Proceedings of IDETC/CIE 2005
ASME 2005 International Design Engineering Technical Conferences
& Computers and Information in Engineering Conference
September 24-28, 2005, Long Beach, California USA

DETC2005-84179

ROBUST TRUCK CABIN LAYOUT OPTIMIZATION USING ADVANCED DRIVER VARIANCE MODELS

Matthew B. Parkinson
Engineering Design
The Pennsylvania State University
University Park, PA 16802
email: mparkins@psu.edu

Matthew P. Reed
University of Michigan Transportation Research Institute
Ann Arbor, MI 48109
email: mreed@umich.edu

Michael Kokkolaras
Department of Mechanical Engineering
University of Michigan
Ann Arbor, MI 48109
email: mk@umich.edu

Panos Y. Papalambros
Department of Mechanical Engineering
University of Michigan
Ann Arbor, MI 48109
email: pyp@umich.edu

ABSTRACT

One important source of variance in the performance and success of products designed for use by people is the people themselves. In many cases, the acceptability of the design is affected more by the variance in the human users than by the variance attributable to the hardware from which the product is constructed. Consequently, optimization of products used by people may benefit from consideration of human variance through robust design methodologies.

We propose that design under uncertainty methodologies can be utilized to generate designs that are robust to variance among users, including differences in age, physical size, strength, and cognitive capability. Including human variance as an inherent part of the product optimization process will improve the overall performance of the product (be it comfort, maintainability, cognitive performance, or other metrics of interest) and could lead to products that are more accessible to broader populations, less expensive, and safer. A case study involving the layout of the interior of a heavy truck cab is presented, focusing on simultaneous placement of the seat and steering wheel adjustment ranges. Tradeoffs between adjustability/cost, driver accommodation, and safety are explored under this paradigm.

INTRODUCTION

Humans are highly variable on many functional measures that are related to artifact design variables. The wide ranges of adult standing height, hip breadth, and other body dimensions are readily observed and often considered quantitatively in design. Variability in human perception, behavior, and performance can be equally or more important than dimensional variability, but these factors are less commonly considered in a quantitative manner. Human adaptability diminishes but does not eliminate the impact of inter-individual variability on artifact performance. The ubiquity of "one-size-fits-all" is a testament to adaptability, but is not a prescription for good design, particularly in cases where performance is important and people interact with the artifact through multiple interfaces. Designing for people requires the quantitative consideration of all relevant aspects of human variability.

The design of a vehicle interior is one problem in which human (occupant) variability is a primary concern. The layout of the driver's workstation in a truck cab includes the selection of locations for the seat, steering wheel, pedals, and other components, subject to boundary constraints (such as floor height, roof height, firewall position, and cab length). Within these and other

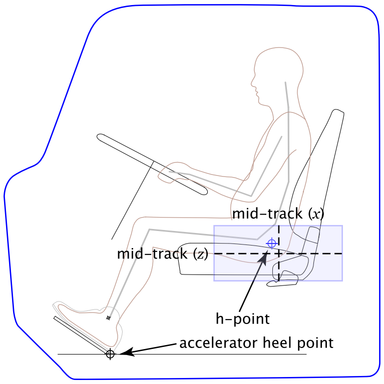

Figure 1. A typical cab “driver packaging” problem involves the design of the interior environment so that a large population of drivers is accommodated. The accelerator heel point (AHP) is a fiducial point to which other cab components are referenced.

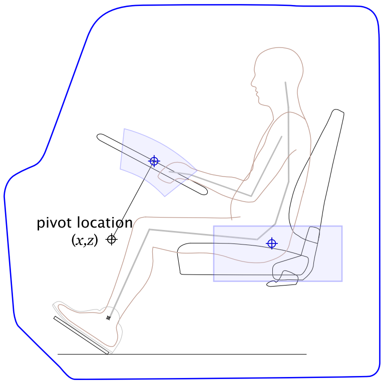

Figure 2. Adjustability in both the steering wheel and the seat increases accommodation. The adjustment ranges depicted are larger than typical values to improve the clarity of the illustration

constraints, the vehicle interior is engineered to maximize the *accommodation* of the design population, where accommodation means that a person is able to perform all required tasks while seated in a comfortable posture. A person is usually considered to be accommodated as a driver if he or she can choose component locations and a posture without encountering the limits of adjustment ranges [1]. However, even among accommodated individuals, a vehicle usually provides a wide range of performance on other important measures, such as headroom and exterior vision.

