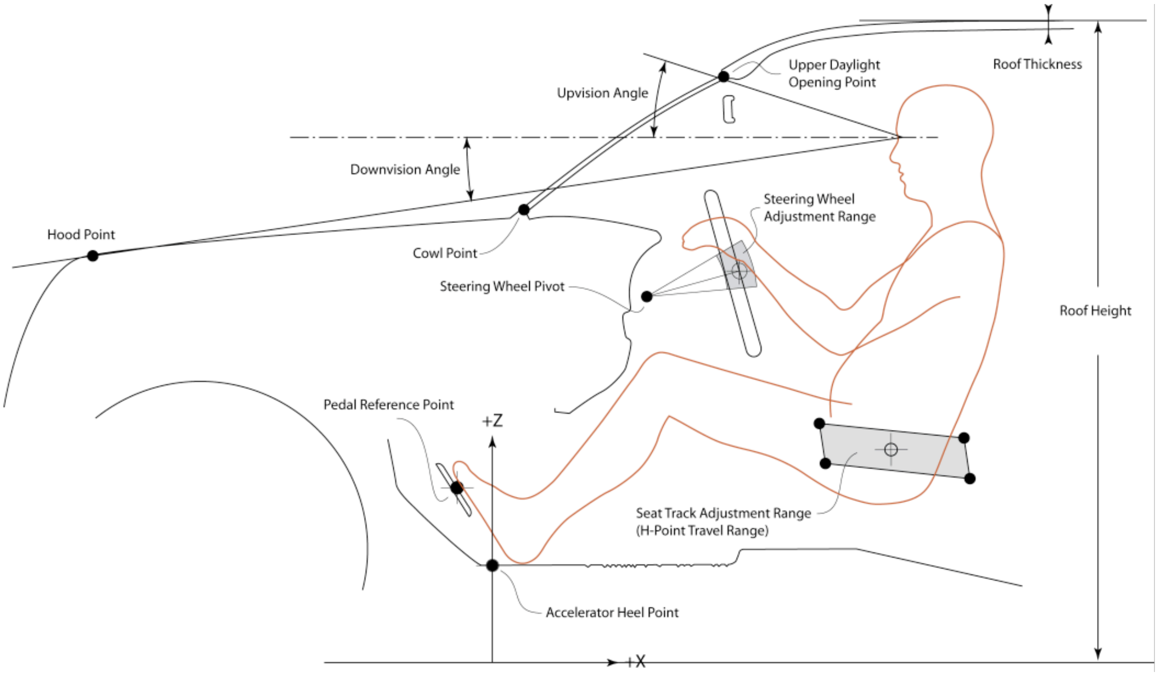

Figure 1: Dimensions and reference points used in package optimization.

For the current analysis, the knowledge of the posturing models allows a more accurate selection of boundary manikins than would ordinarily be possible. Specifically, the posture models depend only on stature, erect sitting height, and body mass index. Consequently, only these three measures were included in the selection of boundary cases. As noted above, two transformations were performed to simplify the process by reducing correlations among the variables. First, the ratio of erect sitting height to stature was substituted for erect sitting height. The log transform of BMI was also used to reduce correlation with stature and to achieve a better representation by the normal approximation.

For each gender, boundary manikins were selected to lie on the surface of an ellipsoid that enclosed 95 percent of the population, approximated by a multivariate normal distribution with the covariance matrices given in Table 2. If accommodation is determined on the boundaries of the anthropometric distribution, which is the case for the current analysis, then selecting cases in this manner is appropriate (HFES 300 Committee 2004). Boundary manikins were chosen at the extremes on each axis of the enclosing ellipse (six manikins) and at eight intermediate points between axes, as shown in Figure 2. Using this approach, fourteen manikins were generated for each gender. Table 3 lists their body dimensions.

For application of these boundary manikins to human figure models, calculation of all of the body segment dimensions would be required. These calculations are often performed using multivariate regression or through factor analysis (Bittner 2000). The current analysis required only one additional variable to be predicted, namely the height of the head above the eyes. This value was computed for each boundary manikin using a regression on erect sitting height in the data from ANSUR.

Table 3: Body Dimensions of the 28 Boundary Manikins.

