

# **A New Approach to Modeling Driver Reach**

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Reprinted From: **Human Factors in Driving, Seating, & Vision**  
(SP-1772)

2003 SAE World Congress  
Detroit, Michigan  
March 3-6, 2003

**SAE** *International*<sup>™</sup>

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**ISSN 0148-7191**

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**Printed in USA**

# A New Approach to Modeling Driver Reach

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## ABSTRACT

The reach capability of drivers is currently represented in vehicle design practice in two ways. The SAE Recommended Practice J287 presents maximum reach capability surfaces for selected percentiles of a generic driving population. Driver reach is also simulated using digital human figure models. In typical applications, a family of figure models that span a large range of the target driver population with respect to body dimensions is positioned within a digital mockup of the driver's workstation. The articulated segments of the figure model are exercised to simulate reaching motions and driver capabilities are calculated from the constraints of the kinematic model.

Both of these current methods for representing driver reach are substantially limited. The J287 surfaces are not configurable for population characteristics, do not provide the user with the ability to adjust accommodation percentiles, and do not provide any guidance on the difficulty of reaches that are attainable. The figure model method is strongly dependent on the quality of the models used for posturing and range of motion, and, in any case, cannot reliably generate population distributions of either reach capability or difficulty.

A new method of modeling driver reach capability is presented. The method is based on a unified model of reach difficulty and capability in which a maximum reach is a maximally difficult reach. The new approach is made possible by new measurement methods that allow detailed and efficient sampling of an individual's reach-difficulty function. This paper summarizes the experimental approach and presents the structure of the new integrated model of population reach difficulty and capability.

## INTRODUCTION

### SAE Recommended Practice J287

Reach analysis is one of the primary activities in assessing driver workstation layout. Vehicle designers and engineers must verify that the primary and secondary controls can be reached and manipulated by an acceptable percentage of the driver population. The

most commonly used tool for representing driver reach capabilities is the model embodied in SAE Recommended Practice J287 (SAE 2002). The J287 surfaces are parameterized by a packaging factor that combines vehicle interior dimensions, including seat height, fore-aft and vertical steering wheel position, and steering wheel diameter, into a single "G" score. Surfaces are available for several different values of G.

In the laboratory study on which J287 is based (Hammond and Roe 1972), maximum reach data were obtained from 120 men and women in three vehicle package configurations. Figure 1 shows the test apparatus. Drivers grasped the ends of the measurement rods and pushed them forward as far as possible. The rod rack was moved laterally to span the space in front of the driver. No data were collected for vertical or lateral reaches. Testing was conducted with lap belts only and with lap and fixed-length torso belts. The data were analyzed to produce reach surfaces, an example of which is shown in Figure 2. The reach surfaces are interpreted with respect to population capability, as opposed to the capability of individuals with a particular body size. For example, 95 percent of drivers from a 50/50 male/female U.S. driving population are expected to be able to reach to push-button targets that are located aft of the surface depicted in Figure 2. Note that this is *not* the reach capability of a male driver who is 95<sup>th</sup> percentile by stature, or of any other particular anthropometric category.

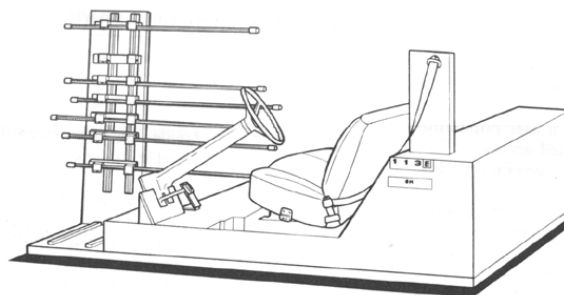


Figure 1. Test fixture used for the SAE driver reach study (Hammond and Roe 1972).

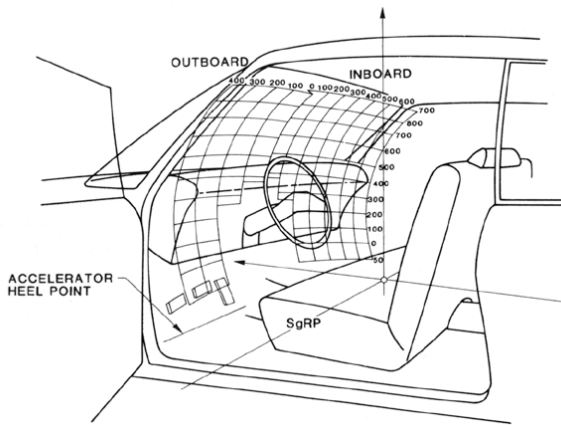


Figure 2. Surface generated from J287 (Roe 1993).

The reach surfaces in J287 are positioned relative to the vehicle seating reference point (SgRP), which corresponds to a seat H-point location obtained with the seat near the rear of the seat adjustment path.

J287 presents reach surfaces for two restraint conditions: lap belt only and lap belt plus fixed-length shoulder belt. The emergency locking retractor used almost universally on modern vehicles, which allows spooling of the belt with low belt tension, was not yet in widespread use when the original study was conducted. Although the lap-belt-only condition would seem to be more representative of the restraint condition in modern vehicles, industry practitioners more commonly use the lap-plus-torso-belt surfaces to develop design guidelines and assess designs. This practice is motivated by the observation that controls located within the more-restrictive surfaces obtained with torso restraint are almost certainly reachable by a large percentage of the driving population. In effect, practitioners use the lap-plus-torso-belt maximum-capability surface as an acceptable-difficulty surface for drivers with modern retracting belts.