During the vehicle design process, a common driver accommodation problem is the selection of the position and size of the seat adjustment range (fore-aft and vertical) with respect to the pedals such that a target percentage of the population is accommodated (Figure 1). The problem is more complicated if both the seat and steering wheel are adjustable (Figure 2). Very large adjustment ranges for all components would accommodate nearly all drivers, but adjustability is constrained by cost, safety, and the desire to reduce cab dimensions to maximize cargo capacity. Frequently, adjustment ranges are limited by carry-over components from current-production vehicles or by a requirement to use commercial, off-the-shelf (COTS) hardware. In this case, the design problem can be simplified to selecting the locations for fixed adjustment ranges, which entails selecting values for four variables defining the fore-aft and vertical positions of the center of the seat adjustment range and the steering-wheel pivot point.

Current industry practice for vehicle interior packaging relies on two toolsets. The Society of Automotive Engineers (SAE) maintains a set of Recommended Practices that define methods and models for component layout [2]. For example, SAE J1517 describes the preferred fore-aft position for seat adjustment ranges as a function of seat height. Vehicle designers also make extensive use of digital human modeling (DHM) software, which places software manikins representing drivers into digital vehicle mockups [3]. DHM software can represent people with a wide range of body dimensions in many possible postures. Virtual environments have progressed and are being used for conceptual layouts. They are, however, insufficient for more refined ergonomics assessments [4].

For purposes of physical accommodation, human variance can usefully be partitioned into dimensional (anthropometric) and behavioral variability. For example, the height of a driver’s eyes above the seat is related to both torso length and torso posture. The most common approach to representing anthropometric variabilty is the use of manikins or templates that represent people at dimensional extremes. The (often implicit) rationale for using only a few ”boundary manikins” is that designs accommodating the anthropometric extremes (for example, an average woman who is 5^{th}-percentile by stature and an average man who is 95^{th}-percentile by stature) will also accommodate people with less-extreme dimensions. Many contemporary research publications approach design problems in this manner, including methods for optimizing workspaces and controls in aircraft cockpits [5–7]. The selection of anthropometric extreme cases has been extended to the use of many boundary manikins selected with consideration of anthropometric covariance [8]. For example, the A-CADRE family of 17 manikins represents much of the multivariate anthropometric variability in an adult population [9]. Boundary-manikin sampling approaches are commonly used with DHM software to create figure models.

Any use of manikins in design requires that they be *postured* in realistic ways. Posturing is often performed manually by the designer, but a number of approaches to posturing driver manikins have been developed [10–12]. The resulting postures are related by statistical models to data gathered from drivers in a variety of laboratory and vehicle configurations. Manikin posturing algorithms are usually deterministic, giving a single

