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DEVELOPMENT OF A NEW EYELLIPSE AND SEATING ACCOMMODATION MODEL FOR TRUCKS AND BUSES

Matthew P. Reed

University of Michigan
Transportation Research Institute

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The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109-2150
U.S.A.

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16. Abstract

Driver posture data from a laboratory study and an in-vehicle test-track study were used to develop and to evaluate a new seating accommodation model and eyellipse for SAE Class-B vehicles. The new statistical models are configurable for population anthropometry; include the effects of steering wheel position; incorporate a new method based on driver preference for using the adjustment range of highly adjustable steering wheels as input to the models; and are customizable to any desired accommodation level. The new seating accommodation model predicts ranges of fore-aft seat-position that are similar to those in SAE J1517, but includes simultaneous prediction of vertical seat adjustment range. The new eyellipse is almost twice as tall as the current J941 Class-B eyellipse, due to the incorporation of vertical seat adjustment. The new eyellipse is narrower in plan view and aligned with the vehicle grid, unlike the J941 eyellipse. Predictions from the new model compared well with driver seat positions and eye locations measured in six test vehicles, although extensive seat-position censoring in four of the test vehicles limited the comparison. The new models are more accurate and much more flexible for application to modern trucks and buses with vertically adjustable seats and tilt/telescope steering columns.

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CONTENTS

1.0 INTRODUCTION

1.1 Occupant Packaging

Occupant packaging refers to the process of laying out a vehicle interior to provide good accommodation, comfort, and safety for the driver and passengers. The primary design variables in packaging the driver's workstation are the locations and sizes of the adjustment ranges for the steering wheel and seat with respect to the accelerator pedal. The positions of these adjustment ranges are selected to provide good exterior vision, clearance to interior components, and comfort for the drivers. The choice of compatible ranges of steering wheel and seat adjustment is critical, because restricting drivers' ability to posture themselves as they would prefer can lead to discomfort and may decrease safety. Increasing the size of adjustment ranges entails additional cost, so providing small, accurately located adjustment ranges is preferred to providing large adjustment ranges.

The history of driver packaging in the U.S. over the past 50 years spans three major innovations in design tools. The template-based approaches developed in the 1950s were superseded over the following decades by population accommodation models. During the 1990s, digital human modeling was developed as a complement to percentile accommodation models, and even replaced the earlier percentile accommodation models in some companies.

1.2 Template Approaches

The application of engineering anthropometry to vehicle layout began in the 1950s, including pioneering work by Wilfred Dempster (Dempster 1955). Two-dimensional templates that were scaled to accurately represent percentiles of human body dimensions were laid on paper package drawings to represent the spatial requirements of large men. This approach was codified in SAE Recommended Practices[1] in 1962 with the adoption of SAE J826, which defined a weighted, three-dimensional manikin for measuring seats and legroom (the SAE H-point machine) and a two-dimensional template with a similar profile and leg segment lengths. The SAE J826 H-point machine remains the standard tool for defining seat H-point (a reference point approximating human hip location) and

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[1] The SAE practices, identified by J*xxxx* numbers, can be found in the SAE Handbook, which is published in hardcopy and electronically every year (SAE 2005).

for measuring seat back angle. Recently, a new H-point machine (HPM-II) was adopted in SAE J4002 and is being applied in some companies, particularly for seat design. Although the original H-point machine was originally conceived as a "comfort dimensioning tool" to ensure adequate legroom in vehicles, better methods have been developed for determining the appropriate range of seat positions to accommodate a population of drivers.

1.3 Population Accommodation Models

The second major innovation in driver packaging was the *eyellipse* (the word is a contraction of *eye* and *ellipse*). In the early 1960s, General Motors, Ford, and Chrysler collaborated on a large-scale study of driver eye locations. The researchers performing the study were motivated by the observation that template-based approaches, with eye location estimates scaled solely by body dimensions, did not adequately account for the observed variability in eye locations. The eye locations of over 2300 men and women were recorded by stereophotogrammetry as they sat in three convertibles (Meldrum 1965). The researchers noted that the resulting distribution of eye locations was approximately normal (Gaussian) in three dimensions. They represented this distribution for vehicle design purposes by a single ellipse in side view and two ellipses (representing the distributions of the left and right eyes) in plan view. To take into account vehicle dimensions, the eyellipse was located within vehicle package space by reference to the height of the seat above the floor and the available seat track length. Subsequent studies added the effect of fixed seat back angle to the locator equation.

During the early 1970s, SAE and its member companies conducted a large-scale research study of driver reach. Again, experience in the auto companies had shown that template-based approaches did not accurately predict the percentage of drivers who could reach a particular location within the vehicle. In the SAE Controls Reach Study (Hammond and Roe, 1972) a sample of drivers demonstrated their maximum reach capability in two different belt restraint conditions. The data were used to create a statistical model predicting selected percentiles of driver reach capability at a mesh of locations in front of the driver. This model, now in SAE J287, combines the effects of driver population, package variables, and individual reach capability.

During the 1980s, another SAE-sponsored study of truck driver posture led to the development of population accommodation models for heavy trucks (Phillipart et al. 1985, Stanick et al. 1987). Applying the same conceptual methodology used for the development of the passenger car eyellipse and reach models, SAE committees developed an eyellipse (J941), accommodation tool locating procedures (J1516), seating accommodation curves (J1517), and head and hair contours (J1052) for application to SAE Class-B vehicles (i.e., vehicles with design seat height, SAE H30, greater than 405 mm). In addition, the committees developed two practices exclusively for application to truck packages: driver shin/knee contours (SAE J1521), and truck-driver belly contours (J5122).

The SAE study that produced the data used to generate these models was large-scale, well-conducted study. Sanders and Shaw (1985) used stereophotogrammetry to measure the postures of 183 male and 58 female truck drivers as they sat in a reconfigurable cab mockup. Test conditions included a wide range of steering wheel positions and seat heights. Data were gathered with both fixed and vertically adjustable seats. Unfortunately, the data were not analyzed and presented in a way that would be useful for current vehicles. In particular, only the data for fixed-height seats were used to create the models, the models are not configurable for changes in driver anthropometry, and the important effects of steering wheel position with respect to the pedals were neglected. During the late 1990s, UMTRI made an unsuccessful effort to recover the data from this study for reanalysis, including contacting people at SAE, at the companies involved, and researchers involved in the study. The data have apparently been lost.

Since about 1990, digital human figure models such as Jack and RAMSIS (Seidl 1997) have been increasingly used for packaging and ergonomic analysis during vehicle interior design. The trend has been particularly important in truck and bus development, because the widespread use of height-adjustable seats in these vehicles and anthropometric trends in driver populations have made the SAE tools largely inapplicable. Figure model analyses are valuable for many aspects of vehicle interior design, but population models are needed for making accurate quantitative assessments of accommodation and vision (Reed and Flannagan 2000).

For the past decade, UMTRI researchers have been developing updated versions of the SAE vehicle packaging tools for passenger cars and light trucks (SAE Class-A vehicles). Using driver-posture data from extensive studies in vehicles and in laboratory mockups, the research has led to a new H-point machine (J4002), a new seating accommodation model (J4004), a new eyellipse (J941) and a new head-position contour (J1052) (Flannagan et al. 1998, Manary et al. 1998, Reed et al. 1999a). In related work, new statistical models to predict driving posture were developed (Reed et al. 2002).

Beginning in the late 1990s, the measurement and analysis methods used to develop these new tools for passenger cars were applied to trucks and buses. A laboratory study of 63 drivers in a truck cab mockup was conducted along with an in-vehicle study of 24 truck drivers in six trucks. The data were analyzed to develop posture prediction models that are used with the Jack human figure modeling software.

This report presents the development of new seat-position and eyellipse models based on the data from these two studies. The new models are intended for use in modern trucks and buses with highly adjustable seats and steering wheels. Using methods similar to those used to develop the recent revision of the J941 Class-A eyellipse, the new models respond to the vehicle features that most influence driver posture and position and allow the user to define the driver population with respect to body dimensions and gender mix.

2.0 METHODS

2.1 Background on Seating Accommodation and Eyellipse Models

The objective of a seating accommodation model, such as the Class-B model in J1517, is to predict the distribution of driver-selected seat positions represented by translated H-point location. The H-point location with respect to the seat is defined with the seat in the "design" position, such that the H-point is coincident with the seating reference point (SgRP). The seat position selected by the driver is quantified by applying the fore-aft and vertical translation of the seat from the design position.

The appropriate selection of the size and location of the H-point travel path is a critical part of driver packaging. As the analyses in this report show, trucks are often designed with inappropriate adjustment ranges that result in a large percentage of drivers being unable to place the seat in their preferred positions. These findings highlight the need for a new seating accommodation model, since these vehicles were likely designed using either 1987 J1517 model or digital human figure models. Unlike previous seating accommodation models, the model presented in this report is designed for seats with both fore-aft and vertical adjustment, which covers the majority of trucks and buses now built in the U.S.

The eyellipse is a graphical depiction of a multivariate normal distribution used to approximate the distribution of driver eye locations. A critical innovation in the development of the eyellipse was the representation of this distribution using an ellipse chosen to have a specified "cutoff" characteristic. Rather than constructing an ellipse that enclosed 95% (or some other percentage) of the distribution, the ellipse was constructed such that a tangent to the "95% eyellipse" divided the eye location distribution into 95% and 5% fractions ("cutting off" 95% of drivers' eye locations. The utility of this approach for vision analyses is illustrated in Figure 1. To assess the 95th percentile of driver upward vision (upvision) angles through the windshield, a tangent to the 95% cutoff eyellipse is constructed through the lowest point of interference. Because 95% of drivers' eyes lie below the tangent line, the angle of the tangent line with respect to vertical represents the 95th-percentile upvision angle.