One of the strengths of the J287 approach is that it incorporates an implicit seat-position model. The maximum reach of a driver relative to the vehicle is a function of the driver's capabilities (including those determined by body dimensions) and the driver's seat position and torso posture. The locating functions in J287 take into account the effects of vehicle package geometry and body dimension distributions on driver-selected seat position. However, the seat-position model implicit in J287 cannot be separated from the reach model, and hence the accuracy of the reach capability assessment is dependent on the extent to which the G-factor equation accurately reflects the effects of package variables on driver-selected seat position. Recent research leading to the development of a new seat-position model (Flannagan et al. 1998) suggests that the range of package variables used in the original study may have been insufficient to yield an accurate seat position model.

There is also no capability within J287 to adjust for a different population (taller, shorter, or more obese, for example). Most critically, J287 provides no information on how difficult an attainable reach will be. If the model is accurate, a control located just inside the 95th-percentile surface (for example) would be unreachable by only 5 percent of the driving population. However, the distribution of reach difficulty for the 95 percent who are capable of reaching the control is unknown. Hence, the practice provides no guidance for optimizing control locations within the attainable reach zone. As noted above, the common work-around for this limitation is to use the more-restrictive lap-plus-shoulder-belt surfaces, rather than the lap-belt-only surfaces that might be thought to be more applicable to drivers in modern vehicles. However, this approach may be unnecessarily restrictive. As the number of controls presented to the driver increases, the need for a more robust and flexible model of driver reach capability and reach difficulty has become more apparent.

### The Figure Model Approach

Over the past decade, digital human figure models (computer manikins) have been used for an increasing number of driver workstation assessments (Porter et al. 1993; Chaffin 2001). Manikins are commonly used to simulate reach to controls, with the outcomes of the manikin-based studies used to assess control locations. The primary advantage of manikin-based reach assessments is that the visual depiction of a person performing a task has considerable value for communicating the analysis results. The intended meaning of a task assessment depicted with a figure model is much clearer to an audience unfamiliar with ergonomic assessment than the same problem analyzed using the SAE J287 reach surfaces.

However, manikin-based approaches to modeling driver reach capability provide considerably less information than the statistically based models. Reach information from a single manikin, representing a single set of body dimensions starting from a particular driving posture, provides little information that is useful for making a quantitative assessment of a vehicle interior design. Most users of figure models will repeat a reach analysis with a family of manikins having different body dimensions, but this approach provides only the appearance of capturing the range of variability in reach capability within the driver population.

The primary limitation in reach analyses using figure models is that variance in body dimensions is only one factor influencing reach capability. Equally important is the driver's posture and position, which are the starting conditions for the reach. People who are anthropometrically similar often sit with widely different seat positions and torso recline angles. For example, Flannagan et al. (1998) found that the standard deviation of fore-aft seat position for people of the same stature in

passenger cars and light trucks is about 30 mm. Since fore-aft seat position is a primary determinant of what a driver can reach in package space, any single seat position used with a particular figure model will be at best a rough approximation of the reach capability of people of that size. Monte-Carlo statistical techniques can be used to perform analyses in an automated fashion by combining variance in seat position and torso posture with sampled sets of anthropometric variables. However, the data required to validate such an approach could be used to generate a statistical model that could be much more easily implemented.

Moreover, reach envelopes generated from figure models rely on assumptions about joint ranges of motion (ROM). Although joint ROM is configurable in most human models, distributional data for joint ROM across individuals, and the association between joint ROM and anthropometric variables, is not available within most human modeling software packages. Hence, reach analyses are usually done with a wide range of manikin sizes but only one or a few sets of joint ROM.

Figure models are able to predict comfort or discomfort ratings for the terminal posture of a reach, but this information cannot be reliably linked to population distributions of ratings. If the discomfort rating from one of a family of ten manikins used to simulate a reach exceeds some criterion, it is not generally accurate to conclude that 10 percent of drivers would also rate the reach discomfort above the criterion. Even if the manikins are selected to be anthropometrically representative of the population, the postural variability that is unrelated to anthropometry will not be represented in the analysis.

### Other Population Studies

The design of the SAE driver reach study (Hammond and Roe 1972) was probably influenced by previous reach studies. Figure 3 depicts maximum reach envelopes for Air Force pilots from Kennedy (1964). In that study, pilots sitting on a rigid seat and restrained by a torso harness pushed against measurement rods to demonstrate their maximum reach capability. The measurement rods were rotated around the pilot to map out the maximum reach envelope in a cylindrical coordinate system. Envelopes for 5th, 50th, and 95th-percentile maximum reach were presented graphically and in tabular form.

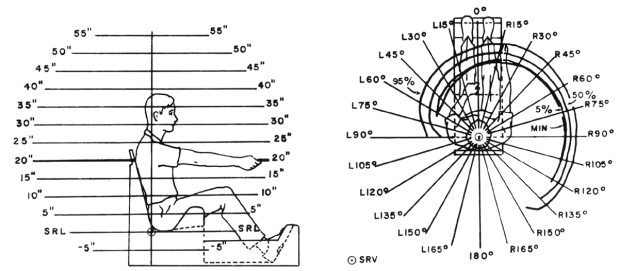


Figure 3. Typical data from Kennedy (1964), showing selected percentiles of grasp reach for pilots on one horizontal plane.