Gender	Stature (mm)	SH* (mm)	SH/S**	log(BMI)	Mass (kg)	BMI (kg/m^2)
F	1766	866	0.490	3.049	65.8	21.1
F	1659	855	0.515	3.444	86.3	31.3
F	1738	951	0.547	3.147	70.3	23.3
F	1492	829	0.556	3.239	56.8	25.5
F	1599	849	0.531	2.844	43.9	17.2
F	1520	758	0.499	3.141	53.4	23.1
F	1469	782	0.533	3.024	44.4	20.6
F	1595	894	0.560	3.027	52.5	20.6
F	1505	787	0.523	3.370	65.8	29.1
F	1630	898	0.551	3.374	77.6	29.2
F	1628	806	0.495	2.914	48.8	18.4
F	1753	917	0.523	2.918	56.9	18.5
F	1663	808	0.486	3.261	72.1	26.1
F	1789	918	0.513	3.264	83.7	26.2
M	1904	928	0.487	3.187	87.8	24.2
M	1791	935	0.522	3.552	111.9	34.9
M	1649	821	0.498	3.273	71.7	26.4
M	1606	890	0.554	3.271	67.9	26.3
M	1719	893	0.519	2.906	54.0	18.3
M	1861	1012	0.544	3.185	83.8	24.2
M	1709	944	0.552	3.042	61.2	20.9
M	1587	834	0.526	3.092	55.4	22.0
M	1751	970	0.554	3.414	93.2	30.4
M	1628	859	0.528	3.465	84.8	32.0
M	1882	967	0.514	2.993	70.6	20.0
M	1759	857	0.487	3.044	64.9	21.0
M	1923	991	0.515	3.366	107.2	29.0
M	1801	881	0.489	3.416	98.7	30.5

*erect sitting height
**ratio of erect sitting height to stature

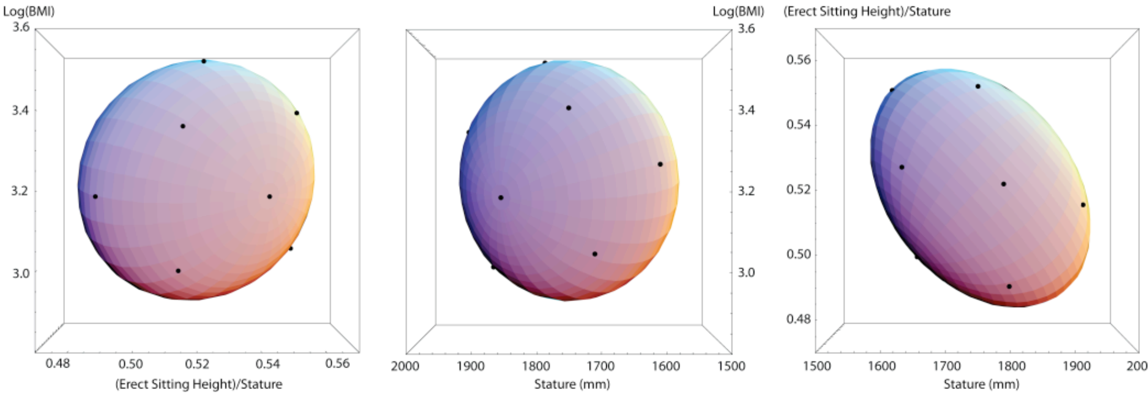

Figure 2: Schematic depiction of boundary manikin definition for men in three orthogonal views. The ellipsoid encloses 95% of the multivariate normal distribution for the three defining variables. Sampled boundary manikins (a total of 14) are shown as dots on the ellipsoid.

EXPERIMENTAL POPULATIONS Design analyses were conducted using three populations of simulated drivers. The population of 1000 drivers sampled randomly from the anthropometric distributions for each gender, and including random variance in posture-selection behavior, was termed RS (random sample). The group of 28 boundary manikins (with no associated random variance), was termed BM. To help to clarify the role of random postural variance in determining accommodation, a third population was defined by instantiating each of the 28 boundary manikins 10 times, each time with randomly sampled postural variance values. This population was termed BMR (boundary manikin—random).

POSTURING FUNCTIONS Each sampled driver was postured in the vehicle using the Cascade Prediction Model (CPM) described in Reed et al. (2002). The CPM is a cascaded series of regression models based on a statistical analysis of driver posture data in a wide range of vehicle configurations. The posturing process proceeded as follows: Based on the specified steering wheel pivot location, the mean expected preferred location for a driver with the specified anthropometry was calculated. The desired steering wheel position was censored (i.e., limited) to the available range of tilt and telescope. The resulting steering wheel location and body dimensions were used along with body dimensions to calculate the desired seat position (fore-aft and vertical). Seat position was also censored to the available range. Hip location was calculated as an offset from seat H-point, and eye location was calculated at a distance and angle relative to hip location. The prediction of each degree of freedom included an appropriate random variance component sampled from an independent normal distribution for each driver (Reed et al. 2002).