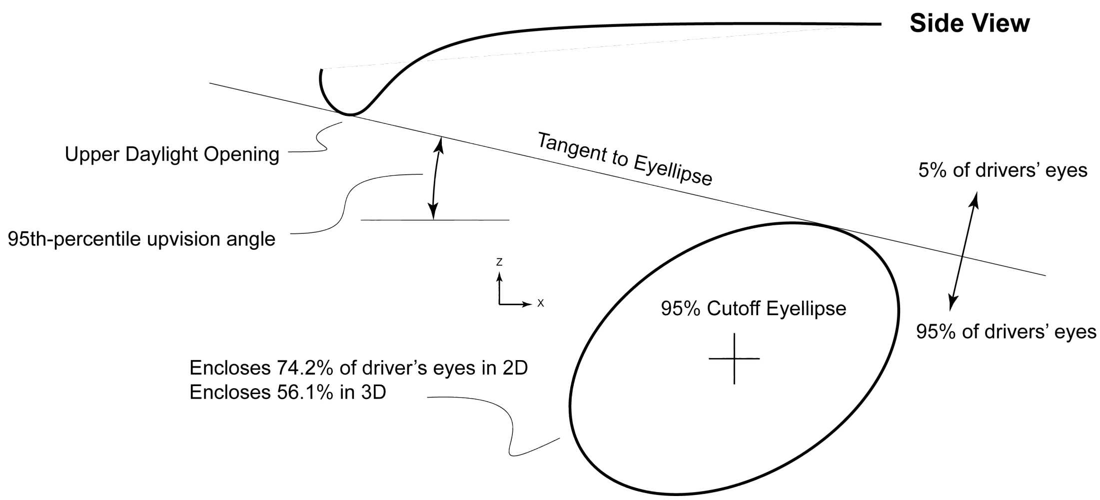

Figure 1. Illustration of side-view eyellipse with 95% cutoff characteristic.

2.2 Data Sources

The data used in this report were gathered in two studies of driving postures. Data from a study of 63 drivers in a laboratory mockup were used to develop the models. The models were tuned and validated by comparison to data from 24 drivers in six trucks driven on a test track.

Laboratory Study

In the first study, the postures of 49 men and 14 women were measured in a laboratory mockup in 27 different test conditions. Among the men, 32 were experienced truck drivers, 4 were bus drivers, and 13 had no truck- or bus-driving experience. Among the women, 3 were experienced truck drivers, 3 were bus drivers, and 8 had no truck- or bus-driving experience. Overall, 42 of the 63 participants had experience driving a truck or bus. Driver stature ranged from 1478 to 1919 mm, with a mean of 1724 mm. Body weight ranged from 105 to 274 lb. Mean body mass index was 28 kg/m^2, with a range from 17 to 38 kg/m^2.

The test conditions included manipulations of seat height, steering wheel height, steering wheel diameter, fore-aft steering wheel position, and clutch stroke. Previous analyses of these data for purposes of developing posture-prediction models showed that the effects of steering wheel diameter and clutch stroke could be neglected. For the development of the new models, data from the test conditions listed in Table 1 were analyzed. The nine conditions comprise a 3 x 3 orthogonal matrix of steering wheel fore-aft and vertical locations, as shown in Table 2.

Group A conditions lie at the corners and the center of the 3 x 3 matrix. The four midpoints on each side of the square matrix were included in Group B. All participants were tested in condition group A, and a subset of 25 subjects distributed throughout the stature range were tested in condition group B.

Table 1
Laboratory Test Conditions

Condition	Condition Group	Steering Wheel X re AHP (SAE L11)		Steering Wheel Z re Floor (SAE H17)	
		Level	mm	Level	mm
1	A	Low	93	Low	735
2	A	High	243	Low	735
3	A	Mid	168	Mid	810
4	A	Low	93	High	885
5	A	High	243	High	885
6	B	Mid	168	Low	735
7	B	Low	93	Mid	810
8	B	High	243	Mid	810
9	B	Mid	168	High	885

Table 2
Laboratory Test Conditions as Matrix

		Steering Wheel Fore-aft Position (SAE L11, mm)		
	Condition Number	93	168	243
Steering Wheel Height (SAE H17, mm)	885	4	8	5
	810	7	3	9
	735	1	6	2

For each trial, the steering wheel was set to the specified location with respect to the accelerator heel point, the steering wheel was set to a neutral angle, the seat was set to a midrange position, and the seat back angle was set to a neutral angle. The participant entered the mockup and adjusted the seat fore-aft position, seat height, seat back angle, and steering wheel angle to achieve a comfortable driving posture. The posture was then digitized, using procedures developed at UMTRI for measuring driver posture (Reed et al. 1999a, Reed et al. 20000). The locations of landmarks on the seat were used to calculate the translated seat H-point location, referencing H-point calibration data obtained with the SAE J826-1995 manikin. Cyclopean eye location was estimated using the vertical location of the corner of the eye, the fore-aft location of the infraorbitale landmark, and the lateral location of the glabella landmark. The translated H-point ("seat position") and eye location data were referenced to the accelerator heel point (AHP) in all conditions.

In-Vehicle Study

An in-vehicle driver-posture study was conducted at a truck manufacturer's research facility. Details of the methods are reported in Jahns et al. (2001). The ranges of seat and steering wheel adjustment were measured in each vehicle using a FARO Arm digitizer. The H-point location with respect to seat landmarks was quantified using the SAE J826-1995 H-point machine. Testing was conducted in the six vehicles listed in Table 3. Class-8 tractors from four manufacturers with wide ranges of seat and steering wheel adjustment were tested. An International 4700 Class-6 straight truck and a Class-5 DAF 45 were included. The International 4700 was tested without steering wheel adjustment, and the DAF-45 was tested without seat height or steering wheel adjustment. Table 4 lists package data for the six trucks.

Testing was conducted with 17 men and 7 women (24 total), all holders of commercial driver licenses. Fourteen of the participants were current or former professional drivers, seven were students in training to become truck drivers, and three were engineers who had undergone basic driver training. Drivers with a wide range of stature and weight were chosen. Stature ranged from 1546 mm to 1924 mm, with an average of 1758 mm. Body weight ranged from 120 to 358 lb. Body mass index ranged from 21 to 50 kg/m^2, and half of the participants were obese (BMI ≥ 30 kg/m^2).

Table 3
Test Vehicles and Adjustable Components

	Seat					Steering Wheel	
Truck Model	Fore-aft	Height	Recline	Cushion Angle	Cushion Length	Tilt	Telescope
Peterbilt 379 (Class 8)	x	x	x	x	x	x	x
International Eagle (Class 8)	x	x	x	x	x	x	x
Freightliner Century (Class 8)	x	x	x	x	x	x	x
Volvo VN (Class 8)	x	x	x	x	x	x	x
International 4700 (Class 6)	x	x	x				
DAF 45 (Class 5)	x		x				

Table 4
Package Data for Test Vehicles*

Truck Model	Steering Wheel Fore-aft Position re AHP (SAE L11, mm)	Steering Wheel Vertical Position re AHP (SAE H17, mm)
Peterbilt 379 (Class 8)	220	857
International Eagle (Class 8)	165	843
Freightliner Century (Class 8)	172	799
Volvo VN (Class 8)	195	807
International 4700 (Class 6)	260	799
DAF 45 (Class 5)	201	765

* Steering wheel position defined at the side-view geometric center of tilt/telescope travel path of the steering wheel center point. DAF 45 and International 4700 were tested with fixed steering wheel positions (see Figure 8).

The participants drove the six trucks in random order around a test track using both a high-speed oval and a durability road course. After instruction regarding the seat and steering wheel adjustments, the driver was given 5 to 10 minutes to become familiar with all of the controls. The driver set all of the components to preferred positions and drove the vehicle out onto the test track. The total amount of time driving a single vehicle was usually less than 15 minutes, with two laps of the high-speed track and two laps of the durability track being typical. If the driver needed more time to make seat and wheel adjustments, additional laps of the track were taken.

The high-speed track consists of a 1.6-mile oval with two 15-ft lanes and 800-ft-radius curves. The curves are banked at 12% and 29% for equivalent "hands off the wheel" straight line driving at 35 and 60 mph respectively. On this portion of the track drivers remained on the inside lane at 35 mph. The durability track consists of a 1.5-mile loop inside the high-speed oval. The lane used for this test contained no durability events (i.e. chuck-holes, chevrons, broken concrete, etc.). The lane is about 12 feet wide and there are a series of gentle right and left corners on the course, as well as full 90-degree corners to get onto, and off of the track. The durability track was traveled at a speed of 25 to 30 mph. Using both tracks allowed the drivers several opportunities to brake and shift, as well as manipulate the steering wheel in a manner representative of normal street driving.

At the end of the drive, the participant drove the vehicle into a shop facility bay, where the FARO Arm was used to digitize various body, seat, and vehicle landmarks to define the driving posture and position. Seat position and eye location were calculated from the landmark data in the same manner as with the laboratory data.

2.3 Statistical Modeling Approach

The data analysis and model development in this report is based on linear regression analysis and exploits some of the statistical characteristics of linear regression. In general, a dimension of interest, such as fore-aft eye location, is expressed as a linear function of potential predictors, such as steering wheel position and driver stature. The models have the form

$$y = c_0 + c_1 x_1 + c_2 x_2 + \ldots + e(0, s^2) \qquad [1]$$

where y is the dependent measure to be predicted, the c_i are constant coefficients obtained by fitting to the data, the x_i are the predictors (vehicle and driver body dimensions). The final "error" term $e(0, s^2)$ is a random, normally distributed variable with zero mean and variance s^2, where s is the root mean square error (RMSE) of the regression. In computational terms, the RMSE is the standard deviation of the data vector that is obtained by subtracting the regression prediction from each data observation. This residual variance is a crucial part of the modeling in this report.

Figure 2 shows a linear regression for fore-aft seat position, using (for purposes of illustration) stature as a single predictor. The residual variance, quantified by the mean square error, is modeled as normal distribution centered on the predicted value. Under the assumptions of linear regression, the residual variance is independent of the predictors. The analysis of the driver posture data shows that this assumption is well supported for these models. As an example of the interpretation of the constant-variance assumption, the standard deviation of fore-aft eye location for men who are 1700 mm tall is the same as the standard deviation of fore-aft eye location for men who are 1800 mm tall.

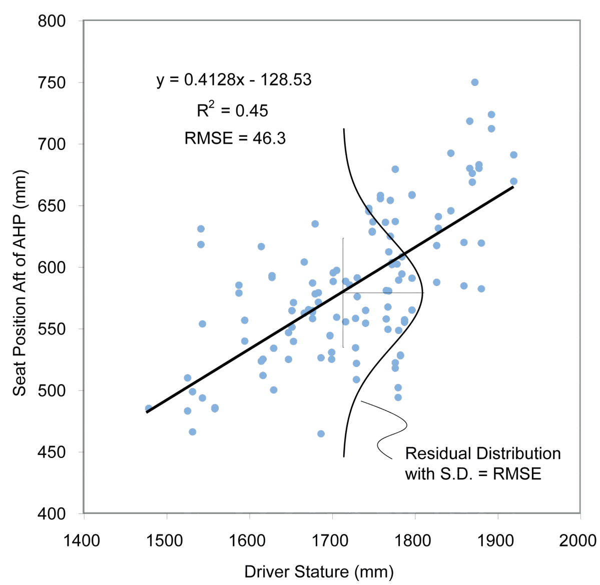

Figure 2. Plot of stature vs. fore-aft seat position for one test condition in the laboratory to illustrate regression analysis principles.

