TRANSIT COOPERATIVE RESEARCH PROGRAM

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TCRP Report 25

Bus Operator Workstation Evaluation and Design Guidelines

Summary

Transportation Research Board
National Research Council

T R A N S I T   C O O P E R A T I V E   R E S E A R C H   P R O G R A M

Report 25

Bus Operator Workstation Evaluation and Design Guidelines

Summary

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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions*, published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transit Association (APTA), *Transportation 2000*, also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA; the National Academy of Sciences, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended end users of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

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The members of the technical advisory panel selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the National Research Council, the Transit Development Corporation, or the Federal Transit Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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FOREWORD

By Staff
Transportation Research Board

This report will be of interest to transit managers, bus specification engineers, bus manufacturers, and bus operator workstation component manufacturers and suppliers concerned with improving the ergonomic design of the bus operator workstation to improve bus operator comfort, and reduce bus operator injuries and related absenteeism and workers' compensation claims. The report provides scientifically validated design guidelines that ergonomically accommodate operators from the 5th percentile female to the 95th percentile male population. The design guidelines address all aspects of the bus operator workstation including the seat, steering assembly, pedals, instrument panels, farebox, and other equipment. While attempting to minimize the amount of required component adjustability to contain cost, adjustment is included in several key components including instrument panels, seat, and steering assembly. It is estimated that the workstation improvements identified in the design guidelines would increase the price of a standard transit bus by approximately $6,000, with a payback period of between 3.5 and 8 years based on direct cost savings associated with estimated reductions in bus operator injuries. Indirect cost savings such as the need for fewer replacement operators would further reduce this payback period.

The cost associated with bus operator injuries is a major concern of the transit industry. A significant portion of these injuries is associated with inadequate ergonomic design of the bus operator workstation. Injuries that can result from poor design or vibration include cumulative trauma disorders, soft tissue injuries, and musculoskeletal injuries. To reduce such injuries, bus operator workstations should be ergonomically compatible with the range of physical dimensions and functional capabilities of the bus operator population.

The automotive and air transportation industries historically have placed a high priority on matching equipment to the dimensions and capabilities of the operator. In contrast, bus manufacturers are only recently, concurrent with requests from transit agencies, indicating the possibility of major design changes to the operator workstation.

Under TCRP Project F-4, research was undertaken by the Pennsylvania Transportation Institute (PTI), Pennsylvania State University to develop design guidelines for bus operator workstations using sound ergonomic/biomechanical principles to accommodate the 5th percentile female to the 95th percentile male of the U.S. adult population, and to validate the guidelines by testing a full-scale prototype of the workstation. The areas addressed in the research included the design and location of the operator seat, steering assembly, pedals, farebox, radio, transfer tray, public address system, sun visor, modesty panel, stanchions, controls, gauges, and other displays. The employment of control and display technology more advanced than technologies presently in use was encouraged as part of this research to enhance the safety, health, and comfort of bus operators.

To achieve the project objectives, the researchers first reviewed previous bus operator workstation design efforts, and conducted a task analysis of bus operators to define how they interact with the workstation. A bus operator survey was then conducted to obtain recommendations from bus operators on the design and location of workstation elements. Approximately 140 bus operators responded to the survey, and this input was considered in the development of a workstation design concept. Based on this concept, a mock-up was constructed and evaluated by over 100 individuals on the basis of several factors, including visibility, reach, and comfort. In addition, a workshop was held with representatives of bus manufacturers, and bus operator workstation component manufacturers and suppliers to obtain their important input into the design concept. A CAD-based analysis was then performed to validate the workstation design concept that had been developed. Through an iterative process, the workstation design guidelines were further refined. A prototype of the workstation was then constructed on a full-sized transit bus. The prototype was tested and evaluated with the assistance of 24 bus operators on PTI's closed-course test track. Each operator drove the prototype for approximately 2 hours, simulating various operating conditions. The driving schedule was similar to a typical transit service route. A video camera recorded various reaches and driving postures, and other instrumentation recorded vibration and operator force information. In addition, operators were asked for their personal evaluation of the workstation. At the conclusion of the prototype testing, final design guidelines were developed. These guidelines present the essential features that should be included in a workstation. Features include an 18-in. steering wheel, hanging pedals, and instrument panels divided into 3 areas according to function. Specific dimensional data is provided to facilitate the use of the guidelines in the specification and construction of future buses.

This report represents an executive summary of the research performed in this project. An unpublished companion report, prepared under this project and entitled *Bus Operator Workstation Evaluation and Design Guidelines-Final Report*, provides the details of all the various technical analyses performed during the course of the project. This companion document is available on the World Wide Web in the Transportation category of the National Academy Press' Reading Room: www.nap.edu/readingroom.

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CHAPTER 1. INTRODUCTION

An unusually high rate of absenteeism (sometimes 3 times as great as the average rate for blue collar workers) and illness occur among transit bus operators (*1*,*2*). This has significantly increased the number of worker's compensation and disability claims in the transit industry. Many factors contribute to the higher than normal morbidity and mortality rates of transit bus operators.

Epidemiological studies have concentrated on identifying the primary diseases that strike transit bus operators. Researchers have identified three main categories: cardiovascular disease, gastrointestinal illness, and musculoskeletal problems. The most prevalent health problems are musculoskeletal, relating to neck and back pain (*3*). Studies have found that 80.5 percent of operators have experienced some degree of back and neck pain, compared with 50.7 percent of nonoperators, and the incidence of reported low back pain is 20 percent higher for operators than nonoperators (*4*). Frequent awkward postures, muscular effort, vibration, and shock as well as exposure to whole body vibration and prolonged sitting in a constrained position contribute to overworking the lumbar spine and its supportive structures, causing low back pain (*5*).

Several organizations have attempted to design a workstation based on ergonomic principles (*6*,*7*). Carrier et al. (*6*) created a mock-up of a transit bus operator workstation by using a computer program. This program, developed by Genicom, combines both the statistical approach of building a model around three-dimensional "zones" with the theoretical modeling approach in which actual subjects are simulated by changing numerical parameters. The researchers received input from transit authorities, bus manufacturers, and bus operators on the mock-up and presented several recommendations for future workstations.

One of the key findings from Carrier et al. is that steering wheels, because of their size, interfere with visibility and can "penetrate" the operator's abdomen or thighs if he or she attempts to orient the wheel to achieve maximum visibility. The researchers concluded that steering wheel orientation should be more vertical than horizontal and that it is impossible to accommodate 95 percent of the population with existing components. A primary concern of workstation design is the relationship between the seat, steering wheel, and pedals, with which the operator is required to stay in constant contact, because the location of these controls dictates the operator's posture. However, operators have demonstrated leg comfort is a higher priority than arm reach when positioning their seats (*8*).

BC Transit of Vancouver, British Columbia, has addressed some of these concerns (*9*). BC Transit developed a set of standards that are applied to the workstations of every new bus it purchases. The modifications include replacing spring suspension seats with pneumatic ride seats, installing tilting and telescoping steering columns, installing power-assist steering, installing left-side convex mirrors, and relocating the farebox. These modifications have reduced the frequency of workstation-related injuries by 78 percent and have resulted in an 86 percent reduction in the amount of time off per injury, which indicates the severity of the injury (*5*). Similar design requirements have been adopted by Seattle Metro (*10*).

The workstation proposed in this report considers the design and location of the seat, steering wheel, pedals, and instrument panel. To accommodate the entire spectrum of the population, components are made adjustable. However, every adjustment adds cost, which needs to be minimized. The intention of this work is to develop design guidelines that minimize actual mechanical adjustment, yet accommodate the 5th percentile female to the 95th percentile male.

The report is presented in the following manner:

1. A task analysis to ensure reader appreciation of the bus operator's functions
2. Results from an operator survey to determine the importance of controls and problems facing operators
3. Evaluation of the concept and component adjustments through jury evaluation of a laboratory mock-up
4. Investigation of proper adjustment ranges for the bus operator workstation using a scientific approach based on several design variables and the neutral seating reference point (NSRP)
5. Evaluation and validation of adjustment ranges using the JACK human simulation program
6. Testing of a prototype, constructed from a 1973 GMC bus, using 24 bus operators in a driving session with left and right turns and simulated stops

CHAPTER 2. BACKGROUND

Bucciaglia (*11*) conducted a task analysis of operators to define how they interact with the workstation. The analysis was conducted by direct and video observation of several operators in State College, Altoona, Johnstown, and Harrisburg, Pennsylvania. The tasks were broken down into groups and itemized (Table 2.1).

A survey was developed to obtain recommendations from bus operators on the design and location of workstation elements. The survey was distributed September through October 1994 to four transit districts in Pennsylvania. A total of 138 operators responded to the survey, and this input was used to develop the workstation that will be presented later. The average respondent was 175 cm tall, with a standard deviation of 6.6 cm. The shortest operator was 155 cm, and the tallest was 196 cm. There were 122 male and 16 female respondents. Table 2.2 presents the operators' responses relating to the use of controls. Because the steering wheel and brake and accelerator pedals are essential and could overshadow other controls, they were not included in the survey. The top rankings shown are not statistically different from one another. Also, all operators were presented with the same survey; therefore, some ordering effect may be present.

Through open-ended questions, the survey asked the operators to comment on their present vehicle workstations. The comments were analyzed through a keyword count to show the operators' major concerns. Many operators, particularly large operators, complained of hitting the farebox with their knees or other body parts when ingressing and egressing. Many large males also complained of hitting the steering wheel, and several operators commented that the seat did not travel far enough back to allow proper egress. Power steering, plenty of leg room, and a comfortable seat were cited as positive features. Complicated seat adjustments, lack of outside mirror controls, and poor layout of controls were cited as elements of deficient workstation design.

CHAPTER 3. WORKSTATION CONCEPT

The objective of the design methodology is to develop a workstation that will accommodate population extremes, with minimum mechanical adjustment. Priority was given to design concepts that do not degrade safety. For example, the operator should be able to keep his or her feet firmly planted on the pedals, and, for safety reasons, the pedal mounting points should be fixed to the bus. Previous approaches suggested a movable pedal to accommodate operators of different heights (*6*). This type of adjustment was discarded because of safety concerns. Another objective of the design methodology is to develop a workstation in which visibility, reach, comfort, and adjustability are enhanced.

This study has suggested novel design concepts for the workstation components of transit buses (e.g., the steering wheel, pedals, and instrument panel) to resolve the problems described by the operators and discussed by other researchers. A systematic design approach was developed to determine the position, orientation, and adjustment ranges of the components, which will be discussed in the following section.

The steering wheel was designed in terms of its orientation, size, and adjustment mechanism. Carrier et al. (*6*) pointed out that the steering wheel should be oriented more vertically than the wheels commonly used. This would decrease the range of motion of body parts used to maneuver the steering wheel (i.e., back, shoulder, elbow, and wrist) for the typical operator; therefore, his or her fatigue level would decrease and the 5th percentile female would be able to operate the steering wheel in a more appropriate and biomechanically efficient manner.