Several studies of driver reach have been conducted since the original SAE controls reach study, but none has had an important effect on industry practice in the U.S. Stoudt et al. (1970) published reach data obtained in a study of over 1000 men and women. However, the data were collected in a vehicle mockup with a rigid seat and without a steering wheel. The data were also presented with respect to the seat, rather than the vehicle package, so the data could not effectively be used for vehicle design. The increased prevalence of seat belts during the 1960s and 1970s led several investigators to conduct studies of the effects of restraints on reach (Haslegrave 1970; Bullock 1974; Asfour 1978; Garg et al. 1982). None of these studies included populations and test conditions appropriate to the development of generalized models of driver reach. All noted that adding fixed-length torso belts decreased functional reach, but these data are not applicable to belts with modern retractor systems.

An important limitation of previous reach studies, including the SAE study, is that the results are presented in tabular form. None of the publications presents a general model of reach capability that includes configurability for the characteristics of the population. The J287 model includes configurability for task constraints (vehicle geometry), but only to direct the reader to a particular table. As recently as 2000, reach data are still being presented in tabular form without configurability for population anthropometry (Sengupta and Das 2000).

In early studies, the authors could assume that readers did not have access to computers that could rapidly calculate and render surfaces from mathematical expressions. Now, however, mathematical expressions of study outcomes have more utility than tabular data, because they can be more reliably and easily transferred to computer-aided-design (CAD) systems. The expression of the results of a reach study in mathematical terms also allows the modeler to include the effects of anthropometric and task factors without having to add multiple tables of numerical values to a publication.

## An Integrated Approach to Reach Capability and Difficulty

This paper outlines a new approach to modeling driver reach that has several unique features intended to overcome some of the limitations of existing models:

1. Data are collected using a computerized target positioning system that improves the efficiency and accuracy of data collection over previous methods.
2. The model addresses reach difficulty and represents the maximum attainable reach as a maximally difficult reach. Population distributions for reach-difficulty ratings within a large volume are predicted.
3. The model is explicitly designed to be compatible with contemporary vehicle design practices, including new seat position models (Flannagan et al. 1998) and the new SAE eyellipse (Manary et al. 1998). Like those models, the new reach model is configurable for driver anthropometry distributions and gender mix. The seat position model is an integral part of the reach model.
4. The model is configurable for package dimensions (seat height, steering wheel position, etc.) through the integration with seat position model.

The data collection and modeling approach was evaluated in a pilot study of eleven men and women. This paper presents the data-collection and modeling methodologies along with sample results.

## METHODS

### Computer-Controlled Target Positioning Apparatus

Previous studies have measured participants' maximum reach capability by asking them to grasp and push rods (Kennedy 1964; Hammond and Roe 1972). Because a central goal of the current research is to record subjective ratings of submaximal reach difficulty, a different approach is required. The test seat is mounted on a motorized, rotating platform, as shown in Figure 4. A push-button target is located on a motorized apparatus that can move vertically and horizontally. The angle of the button-mounting box can also be rotated around a horizontal axis. By rotating the seat platform and adjusting the horizontal and vertical target position, the target can be placed anywhere within the participant's reach envelope. The entire system is under computer control, so that a specified target location in a seat-centered coordinate system can be obtained automatically.

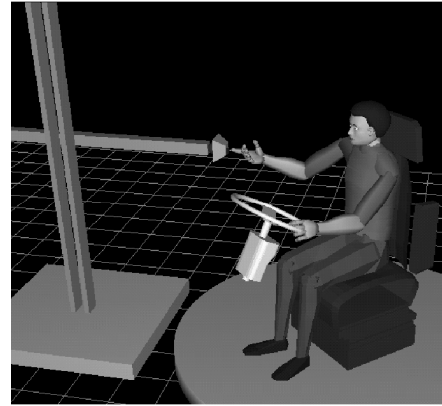


Figure 4. Model of test facility, showing rotating seat and computer-controlled target-positioning apparatus.

### Pilot Study

A pilot study was conducted using mockups of driver stations from a passenger car and heavy truck. Figure 5 shows a participant completing a reach in the truck mockup. Each participant was tested using 216 target locations distributed throughout the right-hand reach envelope. After receiving a visual signal, the participant performed a right-handed reach to the target, pressed the button for two seconds with his or her index finger, and returned to the home position. The participant rated the difficulty of the reach by moving a labeled slider on the steering wheel. The participants were instructed to rate reaches that were at the edge of their reach capability as 10, with submaximal reaches rated on a continuous scale from 1 to 10. Targets that were unreachable were scored as 11.

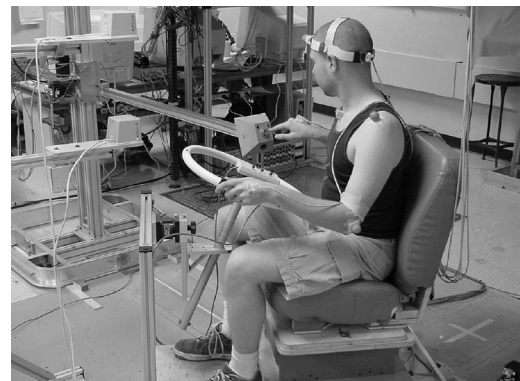


Figure 5. Participant in the pilot study, showing truck driver station mockup (steering wheel, seat, pedal plane fixture) and target positioning apparatus. The participant is wearing targets used to track motions.

A target location matrix was constructed with target locations on six radial planes and five vector directions with respect to horizontal. Figure 6 shows the sampling planes with respect to the seat H-point and centerline. The target locations were scaled using initial measurements of each participant's maximum vertical, lateral, and forward reach. The scaling was designed to

place about 15 percent of the reach target locations beyond the participant's maximum. Target locations were concentrated in the outer regions of the reach envelope where the reach difficulty was expected to change more rapidly with increasing distance from the H-point. Because the steering wheel interfered with forward reaches, the origin for the sampling vectors on the -30, 0, and 30-degree planes (see top view in Figure 6) was at shoulder height, rather than at H-point height. Figure 7 shows the target locations as a mesh along with the exclusion zone around the participant.

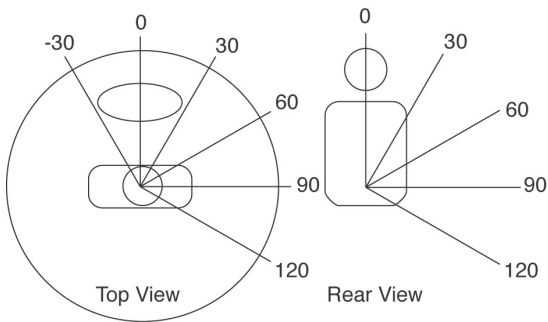


Figure 6. Target location vectors for pilot study. Angles in degrees.

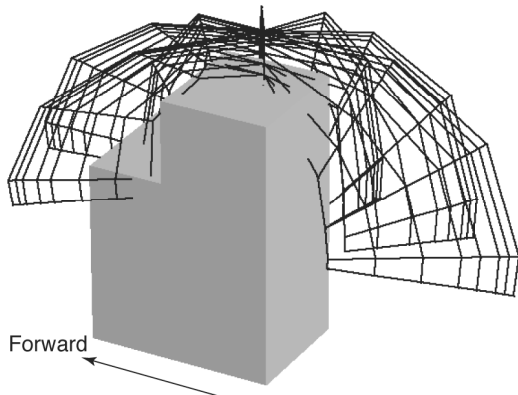


Figure 7. Target locations as a mesh, showing the exclusion zone surrounding the participant.

## RESULTS

Figures 8 and 9 show ratings data for one participant in the truck mockup by sampling plane and radial distance. As expected, reach difficulty was a strong function of radius, with the rate of increase in difficulty with radius increasing near the maximum reach. Reaches on the 120-degree plane (reaching to the rear of H-point) were more difficult than those on other planes. Steering-wheel interference caused a steep difficulty gradient on the forward reaches, with a moderately difficult reach becoming impossible with only a small increase in radius due to torso contact with the steering wheel.

A preliminary examination of the data suggested that a simple linear function with an exponential term could model the shapes of the radially organized data with reasonable fidelity. The data for each radial vector were fit with a function of the form

$$D(r) = a + b r + \text{Abs}[c] \text{Exp}[r / d] \quad [1]$$

where  $D(r)$  is the difficulty rating at a particular radial position  $r$  and  $a$ ,  $b$ ,  $c$ , and  $d$  are constants. For the current analysis,  $d$  was set to a constant value of 250 and  $a$ ,  $b$ , and  $c$  were fit by a least-squares method.

Figure 10 shows the fits (dark lines) overlaid on the data from Figure 9. Preliminary examination of the residuals suggests that the errors are normally distributed with a standard deviation of about 0.5 to 0.75 ratings points across subjects. The suitability of equation 1 for representing the form of the radial difficulty function was assessed by examining the residuals across the sampling vectors. The mean and standard deviation of the residuals has not been found to be related to either the sampling vector direction or radius, suggesting that the form of equation 1 is adequate.

A three-dimensional analog of equation 1 in spherical coordinates can be used to fit the data from a participant. The resulting function can be solved for a particular ratings level to obtain isorating surfaces on which the reach difficulty is uniform. Figure 11 shows isorating surfaces for one participant.

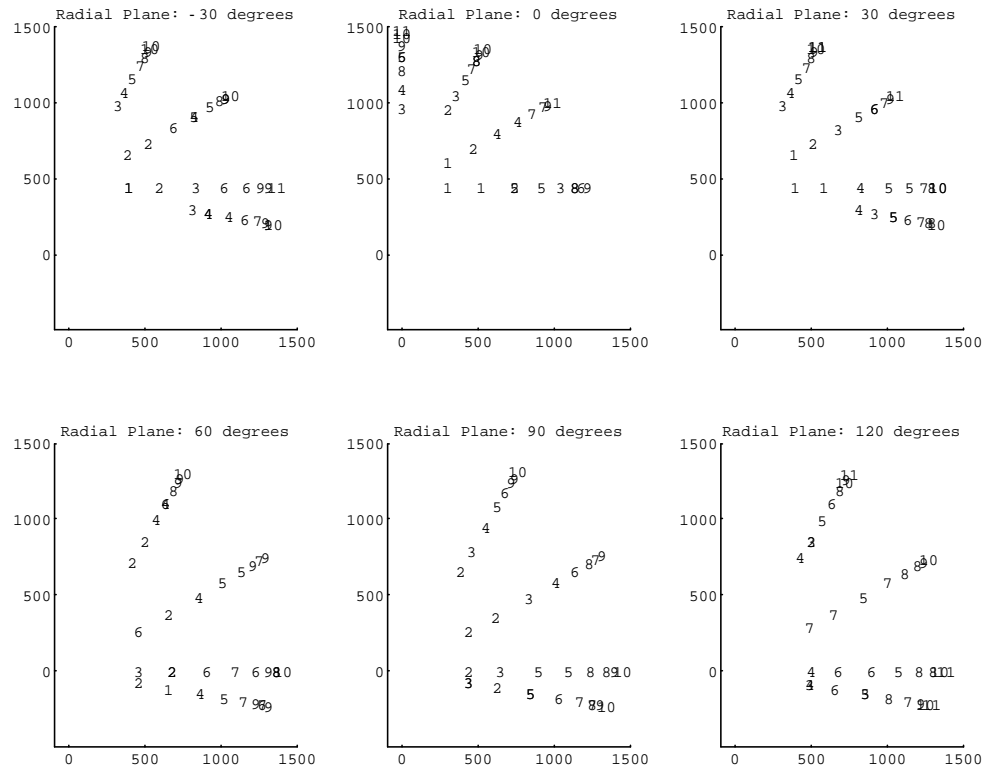


Figure 8. Reach difficulty ratings for one subject in the truck mockup. Radial planes are labeled as in Figure 6. Origin is at seat H-point on seat centerline; axes in millimeters.

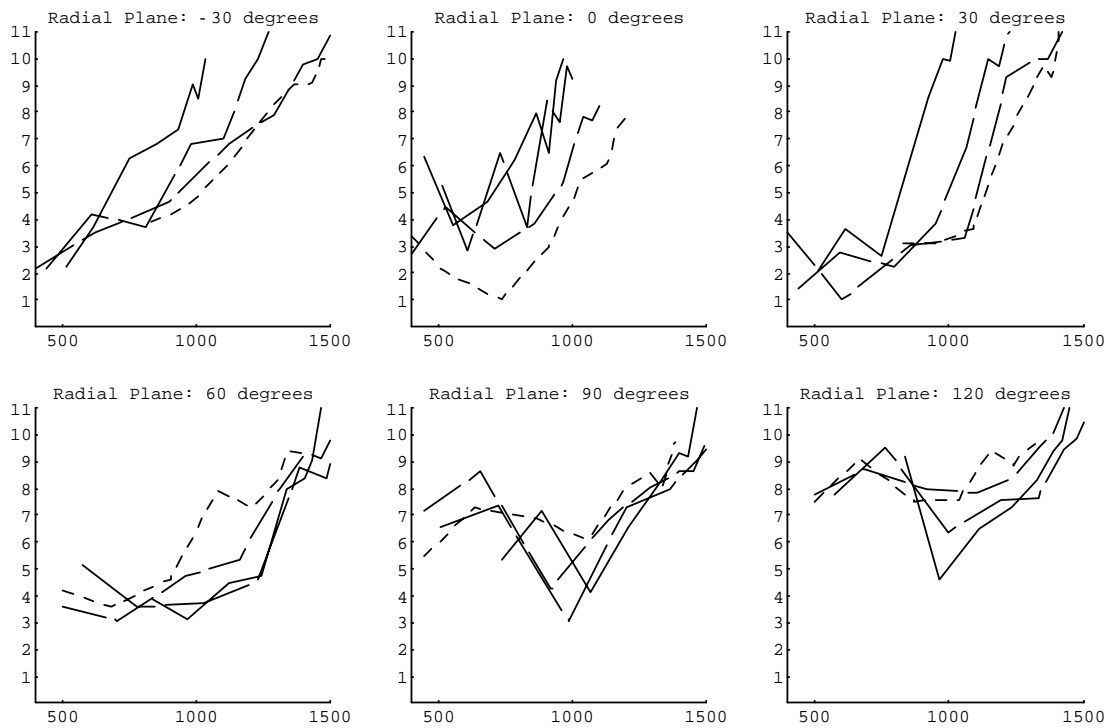


Figure 9. Reach difficulty ratings one participant in the truck mockup. Radial planes are labeled as in Figure 6. Origin is at seat H-point on seat centerline; axes in millimeters. Each line connects data from a single sampling vector. Vectors closer to vertical are shown with longer dashes. Solid line shows data from the most-vertical vector in the plane.



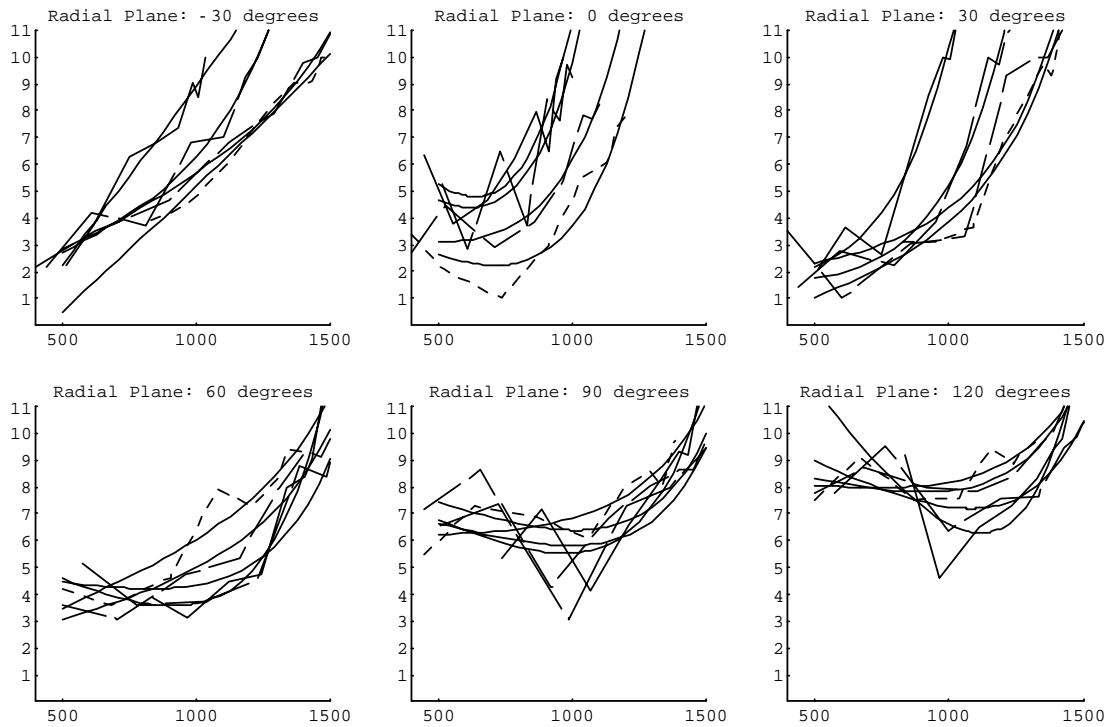


Figure 10. Reach difficulty data from Figure 9 with overlaid with fitted functions.

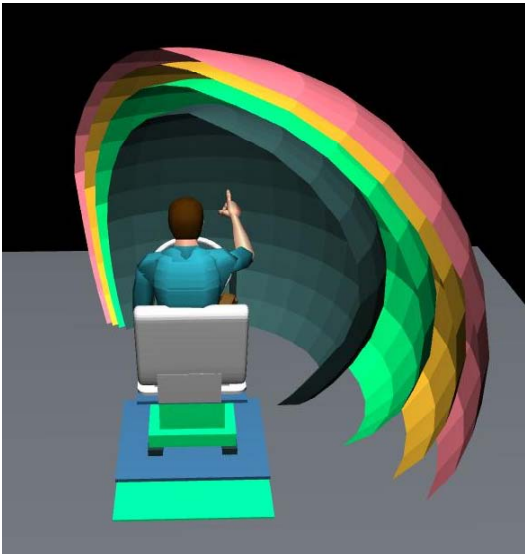


Figure 11. Isorating surfaces for one participant.

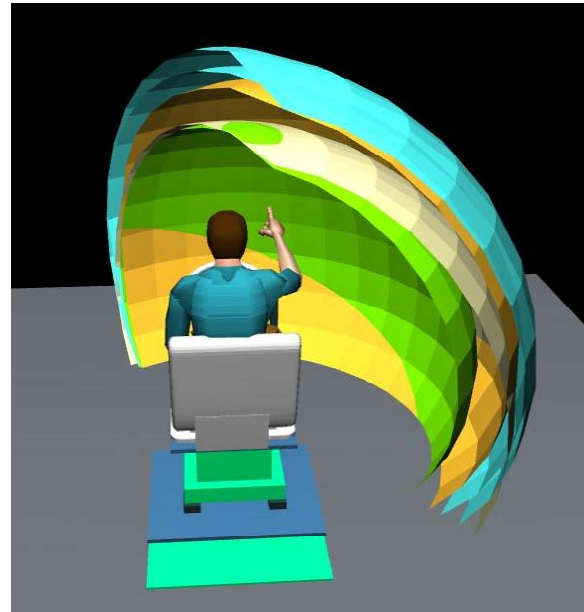


Figure 12. Surface for rating = 8 for five participants in the truck seat.

The parameters of the models fitted to individual participants' data were analyzed with respect to anthropometric variables and task conditions (truck vs. car seat, for example). The resulting relationships can be used to predict the reach difficulty function for an individual. The data from the pilot study show that, after accounting for overall scale, reach difficulty functions are similar across participants. Figure 12 shows isorating surfaces for rating = 8 for five participants in the truck seat.

Creating useful population models from the findings from individual participants requires a more complicated modeling procedure. Figure 13 illustrates the approach schematically. Experimental data are analyzed to determine (1) the structure of individual's reach difficulty functions and (2) the relationships between the parameters of these functions and anthropometric and task variables. Since these models will not account for

all of the variance across individuals, the residual variance will be noted for use in subsequent modeling. In predicting reach functions for a particular vehicle, the process begins with the distributions of anthropometric variables for the target driving population (usually stature distributions and gender mix). The anthropometric information is used to generate population distributions of reach difficulty functions with respect to the seat H-point. Depending on the final form of the models, it may be possible to do this in closed form, but, more likely, this step will be performed numerically by simulating a large number of drivers, predicting their reach difficulty functions from anthropometric variables, and including the random residual variance in the reach difficulty parameters.

The next step is to apply the appropriate distribution of seat positions. In previous research (Flannagan et al. 1998), a model that predicts the distributions of driver-selected seat position from vehicle and anthropometric factors has been developed. When applied using a numerical simulation approach, the residual variance in this model can also be incorporated. Each simulated reach difficulty function from the previous step, representing one driver, is positioned using the predicted seat position from the seating accommodation model. The result is a population of reach difficulty functions positioned within the vehicle package space. These functions can then be processed in a number of ways to perform design analyses.

Perhaps the easiest way to apply the reach difficulty functions is to calculate isorating surfaces analogous to the familiar surfaces in J287. For example, the reach difficulty functions can be solved for the rating = 10.5, which is midway between unreachable (rating = 11) and the maximum-difficulty attainable reach (rating = 10). This isosurface is equivalent to the maximum reach envelope for an individual. Computing across a simulated population, the surface in package space to which, for example, 95 percent of the selected population can reach, can be computed. A model similar to J287 could be constructed by choosing a few populations of interest and solving for a set of typical surfaces (say, 95 percent of the population rating < 7). The positioning of these surfaces in package space would be determined by a linear equation of package variables, most likely a constant offset from the median population seat position given by Flannagan et al. (1998).

For more sophisticated analyses, the simulated population distributions of reach difficulty would be retained. In one potential application, the difficulty of reaching to two alternative locations for an in-vehicle information device could be evaluated by computing the population distributions of reach difficulty for each location. An overlay of the cumulative ratings distributions for the two locations would show clearly the extent to which a change in the control position would affect the difficulty of reach to the control.

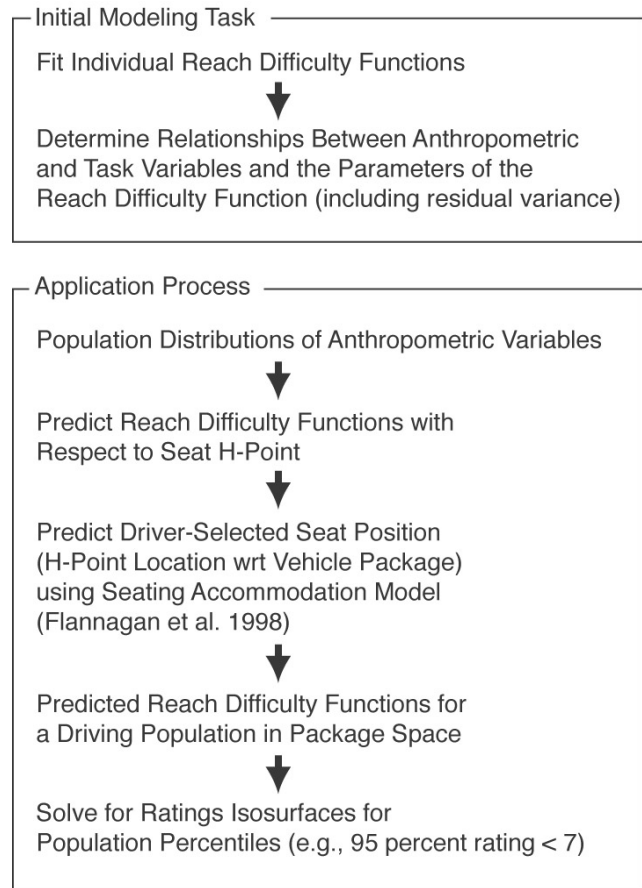


Figure 13. Schematic of the development and application of reach difficulty models.

## DISCUSSION

This paper presents a new, integrated approach to measuring and modeling reach difficulty and capability that is much more complicated than any previous method. Yet, the additional complexity is needed to provide human-factors practitioners with the predictive power needed to make quantitative design decisions. The data collected in previous studies could have been used to generate more complete and flexible models of reach capability, but the computing power needed to apply such models routinely became available only recently. The current approach is practical only because vehicle design is now conducted using computer systems easily capable of making the needed calculations in real time.

One potential criticism of the current approach is that the method does not determine the maximum reach capability of drivers with the precision of previous approaches, in which every data point is a maximum reach. However, the pilot study revealed that, in the relatively unrestricted conditions typical of modern vehicles, maximum reach varies considerably from trial to trial. That is, maximum reach is a probabilistic concept that should be modeled as such. More importantly, true maximum reach for drivers using

modern seat belts is not of substantial interest for design. The maximum right-hand reach of a typical U.S. driver extends substantially across vehicle and yet no designer would consider putting controls in the outer regions of the reach envelope. Current practice implicitly acknowledges this fact by using data gathered with fixed-length torso belts (J287) or by exercising figure models without moving the torso. As noted above, these approximations do not provide accurate guidance for locating controls.