The model development procedure in this report exploits an important feature of normal distributions, which is that the mean and standard deviation of a linear function of a normal distribution is also a normal distribution. Specifically, if

$$Y = c_0 + c_1 X \qquad [2]$$

where c_0 and c_1 are constants and X is a normal distribution with mean X_{Mean} and standard deviation s_X, then Y is also a normal distribution, with mean

$$Y_{\text{Mean}} = c_0 + c_1 X_{\text{Mean}} \qquad [3]$$

and variance (standard deviation squared) of

$$s_Y^2 = (c_1 s_X)^2 \qquad [4]$$

The sum of two normal distributions is also a normal distribution, with variance equal to the sum of the variances. So, the residual variance from a regression can be included in estimating the distribution of the dependent measures. For example, consider

$$HPtX = c_0 + c_1\, Stature + e(0, s^2) \qquad [5]$$

where $HPtX$ is fore-aft seat position, c_0 and c_1 are constant coefficients from the regression analysis, and s is the root mean square error from the regression. If stature is modeled as a normally distributed random variable, this becomes the sum of two normally distributed random variables. Hence, for this example, $HPtX$ is modeled as a normal distribution with mean

$$HPtX_{\text{Mean}} = c_0 + c_1\, Stature_{\text{Mean}} \qquad [6]$$

and variance

$$s_{\text{Stature}}^2 = (c_1 s_{\text{Stature}})^2 \qquad [7]$$

This formulation is particularly valuable for modeling driver posture because the relevant human descriptors, such as stature and body mass index, are normally distributed within gender or can be transformed to be. If the predictors are correlated, then the calculation of the variance of the independent is slightly different. For the equation

$$Y = c_1 X_1 + c_2 X_2 \quad [8]$$

where X_1 and X_2 are normally distributed random variables with variances s_1^2 and s_2^2 and correlation $r_{1,2}$, the variance of Y is given by

$$s_Y^2 = (c_1 s_1)^2 + (c_2 s_2)^2 + 2 r_{1,2} s_1 s_2 \quad [9]$$

For a difference between two normal random variables

$$Y = c_1 X_1 - c_2 X_2 \quad [10]$$

the covariance ($r_{1,2} s_1 s_2$) is subtracted:

$$s_Y^2 = (c_1 s_1)^2 + (c_2 s_2)^2 - 2 r_{1,2} s_1 s_2 \quad [11]$$

A bivariate normal distribution is represented by a mean vector $\{X_{1,\text{ Mean}} , X_{2,\text{ Mean}}\}$ and a covariance matrix

$$V = \begin{bmatrix} s_{X_1}^2 & r_{1,2} s_1 s_2 \\ r_{1,2} s_1 s_2 & s_{X_2}^2 \end{bmatrix} \quad [12]$$

The first eigenvector of the covariance matrix, which is equivalent to the first principal component of the data, is the direction along which the data have the greatest variance. These calculations are used to determine the appropriate orientation for the eyellipse.

3.0 RESULTS

3.1 Linear Regression Models

Table 5 lists the primary dependent measures of interest. Seat position, quantified as the H-point location translated with the seat, was expressed with respect to accelerator heel point (AHP). Driver eye location was expressed relative to seat H-point, rather than AHP. This allows factors that affect seat position to be reflected in the location of the eyellipse and ensures that the predictions from the two models will be consistent.

Table 6 lists the results of linear regressions predicting the dependent measures from steering wheel position and driver descriptors. The analyses leading to the development of these regression models showed:

- no significant nonlinearities in the effects of steering wheel position or body dimensions;
- approximately normally distributed residual variance;
- consistent residual variance across levels of the predictors (homoscedasticity);
- no important interactions among predictors;
- no significant differences between men and women after accounting for body dimensions; and
- no significant differences between people with and without professional driving experience, after accounting for body dimensions.

The regression models were developed by an iterative process using stepwise regression as a means of discovering the most important predictors. Candidate predictors for each variable were fore-aft and vertical steering wheel position (SAE L11 and H17) and five driver descriptors: stature, erect sitting height, the ratio of sitting height to stature, stature minus sitting height (a measure of leg length), and the natural log of BMI. The log transform of BMI was used to obtain a measure that was approximately normally distributed. Because of correlations among the driver descriptors, particularly those related to stature and sitting height, a variety of alternative models with similar levels of fit to the data could be obtained. The goal was to achieve a parsimonious model for each dependent measure that used the minimum number of predictors required to achieve an R^2_{adj} value within 0.02 of the maximum value achievable. Consideration was also given to the needs of users to configure the models for different driver populations. In particular, measures of both stature and torso length were desired whenever there was evidence of independent effects of these body dimensions.

The regressions results in Table 6 show that fore-aft H-point and eye locations are affected by the fore-aft steering wheel position. The driver's effective leg length (stature minus sitting height) and body mass index also affect the fore-aft seat position. Increases in body mass index result in further-rearward seat positions. Previous analyses of these data for posture prediction have shown that the fore-aft hip locations with respect to AHP are similar for individuals with high BMI, but the fore-aft offset between the driver's hips and the seat H-point is larger. Driver-selected seat height is predicted solely by the vertical position of the steering wheel. Several anthropometric measures had significant effects on H-point height, but the net increase in R^2_{adj} was less than 0.02 when adding body dimensions to the equation.

The fore-aft eye location with respect to the seat H-point was significantly related to fore-aft steering wheel position, with larger values of L11 producing slightly more rearward eye locations (more-reclined postures, effectively). Drivers with a larger ratio of sitting height to stature also sat more reclined. The BMI effect approximately offsets the effect of BMI on moving the seat rearward relative to the sitter's hips. These effects are important to include when driver populations include a substantial portion of obese individuals.

The fore-aft eye location with respect to H-point is shifted forward by 28 mm to account for a difference in driver torso recline between the laboratory and in-vehicle studies. On average, drivers in the vehicles sat 2.5 degrees more upright (as measured on the side-view hip-to-eye vector) than in the laboratory, after accounting for body dimensions and vehicle geometry effects. Applying the 2.5-degree correction to the average eye height in the laboratory study yielded a 28-mm forward adjustment.

Table 5
Definition of Dependent Measures and Predictors

Variable	Intercept
HPtXAHP	Fore-aft location of translated seat H-point aft of Accelerator Heel Point
HPtZAHP	Vertical location of translated seat H-point above Accelerator Heel Point
EyeXHPt	Fore-aft location of cyclopean eye* with respect to translated seat H-point
EyeZHPt	Vertical location of cyclopean eye with respect to translated seat H-point
L11	Fore-aft location of center of steering wheel with respect to AHP (see J1100)
H17	Vertical location of center of steering wheel with respect to AHP (see J1100)
S	Stature (erect standing height without shoes)
SH	Erect sitting height
SH/S	Ratio of erect sitting height to stature
SSH	Stature minus erect sitting height
Log(BMI)	Natural log (log to the base *e*) of body mass index (BMI). BMI is defined as body mass in kg divided by stature in meters squared.

* Cyclopean eye was estimated at the vertical location of the corner-eye landmark, fore-aft location of infraorbitale, and lateral location of glabella.

Table 6
Results of Regression Analysis†

Dependent Measure	Intercept	L11	H17	SH	SH/S	SSH	Log(BMI)	R^2_{adj}	RMSE
HPtXAHP	-53.6	0.6081	-0.3343			0.6394	89.07	0.73	37.7
HPtZAHP	-200.3		0.8545					0.85	22.9
EyeXHPt*	-334.0	0.0809			1142		-87.98	0.30	41.0
EyeZHPt	-47.3			0.7812				0.71	22.3

† Form a linear equation by multiplying the tabulated coefficients by the input variables (mm and $\ln(kg/m^2)$) and adding the intercept. Dependent measures are in mm. Independent variables are defined in Table 5.
* Includes a -28 mm torso recline adjustment (see text).

Rewriting the values from table 6 as equations,

$$HPtXAHP = -53.6 + 0.6081\ L11 - 0.3343\ H17 + 0.6394\ SSH + 89.07\ Log(BMI) \quad [13]$$

$$HPtZAHP = -200.3 + 0.8545\ H17 \quad [14]$$

$$EyeXHPt = -334.0 + 0.0809\ L11 + 1142\ SH/S - 87.98\ Log(BMI) \quad [15]$$

$$EyeZHPt = -47.3 + 0.7812\ SH \quad [16]$$

3.2 Seat Position Model

Development of the Model

The objective of the seat position model is to predict the distribution of driver-selected seat positions (translated H-point locations) in the absence of restriction due to insufficient seat track adjustment range. The target application for this model is the design of seat tracks that accommodate a large percentage of drivers' preferred seat positions.

An important finding from the regression modeling was that the residuals from the regression functions predicting fore-aft and vertical seat position were uncorrelated. This means that the accommodation on the fore-aft axis can be assessed independent of the vertical accommodation.

Because vertical seat position is a function only of steering wheel height (H17), the vertical distribution of drivers' preferred seat positions is modeled for all vehicles as a normal distribution with the mean

$$HPtZ_{mean}\,(mm) = -200.3 + 0.8545\,H17 \qquad [17]$$

and standard deviation

$$s_{\mathrm{HPtZ}} = 22.9 \text{ mm} \qquad [18]$$

following the regression results in Table 6. Using the normal approximation, a seat track height required to accommodate 95% of drivers on vertical position would be at least

$$2\,(22.9)\,\Phi^{-1}(0.975) = 90 \text{ mm} \qquad [19]$$

where $\Phi^{-1}(q)$ is the inverse cumulative standard normal distribution. For example,

$$\Phi^{-1}(0.975) = 1.96 \qquad [20]$$

$\Phi^{-1}(q)$ can be obtained in Microsoft Excel as *normsinv*(*q*).

Obtaining the appropriate bounds for fore-aft seat position is more complex because the regression equation includes two anthropometric variables. The means and standard deviations of SSH (stature minus sitting height) and log(BMI) are needed for the target population. These values can be derived from analysis of a target sample intended to be representative of the driver population, or obtained by weighting other data appropriately. For example, the values might be obtained from NHANES III, ANSUR, or another large anthropometric dataset. The examples in this report use the NHANES III dataset (NCHS 2005). The NHANES III population represents U.S. civilians as of 1990. Table 7 lists distributional data for this population.

Table 7
Means (standard deviations) of Anthropometric Distributions
for Men and Women Ages 18-65 in NHANES III*

Dimension (mm)	Men	Women
Stature (S)	1762 (72.3)	1627 (67.5)
Erect Sitting Height (SH)	923 (38.9)	861 (35.9)
Stature minus Erect Sitting Height (SSH)	841 (46.8)	768 (43.2)
Ratio of Erect Sitting Height to Stature (SH/S)	0.523 (0.0134)	0.528 (0.0138)
Log(BMI)†	3.281 (0.1703)	3.293 (0.2251)

* Means and standard deviations estimated to obtain an accurate fit at the 5th and 95th percentiles of the distributions when using a normal approximation. These are not necessarily the actual means and standard deviations of the data.

† Units are *natural log* (kg/m^2)

The distribution of fore-aft seat position for a single-gender population (male or female) is modeled as a normal distribution. The mean value is obtained by plugging in the steering wheel location (L11, H17) and the mean values of SSH and log(BMI) from Table 7 into the equation 13. The standard deviation is obtained by the equation

$$s^2_{\mathrm{HPtXAHP}} = (0.6394\, s_{\mathrm{SSH}})^2 + (89.07\, s_{\log(\mathrm{BMI})})^2 + (37.7)^2 \quad [21]$$

Note that because *log(BMI)* and *SSH* are uncorrelated, the covariance can be neglected. The constant squared term is the root mean square error from the regression.

For this population, the fore-aft seat position distribution for the population described in Table 7 is then described by two single gender normal distributions with (mean, variance):

$$\textit{Male Seat Position X (mm)} \sim N(761.2 + 0.6081\, L11 - 0.3343\, H17, 49.3^2) \quad [22]$$

$$\textit{Female Seat Position X (mm)} \sim N(711.9 + 0.6081\, L11 - 0.3343\, H17, 48.0^2) \quad [23]$$

For a mixed-gender population, selecting bounds on the fore-aft seat adjustment range to accommodate a target percentage of the population (or, equivalently, to disaccommodate a specified fraction at each end) requires an iterative solution. Taking m as the fraction of males in the population, the fraction of the combined male female population that lies to the forward of x_1 is

$$F_1 = m\,\Phi((x_1 - x_{\mathrm{Mean,Male}})/s_{\mathrm{HPtX,Male}}) + (1\text{-}m)\,\Phi((x_1 - x_{\mathrm{Mean,Female}})/s_{\mathrm{HPtX,Female}}) \qquad [24]$$

Where Φ (x) is the cumulative standard normal distribution. For example, Φ (1.64) = 0.95. The fraction rearward of x_2 is

$$F_2 = m\,(1 - \Phi((x_2 - x_{\mathrm{Mean,Male}})/s_{\mathrm{HPtX,Male}})) + (1\text{-}m)\,(1 - \Phi((x_2 - x_{\mathrm{Mean,Female}})/s_{\mathrm{HPtX,Female}})) \qquad [25]$$

The accommodation problem is then to find x_1 and x_2 such that, for example, 95% of drivers' preferred seat positions lie within the bounds. The solution is obtained by iteratively varying x_1 and x_2. (See the Excel spreadsheet accompanying this report for an annotated guide to the calculations.)

Multivariate Accommodation

In practice, a designer will likely want to accommodate a target percentage of drivers on fore-aft and vertical position simultaneously. The total seat-position accommodation can be solved as shown in Figure 3. Suppose the target is 95% accommodation on both vertical and fore-aft seat position. The total percentage disaccommodated is the sum of the fractions disaccommodated on the front, back, top, and bottom of the adjustment range, minus the double-counted individuals in the corners. Because fore-aft and vertical seat positions are uncorrelated in this dataset, the corner fractions are simply the product of the adjacent fractions. For example, if 2.5% of drivers are disaccommodated at the top of the travel and 2.5% at the front of the travel, the percentage of drivers who prefer a seat position both above and forward of the adjustment range is $(0.025)^2 = 0.0006225$. With symmetrical disaccommodation of p in each of the four directions, the total accommodation A is

$$A = 1 - 4\,p + 4\,p^2 \qquad [26]$$

Solving the quadratic equation for p gives

$$p = 0.5 - 0.5\,(A)^{1/2} \qquad [27]$$

So, to accommodate the central 95% of the population, the disaccommodation at the top, bottom, front, and back of a rectangular seat track must each be not more than approximately 1.3%. For the population in Table 7, this corresponds to a rectangular seat adjustment range that is 241 mm long and 102 mm high.

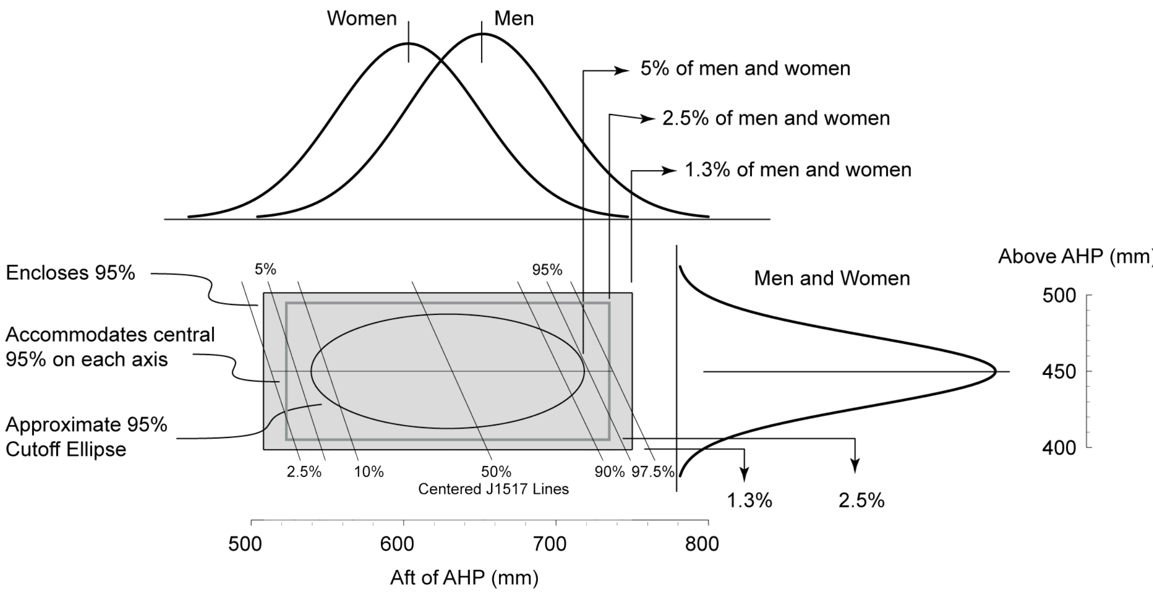

Figure 3. Calculating two-dimensional seat-position accommodation for the driver population in Table 7. Normal approximations to male and female seat position distributions are shown.

Comparison with J1517

Figure 3 shows the Class-B seating accommodation lines from SAE J1517 overlaid on the track travel required for the example population. Because J1517 does not include the effect of steering wheel position (seat height is the only vehicle-dimension input), the fore-aft position of the accommodation range from the new model will in general not be aligned with the J1517 model. However, to compare the fore-aft range predicted by the two models, the J1517 50/50 male/female model was translated fore-aft to align the 50th-percentile line with the center of the accommodation range in Figure 3. Because J1517 is a univariate (fore-aft) accommodation model, the meaningful comparison is between the width of the inner rectangle in Figure 3 and the 2.5% to 97.5% range in the J1517 model. The fore-aft travel range predicted by the J1517 model is about 14 mm longer than the univariate fore-aft accommodation in the new model (226 vs. 212 mm). This difference may be due to a difference in population anthropometry or to the use of a horizontal, fixed-height seat track in the test conditions used to develop the J1517 model.

Overall, the new model is reasonably consistent with the J1517 seating accommodation model, but the new model provides greater accuracy and flexibility because it takes into account steering wheel position, is configurable for driver body dimension distributions, and was developed for height-adjustable seats.

3.3 Eyellipse

Overview

The construction of the eyellipse is divided into two stages. First, the dimensions of the eyellipse are determined. Second, the eyellipse is located in the package with respect to the AHP. The new eyellipse is designed to be used with the seating accommodation model presented in the previous section. In fact, the first step in the process of locating the new eyellipse within the vehicle package is calculating the mean fore-aft and vertical seat position. The eyellipse was developed using statistical procedures that are very similar to those that were used to develop the new (2002) J941 Class-A eyellipse. As with the seat-position model, the eyellipse is configurable for the body dimension distributions of the driver population and gender mix. The steering wheel position is the only vehicle package information that is used, but a new procedure based on driver preference data is used to calculate the effective steering wheel position for input to the model.

The eyellipse models the distribution of driver eye locations as a three-dimensional normal distribution. Specifically, the data analysis suggests that the distribution of right or left eye locations for a single gender population in a vehicle with minimal censoring due to seat track limitations, headroom, knee room, and other clearance dimensions will be normal on each axis. Because the male and female eye location distributions overlap substantially, and because conducting analyses with separate male and female eyellipses would be cumbersome, a procedure has been developed to create a single eyellipse that approximates the cutoff behavior that would be obtained through weighted analyses using single-gender eyellipses.

Developing the Eyellipse

To compute the dimensions of the eyellipse, the eye location data for each of the nine laboratory test conditions were centered on the condition means. Figure 4 shows a trend toward lower eye locations toward the front of the distribution. The correlation between the fore-aft and vertical coordinates is 0.36.

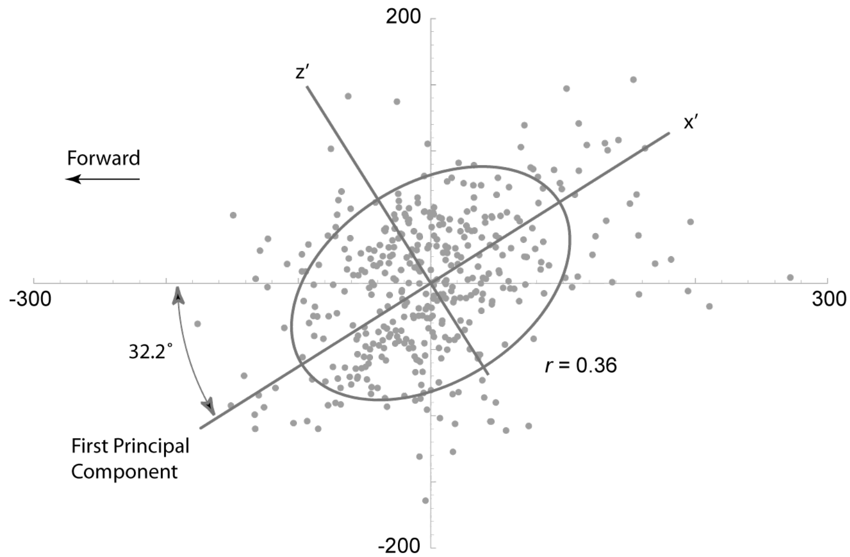

Figure 4. Fore-aft and vertical eye-location data (mm) from laboratory study, centered for each condition and overlaid. First and second principal components (eigenvectors of covariance matrix) are shown, along with a 95% cutoff (74% inclusion) ellipse constructed assuming bivariate normality.

