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ABSTRACT

The development of a new carrier route vehicle for the U.S. Postal Service began with the design of the vehicle interior from an operator-centered perspective. A task analysis of the postal worker while driving and while performing mail-handling operations guided the layout of the vehicle interior. The Jack™ human modeling software was used, along with SAE Recommended Practices and other tools, to create a vehicle environment that will accommodate a large percentage of the operator population. The challenges of designing for this unique work environment provided a good opportunity to evaluate the relative strengths and weaknesses of the available human factors tools, including the Jack™ digital human figure model. This paper describes the development of the vehicle interior, discusses some lessons learned, and concludes with recommendations for increased functionality and improved integration of vehicle interior design tools.

INTRODUCTION

In 2003, the United States Postal Service (USPS) began the process of acquiring a new carrier route vehicle (CRV). The Postal Service currently operates a fleet of over 200,000 vehicles, of which approximately 140,000 are CRVs known as Long-Life Vehicles (LLV). The USPS put the LLVs into service between 1986 and 1993 and anticipates retiring them over the next 12 to 14 years. The new third-generation (G3) CRV is expected to have a 24-year design life and to be the mainstay of the USPS fleet by the end of this decade.

Vehicle ergonomics is a primary focus of the G3 procurement. As the first step in the process, the USPS commissioned a program to develop an all-new vehicle cab using human-centered design principles. The program was executed by a team led by AM General that included staff from Engineering Solid Solutions, Design Systems, Inc., Henry Dreyfuss Associates (HDA), UGS, and the University of Michigan Transportation Research Institute (UMTRI). HDA, UGS, and UMTRI were responsible for the design and human-factors engineering of the vehicle interior with input from the rest of the team.

This paper presents an overview of this human-centered design program, with an emphasis on the use of digital human modeling and other vehicle interior design tools. In its solicitation for the cab design program, the USPS specifically required the use of digital human modeling as part of the design process. The design team used the Jack™ human modeling software (UGS) in conjunction with a number of other design tools and methodologies to produce a cab design that attempted to maximize the accommodation and safety of the operator within the applicable constraints.

METHODS

Design Constraints

Although the cab design process was focused on ergonomics, the design was constrained by the necessity of creating a cab that could be used with a readily available vehicle chassis. A completely new vehicle could have been developed to specifically address the unique operating conditions of the CRV, but the cost would have been unacceptably high. Instead, the G3 cab was designed for application to a high-production-volume, front-engine, rear-wheel-drive light-truck chassis. This decision defined some constraints on the vehicle, such as the minimum height of the vehicle floor, the fore-aft position of the driver with respect to the engine, and the maximum feasible downvision angles for forward visibility. The USPS specification also added many constraints, including vision requirements and a maximum height and width for the vehicle.

The packaging of the driver in the CRV posed a set of challenges different from those for most private and commercial vehicles. Conflicting objectives necessitated tradeoffs between some of the key vehicle dimensions.

Diverse mail carrier population — Based on USPS data, about 40% of the users of the new CRV will be female. Mail carriers are members of all of the major ethnic groups in the U.S. in proportions similar to their representation in the population as a whole. From the perspective of vehicle interior design, the primary consideration is the population gender mix. The near-equal fractions of men and women in the design population necessitate a vehicle design approach more similar to that used for passenger cars and light trucks than to that used for medium and heavy trucks, whose drivers are predominantly male. Accommodating large men and small women for both driving and mail-handling tasks is a substantial challenge, necessitating careful selection of component locations and adjustment ranges.

External reach for curbline delivery — Delivering the mail to curbline mailboxes imposes some constraints on the vehicle interior design. Ideally, driver shoulder locations would be just above the height of the mailboxes and the driver seat would be positioned as far outboard as possible to minimize torso bending. However, these objectives conflict with some other design goals, notably the desire to maximize external vision for the driver. The optimal driver position for external vision is higher and more inboard than the optimal position for curbline delivery, but the ergonomics of curbline delivery must be considered.

Ingress/Egress — Mail carriers with park-and-loop routes can mount and dismount the vehicle hundreds of times per day, making ease of ingress and egress a high priority. A midrange floor height and seat height provide the easiest ingress and egress. Access is more difficult with low vehicles (sports cars) and high vehicles (heavy trucks). The ingress/egress requirements interact with the external vision requirements, in that a high eye point with respect to the vehicle structure is desirable for external vision. Obtaining a high eye point with an acceptable seat height requires a relatively high floor, and ingress/egress becomes more challenging with a higher floor.

Internal/external reach for mail handling — Mail handling within the cab is facilitated by a relatively upright torso posture, which is facilitated by a relatively high seat height above the floor and a relatively high mail tray location. A more upright torso posture is consistent with the desire to have a high eye point, but conflicts with the need for a moderate seat height to accommodate the smaller members of the diverse mail carrier population. The mail tray must be adjustable in height to allow mail to be easily loaded onto the mail tray from outside the vehicle as well as to provide easy access to the mail from the driver seat.

Eye height with respect to vehicle structure for external visibility — The operating environment for the CRV, which includes predominantly low-speed, stop-and-go operation in neighborhoods, necessitates excellent external visibility for safe operation of the vehicle. External visibility is maximized by increasing driver eye height within the vehicle so that the driver can see targets that are closer to the vehicle over the hood and fenders and through the side windows. However, eye height is constrained by the maximum overall height of the vehicle and by the need to maintain sufficient upvision to see traffic control devices and signs. A higher eye point is also constrained by the need for a moderate seat height to accommodate small drivers and the desire for a lower floor to facilitate ingress/egress.