DEFAULT VEHICLE DESIGN The design scenarios were examined using a generic vehicle package as a starting point. Table 4 lists the parameter values. Refer to Figure 1 for definitions.

PACKAGE OPTIMIZATION APPROACH Figure 3 shows the general optimization method schematically. There are four primary components: vehicle definition, population definition, posturing model, and optimization.

For the current analysis, the horizontal and vertical location of the seat track (x and z) as well as its length and vertical adjustability (Δx and Δz) are the design variables, $\mathbf{x}$. Depending on the scenario, one of three driver populations is selected (BM, BMR, or RS). A preferred posture is determined for each of the manikins in the selected population, yielding a preferred seat location (x_{pref}, z_{pref}). If the seat can be adjusted to the desired location, the driver is said to have been *accommodated*. When the desired location is not within the available range of seat adjustment, the nearest feasible location, (x_{act}, z_{act}), is calculated and the spatial difference between the two locations is retained as a measure of *disaccommodation*. The disaccommodation for a single driver is then

$$d = \sqrt{(x_{pref} - x_{act})^2 + (z_{pref} - z_{act})^2}. \tag{1}$$

The total number of accommodated drivers, NA, for the selected population is obtained by summing the number of drivers for whom $d = 0$. The percentage of accommodated drivers, FA is given by the equation

$$FA = 100\frac{NA}{n}, \tag{2}$$

Table 4: Initial vehicle dimensions.

Dimension*	x (mm)	z (mm)
Accelerator Heel Point (AHP)	0	400
Steering Wheel Pivot re AHP	325	570
Telescope Range from Pivot	175	225
Steering Wheel Angle Range (deg)	10	40
Upper Daylight Opening	500	1400
Steering Wheel Diameter	355	-
Cowl Point	200	1150
Roof Height	-	1600
Roof Thickness	-	20

*Origin is ground plane at fore-aft location of AHP.

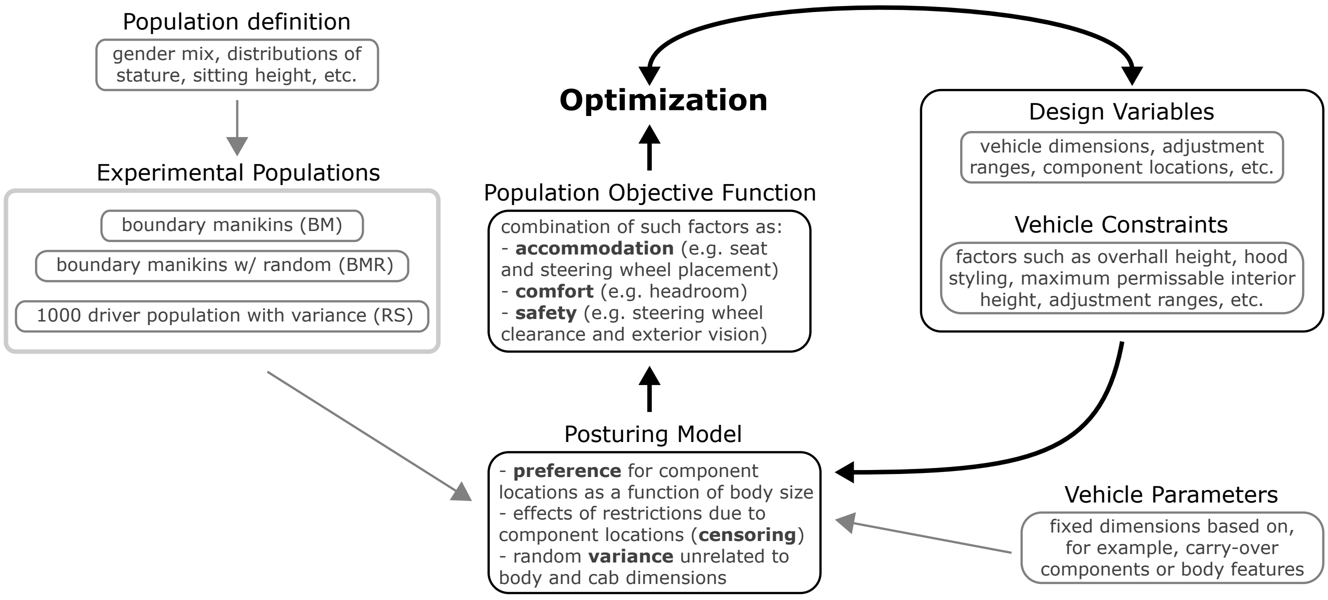

Figure 3: Schematic of package optimization process.

where n is the total number of drivers in the population ($n = 28$ for BM, $n = 280$ for BMR, and $n = 1000$ for RS).