TABLE 2.1 Transit bus operating task analysis

Predriving Tasks	On-Road Driving Tasks	Passenger Pick-up/Delivery
enter bus	accelerate/decelerate bus	activate four-way flashers
store personal items	turn the bus	decelerate and approach stop
adjust seat	communications	stop the bus
adjust steering wheel	climate controls	activate the kneeling mode
adjust mirrors	defrost mirrors and windshield	open bus doors
apply safety belt	monitor stop request	inspect passenger ingress
start engine	enter/exit traffic	check farebox
diagnostic check		update ride passes
climate controls		distribute transfer tickets
defrost mirrors & windshield		record passenger data
change destination sign		close bus doors
engage transmission		deactivate kneeling mode
release parking brake		check passengers for seating status
		deactivate four-way flashers
		release parking brake
		accelerate bus

TABLE 2.2. Top-ranked controls and displays

No.	Frequency Ranked by Average	Importance Ranked by Average
1	Turn Signals	Turn Signals
2	Door Open	Hazard Lights
3	Hazard Lights	Air Pressure
4	Air Pressure	Door Open
5	Speedometer	Defrost
6	Destination Sign Control	Speedometer
7	Hand Brake	Hand Brake
8	Heater	Heater
9	Stop Request	Windshield Wiper
10	Air Conditioner	Destination Sign Control
11		Air Conditioner
12		Ventilation
13		Mirror Adjustment
14		Stop Request
15		Horn

As for wheel size, a large horizontal steering wheel whose diameter ranges from 508 to 559 mm causes many operators to reach forward and therefore reduce contact and support between the torso and the seat back. Society of Automotive Engineers (SAE) J1100 recommends a steering wheel diameter of 450 to 560 mm for Class B vehicles. The wheel diameter was determined to be 457 mm in this study, which is within the recommended range in which operators can maintain a comfortable posture for steering. Finally, to accommodate all positions and orientations needed to provide sufficient visibility and a comfortable reach for small and large operators, the wheel must have three adjustments: (1) a hub orientation adjustment, (2) a column telescope adjustment, and (3) a column tilt adjustment at the base of the steering column. Because an existing steering wheel system provides the first two adjustments, only a column tilt adjustment was added to the wheel assembly.

The selection of pedal style is critical in the pedal design. Currently, the majority of transit buses use treadle pedals with an orientation angle between 40 and 50 deg (*12*). The treadle pedal allows for little variability for placement of the operator's heel, assuming the heel must be at the base of the treadle pedal for efficient and safe pedal activation. In addition, for most small operators, the extremely steep orientation of the accelerator pedal results in an uncomfortable lower leg posture, which can cause unnatural extension or rotation about the ankle. To resolve the problems resulting from the use of treadle pedals, a hanging pedal was used and evaluated in this study. The hanging pedal allows the operator to place his or her the heel at more locations on the workstation platform than the treadle pedal. Using a kinematic model developed in this study (Appendix E of the Final Report), the orientation, activation angle, and location of the accelerator and brake pedals when a hanging pedal is used were determined based on comfortable reach of the right leg.

The instrument panels, which contain displays and controls, were investigated in terms of adjustment range, panel layout, size, and location (Appendix F of the Final Report). All instrument panels are adjustable to accommodate visibility and a comfortable reach for all bus operators. Displays and controls are grouped according to function and systematically arranged into three areas: the left, central, and right instrument panels. The left instrument panel provides easy access for all operators to secondary controls, or controls used during predriving tasks:

- Parking brake
- Exterior mirror remote adjustment knobs
- Exterior mirror defrost control
- Internal and external public announcement systems
- Radio controls
- Run selector knob
- Transmission
- Ignition switch

The size of the left instrument panel is determined by the space required for the controls, and the instrument panel is located in the side and plan views based on comfortable reach of the left arm.

The central instrument panel is intended to provide the operator with information on the operating status of the bus. Any information that does not require continuous monitoring by a particular gauge is displayed with an indicator light. To accommodate tell-tale indicators without giving up 0.95 cm by 1.27 cm of space for each, a small screen that can display indicators in color and with required alarms is proposed for the central instrument panel. Because time is a large concern for operators and an important component of a significant number of their duties, a clock is provided. The speedometer and air pressure gauge are the two most regularly monitored items on the central instrument panel. For this reason, traditional large dial readouts are provided. The goal of mounting the instrument panel directly on the steering column is to improve downward visibility.

The right instrument panel contains primary controls for driving and picking up and depositing passengers. These controls are placed on this panel because they are used frequently and need to be easily accessible to bus operators. The right instrument panel will contain an operator digital assistant (ODA) consisting of a keypad with a small display. The ODA can be used for the following purposes:

- Presenting the bus route schedule
- Controlling the farebox
- Performing automatic counting and categorization of fares if used in conjunction with a card reading farebox, performing manual inventorying of passengers if using a traditional farebox
- Printing transfer tickets
- Monitoring fuel efficiency
- Changing the destination sign
- In the future, possibly linking with the Global Positioning System (GPS) for real-time location of buses and planning routes to avoid delays

Data collected by the ODA can be downloaded easily at the end of the workday to a "home base" computer for analysis.

The dimensions of the right instrument panel are based on the controls it will contain. Also, comfortable reach of the right arm is considered in determining the location of the right instrument panel.

A minimum visibility marker (an imaginary point in front of the bus) was used to define the visibility constraint under which all controls must be located. The steering wheel was located below this constraint, but above a minimum boundary layer that surrounds the operator and within comfortable arm reach. The lateral locations of the accelerator and brake pedals were determined in the plan view based on the reachability of the operator's legs, whereas the right and left dashboards were located in the elevation and plan views based on the reachability of the operator's arms. This process was repeated for the large operator. The required ranges of adjustment for workstation controls can be extracted from an overlay of the two resulting workstations.

CHAPTER 4. OPERATOR WORKSTATION MOCK-UP AND EVALUATION

The workstation mock-up was created to (1) confirm the standard posture chosen for this design, (2) record the positions of the controls selected by a jury with a wide anthropometric range, and (3) verify the workstation's visibility, reachability, and comfort. The mock-up included the entire workstation and the first 200 cm of a typical bus. The bus width was taken to be 244 cm, and the dimensions for the doors, steps, and fire wall were obtained from a current transit bus. Figure 4.1 presents an actual workstation; Figures 4.2a, 4.2b, and 4.2c illustrate the dimensions used in the mock-up.

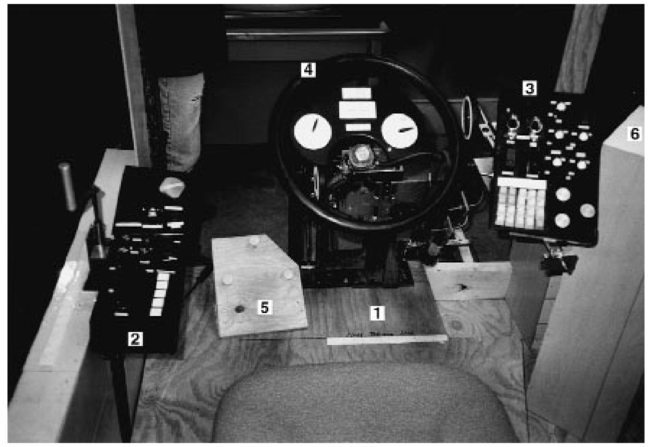


Figure 4.1. View of workstation mock-up: (1) hanging pedals, (2) left instrument panel, (3) right instrument panel, (4) center instrument panel mounted on tilt-telescope-tilt steering wheel, (5) turn signals and high beams, and (6) farebox.

Each juror's height, weight, age, and so on were recorded. The jurors were asked to position the seat and steering wheel so that their feet reached the pedals and they had a downward view over the top of the steering wheel as specified by APTA (*13*). They were then asked to make final adjustments based on comfort. Their anthropometric joint angles and component adjustments were then recorded. The jurors, after a brief explanation of the controls and tasks, were instructed to perform a simulated driving task with a videotape acting as a prompt for turns and other actions. This way all jurors performed the same tasks in a quasi-dynamic simulation. The jurors were observed during their simulated driving for their ease of reach. Finally, the jurors evaluated the

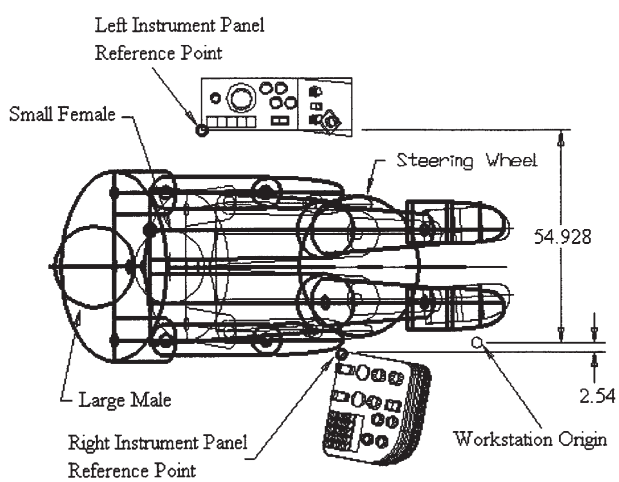


Figure 4.2a. Mock-up dimensions, top view. (Lengths are in cm. Reference points were mock-up specific; they were changed after mock-up evaluation.)

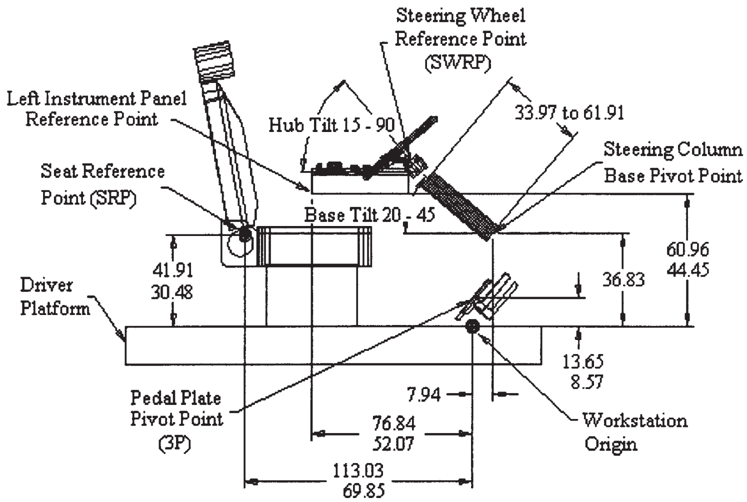


Figure 4.2b. Mock-up dimensions, side view (right instrument panel not shown). (Lengths are in cm. Angles are in deg. Reference points were mock-up specific; they were changed after mock-up evaluation. Minimum and maximum adjustment ranges are indicated where two numbers appear.)

mock-up on the basis of several factors such as visibility, reach, and comfort.