Indirect vision — Mirror field of view is another critical vision consideration. Because the CRV has no direct or indirect vision through the back of the vehicle (no rear window), excellent mirror coverage to the rear and sides of the vehicle is required. Visibility to the left (the traffic side) of the vehicle is also critical, since the mail carrier, positioned on the right side of the vehicle, has a reduced direct field of view of adjacent traffic than a driver on the left side of the vehicle would have. Increasing the size of the mirrors and moving them closer to the driver expands and improves the quality of the indirect field of view, but the mirrors themselves can pose serious direct-vision obstructions. Optimizing direct and indirect vision involves using larger mirrors but placing them above or below the drivers' eye locations to minimize the impact of direct vision obscuration. Many commercial vehicles operated in urban environments, particularly buses, place the mirrors above the driver's eyes so that direct-vision targets near the horizon are unobstructed and the mirrors are less likely to contact pedestrians or fixed objects during close maneuvering. The same approach was necessitated for this vehicle to allow the mirrors to clear mailboxes and other curbside obstructions. However, the raised mirrors required extensive design effort to create window openings that would permit unobstructed views of the mirrors for all drivers.

Application of the Jack™ Human Modeling System

Detailed ergonomic analyses were performed using the Jack™ human modeling software from UGS. Jack™ is a widely used ergonomic tool that simulates human dimensions and capabilities in virtual mockups of vehicles and workplaces. The Jack^{TM} software was also used extensively to visualize the design and to assess the mail carriers' direct vision. The software provides the ability to view the design from the vantage point of a person of any size. Quantitative studies were performed from the eye locations of the small female and large male carriers required in the USPS specification, as well as from other locations corresponding to other potential eye locations. Jack^{TM} was also used to examine mail loading and other tasks not related to operating the vehicle.

The USPS specified that analyses should be conducted using manikins sized to represent "95th percentile male" and "5th-percentile female" individuals. In discussions with the USPS, a more complete definition of the manikins was agreed upon. The manikins were specified using 5th-percentile female and 95th-percentile male values for the U.S. population for both stature and weight, using data from NHANES III (NCHS 2000). Table 1 lists these values. The body segment lengths corresponding to these reference stature, gender, and weight values were generated in the Jack^{TM} software using regression equations from the ANSUR database (Gordon et al. 1989). For a variety of reasons, the common practice of using a family of manikins was not employed in this project. (See the Discussion for more on this decision.)

Table 1
Reference Anthropometry for Jack Manikins*

Manikin	Stature (mm)	Stature (in.)	Weight (lb)	Weight (kg)
5th-Percentile Female	1504	59	106	48
95th-Percentile Male	1880	74	244	111

* Other body dimensions were obtained using the scaling functions in Jack, which are based on multivariate regression analyses of anthropometric data.

Posturing the Jack Manikins

Accurate posture prediction is critical for obtaining meaningful results from manikin-based analyses. For driver-station analyses, the Jack manikins were postured using the Jack^{TM} Occupant Packaging Toolkit (OPT). The OPT uses posture-prediction models developed at UMTRI for application to passenger car, light truck, and heavy truck drivers. The package specification for the CRV lies in the upper range of SAE Class A, which includes vehicles having a design seat height less than 405 mm. The Class-A posture-prediction model in the OPT was developed and validating using lower-seat-height vehicles with larger cushion angles than the design cushion angle of the CRV G3 (Reed et al. 2003). Consequently, the Class-B prediction equations, which were developed with a wide range of commercial vehicle package geometries, were used instead (Reed et al. 1999). These prediction models have been validated against data gathered in vehicles driven by experienced commercial vehicle operators (Jahns et al. 2001). The OPT posture prediction places the hips and eyes of the Jack^{TM} manikins at the most likely locations with respect to the pedals and steering wheel for drivers with the same body dimensions.

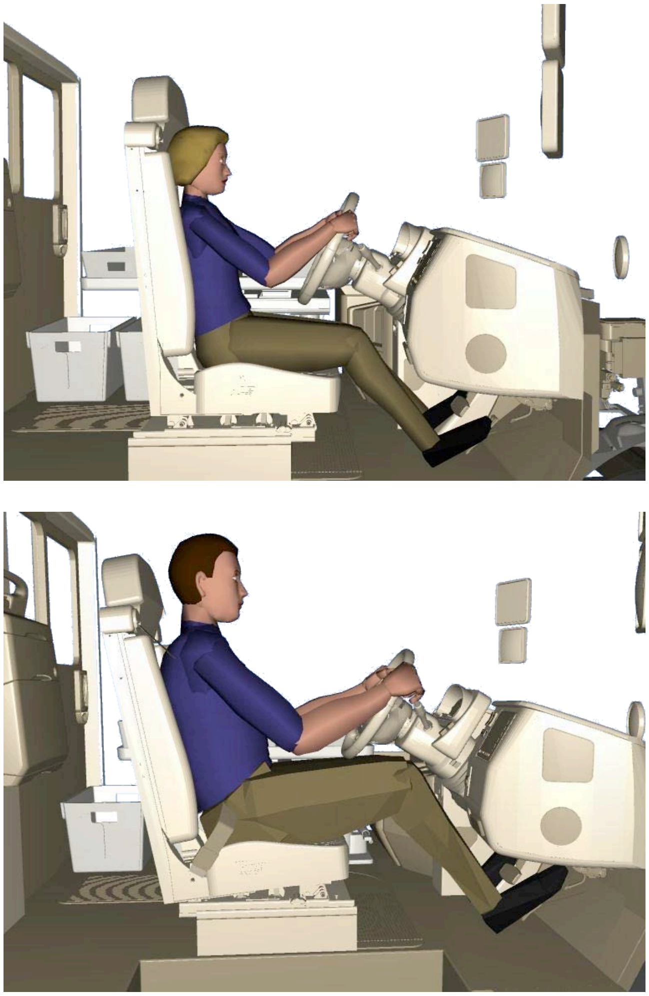

Figure 1. Small female and large male Jack^{TM} manikins shown in normal driving posture in the vehicle interior.