In each of the design scenarios described in the next section, the problem formulation is population-appropriate. When the boundary manikin populations are used (the *a* and *b* formulations), each of manikins must be accommodated, so $FA = 1$ is a constraint in the optimization. A fractional accommodation of 95% ($FA \geq 0.95$), a typical design target, was chosen for scenarios involving the entire RS population (the *c* formulation).

The optimization algorithm selects values for the design variables (seat track location and adjustability) and the resulting package is scored using the product of the vertical and fore-aft adjustment ranges, which is approximately the side-view area of the adjustment range:

$$A = \Delta x \Delta z. \tag{3}$$

One measure of "cost" is the total amount of adjustability required to accommodate a desired fraction of drivers (e.g., 95% or $FA = 0.95$). At the expensive extreme is a vehicle with ample adjustability that accommodates every driver ($FA = 1$), no matter their size or behavioral preferences. In contrast, a vehicle with no adjustability might be inexpensive to produce but the fraction of accommodated drivers would be very low. The objective function for the current analysis was to minimize the value of A, i.e., the size of the seat track adjustment range, while maintaining accommodation for a specified fraction of drivers. The general optimization problem is

$$\begin{aligned} \text{minimize} \quad & f(\mathbf{x}) = A \\ \text{subject to} \quad & 500 \leq x \leq 1000 \\ & 150 \leq z \leq 350 \\ & 100 \leq \Delta x \leq 300 \\ & 1 \leq \Delta z \leq 100 \\ & \begin{cases} FA = 1 & \text{if BM;} \\ FA \geq 0.95 & \text{if RS.} \end{cases} \end{aligned} \tag{4}$$

The simple bounds on $\mathbf{x}$ were selected so that the design space encompassed by these values exceeds typical design space given the fixed vehicle geometry in Table 4 and described below. This ensured that no variable was at its limit when the algorithm converged to the optimum. A global optimization algorithm, DIRECT (Jones, 2001) was utilized for the examples, but the methodology is not algorithm-specific. The maximum number of evaluations, which is a required input to the DIRECT algorithm, was arbitrarily chosen to be 5000. Additional constraints were incorporated into the formulation as the scenarios described below required them.

DESIGN PROBLEMS The optimization formulation, Eq 4, was solved under conditions defined by four design problems. They were selected to show the utility of the approach and to assess the suitability of the boundary manikins to replace the much larger randomly sampled population for design assessments.

There are three steps in each scenario, *a*, *b*, and *c*. In *a* the problem is solved using the BM population and the typical boundary manikin approach—residual posture variance is not considered. The resulting design is then evaluated for accommodation using the other two populations, BMR and RS. Vertical disaccommodation is not penalized, in keeping with current SAE practice (see J4004, SAE 2005). In *b*, the same design is evaluated, but a vertical adjustment range of 40 mm is added. Vertical disaccommodation is considered, and the resulting accommodation for the BMR and RS populations is calculated. In *c* the optimization problem is solved again, but this time using the RS population. This gives an estimate of the true magnitude of adjustability required to accommodate 95% of the population under the specified conditions.

Scenario 1 Given a particular steering wheel position, find the adjustability requirements and location for the seat track such that 95% of the driver population can sit in their preferred location (not more than 5% are censored on seat position).

Scenario 2 In the previous scenario, drivers whose desired posture was censored even a small amount were considered disaccommodated. Permitting some small level of disaccommodation, for example 10 mm, might allow a cost-saving reduction in seat track adjustment range while having a minimum impact on the overall acceptability of the design. It also better reflects the sensitivity of a person to their seat position, since the “just noticeable difference” for seat position is approximately 10 mm. This scenario explores the adjustability requirements and location for the seat track such that 95% of the driver population can sit within 10 mm of their preferred location. The calculation of NA was adjusted accordingly.

Scenario 3 The first two scenarios included a telescoping steering wheel, which may reduce the required range of seat adjustment. Scenario 3 quantifies that effect of steering wheel telescope by repeating Scenario 1 with a non-telescoping wheel (tilt only).

Scenario 4 Upvision and downvision requirements are incorporated into the design. This design was completed in two steps. First, the optimization procedure was used to determined the location of the steering wheel pivot $\mathbf{SW}$ that maximizes average downvision, DV, while ensuring that either 100% (for BM population) or 95% (RS population) of drivers have at least 10 degrees of upvision. The problem was posed as:

$$\begin{aligned} \text{minimize} \quad & f(\mathbf{SW}) = 1/DV \\ \text{subject to} \quad & 100 \le SW_x \le 500 \\ & 400 \le SW_z \le 700 \\ & \begin{cases} FA = 1 & \text{if BM;} \\ FA \ge 0.95 & \text{if RS.} \end{cases} \end{aligned} \tag{5}$$

where FA was calculated using the upvision criteria rather than seat location.

Once the steering wheel location is determined, we returned to the protocol used on the previous example. Eq. 4 was solved to determine the smallest seat track that will achieve 95% accommodation on seat position, upvision, and maintaining the maximum average downvision angle obtained earlier.

RESULTS

The results for each of the scenarios and conditions are reported in Table 5 and shown visually in Figure 4.

SCENARIO 1: SEAT TRACK LOCATION AND ADJUSTABILITY LIMITS Using the initial steering wheel design, the minimum seat track adjustment range to accommodate all of the BM population was determined, using the fore-aft and vertical location of the seat track (x, z) and its horizontal and vertical adjustment ranges (Δz, Δz) as design variables. The results are listed in Table 5, Row 1a. The linear seat track (no vertical adjustment) for the BM population results because fore-aft and vertical seat position is predicted by linear functions that predict the most likely (mean expected) seat positions for people with the specified body dimensions (Reed et al. 2002). The BM population does not include the random variance in seat position that is not associated with the vehicle and anthropometric descriptors.

The accommodation of the BMR and RS driver populations were assessed in the design obtained with the BM population. Vertical disaccommodation was not considered, mirroring current SAE procedures, which predict only fore-aft accommodation (SAE 2005). Eighty-nine percent of BMR was accommodated within the specified fore-aft range, and 96.3 percent of RS. For this one-dimensional problem, accommodating the boundary manikins, which nominally represent 95 percent of the population, resulted in a slightly conservative design.

A better estimate of accommodation for BMR and RS can be calculated by including disaccommodation on vertical seat position. A typical vertical adjustment range for a passenger car is 40 mm. Centering a 40-mm adjustment band on the seat track length optimized for the BM population gives package 1b (Table 5, Row 1b) with an area of adjustability of 7880 mm^2. When both fore-aft and vertical accommodation are considered, the seat track developed with the BM population accommodates only 79 percent of BMR and 81.5 percent of RS. Recall that a BM analysis would indicate 95 percent accommodation in this design.

The seat location and adjustability required to achieve 95 percent accommodation of RS was obtained through another optimization run with the same four design variables: x, z, Δz, and Δz (scenario 1c). The resulting seat adjustment range is 207 mm long and 63 mm high, with a required adjustability area of 13000 mm^2. As expected from the univariate optimization results, the seat track is only slightly longer than that given by the optimization with the BM population, but now the needed range of vertical adjustment is taken into account.

SCENARIO 2: MARGIN OF ACCOMMODATION If 10 mm of seat-position disaccommodation is permitted,

Table 5: Optimization results.

Scenario		Boundary Manikin (BM)					Boundary Manikin with Random (BMR)		1000 Driver Population with Variance (RS)					
		x	z	Δx	Δz	FA	A	FA	x	z	Δx	Δz	A	FA
seat track	1a	708	270	197	1	100		89						96.3
seat track	1b	708	250	197	40	100	7880	79					7880	81.5
seat track	1c								703	240	206	63	13000	95.0
margin	2a	711	270	184	1	100		90						96.9
margin	2b	711	250	184	40	100	7360	89					7360	94.0
margin	2c								708	251	201	38	7640	95.0
non-tele wheel	3a	711	281	197	1	100		89						96.0
non-tele wheel	3b	711	261	197	40	100	7880	74					7880	77.2
non-tele wheel	3c								688	252	249	61	15200	95.0
vision	4a	765	200	198	1	100		60						70.9
vision	4b	765	180	198	40	100	7920	55					7920	62.2
vision	4c								716	171	299	85	25360	95.0

x Fore-aft location of the full-down, full-rear corner of the seat adjustment range.
z Vertical location of the full-down, full-rear corner of the seat adjustment range.
Δx Fore-aft length of seat adjustment range.
Δz Vertical height of seat adjustment range at each fore-aft position.
A Sideview area of seat adjustment range.
FA Fraction of population accommodated.

the required track length for BM decreases by 13 mm to 185 mm. Neglecting vertical disaccommodation and including the 10-mm margin, this track would accommodate 90 percent of BMR and 96.9 percent of RS. Adding 40 mm of vertical adjustment to this track length and position accommodates 89 percent of BMR and 94 percent of of RS, when vertical accommodation is considered. In the RS population, 806 drivers were able to sit in their preferred location and an additional 134 were within 10 mm of it. These results are in Table 5, Rows 2a and 2b.

Rerunning the optimization with RS produced a track 202 mm long and 38 mm high (Table 5, Row 2c) to accommodate 95 percent of the target population with less than 10 mm of seat-position censoring. Of the 950 drivers, 799 were in their desired seat location and 151 were within 10 mm of it. Comparing the results with scenario 1, permitting up to 10 mm of censoring allows 95 percent of drivers to be accommodated with a vertical seat track adjustment range that is about 60% of the height and 5 mm shorter for a total adjustment area reduction of 41% (Figure 4, Cells 1c and 2c).

SCENARIO 3: NON-TELESCOPING STEERING WHEEL The steering wheel was allowed to pivot (as in previous examples), but not telescope (previous examples had 50 mm of range). The same procedure for determining fractional accommodation was followed. The results are detailed Table 5, Row 3a.

Compared to Scenario 1, the adjustment range and horizontal location of the seat track are the same, but its vertical location is higher (Figure 4, Cells 1a and 3a). Accommodation levels are only slightly lower for *a* and *b* (Table 5, Row 3a and 3b). When optimized for the RS population, the required area, A is 17% larger, achieved through greater Δx (Figure 4, Cells 1c and 3c). In other words, inclusion of a steering wheel with a 50 mm telescope range allowed a 17% reduction in the size of the seat track required to achieve the same level of driver accommodation.

SCENARIO 4: INCORPORATING UPVISION AND DOWNVISION Using optimization to place the steering wheel pivot location, $\mathbf{SW}$, for *a* yielded $(391, 518)$. This location is rearward and downward of the original location. The maximum average downvision angle was 6.1 degrees. The 280 BMR drivers, postured without restriction on seat position, had maximum average downvision of 6.0 degrees. The 1000 RS drivers had maximum average downvision of 6.1 degrees. The 280 BMR drivers with 40 mm of vertical adjustability had maximum average downvision of 6.0 degrees.

Using the full RS and optimizing for them achieves accommodation in both seat position and upvision while slightly increasing maximum average downvision (to 6.9 degrees). This is achieved by moving the steering wheel forward 27 mm, expanding the size of the seat track, and moving it forward and down. To meet the 95% accommodation criteria, all the drivers disaccommodated on upvision must be accommodated on seat location. Consequently, the adjustment range is very large—effectively allowing all the drivers to sit where they would like (Figure 4, Cell 4c). Using a multiobjective approach and solving the optimization problems simultaneously might reduce the required size, depending on the relative weights given to disaccommodation on upvision and seat position.

A final analysis was performed that was similar to that in Scenario 2. The full RS was used for an optimization in which drivers within 10 mm of their preferred seat location were considered accommodated. This reduced the overall area of the adjustability range by 30%. The final design is shown in Table 6 and, to facilitate comparison with the previous scenarios, in Table 5, Rows 4a-4c.

DISCUSSION

This paper presents a new approach to driver accommodation modeling based on the application of optimization methods. The approach combines many of the advantages of the current percentile-accommodation models in SAE Recommended Practices with the flexibility of human-figure-model approaches. The two most innovative aspects of the new approach are (1) the formulation of the packaging problem as an optimization, and (2) the inclusion of the variance in posture and other outcome measures (e.g., subjective assessments) that is not related to vehicle factors or occupant descriptors. This variance is included in percentile accommodation models but is commonly ignored in figure-model analyses.

The driver population used in this study, described by military data from ANSUR, is not representative of the typical target population for a passenger car. However, the methods are independent of the choice of target population. Because of the large number of anthropometric measures that were included in the study, the ANSUR data are a good choice for algorithm development. For application of this method, an appropriate design population should be identified for each new vehicle, including a detailed anthropometric description and the target gender mix. Relatively small changes in gender mix can change the optimal package for a vehicle substantially.

Boundary manikin methods are widely used for figure model analyses in an attempt to capture anthropometric variance in the target population without performing analyses with hundreds of manikins. However, as the current analysis demonstrates, boundary manikins often do not provide results comparable to those obtained with large, representatively sampled populations. As computer power has improved, the rationale for using boundary manikins has eroded, because it is now feasible to perform most figure-model analyses programmatically. Using rapid, deterministic posture prediction approaches, such as the Cascade Prediction Model, thousands of drivers can be evaluated in a design in under a second of processing time on conventional desktop computers.

The boundary manikins used in this paper were sampled using an approach that improves on the methods typically used. In particular, the three anthropometric variables that were selected were already known to be those that influence the outcome measures. In most boundary manikin applications, body dimensions are included in the principal-component or factor analysis that affect only one or a few of the possible outcome measures. Hence, the current boundary manikin evaluation represents a best-case performance for the method; the results would often be worse, relatively to the large randomly sampled population, in typical usage. This is perhaps the most important conclusion from the boundary manikin evaluation: the main drawback of using boundary manikins is that the actual accommodation remains unquantified, and may be quite different from that expected by accommodating all of the boundary manikins. The addition of random postural variance to the boundary manikins improved their ability to represent the larger population. However, the problem of accurately estimating total population accommodation remains, because it is not clear how to cost the disaccommodation of one or two boundary manikins.

The current SAE tools remain the industry standard for packaging and provide well-validated results. The seating accommodation model in J4004 and the eyellipse in J941 have both been completely revised in the last five years and can be used effectively for most vehicles. However, these tools do not consider some important adjustment features in newer vehicles, such as adjustable pedals. They are also not well suited to quantitative tradeoff studies, in which, for example, the relative costs of adding adjustability to the seat and steering wheel are considered. By design, the current methods can reproduce the seat position and eye location distributions that underlie the J941 and J4004 models when the appropriate constraints are applied (i.e., fixed steering wheel position, no costing of vertical seat accommodation, and no postural effects of headroom or vision). However, the optimization formulation and the ability to experiment using a large number of virtual drivers makes the new approach much more flexible.

The new method has broad applicability to vehicle design problems. The central tenet of this approach is that variance in outcome measures, whether postural or subjective, should be partitioned among vehicle factors, occupant factors, and the residual not accounted for by the other two categories. The corresponding primary limitation of the method is that it can only be used when good estimates of variance in these three categories are available. Developing these estimates usually requires relatively large, carefully designed studies of occupant behavior and subjective response. The scope of work required to develop appropriate models often causes manufacturers to short-circuit the process by relying on heuristics and benchmarking, yet the cost of remedying errors that would have been prevented by well-developed models is often an order of magnitude greater than the cost of gathering the needed data.

Another strong advantage of the new approach is that the analysis tools are constructed in the context of an optimization framework. The process of repackaging a vehicle when constraints are changed often takes too long for packaging issues to be taken into account in dynamic

Table 6: Summary of RS results from upvision and downvision scenarios utilizing three approaches.

	SW_x (mm)	SW_z (mm)	x (mm)	z (mm)	Δx (mm)	Δz (mm)	A (mm^2)	DV degrees	FA %
traditional	391	518	765	200	199	not considered	n/a	6.1	70.9
traditional +40 mm	391	518	765	180	199	40	7920	6.1	62.2
strict accommodation	364	520	716	171	300	85	25360	6.9	95.0
marginal (10 mm) accommodation	364	520	727	180	280	64	18160	6.9	95.0

trade-off studies. Implementations of the SAE packaging models as macros in computer software has reduced these turnaround times, but missing from those systems is the ability to optimize the design in the face of multiple constraints and objectives. In any case, the optimization can only be performed when the appropriate cost functions, derived from human-subject studies, are available. The next steps in the development of this new methodology will be case studies that explore the range of potential applications, incorporating factors such as crash safety and financial cost, and the conduct of new experiments to increase the number of subjective cost functions that are available.