For purposes of data reduction, the jury was divided into height categories of small, medium, and large (Table 4.1). The 103 jurors, which consisted of 64 males and 39 females, 14 of whom were professional bus operators or transit personnel, evaluated the mock-up. The average small female was actually 0.8 cm taller than the 5th percentile female specified in SAE J833; the average large male was 1.5 cm shorter than the 95th percentile male defined in SAE J833. The standard deviations for both groups extend beyond the 5th percentile range and the 95th percentile range, respectively. The weight of the average subject was 74 kg, which compares well with the SAE J833 value of 73 kg.

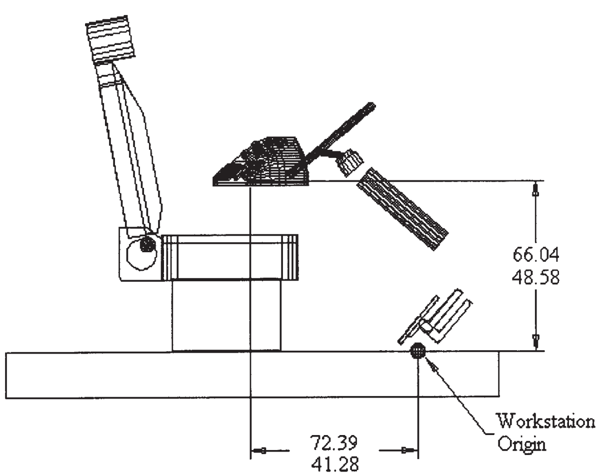


Figure 4.2c. Mock-up dimensions, side view (left instrument panel not shown). (Lengths are in cm. Reference points were mock-up specific; they were changed after mock-up evaluation. Minimum and maximum adjustment ranges are indicated where two numbers appear.)

The jurors were asked to rate the mock-up for visibility, reach, comfort, and ingress/egress. The evaluation scale was as follows:

1 = Unsatisfactory
2 = Poor
3 = Satisfactory
4 = Good
5 = Very good.

Figure 4.3 shows the jurors' responses, which show that no great differences existed between gender or stature groups. The relative flatness of the plots (with the exception of ingress/egress) show that the workstation received similar ratings from all population groups. Transit bus operators tended to evaluate the workstation more highly than non-operators. For all population groups, the subjects were able to assume postures within anthropometric comfort angles.

The standard deviations for visibility, reach, comfort, and adjustability are close to each other, at values about 0.6. The measure of ingress/egress, a topic on which many people offered comments, had a larger standard deviation, a value about 1. One reason for this may be that many jurors suggested that the seat should swivel. However, a swivel seat may not provide sufficient mechanical reliability.

From the workstation mock-up evaluation, adjustment range results were obtained (Table 4.2). Note that the pre-

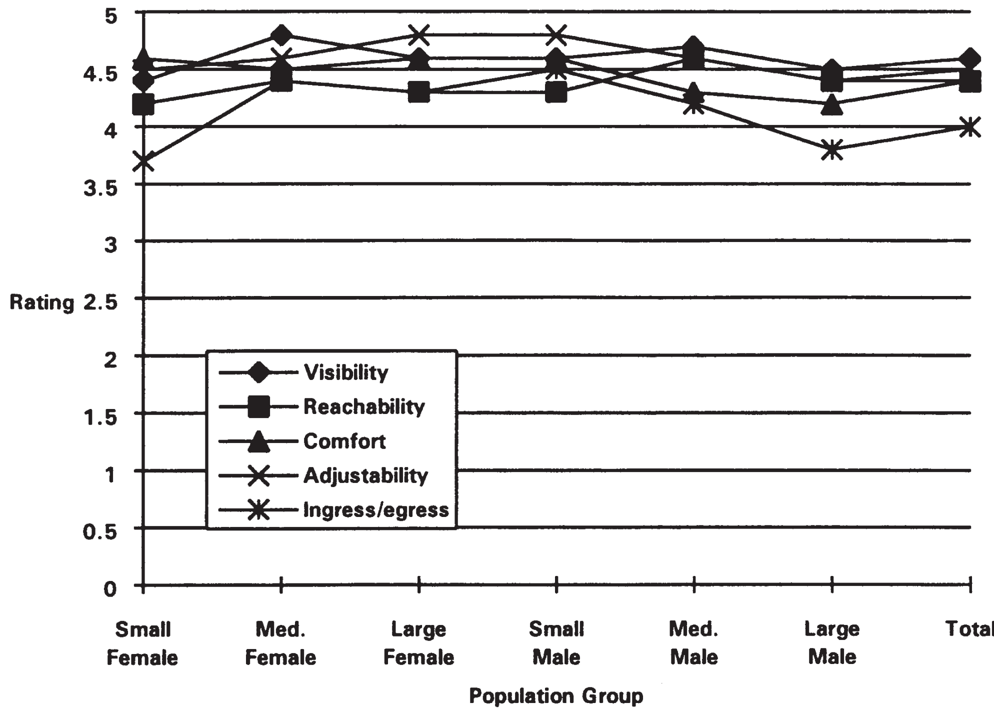


Figure 4.3. Subjective evaluation of mock-up.

liminary computer-aided design (CAD) approach was, in general, a more conservative approach with larger adjustment ranges than necessary. Also, the adjustment ranges under the "Prototype" heading are preliminary values based on the mock-up and CAD approach. The ranges were later refined using the NSRP approach and JACK simulation, discussed later in this summary.

CHAPTER 5. NEUTRAL SEATING REFERENCE POINT APPROACH

The NSRP design approach was a more rigorous approach to designing the bus operator workstation than the preliminary CAD approach discussed earlier. The approach is based on the NSRP, which is the 50th percentile seat reference

TABLE 4.1 Mock-up height category definition

	Small (<30th percentile)	Medium (30th to 70th percentile)	Large (>70th percentile)
Male	< 172 cm (8)	172 ~ 179 cm(20)	>179 cm (36)
Female	< 160 cm (13)	160 ~ 166 cm (17)	>166 cm (9)

Note: a number in parentheses denotes the number of jurors of corresponding group.

TABLE 4.2 Mock-up adjustment ranges (in cm)

Component Adjustment	Mock-up as constructed	Mock-up Result using (5% female-95% male)
Seat fore-aft	43	24.77
Seat vertical	10	10.11
Steering column base tilt	25	23
Steering column telescope (degrees)	28	18
Right instrument panel: fore-aft	23.5	13.36
Right instrument panel: vertical	19	11.61
Left instrument panel: fore-aft	27.9	19.56
Left instrument panel: vertical	18.4	11.43

point (SRP). The SRP is a point on the sagittal or medial plane of the body located by the intersection of two planes. One of these planes approximates the compressed seat surface, and the other plane represents the compressed seat back. The SRP can be represented easily by either the hip pivot point (H-point) or seat index point (SIP) (*12*). Design criteria for the workstation were based on four ergonomic/biomechanical principles: (1) visibility, (2) reach, (3) comfort, and (4) force. Also, a standard driving posture was assumed, one that enables the joint angles to be in the middle of the established comfort ranges of each joint.

A hierarchy of design variables was constructed to define the workstation systematically. In this study, the workstation was divided into eight design variables:

1. Seat
2. Steering
3. Pedals
4. Instrument panels
5. Mirrors
6. Windshield
7. Farebox
8. Peripheral workspace

After the workstation was divided into these design variables, their hierarchy was established by stratifying them into four levels:

1. Subsystems
2. Sub-subsystems
3. Dimensional attributes
4. Specific design variables

Table 5.1 illustrates part of the hierarchy of design variables.

To apply anthropometric characteristics to the workstation design, 46 anthropometric variables were selected. These variables also were organized into a hierarchy by following the same procedures used for the design variables. As the hierarchies of the design and anthropometric variables were being constructed, 242 design and 46 anthropometric variables were identified for an ergonomic bus workstation design.

Based on a three-point evaluation, functional design relationships for design variables and anthropometric variables were developed. A functional design relationship of a design variable is the function that represents the geometric relationship between the design variable and its related design and anthropometric variables. The advantage of the functional design relationship is that there is no ambiguity in the final design because every workstation design variable is explicitly determined by defining the geometric relationships of the design and anthropometric variables. Figure 5.1 is an example of the functional relationships developed.

CHAPTER 6. JACK SIMULATION

The workstation designed by the NSRP approach (Figure 6.1) was validated using JACK (a CAD-based human simulation software package), which incorporated workstation geometry, three human models (5th percentile female, 50th percentile person, and 95th percentile male), 17 bus operating tasks, kinematic constraints, and a design evaluation scheme. The kinematic constraints restricted human model behavior so that a human performing bus operating tasks could be simulated more realistically. The simulated human

TABLE 5.1 Example of hierarchy of design variables (each design variable is assigned a code for notation purposes)

1st Level	2nd Level	3rd Level	4th Level	Code
Seat	Seat Back	length	seat back length	SB1
		width	upper seat back width	SB2
			middle seat back width	SB3
			lower seat back width	SB4
		depth	upper seat back depth	SB5
			middle seat back depth	SB6
			lower seat back depth	SB7
		curvature	upper seat back curvature	SB8
			middle seat back curvature	SB9
			lower seat back curvature	SB10
		angle	seat back neutral vertical angle	SB11
		adjustment range	seat back angle adjustment range	SB12
		location	vertical distance from NSRP to lumbar support distance	SB13
		material property	seat back cover texture	SB14
			seat back cushion material density	SB15