Population Tools

Although manikins are valuable for vehicle design, population accommodation models that include the effects of postural variance are a necessary adjunct to manikin-based analyses for vehicle interior layout. These tools have been called percentile accommodation models (Roe, 1993) and have been used for decades in vehicle design. Accurate quantitative assessment of accommodation for many important variables commonly analyzed in vehicle interiors is difficult using a manikin-based analysis because posture cannot be fully determined from on manikin dimensions (Reed and Flannagan, 2000). For example, driver-selected seat position is associated with driver stature and leg length, but only about 75% of the variance in seat position can be accounted for by anthropometric and vehicle variables. Driver eye location is even less well predicted by body dimensions and vehicle package variables, and hence even optimally accurate posture prediction with a family of manikins will not produce accurate evaluation of accommodation with respect to driver vision (Reed and Flannagan, 2000).

Seating Accommodation Model — The location and size of the seat adjustment range (H-point travel envelope) is a critical determinant of driver accommodation. If the seat does not allow a driver to obtain his or her preferred seating position, an uncomfortable or unsafe condition may result. Beginning in the mid-1980s, the statistical models in SAE Recommended Practice J1517 were used to dimension seat tracks to obtain a desired level of driver accommodation. More recently, an improved model of driver-selected seat position was developed at UMTRI (Flannagan et al., 1998). For the current analyses, a version of the UMTRI seating accommodation model from SAE J4004 was used to define the range of fore-aft travel. The required range of vertical travel was calculated using unpublished statistical models from UMTRI based on data from commercial vehicle operators.

Driver Eyellipse — The eyellipse is a statistical construct that represents the distribution of driver eye locations in package space as a three-dimensional multivariate normal distribution. In 2002, the driver eyellipse in SAE J941 for Class-A vehicles was replaced with a new model based on UMTRI research (Manary et al. 1998). Unlike the earlier version, the new Class-A eyellipse includes the effects of steering wheel position, is configurable for population, and does not include design seat back angle as an input variable.

In the current program, the J941 eyellipse supplemented the manikin-based analyses. In typical use, tangents to the 95% cutoff eyellipse were used to assess driver vision. These results confirmed with greater quantitative rigor analyses that were conducted from the manikin eye points. For example, a tangent to the bottom of the eyellipse constructed tangent to the hood on driver centerline demonstrated the point on the ground plane that at least 95% of drivers could see in their normal seated position.

Reach Difficulty Envelopes — Reaches with one or both hands are among the tasks most commonly simulated with human figure models. Since the mid-1970s, driver reach has been assessed using reach surfaces in SAE J287. The J287 model is based on data from laboratory studies in three vehicle packages conducted in the early 1970s. However, the J287 model is not configurable for population anthropometry, does not include consideration of lateral reaches, and is based on data from belt restraint conditions that are not representative of contemporary vehicles. Moreover, the J287 model provides population cutoffs for maximum reach only, and does not provide information about the difficulty of submaximal reaches.

In the current program, a new model of driver reach developed at the University of Michigan was applied (Reed et al. 2003b). Surfaces generated by the model were positioned in the vehicle package space (Figure 2) to assess the reachability of controls, storage, the mail tray, and a curb mailbox mounted in a range of positions specified by the U.S. Postal Service. The reach difficulty model is a valuable adjunct to manikin-based analyses, because it is difficult to determine using a manikin whether an extreme target is truly reachable (Reed et al. 2003a) and how difficult a person would find a particular reach to be. More importantly, the reach difficulty model provides estimates of the percentage of the population who could complete a reach at a specified level of subjective difficulty, an important assessment that is not taken into consideration in current manikin-based approaches.

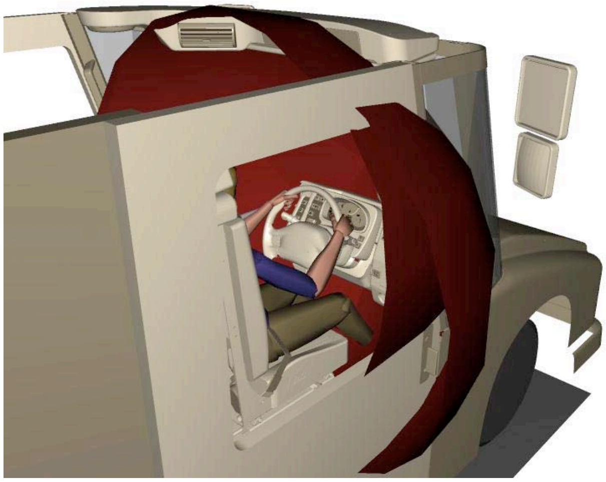

Figure 2. Two of the reach envelopes used to guide the vehicle interior design.

Definition of Tasks and Ergonomic Analyses

For the current analysis, a mail carrier task list was generated based on information in the USPS specification and consultation with USPS representatives. The tasks that were analyzed using the Jack^{TM} software are listed in Table 2. The tasks are grouped according to major activities: loading mail into the vehicle from the left side; getting in and out of the vehicle (ingress/egress); driving the vehicle; performing curbline delivery; and park-and-loop operations.

Tasks were analyzed at three different levels. Level-1 analyses were limited to vision issues and were analyzed using views from the manikin eye points. The manikins were positioned in the normal driving posture for these analyses. Level-2 analyses involved posturing the small male and large male manikins to simulate the specified tasks. Outputs from level-2 analyses were images of the postured figures, showing that the task could be completed without obstruction, and the results of applicable ergonomic analysis tools. Level-3 tasks involved analyses associated with motions, such as ingress and egress. Documentation of the level-3 tasks was based on movement simulations and output from applicable ergonomic analysis tools in the Jack^{TM} software (comfort, low-back loading, strength, etc.).

Human Factors Design Guidelines

The design of the vehicle interior was conducted in accordance with standard human-factors practices. In particular, the instrument panel and related controls and displays were developed with reference to The Measure of Man and Woman (Tilley, 2002). The design included several features intended to improve accommodation, including an instrument cluster that moved with the tilt/telescope steering wheel.