To construct an approximating ellipse, the covariance matrix for the data was calculated. The first eigenvector of the covariance matrix describes the direction along which the data have highest variance, which is taken to be the long axis of the ellipse (x'). The second eigenvector is perpendicular to the first and gives the direction of the side-view minor axis of the ellipse (z'). To determine if anthropometric effects determine the axis lengths, the data were expressed on the x', z' axes given by the eigenvectors (see Figure 4). The x' coordinates were found to be significantly related to stature (S) with

$$x' = -838 + 0.4825\, S,\ R^2 = 0.52,\ RMSE = 52.6 \text{ mm} \quad [28]$$

The z' coordinates were significantly related to stature, but the R^2 value was only 0.11, so this relationship was neglected. Equation 28 is used in the eyellipse construction procedure to identify cutoff points on the long axis of the ellipse. The procedure is described below, after introducing the locator equation.

The centroid of the eyellipse is positioned with respect to the mean predicted seat position. Equations 13 and 14 are used with the mean population values of SSH and log(BMI) to obtain the mean seat position. The mean population value of SSH is

$$SSH_{\text{Mean, Pop}} = m\ SSH_{\text{Mean, Male}} + (1\text{-}m)\ SSH_{\text{Mean, Female}} \quad [29]$$

where m is the fraction of the population that is male. The mean population value for log(BMI) is calculated similarly. A reference eyellipse centroid is then calculated with respect to the mean seat position using equations 15 and 16 with the mean anthropometric measures for the population. The reference centroid is used as a starting point to scale and locate the eyellipse.

The construction procedures, which are illustrated in Figure 5, follow the methods used to create the J941 Class-A eyellipse (see J941 Appendix A).

1. Construct a side-view line passing through the reference centroid oriented at 32.2 degrees from horizontal (down at the front).

2. Find the male centroid by moving along the x' line relative to reference centroid by the distance given by

$$x'_{\text{Centroid, Male}} = 0.4825\ (S_{\text{Mean, Male}} - S_{\text{Mean, Pop}}) \qquad [30]$$

   where $S_{\text{Mean, Pop}}$ is the mean population stature. Similarly, find the female centroid by

$$x'_{\text{Centroid, Male}} = 0.4825\ (S_{\text{Mean, Male}} - S_{\text{Mean, Pop}}) \qquad [31]$$

   The female centroid will lie further forward along x' than the male centroid.

3. Compute the standard deviation of eye location for male and female drivers along the x' axis from the standard deviations of stature by

$$s^2_{\text{x', Male}} = (0.4825\ s_{\text{S, Male}})^2 + (52.6)^2 \qquad [32]$$

   and

$$s^2_{\text{x', Female}} = (0.4825\ s_{\text{S, Female}})^2 + (52.6)^2 \qquad [33]$$

3. Choose the front axis point x'_1 such that a tangent to the ellipse at that point (perpendicular to x') will cut off the desired fraction of the population by iteratively solving for x'_1 in

$$1\text{-}C = m\,\Phi((x'_1 - x'_{\text{Mean,Male}})/s_{\text{x',Male}}) + (1\text{-}m)\,\Phi((x'_1 - x'_{\text{Mean,Female}})/s_{\text{x',Female}}) \qquad [34]$$

where C is the desired eyellipse cutoff (e.g., 95%) and $\Phi(\nu)$ is the cumulative standard normal distribution. Similarly, choose the rear axis point x'_2 to cut off the same fraction:

$$1\text{-}C = m\,(1 - \Phi((x'_2 - x'_{\text{Mean,Male}})/s_{\text{x',Male}})) + (1\text{-}m)\,(1 - \Phi((x'_2 - x'_{\text{Mean,Female}})/s_{\text{x',Female}})) \qquad [35]$$

The x' axis length is $x'_1 - x'_2$. The eyellipse centroid is located at $(x'_1 + x'_2)/2$. In general, this will not be at the reference centroid location, because of differences between men and women in stature variance.

4. Compute the y' and z' axis lengths from the selected cutoff fraction. The y' axis is parallel to the y (lateral) axis of the vehicle (cross-cab). The standard deviation of eye locations on this axis is a constant 19.7 mm. So, the axis length for a cutoff percentage of C (e.g., 0.95) is

$$y'\ axis\ length = 2\ (19.7)\ \Phi^{-1}(C) \qquad [36]$$

where $\Phi^{-1}(q)$ is the inverse standard cumulative normal distribution (e.g., $\Phi^{-1}(0.95) = 1.64$). The z' axis, perpendicular to the x' axis and in the same vertical plane, has length

$$z'\ axis\ length = 2\ (45.6)\ \Phi^{-1}(C) \qquad [37]$$

where the standard deviation on z' is a constant 45.6 mm.

5. The lateral position of the cyclopean eyellipse is aligned with driver centerline, which is usually the centerline of the steering wheel. The right- and left-eye ellipses are obtained by translating the eyellipse left and right by 32.5 mm from driver centerline for a lateral spacing of 65 mm, which is typical interpupillary distance (just as in J941). The new eyellipse has no plan-view rotation angle, unlike the J941 Class-B eyellipse.

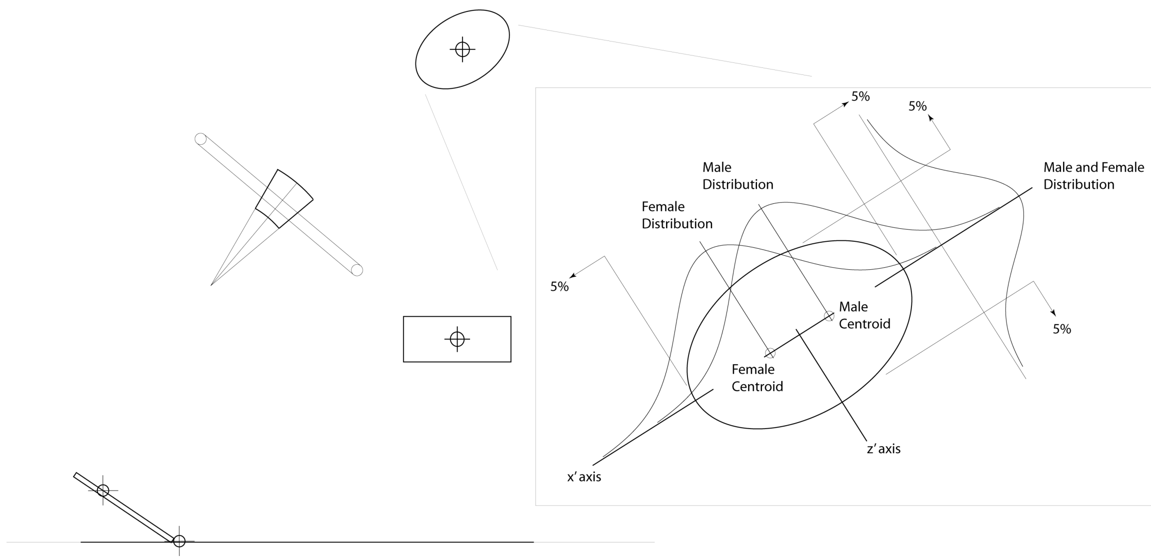

Figure 5. Schematic of eyellipse construction.

Comparison to J941

The SAE Class-B eyellipse, which was adopted in 1987, is currently documented in Appendix E of J941. This eyellipse is not widely used in truck and bus design for reasons described in the Introduction, but it may be useful to compare the new model to the current SAE J941 version. Such comparisons are only approximate, because of the differing structure of the models. The inputs to the old model are driver gender mix, design seat height (SAE H30), and design seat back angle. As is implied by these inputs, the model was developed for fixed-height seats (fore-aft adjustment only) and for seats with fixed seat back angles. Most trucks and buses manufactured for the U.S. market today have seats with seat height adjustment and adjustable seat back angles. The driver population used to create the models (Sanders and Shaw, 1985; Phillipart et al., 1985) also may differ substantially from the driver populations currently of interest.

Nonetheless, the models will be compared for several different truck packages. The driver population will be represented by a generic U.S. adult civilian population with 50% men derived from NHANES III data (NCHS 2005). This population, which is approximately representative of U.S. adults as of 1990, is described using the values in Table 7.

Six vehicle packages are listed in Table 8. For this comparison the steering wheel locations, defined by SAE L11 and H17, are assumed to be fixed. Packages 1-3 were configured using 100-mm increments of L11 and values of H17 calculated to lie on the steering wheel preference line (see section 3.4, below). For packages 1–3, H30 was estimated using equation 17, which gives mean expected vertical seat position in an adjustable seat as a function of vertical steering wheel position (repeated here for convenience):

$$HPtZ_{mean}\,(mm) = -200.3 + 0.8545\,H17 \qquad [38]$$

This equation produces H30 values that correspond well to the seat-position model used as part of the eyellipse calculation. Design seat back angle (A40) for the J941 model was set to 15 degrees for packages 1-3 to isolate the effects of package. Packages 4-6 were taken from Sanders and Shaw (1985), except that the seat back angles were manipulated to minimize the fore-aft discrepancy between the eyellipse centroids.

In package 2, the J941 eyellipse and the new eyellipse are almost exactly aligned fore-aft and the new eyellipse centroid is 12 mm higher. This shows that the vertical spacing between the seat and eyes that is produced by the new model is similar to the old model, and that the fore-aft position with respect to AHP is similar under some plausible conditions. However, when the steering wheel is further forward, the new eyellipse responds by moving more forward than the change in seat height alone would indicate, creating a discrepancy between the old and new models. Of course, this could be eliminated by changes to the seat back angle, since that variable also controls fore-aft positioning in the old J941 model. Following this approach, the back angles required to align the fore-aft positions of the old and new eyellipses in packages 4–6 range from 8.4 to 15.6 degrees, a plausible range. The vertical discrepancies in centroid location for these packages arise because the fixed seat heights (H30) in packages 4–6 do not follow the driver-selected seat height relationship observed with height-adjustable seats.

Figure 6 compares the shape of the J941 95% eyellipse for the 50/50 male/female population with the new eyellipse constructed using the population in Table 7. The fore-aft length of the new eyellipse is similar, but the new eyellipse is approximately twice as tall, due to the vertically adjustable seat.

Table 8
Comparison of Centroid Location with J941 Class-B Eyellipse and New Model (mm)

Dimension	Package					
	1	2	3	4	5	6
L11	100	200	300	64	168	229
H17	855	786	716	840	790	740
H30	531	471	412	531	468	405
A40 (deg)	15	15	15	8.4	13.2	15.6
J941 Centroid X	577	604	630	488	580	633
J941 Centroid Z	1168	1109	1049	1193	1113	1043
New Centroid X	513	605	697	493	582	641
New Centroid Z	1180	1121	1061	1167	1124	1082
Delta X	-64	2	67	0	0	0
Delta Z	12	12	12	-25	13	41

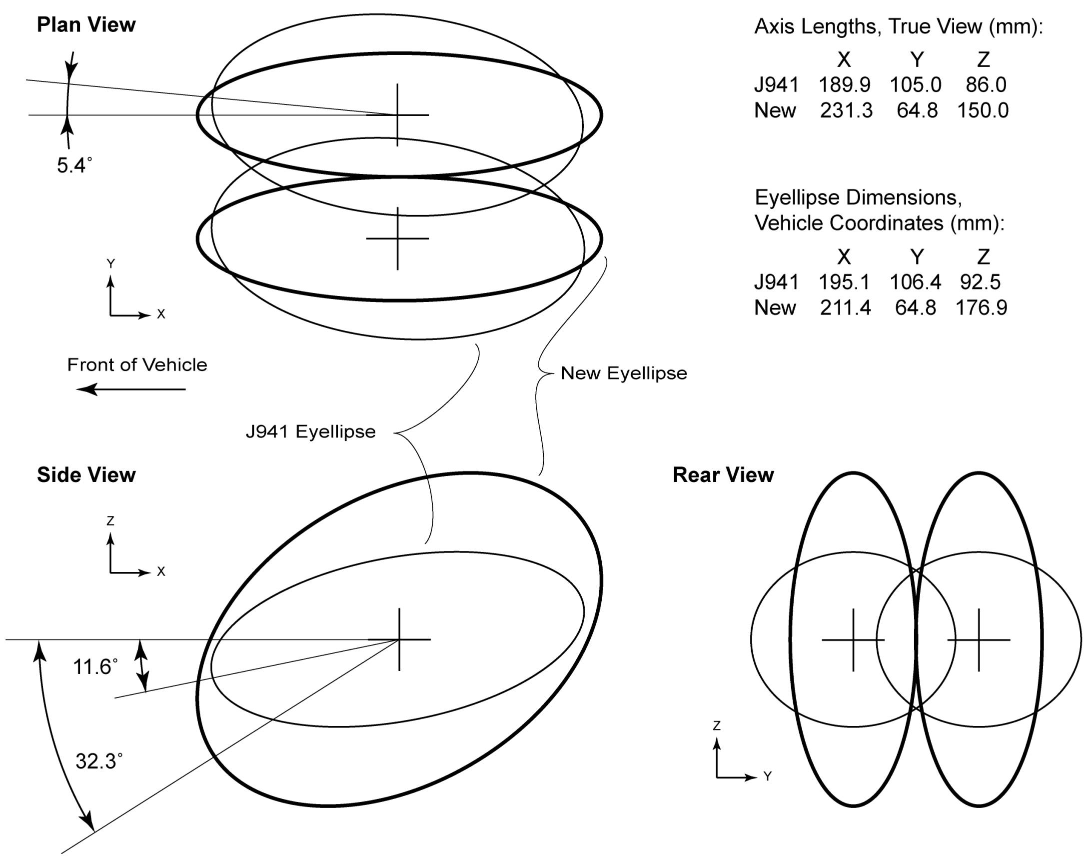

Figure 6. Comparison of J941 and new eyellipses for a 50/50 gender mix and seat track length >133 mm (J941). The new eyellipse was configured with the population from Table 7. Eyellipses are shown with the same centroid, although differences in the locator equations will usually result in different centroids.

3.4 Adjustable Steering Wheels and Preferred Steering Wheel Position

An important additional issue in the use of the new models relates to the treatment of steering wheel position. In the laboratory test conditions used to develop the models, the steering wheel position was fixed relative to the AHP. But many trucks and buses, including those used in the validation study, have adjustable steering wheels, typically with both tilt and telescope. Because the predictive models take fore-aft and vertical steering wheel position as the only vehicle geometry inputs, the question arises as to what location should be used to represent the position of a highly adjustable steering wheel. In the Class-A accommodation models, the "design" steering wheel position, usually at the center of the adjustment range, is used. However, trucks and buses often have a much larger range of steering wheel adjustment than passenger cars. Using the center of the adjustment range, or any other arbitrary position, would not be appropriate if the adjustment range was not centered on the preferred steering wheel positions for the drivers.

To address this issue, a model of preferred steering wheel position was developed using data from the laboratory study. Immediately following each of the trials used to develop the new accommodation models, the participants were permitted to adjust the pedals and floor vertically and fore-aft, effectively varying the steering wheel position with respect to the pedals. After completing these adjustments and readjusting the seat, the posture and preferred component locations were recorded.

The data on preferred steering wheel position with respect to AHP showed that, as expected, preferred steering wheel height is a function of fore-aft position. The slope of the relationship is independent of driver characteristics, but the overall height of the line is significantly related to driver stature. The height of the preferred steering wheel line at a point 175 mm aft of AHP is

$$SWPrefHt@175 \text{ (mm)} = 524 + 0.1613\, Stature,\ R^2 = 0.32,\ RMSE = 23.4 \qquad [39]$$

The average slope of the line is -0.559 (s.d. 0.305). Combining these, the steering wheel preference line is given by

$$SWPrefHt \text{ (mm)} = 524 + 0.1613\, Stature - 0.559\,(x - 175) \qquad [40]$$

where x is the distance aft of AHP.

For purposes of the new accommodation models, the location of an adjustable steering wheel is chosen with respect to the steering wheel preference line. First, the geometric center (centroid) of the travel envelope for the center of the steering wheel in side view is calculated. (The center of the wheel is defined, as in SAE J1100, as the intersection between the axis of rotation of the wheel and a plane lying on the driver side of the wheel.) Next, the point on the steering wheel preference line that is closest to the geometric center of the travel envelope is calculated. If this point lies within the travel envelope, it is used as the steering wheel location to define Ll1 and H17 for input to the models. If the closest point on the preference line to the travel-envelope centroid lies outside the travel envelope, the point of intersection between the travel envelope and the perpendicular line from the preference line to the centroid is used. Figure 7 shows the calculation schematically. This approach provides an objective, data-based method for representing the effects of adjustable steering wheels on driver posture, while also providing some design guidance. The method is illustrated in the next section as the new models are exercised for the vehicles used in the validation study.

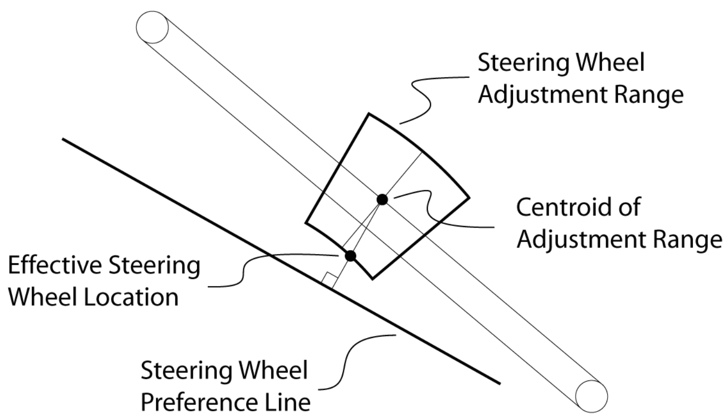

Figure 7. Calculating effective steering wheel location for a case in which the preference line does not pass through the adjustment range.

3.5 Comparison to In-Vehicle Data

The in-vehicle data provide an opportunity to evaluate the performance of the new models. Because the driver population was relatively small (24 drivers), and only seven were women, comparing the results to models constructed for a generic population (e.g., U.S. adults) would not be very meaningful. Instead, the models were tailored to the anthropometric distribution of the driver population, combining men and women. This allows the model performance to be judged independent of the particular driver population. Table 9 lists the distributional data used to configure the models.

Table 9
Anthropometric Distributions for the
In-Vehicle Driver Population (men and women combined)

Dimension	Mean	Standard Deviation
Stature (mm)	1758	102
Erect Sitting Height (mm)	922	42.4
Log(BMI)	3.460	0.216
Stature minus Sitting Height	836	66.2
Sitting Height / Stature	0.525	0.013

Figure 8 compares the new accommodation models to the distribution of driver-selected seat positions and driver eye locations for the six test vehicles. Driver-selected seat positions, steering wheel locations, and eye locations (N=24 in each vehicle) are shown with small black dots. Crosshairs indicate the mean ± one standard deviation on the fore-aft and vertical axes for each landmark. The steering wheel and seat adjustment ranges are represented by polygons joining the extreme points. The 4700 and DAF45 were tested with fixed steering wheel positions. The origin for each plot is the accelerator heel point and the accelerator pedal plane is depicted with a line. The steering wheel preference line is shown as a green line. The geometric center of the steering wheel adjustment range is shown with a red dot. The steering wheel position used as input to the accommodation models (L11, H17) is shown with a blue dot. This point lies on the steering wheel preference line if the line passes through the steering wheel adjustment envelope, at the location of fixed steering wheels, or on the boundary of the adjustment envelope when the line does not intersect the envelope.

The seat position data show substantial amounts of censoring. The “stacking up” of drivers at the rear and sometimes the bottom of the travel path indicates that many drivers were not able to sit in the position that they would have chosen with unlimited seat adjustment range. (The seat position data lie slightly outside the H-point travel path in some cases because the travel paths were defined with unloaded seats.) The prevalence of seat-position censoring across these vehicles (only the Eagle showed largely uncensored seat positions) highlights the need for improved driver accommodation models.

The seat position model is shown using a 95% cutoff ellipse constructed just as the eyellipse is constructed. The mean predicted seat position (ellipse centroid) was calculated using the mean population anthropometry values from Table 9 in equations 13 and 14. The horizontal and vertical axis lengths were determined using the horizontal and vertical standard deviations calculated from equations 18 and 21. In this case, the population was treated as a single-gender distribution, simplifying the calculation of fore-aft axis length. If the model is accurate and the underlying data are normally distributed, approximately 74% of the data points would be expected to lie within the ellipse.

A 95% cutoff eyellipse was calculated as described above, using a single-gender population quantified by the values in Table 9. The centroids of the seat-position eyellipse and eyellipse are shown with blue dots. Because the eyellipse location is based on the predicted seat location, errors in the prediction of seat location will affect the assessment of the eyellipse fit. Consequently, a second eyellipse, displayed with a thin line, was positioned based on the mean observed seat position. This provides a good indication of whether the eyellipse size, shape, and predicted location with respect to H-point match the data well.

The majority of seat positions and eye locations fell within the model ellipses for each vehicle, and the predicted mean lay within one standard deviation of the observed mean value in each case. Among the Class-8 cabs, the worst fit was observed for the seat position data in the Century. Approximately half of the drivers were censored on seat position in this vehicle and the driver-selected steering wheel positions lie primarily aft of the steering wheel position used as input to the model. The reason for the discrepancy may be due to a problem with steering wheel angle, since drivers tended to select positions only in the bottom half of the angle range. However, even in this vehicle, the fore-aft span of seat positions and both the vertical and fore-aft span of eye locations were well captured by the models. In the other Class-8 cabs, the fit to both the seat positions and eye locations was good. The new seat position model clearly shows where the seat adjustment range should have been located to avoid the substantial censoring observed in the 379 and VN, and confirms the well-positioned seat track in the Eagle.

The seat-position model predicts the large amount of censoring at the back of the track travel in the 4700 cab, and the eyellipse captures the eye locations well. In the DAF 45, the model predicted that drivers would have preferred to sit lower than the fixed-height track permitted, given the steering wheel height. The seat-position ellipse and consequently the eyellipse lie below the observed distributions, but the eyellipse based on the mean observed seat positions fits the eye location data very well. The new model is not designed for fixed-height seats, but could be adapted by setting the mean height to the height of the track. In that case, the eyellipse would accurate reflect the vertical eye positions.

Overall, the correspondence between the new models and the in-vehicle data was good. The seat position model accurately predicted the situations in which substantial seat-position censoring would occur. If the vehicles had been designed with the new models, little censoring would have occurred. The eyellipse, which like the seat position model was tailored to this driver population, accurately captured the overall height and fore-aft position of the driver's eyes. A more quantitative analysis of eyellipse shape or cutoff fraction is not possible with this small dataset.

3.6 Simplified Application Procedures

The calculation procedures described in this report allow customization of the models for any driver population and vehicle geometry, and allow selection of the desired seat-track accommodation and eyellipse cutoff. However, in many cases, a generic accommodation model may suffice for initial analyses. Table 10 presents dimensions for seat track adjustment ranges and eyellipses for a 50%-male U.S. adult population, and a 90%-male U.S. adult population. In each case, the seat track dimensions are predicted to accommodate 95% of the drivers and the eyellipse is a 95% cutoff. Note that there is only 10-mm difference in the seat track length for the two populations, due to the large overlap between the male and female seat position distributions.

In practice, users may identify a small number of design populations (e.g., Class-8 owner/operators, bus drivers, or delivery-truck drivers) and compute values similar to those in Table 10 using the equations in this report or in the associated Excel spreadsheet. The application to new designs can then proceed simply, perhaps programmed as a CAD macro that generates and places a rectangular H-point travel path and a pair of eyellipses.

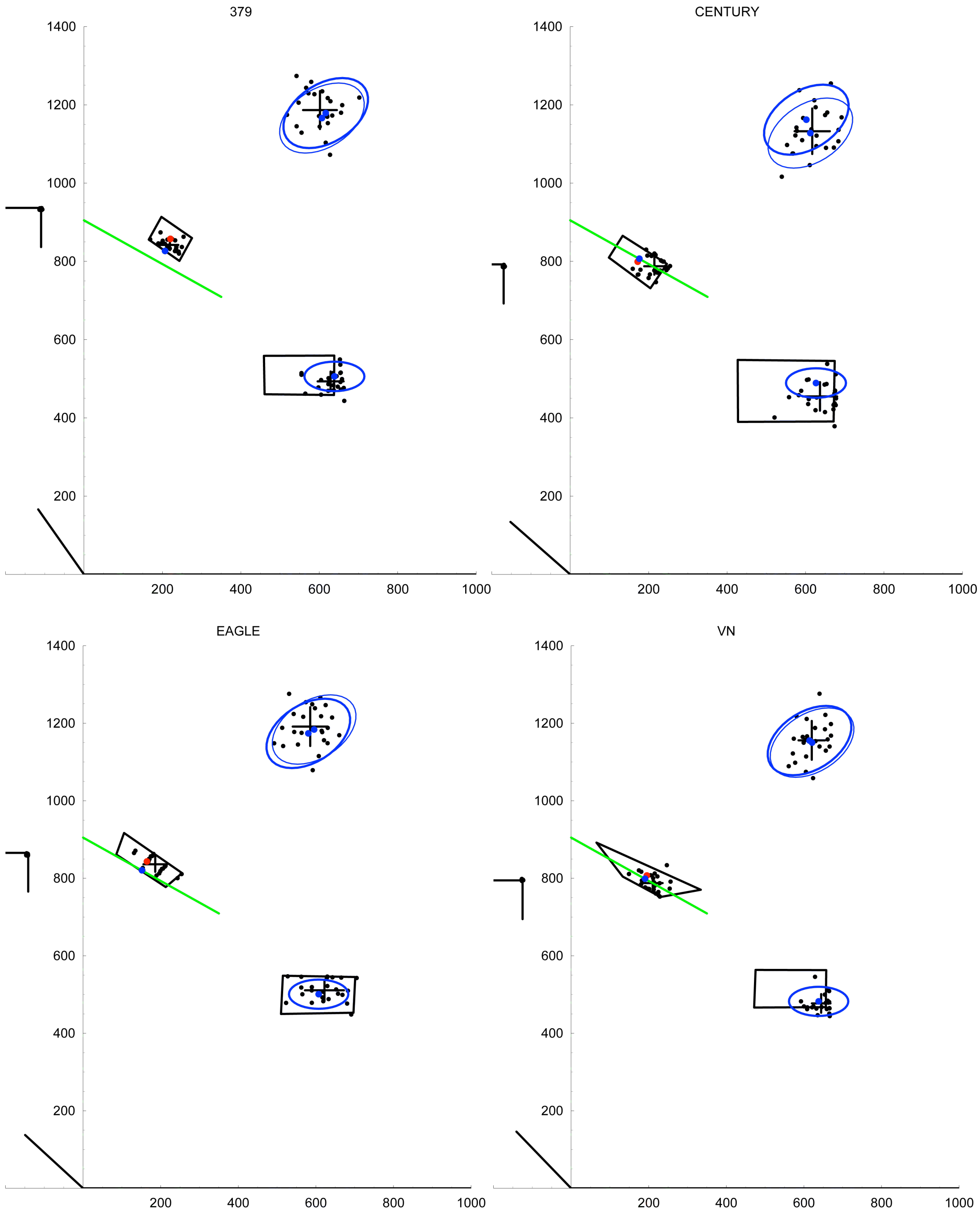

Figure 8. Comparison of accommodation models to in-vehicle driver data for four Class-8 cabs. Driver data are shown with black dots. Steering wheel and seat adjustment ranges are shown with black lines. Green line is steering wheel preference model. The seat position model is shown as 95% cutoff ellipse. The eyellipse based on mean predicted seat position is shown with a thick line. The eyellipse with a thin line is based on mean observed seat position.

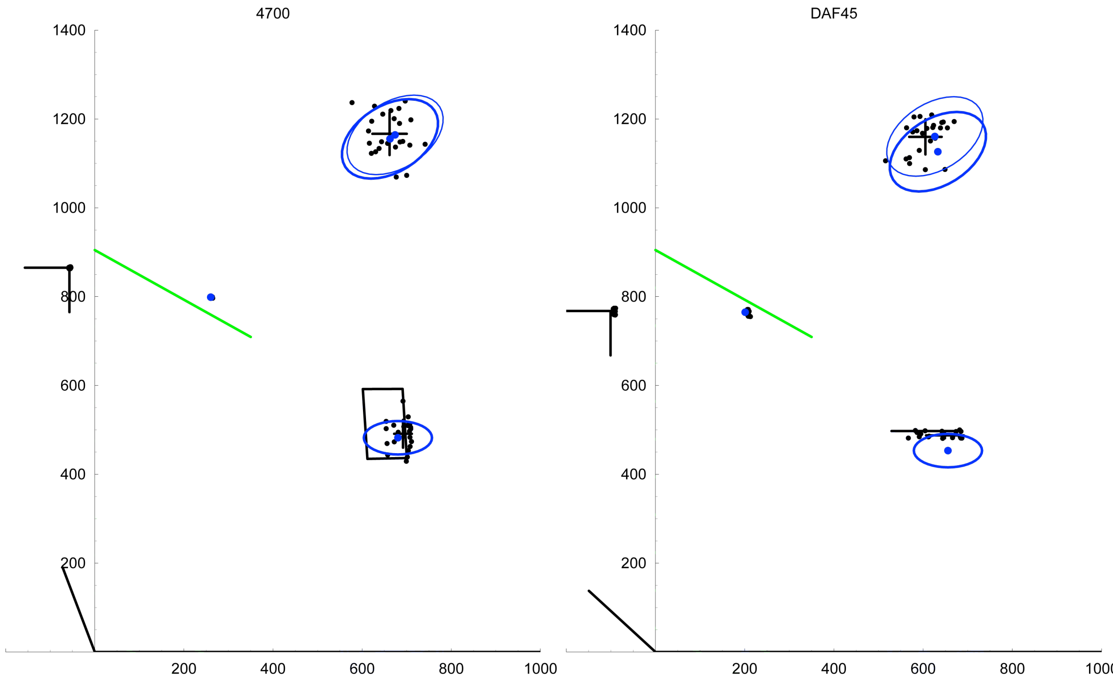

Figure 8 (continued). Comparison of accommodation models to in-vehicle driver data for two straight-truck cabs. Driver data are shown with black dots. Steering wheel and seat adjustment ranges are shown with black lines. Green line is steering wheel preference model. The seat position model is shown as 95% cutoff ellipse. The eyellipse based on mean predicted seat position is shown with a thick line. The eyellipse with a thin line is based on mean observed seat position.

Table 10
Simplified Application for Two Populations*

Dimension	U.S. Adults	U.S. Adults, 90% Male	Vehicle Geometry Effects
Seat Track Length	241	231	
Seat Track Height	102	102	
Seat Track Center X	736.6	756.3	0.6081 *L11* - 0.3343 *H17*
Seat Track Center Z	0	0	-200.3 + 0.8545 *H17*
Eyellipse Centroid X	-6.7	-10.3	(Seat Track Center X) + 0.0809 *L11*
Eyellipse Centroid Z	649.5	668.9	(Seat Track Center Z)
Eyellipse X Axis Length	231	216	
Eyellipse Y Axis Length	65	65	
Eyellipse Z Axis Length	150	150	

* Add the value listed in the population column to the value of the expression in the Vehicle Geometry Effects column to obtain the dimension.

4.0 DISCUSSION

4.1 Accomplishments

The seat-position and eyellipse models presented in this report represent important advancements over the current state of the art in driver population accommodation modeling as embodied in SAE practices. The new models improve on the current SAE tools in at least six ways:

1. The new models are configurable for population anthropometry, so they can be customized for particular driver populations (e.g., school bus drivers or long-haul truck drivers).

2. The new models represent vehicle geometry using fore-aft and vertical steering wheel position with respect to accelerator heel point, rather than seat height, allowing application to vehicles with height-adjustable seats.

3. The new models provide for a rigorous treatment of large steering wheel adjustment ranges based on driver preference data, rather than using an arbitrarily chosen position such as the center of the adjustment range.

4. The eyellipse model is located using the mean seat position obtained from the seat position model, so the predictions obtained from the two models are always consistent.

5. The same data and complementary analysis methods were used to develop the Class-B posture prediction models in the Jack digital human modeling software package, so the results of Jack analyses can be expected to be consistent with the new models.

6. The new models are customizable for different cutoffs and accommodation levels, rather than being limited to a few percentiles of fore-aft seat position and two eyellipse accommodation levels, allowing back-solving to determine actual accommodation levels for candidate designs.

4.2 Limitations

The accommodation models in the SAE practices are based on more driver measurements than the new models. The original eyellipse was based on eye locations of more than

2300 drivers (measured statically). The Class-B models developed in the 1980s were based on fewer than 200 drivers. The new Class-A seat-position and eyellipse models in J941 and J4004 are based on 60 to 120 drivers measured in dozens of vehicles. The current model is based on measurements from 63 drivers in a laboratory study and 24-drivers measured in vehicles.

In spite of the relatively small sample of drivers, experience with the development of the Class-A models suggests that the primary limitation is not the number of drivers per se, but rather the number of vehicles in which mean driving position has been measured. In particular, substantial seat-position censoring was observed in four of the six validation vehicles, limiting the value of the comparison between those data and the model prediction. Consequently, the driver behavior in those vehicles (for example, mean selected seat position) may not accurately reflect the behavior of drivers in vehicles with better positioned seat tracks. However, the model predictions for seat position and eye location matched driver data well in the two vehicles with minimal censoring, and predicted the censoring accurately in the other four vehicles.

Another limitation inherent in studies of this sort is the short duration of the test intervals. Some drivers report frequent changes in posture and position during long drives. The importance of these changes for design may be minimal, however, because the majority of these posture shifts will happen within the range of adjustment required to accommodate the initial postures of a large population of drivers. Measurements of drivers in the vehicles they normally drive will be necessary to quantify these effects.

Although these models are intended for application to any on-road Class-B vehicle, they have not been validated for special populations, particularly school or transit bus drivers. Bus drivers operate different vehicles and in a different environment than truck drivers. The critical nature of driver vision near buses is reflected in the substantially different mirror requirements. Vision requirements may cause drivers to sit differently in a bus than they would driving a truck with a similar steering-wheel-to-pedal relationship. In-vehicle validation measurements are needed to determine the applicability of the new models to that environment.

Overall, the data from the in-vehicle truck study do not support the hypothesis that driver exterior vision is an important determinant of driver posture. Specifically, the model accuracy was similar across the vehicles with height-adjustable seats, but these vehicles had substantially different external vision restrictions imposed by different hood geometries and windshield layouts. If driver vision was an important factor determining, for example, vertical seat height, higher seat positions than predicted would have been expected in the Peterbilt 379, which has a relatively long, high hood. More measurements of driving posture in vehicles driven in actual on-road use will be needed to determine the conditions under which external vision restrictions are important determinants of driver posture.

Due to the limitations of the underlying data, in particular the number of vehicles for which driver data are available, the models presented in this report do not address the issue of statistical *tolerance*. Because all empirical models have error, the models will be more or less accurate across vehicles, resulting in deviations from the expected accommodation. To illustrate using an analogy, calculating the dimensions of a rectangular seat track travel path using the methods in this report can be thought of as trying to place a rectangular box over a pile of sand. If a box sized to enclose 95% of the sand is perfectly centered on the pile, the box will contain the desired percentage. However, any errors in centering the box on the pile will result in less than 95% lying within the box. Errors in the dimensioning of the box will sometimes result in more than 95% inclusion, but the slope of the distribution at the edges means that dimensional errors will also be biased toward reduced inclusion.

Tolerance applies a probabilistic assessment to the model application domain, so that the model includes consideration of the likelihood of actually accommodating the desired percentage of the population in a particular new vehicle. In SAE J4004, a tolerance value of 90% was used to define a set of seat track lengths targeting various levels of accommodation. For example, 95% of a generic U.S. driver population can be accommodated in an average passenger car by an optimally positioned 200-mm-long seat track. However, it is necessary to use a 240-mm-long seat track to accommodate at least 95% of drivers in 90% of new vehicles equipped with seat tracks designed with the model. The tolerance for the Class-A models was estimated by applying the model to dozens of vehicles for which driver seat-position data were available. Unfortunately, the small number of trucks for which driver data are available does not permit a similar calculation for the new seat-position model.

One approach to estimating tolerance for the new model would be to use the percentage increase in seat track length required by the inclusion of 90% tolerance in the Class-A model (i.e., about 20%). This would lengthen the seat track adjustment range requirements for a typical U.S. adult driver population to approximately 288 mm x

120 mm. However, judging from the results of the in-vehicle study, a large improvement in truck driver accommodation can be expected just from the use of the new models without including tolerance. The further expansion of the models to include tolerance would best be left until after more relatively uncensored seat-position data from on-road studies are available.

4.3 Applications

The models presented in this report should be used both to develop new vehicle designs and to assess existing designs, including benchmarking of competitive vehicles. The new-vehicle design process might begin with consideration of the steering-wheel-location preference line introduced in this report. Several of the test vehicles had steering wheel adjustment ranges intersecting the preference line, but others did not. The vertical position of the preference line is customizable for the average driver stature, so the steering wheel position for a school bus, for example, might be located differently than that of a severe-service truck.

From a design steering wheel location on the preference line, a seat track adjustment range can be laid out. The model locates and scales the seat adjustment range based on the effective steering wheel location and the distribution of driver body dimensions. Importantly, the model includes the effects of increasing body mass index on the required seat adjustment range. The seat track travel required to accommodate a population that has a high percentage of obese drivers is located further rearward.

The eyellipse presents a much more accurate representation of the vertical distribution of eye locations in vehicles with height adjustable seats than did the SAE J941 eyellipse. The change in eyellipse dimensions (see Figure 6) can be expected to affect a variety of vision analyses. For example, the top edge of the 95% cutoff eyellipse is about 42 mm higher than top of the J941 eyellipse for H30 at the middle of the vertical seat travel, reducing the estimated 95th-percentile upvision angle. Similarly, the 5th-percentile downvision angle would be reduced. Another consequence of the taller eyellipse is that the estimated headroom requirement would be increased by approximately the additional height of the eyellipse (42 mm). The narrower lateral axis would slightly change mirror field-of-view and pillar obscuration calculations, but these are not likely to be important effects. Cluster visibility analyses may be somewhat eased by the narrower eyellipse. Interestingly, along the axis of downvision to the instrument cluster (approximately 30 degrees to horizontal), the eyellipse dimensions are approximately the same, reducing the impact of the larger eyellipse on cluster visibility analyses (rimblock assessments).

The equations for calculating the centroids of the seat position and eye location distributions are similar to those developed previously for posturing human figure models. Because they are based on the same data, they also produce similar results. For example, putting the mean population anthropometry into the posture prediction models will produce predicted seat position and eye locations that are generally within 10 mm of the centroids calculated using the above procedures. Consequently, an alternative approach to using the models in this report to position a generic seat track adjustment range and eyellipse using posture prediction based on the mean population values. The fit to the data will be essentially identical, as can be readily verified.

4.4 Research Needs

Additional models can be created from the existing data to fill out the family of tools. In particularly, the data are available to create a new shin/knee contour model to replace J1521, and a new belly contour model to replace J15122. The models would be based on the seat-position model and configurable for population anthropometry in the same way the new eyellipse is. A new head contour model can be created based on the new eyellipse. The data are also available to create a lateral clearance model (shoulder, hips, knees, elbows) that will take into account changes in population body dimensions, particularly increases in body mass index. Data on preferred shifter location were gathered in the laboratory study and could be used to create a population model focused on that control.

New data are most urgently needed for special vehicle environments, particularly buses. Data should be gathered from bus drivers in the vehicles they normally drive as well as in laboratory mockups. Other special vehicle populations of interest, such as local delivery vehicles, should also be studied in detail. As part of these studies, driver vision obstructions should be systematically manipulated to quantify the effects, similar to a study conducted previously for Class-A vehicles (Reed et al. 2000b). Any new vehicle studies should be conducted using seat track adjustment ranges that provide good accommodation according to the new model to avoid the problem of excessive censoring. Other factors that should be studied in mockups and in vehicle include the effects of restrictive headroom; different seat features, including motorized tilt adjustments; and transmission type (all testing to date has been conducted with clutches and manual transmissions).

A model for steering-wheel angle adjustment is also needed. The current laboratory and in-vehicle data have not revealed useful patterns of adjustment behavior. For example, drivers' preferred steering wheel angles do not appear to be related to belly clearance or vision to the cluster. It may be that vision to the cluster or belly room only have significant effects when the vehicle package creates a conflict. For example, in a vehicle with insufficient rearward seat track travel, drivers might select a flatter wheel angle to move the rim of the wheel further forward. Driver steering-wheel angle selection behavior might be driven in part by the need to view the instrument cluster. This may have been a factor in the anomalous steering-wheel-angle distribution in the Century, which in turn led to seat positions lower than expected. Careful investigation of this issue, first in vehicle mockups and then in vehicles, will be needed to understand the effects and to develop appropriate models.

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