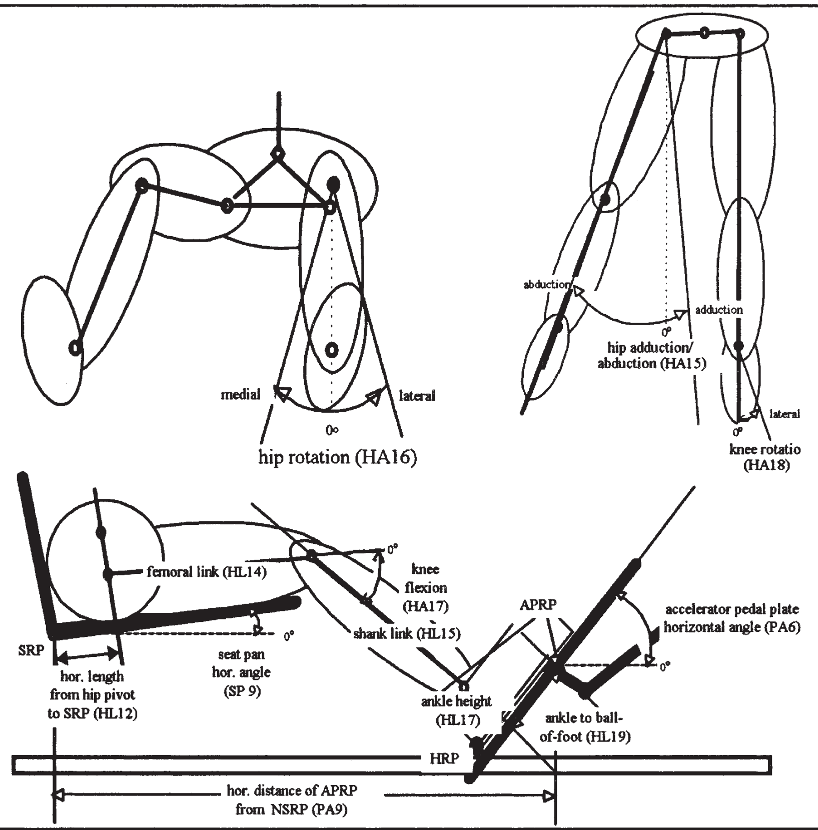
<table>
<tr><td>Design Var.</td><td>PA9. horizontal distance of APRP from NSRP</td><td>Classification</td><td>Master</td></tr>
<tr><td>Related Design Variable (From)</td><td colspan="3">SP9. seat pan neutral horizontal angle (5°)
PA6. brake pedal plate horizontal angle (30°)</td></tr>
<tr><td>Related Anthropometric Variable</td><td colspan="3">HL12. horizontal length from hip pivot to SRP
HL14. femoral link
HL15. shank link
HL17. ankle pivot height from floor with shoes
HL19. horizontal length from ankle pivot to ball-of-foot
HA15. hip abduction (10°)
HA16. hip rotation (0°)
HA17. knee flexion (65°)
HA18. knee rotation (2°)</td></tr>
<tr><td>Related Design Guideline</td><td colspan="3">Diffrient et al.(1981)
- The horizontal distance of pedal plate reference point (touched by the ball-of-foot) should be 77.7 to 94.0 cm, and thus its median value is 85.9 cm (p. 20).
Carrier et al.(1992)
- The median of SRP horizontal distance from heel resting point (HRP) should be 69.0 cm, which is equivalent to horizontal distance from NSRP to pedal plate reference point of 82.4 cm (p. 31).</td></tr>
<tr><td>Key Design Concept</td><td colspan="3">1. maintain the comfortable ROM ranges of the hip, knee, and ankle.
2. maintain reachability of foot controls with the ball of foot on the pedal plate pivot.</td></tr>
<tr><td>Drawing</td><td colspan="3">
</td></tr>
<tr><td>Design Function</td><td colspan="3">$PA9 = \{(HL12 + HL14) \times \cos(SP9) + (HL15 + HL17) \times \sin(90° + SP9 - HA17)$
$+HL19 \times \cos(PA6)\} \times \cos(HA15 + HA16 + HA18)$
= median of [77.3, 95.7] cm = 86.4 cm (range of PA9 = 18.4 cm)</td></tr>
<tr><td>Design Value</td><td colspan="3">PA9 = 86.4 cm</td></tr>
<tr><td>Comment</td><td colspan="3">The horizontal adjustment range of seat (SP11/SP12) needs to incorporate the range of PA9 (18.4 cm) to accommodate the US population from the 5th percentile female to 95th percentile male.</td></tr>
</table>

Figure 5.1. Illustration of functional design relationship.

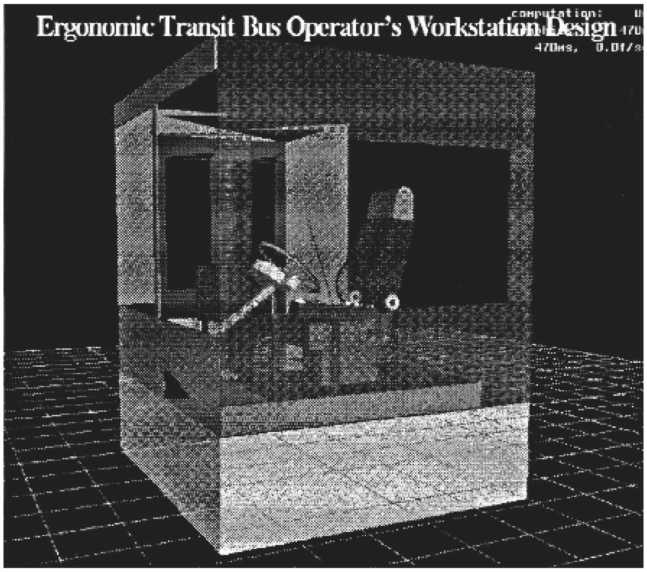


Figure 6.1. Transit bus operation workstation implemented in JACK.

performance for each bus operating task was evaluated in terms of visibility, reach, comfort, and adjustability. Based on the simulation results, the ergonomic workstation design was suggested, incorporating both adjustment ranges and locations of bus workstation components. Iterative design modifications during simulation were made to produce the valid workstation design. Overall, the workstation is appropriate for all three human models and can accommodate the three types of individuals.

CHAPTER 7. INSTRUMENT PANEL DESIGN

When the instrument panel was designed, the type of controls, their sizes, and their general arrangement were considered. Initially, buses manufactured by NovaBUS, Neoplan, and GMC, along with a “request for bids” from Seattle Metro and Centre Area Transportation Authority (CATA), in State College, Pennsylvania, were reviewed. The locations and sizes of the controls on the buses’ instrument panels were recorded. Bus operator survey results were compiled to gain a wider information database. Once the type of controls were determined, a taxonomy of controls was developed. Visibility and reach were considered; viewing cones were used for visibility. Each requirement was based on the population extremes using SAE guidelines. Next, a hierarchical design variable approach was used, as was done with the workstation layout. Functional similarity and sequence of use for the controls were considered.

This information was used within an algorithm to lay out the instrument panels. The layout procedure was conducted in three parts: overall layout, intermediate layout, and detail layout. The overall layout considered frequency of use and importance as the deciding factors. The intermediate layout applied the results from the operator survey, also known as stereotypes. The detail layout relied on functional similarity. A representative view of the instrument panel layout is shown in Figure 7.1. More detail on the approach to instrument panel layout design appears in Appendix F of the Final Report.

CHAPTER 8. PROTOTYPE CONSTRUCTION

A 1973 GMC bus with power steering was obtained from CATA. The bus had the following attributes:

- Treadle pedals
- Manual shifter
- Pedestal seat
- Floor-mounted parking brake
- Nonadjustable steering column
- Fixed instrument panels
- Good visibility

The bus was retrofitted to bring it into accordance with the design concept, with a minimum of compromise. Some compromise, however, was required because of the state of the market and component availability. For example, the accelerator was not electronic, such as hanging pedals currently available on the market. Therefore, a mechanical linkage was used to transmit motion to the treadle pedal from the hanging pedal. The pedestal seat was replaced with a seat selected by vibration testing, which is discussed later. The floor-mounted parking brake was a problem because no conversions exist for it. The parking brake lever arm was shortened and left in its present location, but a control was placed in the instrument panel for appearance and to take up the space.

An 18-in. (457-mm) steering wheel for Class B vehicles was used in the prototype, as specified at the panel/vendor briefing. The existing steering column was completely removed and replaced with a column having a base tilt and telescope. A farebox shell with no electronics was obtained

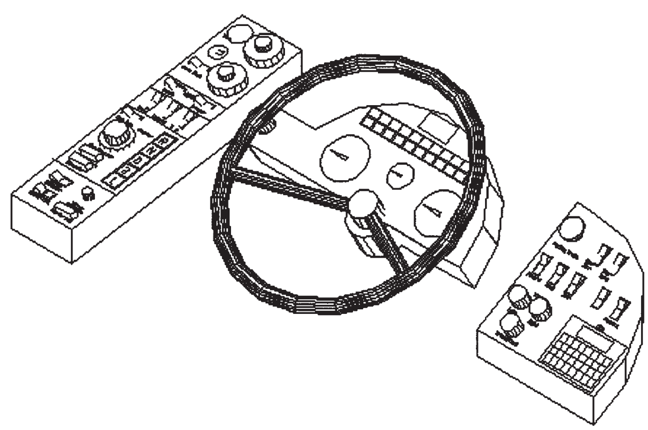


Figure 7.1. Overall instrument panel layout.

from a current manufacturer. Also, a reduced version of the ODA was implemented. This ODA was able to supply or simulate many intended ODA functions as well as withstand the environment.

The mounting location and design of the hanging pedals were determined (see Appendix E) using the population extremes of the 5th percentile female to the 95th percentile male. Acceptable ranges of motion also were considered for the population extremes.

Seven bus operator seats were evaluated using the Pennsylvania Transportation Institute (PTI) ride quality simulator and test track facilities. Seats whose links are pin jointed links appeared to have the best performance. Seats whose suspensions contain a slider appeared to have been subject to some "stiction" in their motion, which could make suspension movement difficult.

Two seats appeared favorable and provide sufficient adjustment in both the vertical and fore-aft directions. These seats also have an independent adjustment for vertical height and suspension stiffness. One seat isolates vibrations over a broad frequency band, whereas the other was better at attenuating vibrations at the specific resonant frequencies of a seated human. The seat that attenuates vibrations at a human's natural frequency was used for the prototype because of concern about lower back injury. More details of this evaluation appear in Appendix D of the Final Report and elsewhere (*14*).

Figure 8.1 shows the original workstation. The prototype workstation is shown in Figure 8.2. Several constraints were encountered during prototype construction. Although they made the task more difficult, these constraints did not adversely impact the prototype testing.

Figure 8.2. Prototype workstation.

CHAPTER 9. PROTOTYPE TESTING

The prototype was tested by 24 bus operators: 5 small females, 5 large males, and 14 individuals in the medium group. The subjects were placed in an unmodified 1973 GMC, and their posture in and ratings of the unmodified bus were recorded. Next, the subjects drove the prototype bus on the test track after components were adjusted to their satisfaction and their posture was recorded along with locations of all adjusted components and visibility measurements.

Figure 8.1. Original GMC operator workstation.

A lap, which was 1 mi in length, consisted of a left turn, right turn, and four simulated stops. The subject drove the prototype bus for 20 laps and then a series of lock-to-lock turns. A video camera was used to record the subject's posture during lap 2, lap 19, and lock-to-lock driving. This video was used to perform a dynamic posture analysis.

Accelerometers were used to measure vibration between the floor and seat for each operator. A force measurement glove was used to measure forces applied by the subject's hand during the lock-to-lock driving segment. A body discomfort assessment was used to measure the subject's comfort during the approximately 90-min drive. The subject's discomfort was assessed before driving, after 10 laps of driving, after 20 laps of driving, and finally after the lock-to-lock driving.