Motion Capture

Complex human motions are difficult to simulate in software, and hence motion capture is the preferred approach for animating figure models when complex movements are required. For the current project, vehicle ingress/egress and mail handling tasks were complex enough to benefit from the use of motion capture. A simple mockup of the preliminary geometry was constructed and movement data were gathered both an electromagnetic tracking system and an infrared camera system that tracked passively illuminated markers attached to the subject. The data from a small woman and a large man getting into and out of the mockup and performing mail-handling tasks were mapped onto the Jack^{TM} figure to allow the movements to be studied with the complete cab geometry in software.

Manikin Analyses

The Jack^{TM} manikins were used for a large number of analyses for the tasks described in Table 2. The analyses can be classified in three categories:

Vision — Both interior and exterior direct vision, and exterior indirect vision using the mirrors, were assessed using the direct eye views from the figure models and using planes representing the figures' lines of sight. This approach is more complete than using fixed eye points, because the effects of head turn can be simulated. Eye views were used to adjust mirror placement interactively, ensuring that the mirror placement was adequate to accommodate both manikins. The vision planes provided design guidance to ensure that controls were visible but not placed in areas that would restrict exterior visibility.

Table 2
Mail Carrier Tasks for CRV-G3 Interior Design

1. Load Vehicle
    1.1. Open left-side door from outside
    1.2. Lift letter trays or bins onto the mail tray
    1.3. Load parcels on or below mail tray
    1.4. Load empty bin for mail collection
    1.5. Load personal items into cab
2. Ingress/Egress
    2.1. Unlock vehicle from outside
    2.2. Unlock vehicle from inside
    2.3. Open/close right-side door from outside
    2.4. Open/close right-side door from inside
    2.5. Stow personal items in vehicle from outside *(See Load Vehicle 1.5)*
    2.6. Mount/dismount the vehicle without satchel
    2.7. Mount/dismount the vehicle with satchel
3. Operate Vehicle
    3.1. Operate controls and access other components (reach targets in Table 3)
    3.2. View exterior direct-vision targets
    3.3. View exterior indirect-vision targets (mirrors and monitor)
    3.4. View interior vision targets
4. Curbline Delivery
    4.1. Open/close right-side window
    4.2. Open mailbox
    4.3. Retrieve mail from mailbox
    4.4. Deposit collection mail in bin
    4.5. Gather mail from mail tray(s)
    4.6. Gather small parcel(s) from mail tray
    4.7. Place mail in mailbox
    4.8. Close mailbox
    4.9. Lower flag on mailbox
    4.10. Retrieve large parcels *(See Load Vehicle 1.3)*
    4.11. Ingress/egress with/without satchel *(See Ingress/Egress 2.6 and 2.7)*
    4.12. Access mobile post office supplies
5. Park and Loop Delivery
    5.1. Park vehicle *(See Operate Vehicle 3.2 and 3.3)*
    5.2. Retrieve satchel from front storage *(See Load Vehicle 1.5)*
    5.3. Load satchel *(See Load Vehicle 1.5)*
    5.4. Ingress/egress *(See Ingress/Egress 2.6 and 2.7)*
    5.5. Access scanner
    5.6. Deposit collection mail *(See Curbline Delivery 4.3)*
    5.7. Access mobile post office supplies *(See Curbline Delivery 4.12)*

Reach — The accessibility of all of the controls and storage areas was assessed using the two Jack^{TM} manikins. Reach zones were generated for both the large male and small female to provide guidance for control placement. As noted above, a population-based reach model was used when greater quantitative rigor was required, but the manikin-based analysis provided a quick way to identify easily accessible areas as well as potential problems.

Clearance — Shoulder, hip, and foot clearances were assessed using the large male manikin. Rather than create new manikins representing, for example, a person with particularly wide hips, the assessment was conducted by applying an appropriate clearance margin to the large male manikin.

RESULTS

The CRV G3 cab developed in this program met or exceeded all of the design objectives. The human-centered design approach combined human figure modeling with population-based statistical models to address a wide range of design issues.

Vision

Driver exterior vision, which was a major emphasis of the design effort, was improved substantially over the LLV. Figure 3 shows some of the vision analyses that were conducted. The cab design emphasized direct vision close to the bumper in front of the vehicle and near the right front fender. Indirect vision was enhanced by using wider mirrors that were positioned to produce less direct vision obstruction than previous designs.

Curbline Mail Delivery

The CRV is used primarily for two types of delivery. In park-and-loop operations, the postal worker parks the vehicle, takes a bag of mail or parcels from the back of the truck, and walks a loop, delivering and pickup up mail. In curbline delivery, the driver remains seated in the vehicle and drives between mailboxes, delivering mail stored in the tray to the left of the driver, and retrieving outgoing mail. Curbline delivery requires the driver's station to become a manual materials handling station, and the high frequency of bending and twisting required for these tasks necessitated considerable scrutiny. Many geometric aspects of the task are externally constrained. For example, mailbox height and position with respect to the curb is defined by a USPS specification. The dimensions and position of the mail storage tray are constrained by the geometry of the tubs and trays of mail that are currently used by the USPS. Within these constraints, the Jack^{TM} software was used to evaluate alternative designs for the mail tray, particularly adjustment ranges, and to confirm that large and small postal workers could successfully deliver the mail. The results were benchmarked against current vehicles to ensure improvement.

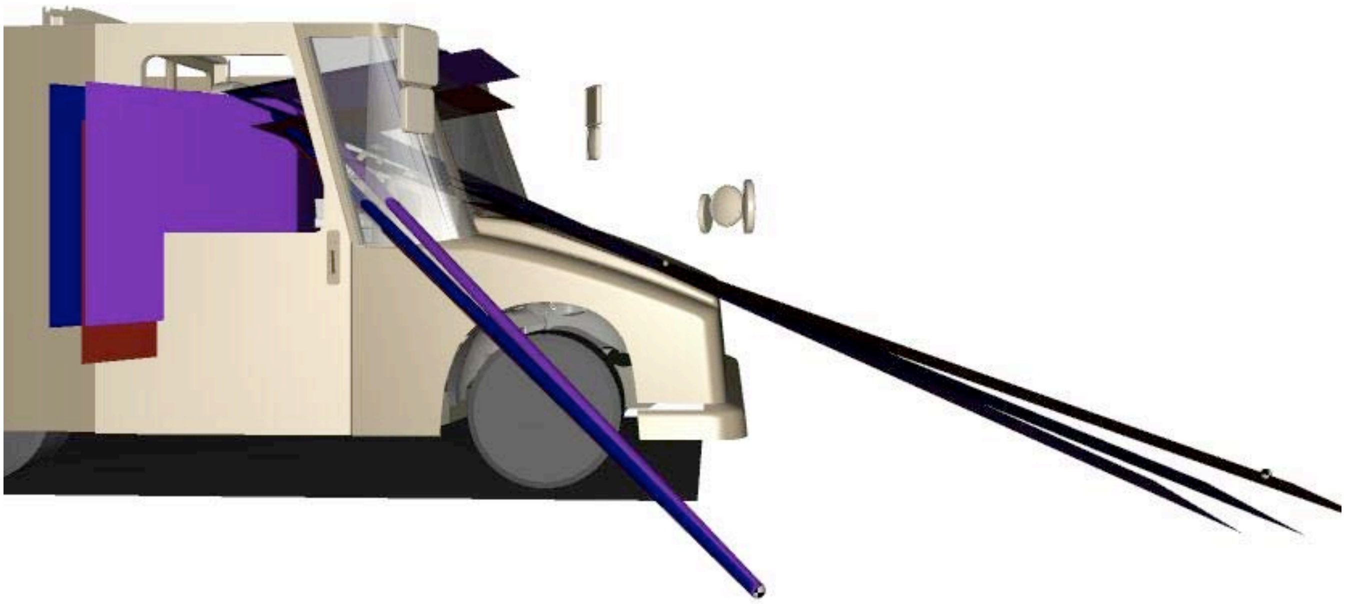

Figure 3. Illustration of some of the vision vectors and planes used to assess direct exterior vision.

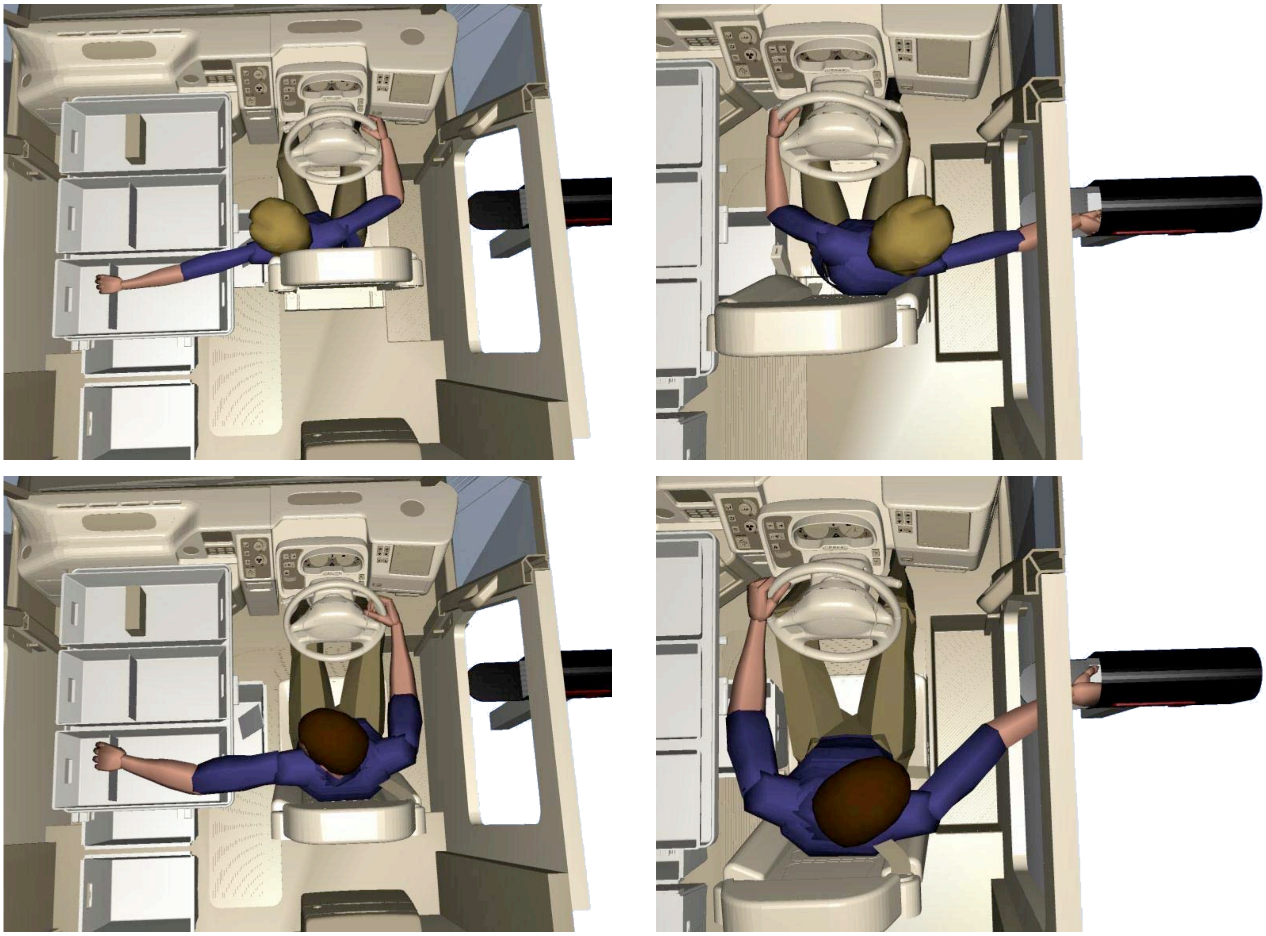

Figure 4. Simulating curbline mail delivery.