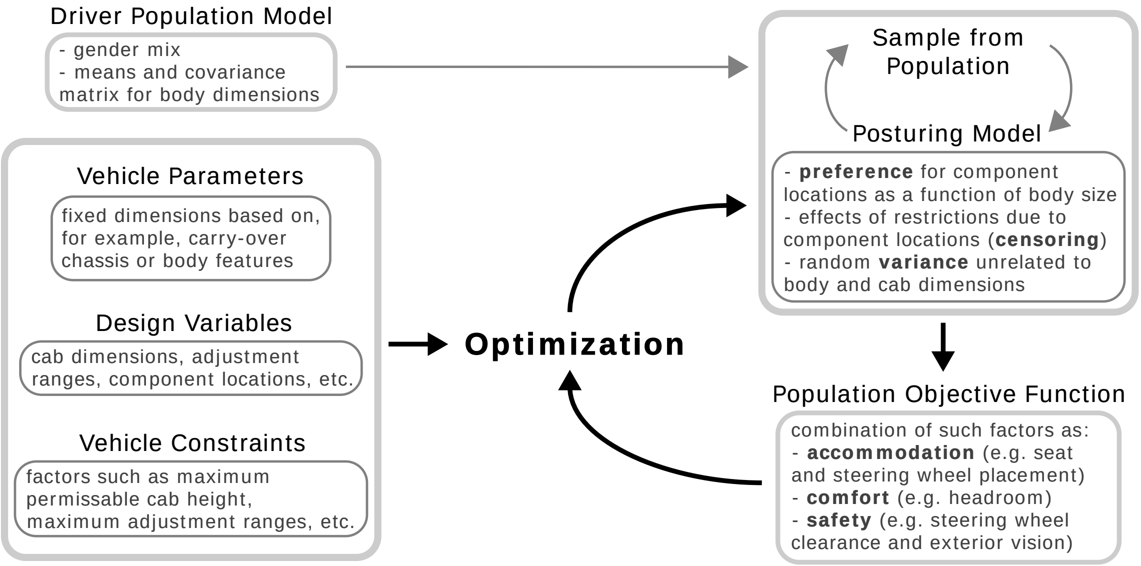

Figure 3. Schematic of optimization methodology, showing submodels and information flow.

posture for a particular combination of manikin body dimensions and task constraints. However, people who have the same body dimensions often drive with substantially different postures [10, 12, 13]. As a consequence, manikin-based design approaches, even with ideally accurate posture prediction, are insufficient for quantitative assessment of accommodation [12,14].

The effects of postural variance that is unrelated to body dimensions must be taken into account in vehicle design. The SAE Recommended Practices for vehicle design accomplish this by the use of unified statistical models that encompass population variance in both body dimensions and behavior. For example, the *eyellipse* (SAE J941) approximates the distribution of driver eye locations in vehicle space as a three-dimensional normal distribution. Because it models eye location directly, rather than attempting to predict it from the combined effects of anthropometric and postural variability, the eyellipse has been one of the most elegant and effective tools ever developed for human factors analysis [1]. A recent update to J941 replaced the original model for passenger cars from the 1960s with a more flexible model developed in modern vehicles [15].

Unfortunately, the versions of the J941 driver eyellipse and the seating accommodation model in J1517 that are applicable to trucks and buses (SAE Class B) are substantially out-of-date and limited in ways that make them inadequate for many design situations. First, the driver population used to develop those models differs substantially from current driver populations with respect to anthropometric variables, particularly those related to body weight. Second, the SAE models do not take into account the large range of adjustability common on modern trucks, particularly steering wheel tilt/telescope and seat height adjustment. Third, the SAE tools are essentially univariate, dealing with only one variable at time (fore-aft seat position or eye location). The SAE Recommended Practices do not provide any way to consider, for example, the effects of restricted seat adjustment range on eye location. New vehicle interior design methods are needed that allow simultaneous consideration of multiple constraints and objectives, while preserving the quantitative rigor associated with the SAE occupant packaging tools. This paper presents a new approach to vehicle interior design that applies population sampling and stochastic posture prediction in an optimization environment to achieve optimal designs that are robust to human variability.

METHODOLOGY

This paper outlines a methodology for applying optimization techniques to solve a vehicle packaging problem. The combination of optimization with sophisticated use of multivariate models of driver behavior and preference creates truck packages that are robust to the variation in size and behavior of drivers while satisfying constraints imposed by other aspects of the design, including safety and other regulations. Driver variance is represented in the optimization problem by models of anthropometric variability, postural variability, objective performance criteria, and subjective responses.