Seat acceleration testing in the prototype bus indicated that the floor accelerations were a little less than those found in the bus operator seat evaluation previously discussed. However, the suspension accelerations were comparable to those from previous tests. Root mean square (RMS) should not be considered in a transmissibility study because RMS represents an overall average of the time series. Therefore, only the transmissibility on a frequency basis was considered, as was done in previous tests. Specifically, the transmissibility at frequencies of 4.25 Hz and 7 Hz were examined.

Figures 9.1 and 9.2 show the average power spectral densities (PSDs) of the floor and seat accelerations. Figure 9.3 demonstrates that the transmissibilities for both the prototype bus seat testing and the previous seat testing were comparable, with a peak around 2 Hz and attenuation at higher frequencies. Specifically, the seat performed better at attenuating vibrations at 4.25 Hz (lower back resonance) in prototype

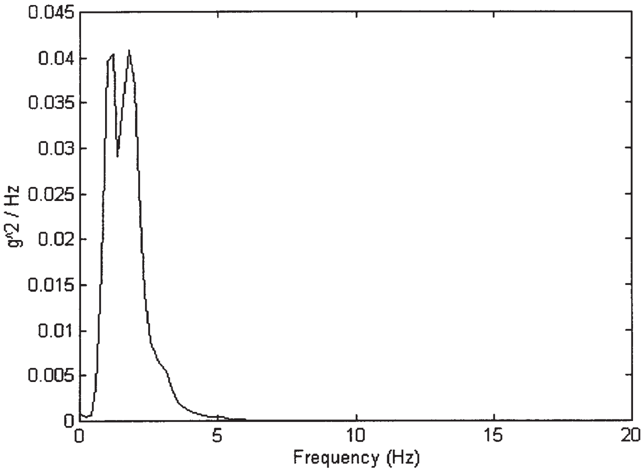


Figure 9.1. *Prototype average floor accelerations.*

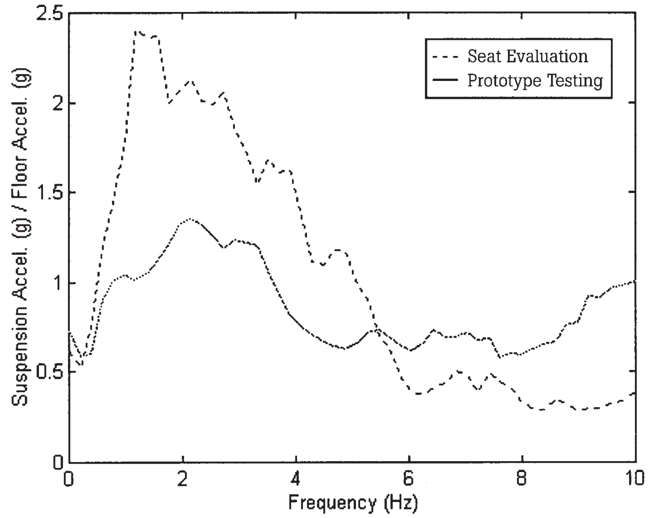


Figure 9.3. *Prototype and seat evaluation transmissibilities.*

testing, which indicates the validity of the ride quality simulator testing.

Seven aspects of the standard bus and prototype bus workstations were evaluated under static and dynamic driving conditions:

1. Visibility
2. Postural comfort
3. Reach
4. Adjustability
5. Ease of ingress
6. Ease of egress
7. Ride quality

As indicated earlier, 24 transit bus operators participated in the evaluation. Three stature groups were defined: the 5th percentile female and the 15th percentile female, defined as small, and the 85th percentile and larger male, defined as large. The jury was composed of about 20 percent small females (a mean height of 158.5 cm) and 25 percent large males (a mean height of 186.7 cm). The remaining 55 percent fit in the medium size group (a mean height of 172.9 cm).

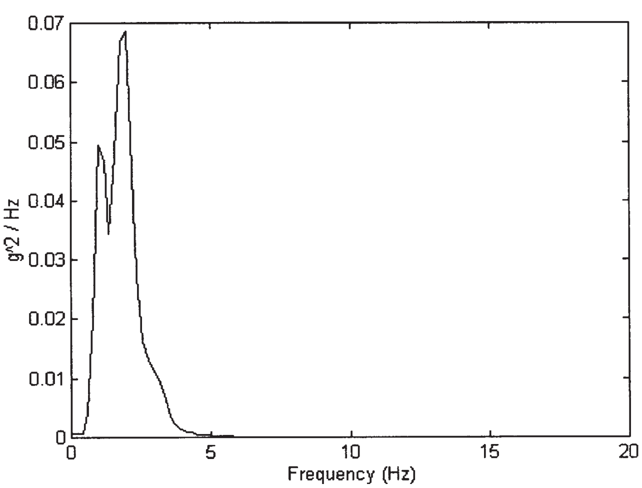


Figure 9.2. *Prototype average suspension accelerations.*

According to the evaluation, visibility was not significantly different between the standard bus workstation and the prototype bus workstation for two reasons: (1) the windshield height and body frame structure of the standard bus, which provide sufficient downward visibility, were the same as those of the prototype bus and (2) comfort, reach, adjustability, ease of ingress, and ease of egress were significantly improved in the prototype design. All 24 operators rated the prototype bus workstation better than the standard bus workstation for each of these criteria.

The reference point locations of each workstation component (seat, steering wheel, and left and right instrument panels) adjusted by the bus operators were recorded for the standard and prototype bus workstations. The results indicated that the seat in the prototype was located at a lower position and the steering wheel and right instrument panel of the prototype were located at a farther and higher location from the seat than those of the design specifications. This produced shoulder and elbow flexion angles during driving that were larger than the assumed standard driving postures. However, these angles were still within recommended comfort ranges. The stretched-out shoulder-arm posture could be the result of driving preferences developed by operators driving buses with conventional workstations.

Static driving postures were measured in the standard bus and prototype bus. The joint angles measured were converted into postural comfort scores by using the postural comfort evaluation scheme, which quantifies the magnitude of joint angle deviation from the standard driving posture within the corresponding comfort range of motion. The integrated comfort scores combining the scores of the shoulder, elbow, hip, knee, and ankle are 3.4 out of 5 for the standard bus, 3.9 for the prototype bus, and 4.2 for the standard driving posture. It was determined that the prototype improved the shoulder and elbow flexion angles for holding the steering wheel by providing a steering column telescope-tilt mechanism and a smaller (18 in. in diameter) steering wheel for the operators.

Dynamic driving postures in the prototype workstation were analyzed to evaluate bus operators' continuously changing postures as they maneuvered the prototype. The elbow and shoulder movements were graded into comfort scores according to the postural comfort evaluation scheme. The comfort scores of both static and dynamic driving postures were used to identify significance of stature, joint (elbow and shoulder), and test condition (static and dynamic driving) effects. Only the joint effect was found to be significant; the other effects were insignificant. This indicated that the shoulder comfort scores were significantly lower than the elbow scores for all three stature groups regardless of test condition (static or dynamic). In turn, this result implies that the prototype workstation provided statistically equivalent amounts of postural comfort for the different size operators throughout the testing.

Body part discomfort was evaluated four times using a rating scale from 7 (most comfortable) to −7 (most uncomfortable) during the course of prototype testing:

1. Before driving
2. After driving 10 laps on the oval track
3. After driving 20 laps on the oval track
4. After completing all driving (after lock-to-lock driving)

Increasing negative numbers indicated increasing discomfort during the course of testing. This trend was found for the upper and lower back, left and right hip/thigh regions, right knee, right ankle, and right foot. The first four are primarily influenced by seat design. Thus, even though, based on vibration isolation, the best of the available seats was selected, the seat still may not be optimum and may lead to fatigue over time. On the other hand, the comfort of the right knee, ankle, and foot do depend primarily on pedal design. In this particular case, the original mechanical design with a high accelerator spring constant limited the positive effects of the hanging pedal design. Small operators experienced a significant increase in discomfort during 10 laps of oval track driving; however, only a slight discomfort change for the rest of the drive indicated that the greatest changes were experienced in the lower back and right and left hip/thigh regions. All these are most affected by seat design (including seat pan length and seat pan width) and least by workstation design.

RMS grip forces during prototype bus testing ranged from 0.9 percent to 9.4 percent (with a mean value of 5.8 percent) as normalized to each individual's maximum grip force, which indicates that no evidence for muscle fatigue in grip exertions during steering in the prototype bus could be found. In terms of the relative proportion of maximum grip force used when steering the prototype workstation, there was not any significant gender, stature, or transit experience effect (i.e., females or small individuals did not use more than their available maximum grip force than did males or large individuals). Similarly, novice bus operators did not use more force than did experienced bus operators. This is a good result from the standpoint of developing cumulative trauma disorders (CTDs). In many industries, new and inexperienced employees may exert force levels that are higher than necessary and thus become more susceptible to CTDs.

CHAPTER 10. FINAL DESIGN SPECIFICATIONS AND GUIDELINES

The workstation should contain several features that are essential for accommodating the population extremes. Figures 10.1 through 10.4 are photographs of the prototype workstation. The essential features of the workstation are as follows:

- A 457-mm (18-in.) steering wheel
- Hanging pedals
- Tilt-telescoping steering column (minimum requirement); tilt-telescoping-tilt steering column (ideal)
- Low-profile farebox (not to exceed 91.4 cm [36 in.])
- Pin joint suspension operator seat
- Seat with air-actuated lumbar and back side bolster support features (preferred)
- Turn signal platform located on the floor angled at 30 deg housing the turn signals and high beam switch
- Adjustable (height and fore-aft) instrument panels divided into left, center, and right
- An ODA to act as the central interface to the bus electronics system
- Remotely activated mirrors

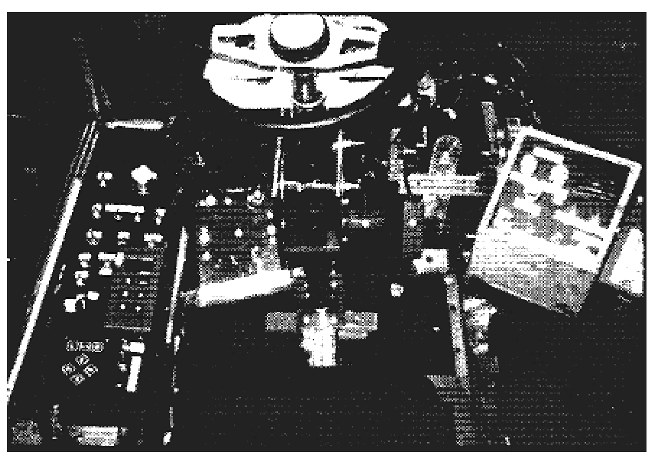


Figure 10.1. Left and right instrument panels.

Figure 10.2. Center instrument panel.

Figure 10.4. Prototype workstation.