Ingress and Egress

In park and loop operations, the mail carrier can mount and dismount the vehicle one hundred or more times in a day. Ensuring that ingress and egress could be performed comfortably and safely by a wide range of workers was of paramount importance. Because it is difficult to simulate movements of this complexity, motion capture was used in conjunction with Jack^{TM} to simplify the creation of accurate simulations. Several issues were identified and resolved using this approach. Clearance for the head near the door frame was identified as an issue, as was foot clearance between the seat and the door frame. Figure 5 shows images from the animations used to assess clearance for ingress and egress.

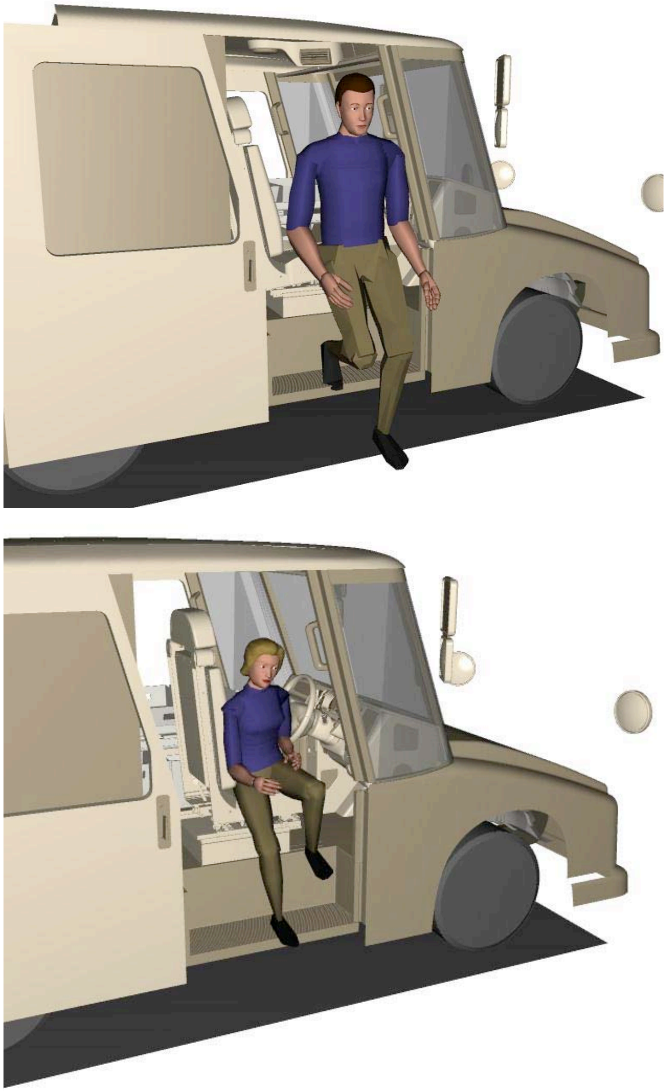

Figure 5. Images from egress animations created using motion capture.

Mail Loading

Loading the mail into the vehicle was identified by the Jack^{TM} analyses as being the most stressful set of tasks. Bins of mail and parcels to be loaded into the left side of the cab can weigh as much as 31 kg (70 lb). Loading mail onto the tray challenges the shoulder strength of small women, and loading mail below the tray poses a low-back risk for large men, as illustrated in Figure 6. The mail tray was designed with an adjustable height to improve access to the tray for both loading and mail delivery, but the primary solution to mail-loading issues is administrative control of the permissible weight of trays, parcels, and bins.

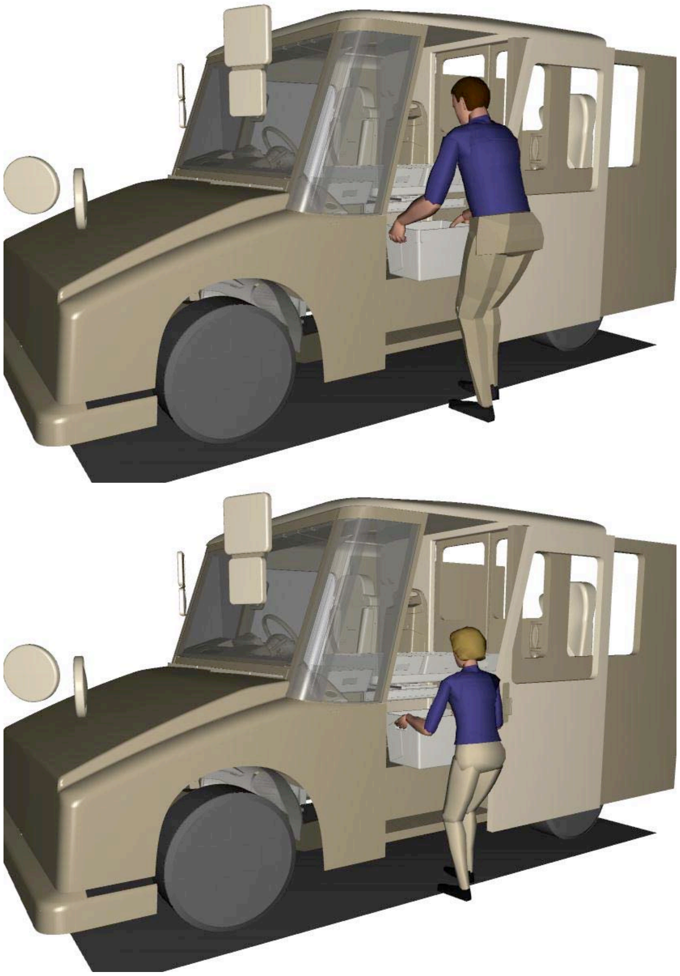

Figure 6. Analysis of loading mail into the left side of the vehicle.