In this initial effort we only consider driver variance as a source of uncertainty in the optimization problem. The emphasis is on the sophisticated modeling and treatment of this uncertainty. The design variables are deterministic and driver variance has an impact solely on the objective function. Nevertheless, the

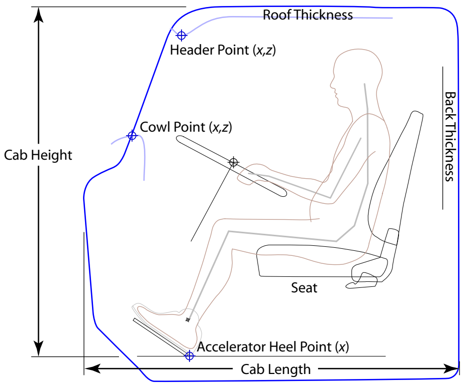

Figure 4. Parameters defining the size of the cab are considered fixed inputs to the models utilized by the optimization algorithms.

proposed design model can be readily augmented to include random design variables as well as probabilistic constraints that can be treated using any of the state of the art techniques for design under uncertainty.

Modeling approach

Figure 3 shows the components of the optimization approach. The driver population is represented by a gender mix (fraction of drivers who are male and female) and by distributions of anthropometric variables, such as stature, sitting height, and body weight. For this paper, the distribution of anthropometric variables within the driver population is taken to be that of the 1988 U.S. Army [16] with a 50/50 gender mix.

The vehicle is represented by a set of parameter values, constraints, and design variables. The categorization of cab features varies across design situations. Usually some features of the cab are fixed by the desire to use an existing chassis or other components. The design variables can include features of the cab architecture, such as cowl height and roof height, but often will be restricted to component locations (Figure 4). In this paper, the design variables define the locations of the seat and steering wheel adjustment ranges (Figure 2). The ranges of the design variables may be constrained by vehicle specifications and other considerations. For example, common design constraints limit the overall vehicle height and cab fore-aft length.

The fitness of a particular vector of design variable values is evaluated by a virtual fitting trial in which a population of drivers is postured. The population is obtained by random sampling from the specified population. The posture models used in this paper were constructed using the Cascade modeling approach [10] applied to data from laboratory and in-vehicle studies of truck-driver posture [12, 17]. The posture models predict the preferred steering wheel and seat positions for each driver as a function of body dimensions and vehicle interior geometry.

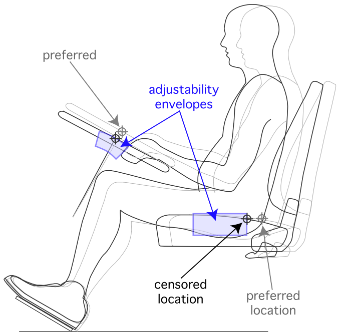

Figure 5. Demonstration of censoring. This driver would prefer to sit further rearward and with the steering wheel higher than the current placement of the components allows. Instead, the driver is positioned at the adjustability limits nearest the desired location and the posture is adjusted accordingly.

Next, the driver's seat position is predicted using a regression model that takes into account leg length and body mass index. Finally, torso posture is predicted from body dimensions, steering wheel position, and seat position, taking into account whether the headroom is restrictive to the individual driver.

Importantly, the residual variance in posture and component-location preference that is unrelated to body dimensions is modeled by random sampling from appropriate distributions. For example, preferred steering wheel position is only weakly related to body dimensions, so including the residual variance is critical to ensuring an adequate adjustment range. To improve the efficiency of the simulation, the vector of random posture components is sampled once for each sampled vector of anthropometric variables, yielding a virtual driver $\mathbf{D}_n$, characterized by body dimensions and preferences relative to other drivers with the same dimensions.

The predicted postures are not always attainable. For example, a tall driver might prefer to position the seat more rearward than the range of adjustment permits (Figure 5). This inability to accommodate the driver's preferred posture is called "censoring" or "disaccommodation". When censoring occurs, the posturing model chooses the nearest achievable posture. Both the preferred and achievable postures are stored for each driver n in $\mathbf{D}(\mathbf{x})$ so that any discrepancy can be included in the calculation of the objective functions. Consequently, the matrix $\mathbf{D}$ contains the anthropometric, postural, and disaccommodation information for each of the drivers.