- Annunciator system that allows push-button activation of prerecorded announcements (preferred); "hands-free" communication system (ideal)

The following figures and tables detail the necessary locations and adjustment ranges for the proposed workstation design. Figures 10.5, 10.6, and 10.7 are illustrations of the locations listed in Table 10.1. The reference points are listed in terms of 5th percentile female, 50th percentile person, and 95th percentile male and are defined in Table 10.2. Table 10.3 details all the design specifications necessary for the workstation.

CHAPTER 11. SAMPLE BID SPECIFICATIONS

The workstation's components will be adjustable to accommodate operators who range in stature from the 5th percentile female to the 95th percentile male as defined by SAE J833. The adjustable components include the seat, steering wheel, left instrument panel, and right instrument panel. The adjustment ranges are to be measured relative to each component's reference point as defined in Table 10.2.

Figure 10.3. Hanging pedals.

The origin of the workstation (i.e., the datum) is denoted as the workstation origin and defined to be the SRP for the 50th percentile person (NSRP) projected onto the bus operator's platform. Relative to the workstation origin, the SRP will be adjustable ±9.3 cm in the horizontal direction and from 29.6 cm to 43.9 cm from the operator's platform in the vertical direction. The SRP for the 50th percentile person will be located a vertical distance of 36.7 cm from the operator's platform. No lateral distance will exist between the SRP and the workstation origin. The seat suspension shall be a pin-jointed linkage type. Features such as air-actuated lumbar and back side support are preferred.

The steering wheel location is defined by the steering wheel reference point (SWRP). Relative to the workstation origin, the SWRP is to range from a location of 48.8 cm in the horizontal and 63.2 cm in the vertical to a point located at 39.8 cm in the horizontal and 69.5 cm in the vertical. The SWRP for the 50th percentile person is located midway between the extremes. No lateral distance will exist between the SWRP and the workstation origin. The steering wheel diameter will be 457 mm.

The left instrument panel is to contain the secondary controls or controls that are used during predriving tasks. These controls are the parking brake, exterior mirror remote adjustment knobs, exterior mirror defrost control, internal and external public announcement systems, radio controls, run selector knob, transmission, and ignition switch. The announcement system preferably should be one that allows push-button activation of prerecorded stop announcements or one that is a hands-free microphone system. The dimensions of the left instrument panel are determined by the space required for the controls. The LIPRP is defined in Table 10.2. Relative to the workstation origin, the LIPRP is

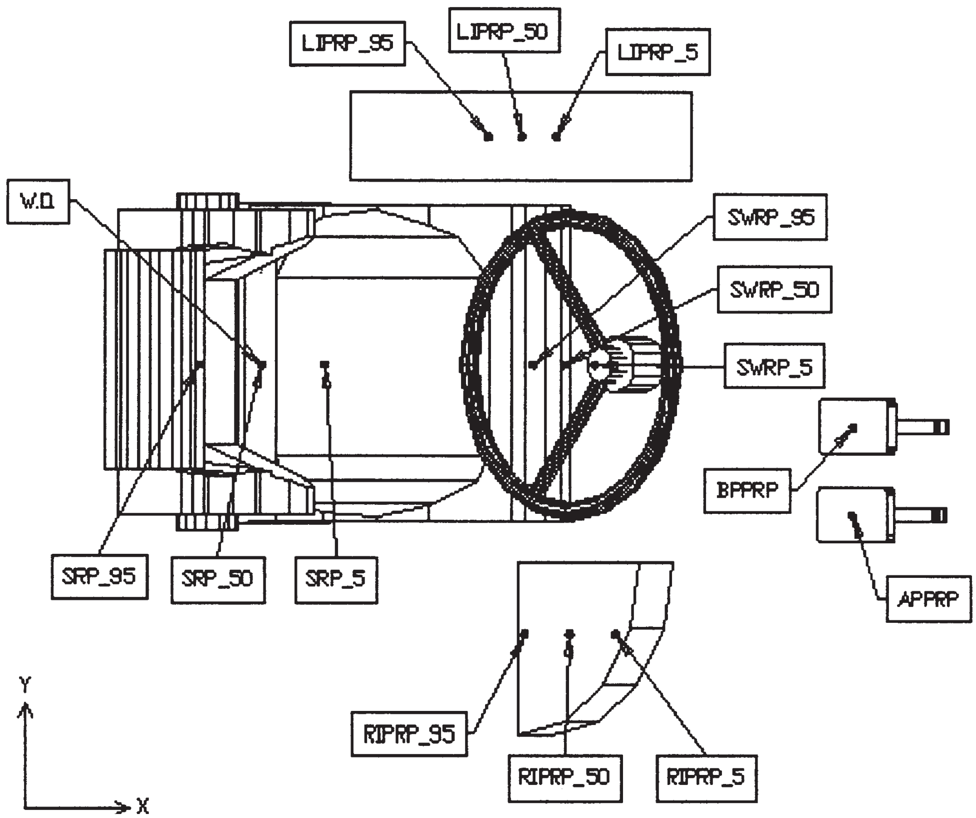


Figure 10.5. Specifications, plan view.

to range from a location 43.1 cm in the horizontal and 47.6 cm in the vertical to a point located 33.2 cm in the horizontal and 51.6 cm in the vertical. The LIPRP for the 50th percentile person is located midway between the extremes. The left instrument panel is to be inclined at an angle of 5 deg. The LIPRP is located 33.0 cm laterally from the workstation origin.

The right instrument panel contains primary controls for driving and picking up and depositing passengers. These controls are placed on this panel because they are used frequently and need to be easily accessible to bus operators. The dimensions of the right instrument panel are based on the controls it will contain.

The right instrument panel will contain a keypad with a small displayCan ODA. The functions that can be accomplished through the ODA include the following:

- Presentation of the bus route schedule
- Control of the farebox
- Automatic counting and categorization of fares if used in conjunction with a card reading farebox or manual inventorying of passengers is used with a traditional farebox
- Printing of transfer tickets
- Monitoring of fuel efficiency
- Changing of the destination sign
- In the future, linking with an inertial navigation system for real-time location of buses and planning of proper routing to avoid delays

The data collected by the ODA can be downloaded easily at the end of the workday to a home-base computer for analysis. The RIPRP is defined in Table 4.2. Relative to the workstation origin, the RIPRP is to range from a location 51.9 cm in the horizontal and 65 cm in the vertical to a point located 38.6 cm in the horizontal and 69.5 cm in the vertical. The RIPRP for the 50th percentile person is located midway between the extremes. The right instrument panel is to be inclined at an angle of 30 deg. The RIPRP is located 37 cm laterally from the workstation origin.

The center instrument panel gives the operator the status of the workings of the bus. Any information that does not require continuous monitoring by a particular gauge (e.g., speed) is replaced with an indicator light. To accommodate tell-tale indicators without giving up 0.95 cm by 1.27 cm of space for each, the center instrument panel will have a small screen that can display any of these indicators with the colors and required alarms. Because time is a major concern for operators and a significant factor in their duties, a clock is provided. The two most regularly monitored items on the center instrument panel are the speedometer and air pressure gauge. For this reason, traditional, large dial readouts are provided.

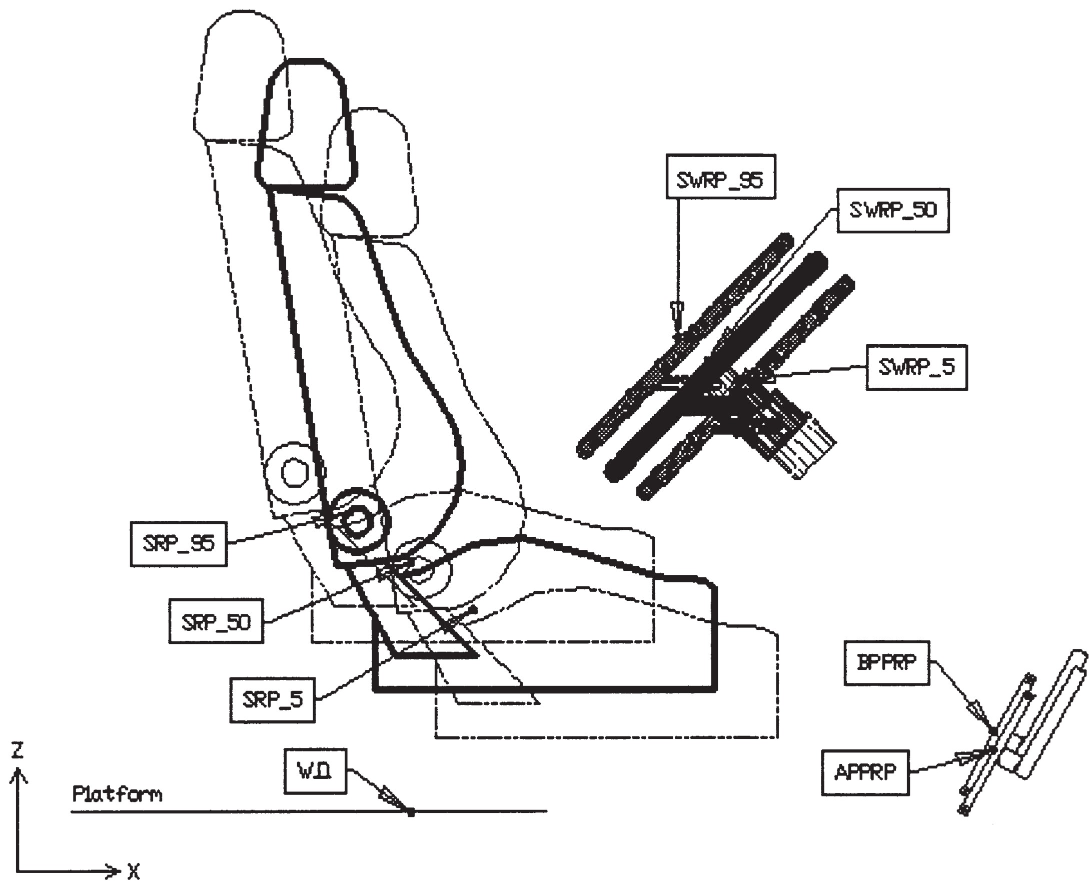


Figure 10.6. Specifications, side view (left instrument panel and right instrument panel not shown). (Solid lines denote 50th percentile positions.)

The intention of mounting the instrument panel directly on the steering column is to facilitate downward visibility.

Pedals will be the hanging type. Relative to the workstation origin, the brake pedal plate reference point (BPPRP) will be located laterally 8.9 cm to the right, 86.6 cm forward, and 11.6 cm above the operator's platform. Relative to the workstation origin, the accelerator pedal plate reference point (APPRP) will be located laterally 21.8 cm to the right, 86.4 cm forward, and 9 cm above the operator's platform.

A turn signal platform will be mounted on the operator's platform to accommodate left-foot-actuated turn signals and high beams as well as the stop announcement switch. The platform will be angled at 30 deg.