Access to Controls

In addition to the assessment using the population-based reach difficulty envelopes, the Jack^{TM} figures were used to assess reach to all of the controls that were intended to be accessible from the driver seat. Although the population-based models provide more reliable quantitative estimates of accommodation, the visualization of the Jack^{TM} figures completing the reach is valuable for verification of results from the other models, assessing clearance during reaches, communication of results, and as an aid to identifying potential obstacles. Among other problems identified and solved, the limitations on small female reach to overhead components necessitated the location of all controls on the instrument panel rather than overhead. Figure 7 demonstrates reach to the left side of the instrument panel from the normally seated position.

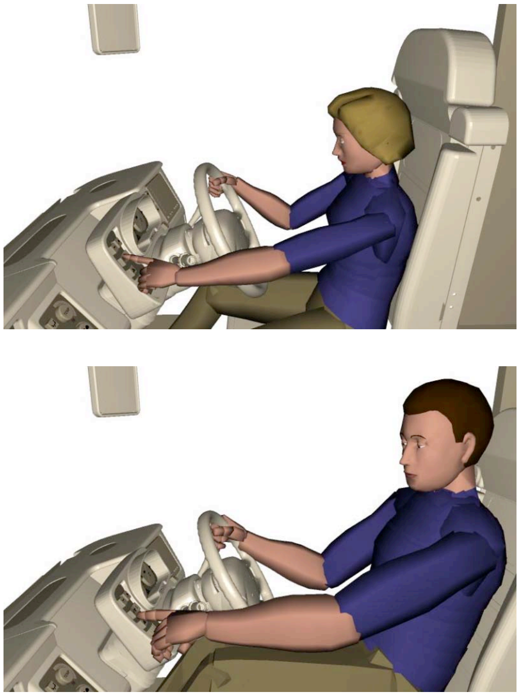

Figure 7. Analysis of control access. The manikin-based analysis was complemented by a population-based analysis using reach difficulty envelopes (see Figure 2).

DISCUSSION

Human Modeling Supported Accelerated Development

The entire cab design was completed with a small team in three months. This rapid timing could not have been achieved cost effectively without the extensive use of the digital human modeling to perform iterative analyses as the geometry was designed and modified. Although the core ergonomics functionality of the Jack^{TM} software was used routinely, Jack^{TM} was also used as a visualization environment during team meetings. The ability to combine ergonomic analyses with review of the geometry, without having to run multiple software packages, improved the productivity of the team.

Why Only Two Jack^{TM} Manikins?

For a variety of reasons, the common practice of using a larger family of manikins for ergonomics analysis was not employed. The use of multiple manikins configured with different combinations of anthropometric dimensions is based on the presumption that variability in body dimensions is the primary determinant of accommodation in the design. However, in modern vehicle interiors with large component adjustment ranges, variability in body dimensions rarely accounts for more than half of the variance in outcome measures of interest, such as the positions of parts of the body. Previous studies have shown that using multiple manikins, selected by such techniques as principal component analysis on anthropometric dimensions, does not provide accurate accommodation assessments unless the residual postural variance is also taken into account (Reed and Flannagan, 2000).

For this analysis, statistical models that predict population accommodation for important design variables, such as driver-selected seat position and eye location, were applied. These models provide better estimates of accommodation than would using even a large family of manikins, and do so with considerably less effort. The development of new seated reach difficulty models allows this efficient population-based analysis approach to be extended to reaches as well as the normal driver seated position.

The use of two manikins in the Jack software provided valuable information that helped to improve the overall design of this vehicle. However, even with the use of the population models, the qualitative analysis of the design would be more compelling with the use of more manikins. Due to the short duration of this project, the effort required to create additional manikins, manipulate them in the design, and document the results was not feasible. Improved automation of tasks using multiple manikins in DHM software would have made this approach more attractive, but it is unlikely that the resulting design would have changed significantly.

Evaluation of the Human-Centered Design Approach

USPS is to be commended for requiring a human-centered design procedure and for specifying a manikin-based analysis. Few commercial vehicle procurements in the U.S. have emphasized ergonomics as a major design objective, and to our knowledge this is the first U.S. government vehicle procurement that specifically required the use of DHM software. As noted above, the use of the Jack^{TM} software allowed the team to evaluate designs more quickly and more effectively than would have been possible without the figure model and associated ergonomic analysis tools.

However, major improvements in the capabilities of the human modeling software are needed to realize the potential of these tools. The foremost problem is the lack of accurate models of human behavior and the resulting physiological and psychological responses. During the last decade, accurate and general models to predict driving postures have become available and were used in this study. However, valid models to predict reaching motions, and to assess the acceptability of those motions, are not currently available for the tasks relevant to this project. For example, while seated in the vehicle, the mail carrier is required to lean and reach to the left to pick up mail, then lean to the right out the window to deliver to a curbside mailbox.

The new reach difficulty models provide a quantitatively accurate assessment of reach capability, but only for tasks involving little force exertion. Parcels picked up from the tray can weigh several pounds. Existing human modeling tools do not provide accurate and robust simulation of these motions. Even if accurate postures and motions for an individual were obtained from motion capture, the ergonomic analysis would still be substantially limited. For example, joint torques can be computed, and these can be compared to distributional data on static strength, but the analysis tools do not usefully indicate whether a particular reach would be acceptable when repeated hundreds of times per day by people with widely varying capabilities. In spite of these limitations, the combination of the population models and figure models provides dramatically more information about the suitability of the design than would be available without these tools, and the result is a significantly improved design.