ACKNOWLEDGMENTS

The driver-posture research incorporated into this new packaging methodology was conducted over the past 15 years at the University of Michigan Transportation Research Institute with sponsorship from many companies and organizations, including the Motor Vehicle Manufacturers Association, the Association of Automobile Manufacturers, the Alliance of Automobile Manufacturers, BMW, Chrysler, Ford, General Motors, Johnson Controls, Lear Corporation, Mazda, Peugeot-Citroen, and Toyota. The initial investigation of a driver posture implementation in an optimization framework was supported by the Automotive Research Center at the University of Michigan. Subsequent work has also been supported by The Pennsylvania State University.

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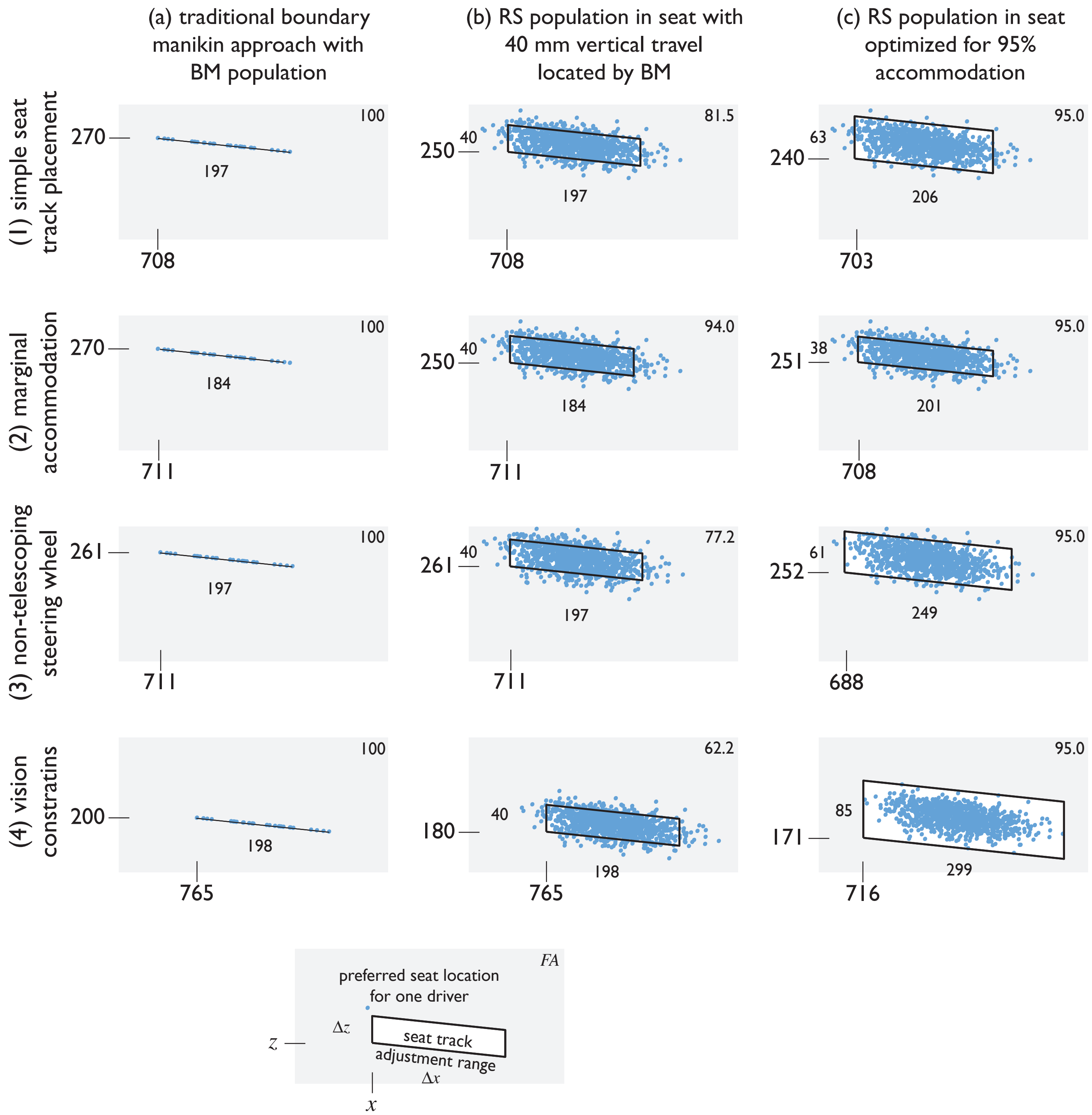

Figure 4: Seat track location and adjustment range results from the four scenarios.