The farebox will be electronically connected to the ODA. The farebox shall be located in a position so that obstruction of the operator's view is minimized. Therefore, a location shall be provided in the bus so that the farebox can be placed with minimal obstruction. The top of farebox shall not exceed 91.4 cm (36 in.) from the floor.

12. BENEFIT-COST EVALUATION

Benefit-cost analysis is a quantitative methodology used for justifying the expenditure of funds for controlling a problem situation or, more simply, the dollars spent per negative utility reduction (*15*). Cost can be defined as the monetary outlay for the incorporation of a device, method, or procedure for a given period. In this particular study, costs included materials, components, and labor associated with developing the recommended bus operator's workstation.

A negative utility or dollar cost is associated with every injury. This cost could include direct costs, such as for medical expenses and worker's compensation, and indirect costs, such as for lost time and replacement operator training. A benefit is defined as the reduction in the negative utility and the decrease in injuries and medical costs. The effectiveness of a corrective measure is evaluated by the ratio of benefit to cost, with larger numbers indicating better utility or effectiveness.

Costs

Many factors need to be included in estimating the costs of the prototype bus workstation. The proposed workstation contains instrument panels that move, which will result in increased maintenance. Also, the wires and cable going into the instrument panels will require sheathing to protect them from vandalism and large loops to prevent failure due to

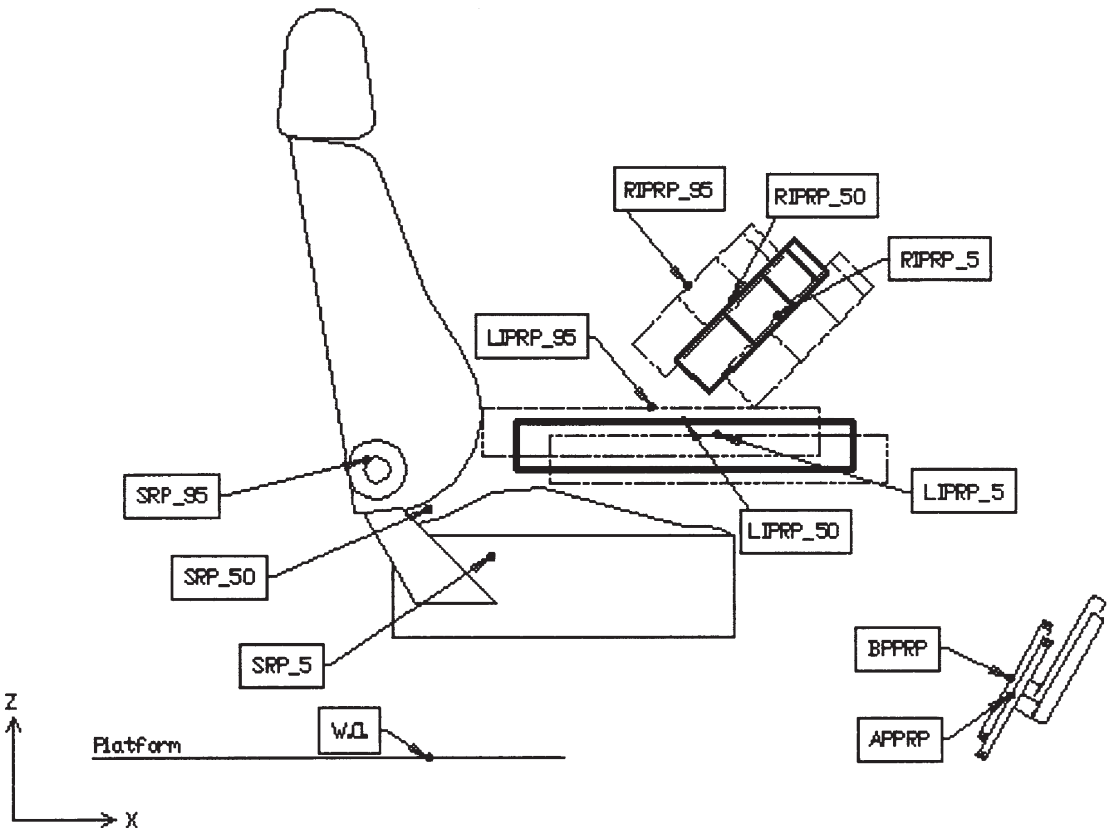


Figure 10.7. Specifications, side view (steering wheel not shown). (Solid lines denote 50th percentile positions.)

fatigue. The instrument panel supports will have to be strong enough to withstand the vibrations generated on a typical transit bus route. During development of the workstation design guidelines, attention was paid to these issues. Of course, each manufacturer will have its own method for implementation.

Costs associated with the ergonomic workstation were developed based on the costs incurred in the development of the prototype workstation. The costs for the prototype's materials, parts, components, and labor totaled $6,131.

Benefits

Benefits of the recommended workstation were estimated based on information from Connecticut Transit (CTTRANSIT) and BC Transit. CTTRANSIT experienced 32 injuries among 515 employees in a 6-month period. This amounts to a yearly injury rate of 12.43 per 100 workers, or an injury rate of 0.1243 per worker.

TABLE 10.1 Guidelines—component locations (in cm)

Reference Point	SAE 5% Female			SAE 50%			SAE 95% Male		
	x	y	z	x	y	z	x	y	z
SRP	9.3	0.0	29.6	0.0	0.0	36.7	-9.3	0.0	43.9
SWRP	48.8	0.0	63.2	44.3	0.0	66.3	39.8	0.0	69.5
LIPRP	43.1	33.0	47.6	38.1	33.0	49.6	33.2	33.0	51.6
RIPRP	51.9	-39.0	65.0	45.2	-37.0	67.2	38.6	-39.0	69.5
BPPRP	86.6	-8.9	11.6	86.6	-8.9	11.6	86.6	-8.9	11.6
APPRP	86.4	-21.8	9.0	86.4	-21.8	9.0	86.4	-21.8	9.0

CTTRANSIT spent $87,000 ($42,000 in direct medical costs and $45,000 in worker's compensation costs) for these 32 injuries, at an average cost of $2,718 per injury. Data from BC Transit indicated average direct costs of $5,962 per injury. These costs were primarily for back injuries (which tend to be more expensive than other types of injuries) resulting from frequent occurrences of the seats bottoming out.

The projected decrease in injuries due to the redesigned ergonomic operator's workstation is based on data from BC Transit. The agency installed upgraded seats and made additional workstation modifications. In the year following the implementation, BC Transit experienced a 78 percent decrease in the injury rate (from 1.92 to .43 per 1 million km) and an 88 percent decrease in the injury severity rate (from 29.42 to 2.72 days lost per 1 million km). These values are similar to those obtained by another industry. More specifically, during a 3-year period after implementation of an ergonomic program (workstation redesign, tool changes, and training) in an automobile carpet manufacturing facility, the number of injuries decreased by 74 percent. Therefore, a projected injury reduction rate of 80 percent for this prototype is not unusual.

Benefit-Cost

The benefit-cost ratio is defined as the dollar cost reductions per workstation implemented per cost of a workstation:

TABLE 10.2 Reference point definitions

Ref. Point	Definition
APPRP	Accelerator Pedal Plate Reference Point. Located on the center of the top surface of the accelerator pedal plate. If the peda plate pivots about the pedal arm, then the reference point is to be located at the pivot location projected normally onto the pedal plate surface.
BPPRP	Brake Pedal Plate Reference Point. Located on the center of the top surface of the brake pedal plate. If the pedal plate pivots about the pedal arm, then the reference point is to be located at the pivot location projected normally onto the pedal plate surface.
LIPRP	Left Instrument Panel Reference Point. Located in the center of the top surface of the left instrument panel.
RIPRP	Right Instrument Panel Reference Point. Located in the center of the top surface of the right instrument panel.
SRP	Seating Reference Point. The point on the sagittal plane located by two intersecting planes - the compressed seat pan and seat back. If SgRP (Seating Reference Point, which is the H-point (hip pivot point) of the 95th percentile person of the US population as defined by SAE J1100) is known from seat manufacturer data, the following equations can be used (SAE J1100, SAE J826): horizontal distance of SgRP from SRP = $HL12 - HL11 \times \cos(SB11)$ vertical distance of SgRP from SRP = $HL11 + HL12 \times \sin(SP9)$ where: SB11 is the seat back neutral vertical angle SP9 is the seat pan neutral horizontal angle HL11 is the vertical length from hip pivot to SRP (9.8 cm) HL12 is the horizontal length from hip pivot to SRP (13.4 cm)
SWRP	Steering Wheel Reference Point. Located in the center of the plane of the steering wheel.
WO	Workstation Origin. Located on the workstation platform directly underneath the NSRP.

$$\frac{\left\{\frac{\text{\# operators(shifts)}}{\text{bus}}\right\} \times \{\text{injury\_rate\_per\_worker}\} \times \{\text{average\_injury\_cost}\} \times \{\text{\%\_reduction}\}}{\text{workstation\_cost}}$$

Typically one bus is used for approximately 14 shifts a week. With each operator working 5 shifts a week, we would expect $^{14}/_{5} = 2.8$ operators per bus. The injury rate per worker from CTTRANSIT is 0.1243. Average injury costs range from \$2,718 to \$5,962, and an 80 percent injury reduction is expected. This results in a cost-benefit ratio ranging from

$$2.8 \times 0.1243 \times \$2{,}718 \times 0.8/\$6{,}131 = 0.123$$

to

$$2.8 \times 0.1243 \times \$5{,}962 \times 0.8/\$6{,}131 = 0.27$$

These are calculated on a yearly basis; therefore, taking the inverse would result in the number of years it would take to pay off the cost of a workstation that decreases medical costs. The payoff time would range from $^{1}/_{0.27} = 3.69$ to $^{1}/_{0.123} =$ 8.1 years. These values are probably low and payoff time could be expected to be shorter because of several variables that are difficult to account for in the direct calculations. Only direct costs are used. There are many indirect costs, such as for lost time, replacement operators, and training for replacement operators, that affect a transit authority. Also, medical and hospitalization costs have been skyrocketing during the past few years and will likely continue to do so. Therefore, these costs may be considerably low and payoff time may be considerably faster.

CHAPTER 13. SUMMARY

This report presents a transit bus operator workstation intended to accommodate a population from the 5th percentile female to the 95th percentile male. The approach taken to develop the workstation was to develop an appreciation of the operator's tasks and an understanding of current workstations through use of a survey and from direct observation. Use of hanging pedals, which are believed to provide better comfort for small operators, was considered.

A preliminary layout of the transit bus operator workstation was developed using various CAD tools along with scale-model mannequins oriented in the preferred driving posture. This resulted in approximate design values and adjustment ranges needed to nominally satisfy the bus operator population ranging from the 5th percentile female to the 95th percentile male. The resulting adjustment ranges are listed in Column 1 of Table 13.1.