Priorities for the Improvement of Digital Human Figure Models for Vehicle Design

1. Posture Prediction and Motion Simulation

Recent advancements in posture prediction for drivers make driving posture one of the most-studied and best-predicted task postures. However, postures and movements associated with other tasks, whether performed from the driver seat or from outside the vehicle, are not well predicted with current tools. For two reasons, posture prediction is the most critical need in human motion simulation. First, posturing of the figure currently consumes a substantial amount of analysis time that could be better spent conducting more analyses (using other figure sizes, for example). Second, and most importantly, the results of many biomechanical analyses, such as low-back stresses and shoulder torques, are strongly dependent on posture. If the analyzed posture is selected based only on the analyst’s intuition, the analysis results have no quantifiable validity. Movement simulation, which can be considered an extension of posture prediction, is likewise needed to analyze real tasks of interest, which typically involve dynamic rather than static exertions. Although few tools are currently available to analyze motions, realistic task simulations require movement.

2. Improved Functionality for Motion Capture

Posture and motion simulation methods are advancing rapidly, but motion capture currently remains the best approach for obtaining realistic postures and motions, particularly for complex tasks. However, the applicability of motion capture to ergonomic analysis is considerably hampered by the lack of flexibility inherent in the data. In the current project, a minimal physical mockup of the vehicle design was used to gather motions from a large man and a small woman. The motions were mapped onto similarly scaled Jack^{TM} figures to visualize the motions in the virtual geometry. The usefulness of the data would have been greatly expanded if the data could be mapped onto different size figures while maintaining the required boundary conditions. With the current technology, applying the ingress motion data to a different size figure results in a motion that violates boundary constraints at the feet (steps), hands (steering wheel), and seat (legs). Motion modification technology has been developed that will allow captured motions to be applied to a wide range of figures while preserving the essential character of the motion and complying with boundary constraints (Park et al. 2004). This technology also allows changes in hand and foot positions, which would allow the simulation of mail delivery from many parts of the tray using only a few captured motions. Integration of motion modification algorithms should be a priority for improving the utility of both figure models and motion capture.

3. High-Level Task Simulation Capability

As noted above, figure model analyses would ideally be conducted with a large number of different figures having widely varying body dimensions and physical capabilities. However, current DHM software provides relatively inflexible task "scripting" capability that does not allow for automatic accounting of gross changes to figure anthropometry or layout. In part, this results from the lack of adequate posture and motion simulation algorithms. More generally, a framework is needed that allows the user to specify tasks for the figure model in such a way that the model is able to complete the tasks even if the geometry or task conditions change considerably. For example, the figure model should be able to retrieve a parcel from any point on the mail tray and deliver it to the curbside mailbox even if some starting positions for the item would necessitate a two-handed rather than one-handed reach This high-level functionality is needed if a large number of simulations are to be run as part of routine ergonomic evaluations.

4. Ergonomic Limits for Manual Activities

For some of the tasks analyzed in this program, applicable analysis criteria were available. For example, the task of loading the mail on the left side of the vehicle could be analyzed in a plausible way using the low-back analysis and static strength tools in Jack^{TM}. As noted above, the accuracy of these analyses is substantially limited by the lack of valid posture prediction. Moreover, other than the NIOSH lifting equation, few quantitative criteria exist for determining whether a task is acceptable. In particular, valid biomechanical criteria for identifying tasks in which the shoulder is at risk are not available. The tasks of ergonomic concern in the current project were primarily those related to mail handling, but similar issues arise in other vehicle designs when analyzing, for example, liftgate opening/closing efforts and the forces required to stow and deploy seating. Developing improved ergonomic criteria is a long-term but essential part of DHM development.

5. Models of Discomfort, Difficulty, and Acceptability

For many of the most important design decisions addressed with human figure models, the issue is not whether the design is safe for the operator, but rather whether it is comfortable or subjectively acceptable. Determining whether a particular target can be reached by a large percentage of the operator population is relatively straightforward, for example, but determining whether such a reach would be acceptable if performed 50 times per day is more difficult. Many human factors texts and design guidebooks recommend reach zones based on body dimensions. SAE J287 goes farther, using a behavioral approach and incorporating population variance. However, none of these methods includes the essential element needed for design optimization, which is the cost of noncompliance with the guideline.

Compromises must be made in nearly every design. For example, insufficient space may be available to place all controls can be located within the recommended reach zone. In that case, the cost in accommodation or acceptability needs to be quantified so that it can be compared with the expense or time required to modify the design. DHM software should include the capability to provide continuous ratings of discomfort, difficulty, and acceptability for a large range of common tasks. These continuous outputs can then be used to assess the value of potential improvements to the design with respect to subjective responses.

Most previous efforts to build subjective assessment capability into human models have been based on joint angles. Unfortunately, joint angles are not strongly related to subjective evaluations of most factors of interest. For example, the appropriate steering wheel adjustment range cannot be reliably and efficiently determined using upper-extremity joint angles, even assuming optimally accurate posture prediction. Useful design models for subjective outcomes are based on data obtained from large numbers of people performing specific tasks, but are limited in applicability to those tasks. The required model output includes not a single rating or evaluation, but rather a distribution of ratings or the percentage of the population producing a rating exceeding a criterion. For an example of this modeling approach applied to headroom assessment, see Reed et al. (2001).

Other improvements in DHM software that are lower priorities but would be desirable include:

- improved body shape representation, including simuating the shape of body surfaces in contact with other objects, such as seats;
- the ability to represent clothing and footwear, including the effects on clearance requirements and range of motion; and
- improved ability to incorporate the range of human limitations with respect to strength and range of motion in both posture/motion prediction and in task evaluation.

CONCLUSIONS

The design of the interior of a new postal vehicle was substantially aided by the use of digital human modeling software in conjunction with population-based models of accommodation. The results demonstrate the potential of human modeling to improve product and workspace design, but also highlight areas in which improvements in the technology are needed.

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