The optimization problem

The design variables, $\mathbf{x}$, are fore-aft and vertical locations of the seat and steering wheel adjustment ranges. The sizes of the adjustment ranges of the seat and steering wheel are fixed parameters. Additional parameters are the location of the accelerator heel point (AHP) and the cab size limitations such as roof height.

The average disaccommodation for the entire population is obtained by summing the censoring metrics for each driver and normalizing by the size of the population:

$$f(\mathbf{x}) = \sum_{n=1}^{N} \frac{w_{track} D_{n,track} + w_{wheel} D_{n,wheel}}{N} \tag{1}$$

where N is the number of drivers in $\mathbf{D}$. The components $D_{n,track}$ and $D_{n,wheel}$ are the magnitudes of disaccommodation in the seat track and steering wheel, respectively. The weights, w_{track} and w_{wheel}, control the relative contributions of the two objectives to the overall measure for the population.

The goal is to accommodate as large a percentage of the population as possible, which is the equivalent of minimizing the disaccommodation across the population. Consequently, the optimization problem is to minimize $f(\mathbf{x})$ subject to deterministic constraints $\mathbf{g}(\mathbf{x}) \leq 0$.

Example

Design Scenario 1 Consider a manufacturer who has a current cab configuration defined by the baseline values in Table 1. The manufacturer would like to bring the back of the cab forward relative to the firewall to increase cargo capacity. The maximum cab length is determined to be 900 mm. The fore-aft distance between the seat H-point and the back of the seat was taken to be 200 mm, so the rearmost end of the seat track travel is constrained to be no more than 700 mm aft of AHP. With a 150-mm-long seat track, this constrains the center of the seat track (one design variable) to lie no more than 625 mm aft of AHP. The optimization problem is then formulated as

$$\begin{aligned} \text{minimize} \quad & f(\mathbf{x}) \\ \text{subject to} \quad & x_{track} - 625 \leq 0. \end{aligned} \tag{2}$$

For this example the two disaccommodation metrics, for the seat track and steering wheel, were equally weighted. The driver population, N, was set to 1000.

As expected, the new steering wheel and seat positions are higher and further forward. The resulting driver package, in Table 1 and Figure 6, provides a slightly better overall level of accommodation than the baseline design (2.3 vs. 3.8). The disaccommodation score (objective function magnitude) is the average level of disaccommodation per driver, in mm. The difference between the baseline and revised package (1.5 mm) is modest. The low disaccommodation value and modest improvement over the baseline design indicate that the modification can be made without substantial cost to driver fit. They also indicate that the seat track and steering wheel could have been better placed in the baseline design.

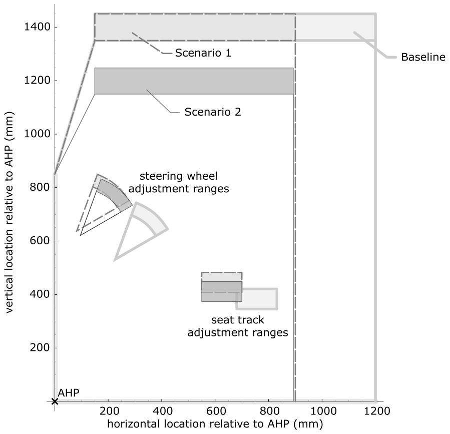

Figure 6. The outline of the cab and the adjustment ranges for the seat and steering wheel in the baseline and modified cab configurations are show. Bringing the seat and steering wheel forward and up allowed cab length to be decreased without sacrificing population accommodation. Simultaneously restricting cab height dramatically reduced accommodation, however, as the seat and wheel were forced down.

Design Scenario 2 As in the first design scenario, the manufacturer desires to move the cab wall forward to improve cargo capacity. However, the design specifications for the vehicle also mandate that the exterior roof be no higher than 2.5 m. With a roof thickness of 0.1 m, and a floor height above the ground (AHP height) of 1.25 m, the inside roof of the cab can be no more than 1.15 m above the floor. The simulation was run with a headroom constraint implemented in the posturing algorithm that forced lower seat heights for drivers who would otherwise have contacted the roof. The seat and steering wheel positions were optimized for this condition while respecting with the back-of-

Table 1. VEHICLE PACKAGES AND OPTIMIZATION RESULTS.

	component locations (mm)				
Design	x_{wheel}	z_{wheel}	x_{track}	z_{track}	Score
baseline	227	532	756	383	3.8
1	83	638	625	445	2.3
2	96	621	625	411	11.3

cab constraint.

The resulting design has the seat track and steering wheel 17 and 33 mm lower, respectively, than in Design Scenario 1 (Table 1). The design is less desirable than the first-scenario solution, with a score of 11.2 mm compared with 2.3 mm for Scenario 1, showing the impact of the combined headroom and cab-length constraints. Enforcing headliner and back-of-cab restrictions simultaneously significantly reduces the number of drivers that can adjust the seat and steering wheel as they would prefer. This may affect marketability, safety, and other performance metrics.

DISCUSSION

The current work differs in important ways from standard industry practice for truck design. Unlike typical computer manikin approaches, the stochastic posturing methods explicitly consider residual variance in posture that is unrelated to body dimensions and cab geometry. This allows more accurate quantification of population accommodation and design fitness. Unlike the current SAE tools, the new method is explicitly multivariate and allows simultaneous considerations of multiple design features while maintaining the quantitative rigor that is the primary strength of the SAE models. Moreover, the current implementation spans a larger range of potential design variables than current SAE tools and can be readily expanded to encompass more. Finally, the new methods allow unambiguous inclusion of both subjective (e.g., comfort) and objective (e.g., safety) metrics in cab optimization.

The cab optimization problem is a specific case of the more general problem of designing for human variability. As noted above, most approaches to including human variability focus on body dimensions but ignore behavior. The methodology outlined in this paper separately models these two sources of variability in outcomes and adds variability in subjective perception. The application of these techniques requires the collection of data describing the outcomes of interest (driver posture and preference, in the current case) and the development of appropriate statistical models (e.g., [10,18]). Of course, the accuracy and utility of this optimization approach is limited by the validity of the underlying models. Better models are needed to describe both postural and subjective responses to censoring of various kinds, particularly for censoring of multiple degrees of freedom. In the cab optimization problem, improved cost functions are also needed for safety related measures such as exterior vision.

In addition to improved models, future work will examine this methodology in the broader context of designing for human variability. For example, since the entire population is currently sampled multiple times during each iteration of the optimization, the computational expense of complex problems can increase rapidly. At any particular step in an cab optimization, only a subset of the current population may be contributing to changes in the objective function. Optimizing for carefully selected subsets of the population prior to evaluation with a large group may provide the best balance between speed and accuracy. Other benefits from the methodology, such as exploring the design space for alternative designs and understanding design tradeoffs are also under investigation.

In this work we focused on improving the score that expresses an aggregation of multiple objectives. We plan to formulate and solve robust multi-objective optimization problems that also reduce score variance. Probabilistic constraints can also be introduced readily to the formulation, which may be one way to treat the multi-objective problems.

NOMENCLATURE

N	number of drivers in population
n	matrix index of a particular driver in the population
$\mathbf{D}(\mathbf{x})$	matrix of population data including anthropometry, posture, and disaccommodation metrics
$D_{n,track}$	Seat track disaccommodation for the n^{th} driver in the population, measured in mm
$D_{n,wheel}$	Steering wheel disaccommodation for the n^{th} driver in the population, measured in mm
x_{track}	horizontal location of the seat track
$\mathbf{x}$	location (x,z) of both the steering wheel and seat track
$f(\mathbf{x})$	normalized disaccommodation for the driver population

ACKNOWLEDGMENT

We gratefully acknowledge the support of the Automotive Research Center and the Human Motion Simuation Laboratory at The University of Michigan. The development of the driver models used in this research was supported by International Truck and Engine Corporation, PACCAR, and Transom Technologies (now UGS-PLM Solutions).

REFERENCES

[1] Roe, R., 1993. “Occupant packaging”. *Automotive Ergonomics*, B. Peacock and W. Karwowski, eds., Taylor & Francis, pp. 11–42.

[2] SAE International, 2005. *Automotive Engineering Handbook*. SAE International, Warrendale, PA.

[3] Chaffin, D., 2001. *Digital Human Modeling for Vehicle and Workspace Design*. SAE International, Warrendale, PA.

[4] Reuding, T., and Meil, P., 2004. “Predictive value of assessing vehicle interior design ergonomics in a virtual environment”. *Journal of Computing and Information Science in Engineering,* **4**(2), pp. 109–113.

[5] Chung, S.-J., and Park, M.-Y., 2004. “Three-dimensional analysis of a driver-passenger vehicle interface”. *Human*

Factors and Ergonomics In Manufacturing, **14**(3), pp. 269–284.

[6] Hamza, K., Hossoy, I., Reyes-Luna, J., and Papalambros, P., 2004. "Combined maximization of interior comfort and frontal crashworthiness in preliminary vehicle design". *International Journal of Vehicle Design,* **35**(3), pp. 167–185.

[7] Berson, B., 2002. "Modernization of a military aircraft cockpit". *Ergonomics in Design,* **10**(3), pp. 11 – 16.

[8] HFES 300 Committee, 2004. *Guidelines for Using Anthropometric Data in Product Design*. Human Factors and Ergonomics Society, Santa Monica, CA.

[9] Bittner, A., C., 2000. "A-CADRE: advanced family of manikins for workstation design". *Proc. Human Factors and Ergonomics Society*, Human Factors and Ergonomics Society, pp. 774–777.

[10] Reed, M, P., Manary, M, A., Flannagan, C, A. C., and Schneider, L, W., 2002. "A statistical method for predicting automobile driving posture". *Human Factors,* **44**(4), pp. 557–568.

[11] Loczi, J., 2000. "Application of the 3-D CAD manikin ramsis to heavy truck design". *Proc. Human Factors and Ergonomics Society*, Human Factors and Ergonomics Society, pp. 832–835.

[12] Reed, M., Lehto, M., and Schneider, L., 2000. "Methods for laboratory investigation of truck and bus driver postures". *Technical Paper 2000-01-3405. SAE Transactions: Journal of Commercial Vehicles.,* **109**.

[13] Flannagan, C., A., Manary, M., A., Schneider, L., W., and Reed, M., P., 1998. "Improved seating accommodation model with application to different user populations". *Proc. SAE International Congress & Exposition*, Vol. 1358, SAE, Warrendale, PA, USA, pp. 43–50.

[14] Porter, J., Case, K., Marshall, R., Gyi, D., and Sims, NO, R., 2004. "Beyond Jack and Jill: Designing for individuals using HADRIAN". *International Journal of Industrial Ergonomics,* **33**(3), pp. 249–264.

[15] Manary, M., A., Flannagan, C., A., Reed, M., P., and Schneider, L., W., 1998. "Development of an improved driver eye position model". *Proc. SAE International Congress & Exposition*, Vol. 1358, SAE, Warrendale, PA, USA, pp. 9–16.

[16] Gordon, C., Churchill, T., Clauser, C., Bradtmiller, B., McConville, J., Tebbetts, I., and Walker, R., 1989. "1988 anthropometric survey of U.S. Army personnel: Methods and summary statistics. final report". *(NATICK/TR-89/027).*

[17] Jahns, S., Reed, M., and Hardee, H., 2001. "Methods for in-vehicle measurement of truck driver postures". *SAE Technical Paper 2001-01-2821.*

[18] Reed, M., and Flannagan, C, A. C., 2001. "Modeling population distributions of subjective ratings". *SAE Technical Paper 2001-01-2122.*