The need for a new model of reach could be questioned on the grounds that there are few complaints regarding control reach in modern passenger cars and light trucks. While this may be the case, there are a number of reasons to believe that a new model of the type proposed is needed. First, the number and complexity of in-vehicle information systems is expected to increase rapidly, particularly in heavy trucks. Heavy trucks already have many more controls than typical passenger cars, and in-vehicle navigation and information systems are adding to the control-design challenge. Second, accommodating an aging population will necessitate increasing the size of controls on already crowded instrument panels, pushing controls farther from the easily reached zones used currently. The current models are not useful for quantifying the implications of these changes on the difficulty drivers will have in reaching the controls. The new models are also expected to find application for the design of future military vehicles in which a large number of computer-based controls are to be accessed by the driver.

The new modeling approach has some limitations that could be addressed in future work. Currently, data have been collected only for push-button reaches. In the near term, the models will be extended to other types of reach (three-finger grasp, for example) using the methods applied in other studies (e.g., Hammond and Roe 1972) by adding or subtracting constant offsets to convert between different target types. The models also do not account for the effects of different seat designs, although the test seats included typical bolsters. Seat-restriction effects would be most apparent in lateral reaches.

The experimental method requires the participant to view the target during the reach and to hold the reach for two seconds. During actual driving, the visual eccentricity of a target relative to the road ahead may impose additional difficulty not accounted for by the current models. For example, two reaches that produced the same difficulty rating in the laboratory experiment might be perceived as having different difficulty if they require different amounts of glance deviation from the primary driving task. A related limitation is that these models do not account for the potential effects of reaches on the performance of the primary task. In evaluating a control location, the effects of alternative locations on driving performance is clearly of interest.

Any empirical approach to modeling reach capability and difficulty will always be limited by the extent to which the study population represents the target population. One particular concern for reach difficulty modeling is accurately capturing the effects of age. In studies intended to be applicable to cars and light trucks used by the general population, an effort to recruit older drivers with a range of age-associated functional limitations will be necessary.

The new methods developed in the pilot study are now being applied in the heavy truck environment. Data collection using these methods has recently been completed with 65 people, including people with experience driving heavy trucks and buses. These data will provide the opportunity to construct and test a complete version of the model.

## ACKNOWLEDGEMENTS

This research was sponsored by the University of Michigan Automotive Research Center and by the partners of the Human Motion Simulation (HUMOSIM) program at the University of Michigan. HUMOSIM partners include DaimlerChrysler, Ford, General Motors, International Truck and Engine, United States Postal Service, U.S. Army Tank-Automotive and Armaments Command, and Lockheed Martin.

## REFERENCES

- Asfour, S.S., Ayoub, M.M., Mital, A., Bethea, N.J. (1978). Reach profiles for males and females under restrained and unrestrained conditions. *Proc. Human Factors Society Annual Meeting*. Human Factors and Ergonomics Society, Santa Monica, CA.
- Bullock, M.I. (1974). The determination of functional arm reach boundaries for operation of manual controls. *Ergonomics*. 17(3), p. 375-388.
- Chaffin, D.B. (2001). *Digital Human Modeling for Vehicle and Workplace Design*. SAE International, Warrendale, PA.
- Flannagan, C.A.C., Manary, M.A., Schneider, L.W., and Reed, M.P. (1998). An Improved Seating Accommodation Model with Application to Different User Populations. Technical Paper 980651. *SAE Transactions: Journal of Passenger Cars, Vol. 107*.
- Garg, A., Bakken, G.M., Saxena, U. (1982). Effects of seat belts and shoulder harnesses on functional arm reach. *Human Factors*, 24(3), p. 367-372.
- Hammond and Roe (1972). SAE controls reach study. Technical Paper 720199. Society of Automotive Engineers, Inc., Warrendale, PA.

Haslegrave, C.M. (1970). Study of reach to car controls while restrained by a lap and diagonal belt. *MIRA Bulletin*, No. 1., p. 11-15.

Kennedy, K. W. (1964). Reach capability of the USAF population. Phase I-the outer boundaries of grasping-reach envelopes for the shirt-sleeved, seated operator. Report No. AMRL-TDR-64-59. Air Force Systems Command, Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio.

Manary, M.A., Flannagan, C.A.C., Reed, M.P., and Schneider, L.W. (1998). Development of an improved driver eye position model. Technical Paper 980856. *SAE Transactions: Journal of Passenger Cars*, Vol. 107.

Porter, J.M., Case, K., Freer, M.T., and Bonney, M.C. (1993). Computer-aided ergonomics design of automobiles. In *Automotive Ergonomics*, ed. B. Peacock and W. Karwowski, 43-77. London: Taylor and Francis.

Roe, R.W. (1993). Occupant packaging. In *Automotive Ergonomics*, ed. B. Peacock and W. Karwowski, 11-42. Taylor and Francis, London.

SAE (2002). *SAE Handbook*. SAE International, Warrendale, PA.

Sengupta, A.K., and Das, B. (2000). Maximum reach envelope for the seated and standing male and female for industrial workstation design. *Ergonomics* 34(9):1390-1404.

Stoudt, H. W., Crowley, T. J., McFarland, R. A., Ryan, A., Gruber, B., and Ray, C. (1970). Static and dynamic measurements of motor vehicle drivers. Report Number DOT/HS 800 261. National Highway Traffic Safety Administration, Washington, D.C.