A laboratory mock-up based on preliminary CAD design values was constructed and evaluated by a jury of more than

TABLE 10.3 Complete guideline specifications for an ergonomic bus operator workstation

Design Variables		Code	Design Value
Seat	horizontal distance of NDEP from NSRP	SH9	5.9 cm
	vertical distance of NDEP from NSRP	SH10	75.8 cm
	seat back neutral vertical angle	SB11	10 deg.
	seat back angle adjustment range	SB12	10 deg.
	seat pan neutral horizontal angle	SP9	5 deg.
	seat pan angle adjustment range	SP10	0 deg.
	seat fore/aft adjustment range	SP11/ SP12	18.5 cm for total of fore- and aft- adjustments
	seat upward/downward adjustment range	SP13/ SP14	14.3 cm for total of upward and downward adjustments
	vertical distance of NSRP from WO	SP15	36.7 cm
Steering Wheel	wheel diameter	TW1	45.7 cm
	wheel plane neutral horizontal angle	TW5	40 deg.
	wheel telescope adjustment range	TW7	11.0 cm
	wheel plane horizontal angle adjustment range	TW8	20 deg.
	horizontal distance of NSWRP from NSRP	TW10	44.3 cm
	vertical distance of NSWRP from NSRP	TW11	29.6 cm
Brake Pedal	brake pedal plate length	PB1	8.0 cm
	brake pedal plate width	PB2	10.0 cm
	brake pedal plate shape	PB4	curved
	brake pedal plate lateral angle	PB5	0 deg.
	brake pedal plate horizontal angle	PB6	40 deg.
	brake pedal plate pivot angle range	PB7	0 deg.
	lateral distance of BPRP from NSRP	PB8	8.9 cm
	horizontal distance of BPRP from NSRP	PB9	86.6 cm
	vertical distance of BPRP from WO	PB10	11.6 cm
	brake pedal actuation angle	PB20	30 deg.
	brake pedal actuation force	PB21	66.8 ~ 155.8 N
	brake pedal recovery force	PB22	22.2 N
Accelerator Pedal	accelerator pedal plate length	PA1	14.0 cm
	accelerator pedal plate width	PA2	5.6 cm
	accelerator pedal plate shape	PA4	flat
	accelerator pedal plate lateral angle	PA5	12 deg.
	accelerator pedal plate horizontal angle	PA6	30 deg.
	accelerator pedal plate pivot angle range	PA7	10 deg.
	lateral distance of APRP from NSRP	PA8	21.8 cm
	horizontal distance of APRP from NSRP	PA9	86.4 cm
	vertical distance of APRP from WO	PA10	9.0 cm
	accelerator pedal actuation angle	PA20	20 deg.
	accelerator pedal actuation force	PA21	31.2 ~ 40 N
	accelerator pedal recovery force	PA22	22.2 N
Left Instrument Panel	left instrument panel horizontal angle	IL5	5 deg.
	left instrument panel horizontal adjustment range	IL6	9.9 cm
	left instrument panel vertical adjustment range	IL7	4.0 cm
	lateral distance of NLIRP from NSRP	IL8	33.0 cm
	horizontal distance of NLIRP from NSRP	IL9	38.1 cm
	vertical distance of NLIRP from NSRP	IL10	12.9 cm
Right Instrument Panel	right instrument panel horizontal angle	IR5	30 deg.
	right instrument panel horizontal adjustment range	IR6	13.3 cm
	right instrument panel vertical adjustment range	IR7	4.5 cm
	lateral distance of NRIRP from NSRP	IR8	37.0 cm
	horizontal distance of NRIRP from NSRP	IR9	45.2 cm
	vertical distance of NRIRP from NSRP	IR10	30.5 cm

100 people, who were grouped according to stature and gender. The average height of the small female was close (within a standard deviation) to that for the 5th percentile female. The average height of the large male was close (within a standard deviation) of the 95th percentile male. Therefore, the population extremes were included in the evaluation and, to some extent, were overrepresented compared with the general population.

The resulting user preferences were tabulated in frequency distributions from which the mean values and 5th percentile tails (i.e., $z_{.05}$ and $z_{.95}$) were calculated. The corresponding parameter values provided the two extreme values for determining the required adjustment range. These values are tabulated in Column #2 of Table 13.1. For most components, the values are actually slightly smaller than initially proposed under the preliminary CAD design. Only the seat fore-aft

TABLE 13.1 Workstation component adjustment ranges

Component Adjustment	1 Preliminary CAD Approach	2 Mock-up Evaluation	3 JACK Simulation	4 Final Design Values (Based on NSRP Approach)
Seat fore-aft (cm)	21.6	29.4	18.5	18.5
Seat vertical (cm)	10.0	11.0	6.7	14.3
Seatback angle (deg)	-	-	10	10.0
Steering wheel base tilt (deg)	25.0	18.7	20	20.0
Steering wheel telescope (cm)	28.0	21.1	11.0	11.0
Left instrument panel fore-aft (cm)	20.4	22.9	9.9	9.9
Left instrument panel vertical (cm)	18.4	12.7	4.0	4.0
Right instrument panel fore-aft (cm)	20.3	14.7	13.3	13.3
Right instrument panel vertical (cm)	19.0	16.3	4.5	4.5

range was larger than expected because of several outliers (i.e., small females choosing extremely close-up seat positions). However, overall, the workstation was able to accommodate a population ranging from the 5th percentile female to the 95th percentile male.

Evaluations indicated that, on average, jury members were satisfied with the preliminary design in terms of visibility, reach, comfort, and adjustability. These ratings are consistent for all population groups. The standard deviations for these subjective ratings are consistent between population groups and subjective measures.

Next, the JACK program was used to validate the design specifications. The workstation layout was imported into JACK, and simulations of typical driving tasks using 5th percentile female and 95th percentile male models were undertaken. The workstation components were adjusted as needed to accommodate the different size models, resulting in the adjustment ranges (with a precision of +1 cm) shown in Column 3 of Table 13.1. These values corresponded closely to previously selected design variables, again validating previous design strategies.

A scientific approach using the NSRP was used to determine the key design variables. This procedure yielded the final design values (the adjustment ranges of which are shown in Column 4 in Table 13.1) used in prototype construction and evaluation. Again, these values were, in most cases, very close to the values found in the previous stages (Columns 1, 2, and 3 in the table). Also, the preliminary CAD approach involved a discrete simulation using two mannequins, whereas the mock-up included postural differences as well as the variation of subject limb lengths. JACK was a discrete simulation with finite resolution. The NSRP approach was much more precise and accurate. In a graphic technique, the accuracy may be ± 5 deg to 10 deg, but in the NSRP approach, specific angles were considered.

The prototype was constructed in a 1973 GMC bus. Any deviations in adjustment ranges, such as for some of the instrument panels, were due to limitations of the mechanical structure of the existing bus. The reduced steering wheel telescoping range resulted from current technological limitations of commercially available telescopic columns.

The purpose of the prototype was to evaluate the performance of the workstation under actual operating conditions on a closed course. A closed course was chosen because of safety considerations, but represented a typical transit bus operating cycle (four stops/mi and average speed of about 15 mph). Because the prototype was constructed on an existing platform, it required compromise in some actual features. For example, the steering gear box location was fixed and could not be moved. This caused some of the workstation components to be located closer than desired; however, it also showed that if the workstation can be built in this existing platform, the workstation can be constructed on most platforms. The seat for the workstation was a commercial unit selected based on vibration isolation properties. The benefit-cost ratio of the workstation as built in the prototype is favorable.

According to the bus operators who tested the prototype, visibility was not significantly different between the standard bus workstation and the prototype workstation. This can be attributed to the fact that windshield height and body frame structure of the standard bus, which provide sufficient downward visibility, were the same as the prototype, whereas every other characteristic (comfort, reach, adjustability, and ease of ingress and egress) was significantly improved in the prototype design. All 24 operators rated the prototype better than the standard bus workstation for each of these criteria.

The results indicated that the seat in the prototype was located at a lower position and the steering wheel and right instrument panel of the prototype were located at a farther and higher location from the seat than those of the design specifications. This produced larger shoulder and elbow flexion angles during driving than the assumed standard driving postures. However, these angles were within recommended comfort ranges. The stretched-out shoulder-arm posture could be the result of an operator's driving preference that developed from driving buses with conventional workstations.

Test results indicated the acceptance of the redesigned workstation by 24 bus operators from various transit systems. The small females did experience some discomfort and an increase in discomfort over time; however, it is believed that this discomfort stemmed from the seat, which was beyond the control of the project. The other population groups remained relatively comfortable throughout the test. The force required to actuate the accelerator pedal did cause some discomfort for the operators; however, again, this was a factor beyond the control of the project because the existing accelerator linkage had to be used.

CHAPTER 14. CONCLUSIONS

The conclusions from this research are as follows:

- The bus operator workstation can be redesigned using ergonomic principles to accommodate individuals ranging from the 5th percentile female to the 95th percentile male.
- The prototype designed and constructed for this project was judged superior to the existing workstation by a representative jury of bus operators.
- It is estimated that the additional cost of incorporating in new buses the final design guidelines developed in this research will be more than offset by savings in terms of reduced operator injuries and worker's compensation claims.

This work resulted in guidelines for the design of a bus operator workstation that accommodates population extremes. This report develops the guidelines through rigorous analysis, synthesis, and testing. The guidelines are presented in two formats: (1) a simple-to-use version that is essentially a set of engineering drawings that can be incorporated directly into a bus specification and (2) a set of functional relationships that serve as guidelines for the design of workstations with specific features and requirements.

Future enhancements can be designed into the workstation as costs permit. Some of these enhancements are as follows:

- A memory that allows operators to type a number into the ODA to move components automatically to preset locations
- Active vibration control in the seat to accommodate a wide variety of road conditions (e.g., roughness) and all population ranges
- A seat pan that is sufficiently adjustable to accommodate all population ranges
- A steering wheel tilt

The prototype constructed in this work did not include a steering wheel tilt because a suitable commercial product could not be located; however, a steering wheel tilt would improve visibility as well as comfort.

To develop a further understanding of the issues involved and to develop cost-effective solutions, more research is needed. Each aspect of this project could be expanded to become a research project unto itself. Recommendations for future research include the following:

- Development of an anthropometric dataset focused on the industry. This would allow refinement of the aforementioned guidelines.
- A critical in-depth study of seating comfort, including vibrations and long-term static comfort. This study should identify how operator manipulation of controls affects vibration levels. In addition, vibration levels found in a typical transit bus should be characterized.
- Future studies focusing on the entire bus and its layout to supplement this project, which dealt with the operator's immediate work area. For example, can the farebox be reconfigured to provide more visibility and room? Is the door in the optimal location? Are the vehicle's dynamic properties such as its pitch natural frequency optimal?
- Development of programs to educate operators about ergonomics, safe postures, and proper use of equipment, such as the seat, that has a variety of adjustments.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transit Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation