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INSTITUTE OF OCCUPATIONAL MEDICINE
Research Avenue North, Riccarton, Edinburgh, EH14 4AP
Tel: +44 (0)870 850 5131 Fax: +44 (0)870 850 5132
e-mail publications@iomhq.org.uk

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Ergonomic Principles in the Design of Underground Development Machines

W.L. Chan
A.J. Pethick
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SUMMARY

The aim of this project was to derive ergonomic guidelines and specifications to improve the design of new development machines based on underground studies of an extensive range of existing machines. Three families of development machines were studied: continuous-miners, drill-loaders and roadheaders.

A standardised data collection methodology was developed which was used for the evaluation of 25 machines representing 80% of the types of development machines in use in UK mines.

The studies identified a wide range of operational and safety problems resulting from limitations in the operator's lines of sight, interface design, workspace layout and working environment. A number of potential improvements were also identified for ancillary tasks and maintenance activities.

Ergonomic design principles and guidelines, based on criteria especially developed and tailored for mining applications, have been formulated to overcome the limitations identified. These were compiled into three separate design handbooks, one for each machine family, for circulation to mining equipment designers as a supplement to existing NCB design

documents. This will ensure that ergonomic issues are routinely considered at both the conceptual and testing stages in the design of new development machines.

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1. INTRODUCTION

1.1 Background to Research

The National Coal Board's (NCB) 'Plan for Coal' and 'Coal 2000' investment programmes have led to an increasing rate of opening new coalfields and extending existing collieries into new seams. This places a great emphasis on efficient roadway drivage, for example 600 km of roadway was driven in 1983 at a cost of £400 million. In addition, the NCB's policy to expand retreat-mining also depends on improvements in roadway-making techniques and equipment. As a result, one of the major growth areas in new machinery design over the last decade has been in roadway development machines.

To maximise machine utilisation, both the NCB and manufacturers have concentrated on the development of multi-function machines. For example, machines are designed to cut or drill the heading and also gather the debris; feeding it either directly to packholes or the stage loader. Similarly, a variety of devices were also developed to assist ancillary heading tasks such as arch-setting and for advancing auxiliary equipment such as ventilation duct, stage loader and materials.

A number of these development machines have been evaluated as part of a previous ECSC funded project (Mason et al, 1980). The findings suggested that the increased complexity in machine functions and in drivers' tasks had, in many cases, led to conflicts between the operator and engineering requirements. The findings showed that ergonomic design could contribute to improving safe and efficient operation of these machines, but that the criteria in the literature were often ill-defined and that there was also a scarcity of practical ergonomic information available to machine designers. It was concluded therefore that ergonomic research could minimise conflicts in the man:machine system, and could thereby improve the overall efficiency of development operations. This project was therefore initiated to address the above issues.

1.2 Objectives of Research

The objective of the project was to identify aspects of development machine design where ergonomic improvements could benefit the health, safety and efficiency of the workforce.

The project was structured to identify:-

(a) major ergonomic limitations of existing machines in their operational environment;

(b) the causes to these limitations;

(c) the consequences associated with them.

This information would allow the relative importance of the ergonomic limitations to be assessed. The priorities for improvement can then be determined to maximise the health, safety and performance aspects of the machine design.

1.3 Strategy for Implementation of Results

Due to the large numbers of new developments in roadheading machines, it would be prohibitively costly for ergonomists to become involved routinely as a member of all the design teams. The most efficient method for effecting ergonomic improvements is therefore to provide ergonomic information in the form of design guidelines or specifications which can be used by designers without further involvement of ergonomists (Simpson and Mason, 1983).

Ergonomic guidelines or checklists have the potential problems of information either being too general or not in the correct context. To allow designers to obtain the optimum ergonomic advice, guidelines are needed on ergonomic aspects of each individual type (or family) of machines. Such ergonomic specifications could, with the approval of the industry, influence design policies for all future development machines.

2. METHOD

2.1 The Ergonomic Principles Approach

The practical difficulties and sometime inhibitingly high costs of undertaking modifications reduces the effectiveness of applying ergonomics solely to existing machines. To maximise benefits from the research, the project therefore aimed to improve the design of new rather than existing machinery.

To influence ergonomic improvements on a large number of development machines, a cost-effective method was necessary which provides suitable ergonomic design specifications for designers to use at the drawing board stage without the necessary involvement of ergonomists.

In order to provide ergonomic information which designers can use independently, the ergonomic information needs to be specific to the context of one type of machine. The criteria for specifications therefore need to be specific to the context of one type of machine and needs to be tailored to take into account of mining considerations and where necessary, conflicts between existing ergonomic recommendations need to be resolved.

The Principles Approach has been designed to provide such information. With this approach, the context is provided by the concept of a machine family which is defined as a group of machines with similar ergonomic features and functions. The Principles Approach and its applications are reported in greater detail by Kingsley, et al (1980), Simpson and Mason (1983).

Briefly the Principles Approach consists of the following six stages:

(a) Define the machine family;

(b) Select a representative sample of machines and sites where they are deployed;

(c) Using a standardised methodology, undertake detailed ergonomic evaluations of these machines in their operational environments;

(d) Collate all ergonomic limitations identified, especially those which occur widely across the sample;

(e) Identify the relevant criteria and derive recommendations necessary to overcome the limitations. If necessary, small studies should be undertaken to establish new criteria;

(f) To prepare the Ergonomic Principles report which defines the problems, specifies the criteria and lists the recommendations.

2.2 Machine Samples

In order that the Principles Approach produces ergonomic guidelines which are applicable to the maximum number of machines possible, two study requirements must be fulfilled. These are:

(a) that the range of machines to be studied be grouped into 'families' according to the similarity of their ergonomic functions and features;

(b) that a representative sample of the types of machines for each 'family' be studied in a wide range of geological conditions, as well as a representative range of mining systems and environments.

Examination of the range of multi-function development machines and their applications in the UK coal mines (Morris, 1978; Watson, 1977; Woodley, 1979) indicates that these can be categorised into three main 'families' of machines. Each have distinct differences in operators' task requirements as a result of different machine functions, and their utilisation in different strata conditions and mining systems. The three machine 'families' are defined as shown in Table 1.

TABLE 1

Operational Characteristics of the Three Families of Development Machines

Machine Family	Type of Strata Suitable	Task Elements in Operational Cycle
Continuous Miner	Coal (mainly)	Continuous cutting/load Set supports Advance auxiliary equipment
Roadheaders	Coal & soft stone	Cut and load Load Set supports Advance auxiliary
Drill-Loaders	Stone (mainly)	Drill Shot fire Set crown Load Set legs Advance auxiliary equipment

The HQ Mining Department helped in the subsequent selection of a suitably representative sample of machine types and sites for study. A total of 25 machines were selected and studied at 19 different collieries in 6 different NCB Areas to reflect a wide range of mining conditions and systems.

Tables 2, 3 and 4 show the number and types of machines selected for each family of development machines and the characteristics of the study sites. The selected sample represents 80% of the continuous-miner types, approximately 75% of roadheader types and 75% of drill-loader types that were in use in UK coal mines in 1981 (National Coal Board, 1981).

The objective of studying three RH22 roadheaders and three MkI dintheaders in different collieries is to examine the degree with which different working conditions (geological, environmental and work systems) interact with or affect the ergonomic requirements for machine

TABLE 2

Characteristics of Machine Types and Study Sites Selected for Continuous-Miners Family

	MACHINE DESIGN CHARACTERISTICS			STUDY SITE CHARACTERISTICS					
	Cutter/Type Action	Rear Discharge	Canopy	Type of Heading	Roadway Support & Dimensions	Gradients	Strata Composition	Environment Conditions
Dosco MkI Dintheader	Transversed	●		Devel. Heading Full	3 piece Holly Banks 3.7 x 1.8 m	Approx. Level	Coal Firm Roof	Wet Cool
Dosco MkI Dintheader	Transversed	●		Devel. Heading Full	3.5 x 2.0 m	1:20	Mainly Coal	Dry Hot
Dosco MkI Dintheader	Transversed	●		Devel. Heading Full	3 piece Holly Banks	Approx. Level	Coal	Surface Water Dust
Dosco Mk2 Dintheader	Transversed	●		Main Roadway Drivage	3 piece Holly Bank 3.7 x 2.9 m	1:8	Coal	Wet Cool
BJD Heliminer	Transversed	●	●	Pillar & Stall Heading	Steel Cross Girder 6.5 x 2.2 m	Approx. Level	Coal	Wet Dust
Joy 8CM Continuous Miner	Transversed	●	●	Pillar & Stall Heading	Steel Cross 4.6 x 2.0 m	Approx. Level	Coal	Dry Dust

TABLE 3

Characteristics of Machine Types and Study Sites Selected for Roadheader Family

	MACHINE DESIGN CHARACTERISTICS				STUDY SITE CHARACTERISTICS				
	Rotary Cutter	Gathering Arm	Scraper Conveyor	Rear Discharge	Type of Heading	Roadway Support & Dimensions	Gradients	Strata Composition	Environment Conditions
Thyssen Titan E134	●		●	●	Devel. Heading Full	3 piece conv. 6.5 x 4.0 m	Down 1:7	Coal & Hard Dirt	Dry, Dusty
Webster 2000 Cutter Loader	●	Bucket			In-Line Rip Half Head	3 piece conv. 5.0 x 3.7 m	Down 1:15	Coal Bottom Dirt Top	Dry, Dusty when Stowing
Anderson Strathclyde RH22	●	●		●	Devel. Heading Full	3 piece conv. 5.2 x 3.7 m	Down 1:4	1 m Coal Top Stone Bottom	Dry Stone Dust
Anderson Strathclyde RH22	●	●		●	Devel. Heading Full	3 piece conv. 5.0 x 3.7 m	Level	Sandstone 1 m Dirt Bottom	Dry, Dusty
Anderson Strathclyde RH22	●	●		●	Devel. Heading Full	3 piece conv. 5.2 x 3.7 m	Down 1:6	Mainly Coal with Thin Band Dirt	Coal Dust, Soft Ground
Anderson Strathclyde RH1/4	●	●		●	Devel. Heading Full	3 piece conv. 5.0 x 3.7 m	Down 1:15	Mainly Shale & Ironstone Band	Dry, Dusty
Anderson Strathclyde Boom Miner	●		●	●	Devel. Heading Full	3 piece Holly Banks 5.5 x 3.7 m	Approx. Level	Mainly Coal Dirt Bottom	Wet, Soft Ground Dusty
Dosco LH1300	●	●		●	Devel. Heading Full	Hollybanks 4.0 x 2.2 m	Approx. Level	1.2 m Top Coal Stone/Dirt Bottom	Dry, Moderate Dust
Dosco SL120	●	●		●	Return Gate Full Heading	3 piece Holly Banks 4.7 x 3.4 m	Approx. Level	Stone Top Dirt Bottom	Soft Ground, Stone Dust
Dosco 2400	●		●	●	Maingate Full Heading	3 piece conv. 5.0 x 3.7 m	Up 1:10	2.5 m Coal Dirt Band	Dry, Soft Ground
Dosco Mk2A	●		●	●	Devel. Heading Full	3 piece Whole 5.2 x 4.6 m	Down 1:10	Mainly Coal & Dirt Bands	Dry, Dusty
Dosco Mk2B	●	●		●	Excavation for Garage Site	3 piece sq. 5.2 x 4.6 m	Approx. Level	Coal Dirt Stone	Dry, Dusty
Dosco Mk3	●	●		●	Drift Heading Full	3 piece conv. 5.2 x 5.0 m	Down 1:25	Mainly Dirt	Wet, Soft Ground

TABLE 4

Characteristics of Machine Types and Study Sites Selected for Drill-Loader Family

	MACHINE DESIGN CHARACTERISTICS					STUDY SITE CHARACTERISTICS				
	No. of Drills	No. of Operators	Bucket Load	Apron/G.A. Load	Dozer Blades	Type of Heading	Roadway Support & *Dimensions*	Gradients	Strata Composition	Environment Conditions
Mindev Duo-Loader 190	1	1	●			Main Gate Rip	3 piece conv. 5.0 x 4.7 m	Down 1:8	Sandstone Rip	Dry
Dosco Twin Drill Jumbo	2	2		●		Devel. Heading Full	3 piece conv. 4.4 x 4.2 m	Approx. Level	Mudstone & Fault LHS	Hot Dry
Eimco 625 DL	1	1	●			Tail Gate Half Head	3 piece conv. 4.6 x 3.0 m	Cross-Grade RH -- LHS	Stone & Dirt Coal Bottom	Hot Humid
Webster 2000 DL	1	1	●			Devel. Heading Full	3 piece conv. 5.0 x 3.7 m	Approx. Level	Sandstone	Dust Humid
Schwarz Drill-Loader	1	1	●		●	Tail Gate	2 piece arch 3.5 x 2.2 m	Approx. Level	Stone	Wet
Gullick Dobson Drill Loader	2	1	●	●		PROTOTYPE SURFACE TRIAL AT TEST SITE				

operation.

2.3 Underground Study Methodology

The underground methodology was designed to obtain information which would meet the following objectives:

(a) to identify machine features which create ergonomic limitations and their operational consequences;

(b) to identify, in ergonomic terms, the variability of machine design;

(c) to identify the types and patterns of use;

(d) to indirectly test the suitability of existing ergonomic criteria for mining applications;

(e) to obtain mining criteria for machine operation;

(f) to identify conflicts in system requirements which could lead to conflicts in ergonomic requirements.

Mason et al (1980) described in detail a machine evaluation procedure developed for use in either surface or underground locations. Many of the data collection procedures described for underground evaluations were employed in this project. The data collected was categorized under three headings:

(a) Measurements carried out on the machine and its surrounding environment;

(b) Observation of operational activities;

(c) Formal and informal interviews with operators and other personnel.

The methods adopted for data collection under each of these categories are described briefly below. A detailed expansion is only given where the method employed differs from that described by Mason et al (1980).

Examples of the data record sheets are shown in Appendix A.

2.3.1 Measurements of the machine and surrounding environment

(i) Controls

Details were recorded of the function, size and shape of each control, its location relative to the operating position, the clearances between it and adjacent controls or machine surfaces, and any other information regarding special features (e.g. detachable) and its state of wear. In addition, measurements were obtained of the operating force, together with its range of movement. A record was made of the relationship between the control and resulting machine movements (i.e. control operation stereotypes).

(ii) Artificial Displays

As with controls, details were recorded of the function, size and shape of each instrument or gauge, and its position relative to the operator and his normal field of view. In addition, a drawing was made of each display to provide details of its component parts including the indicating pointer, scale and graduation markings and any other information contained on the display. Any use of colour to provide contrast or to indicate operating values etc. was also documented. Finally, a note was made of its general condition and the cause of any damage if known.

(iii) Labels

All labels of controls, artificial displays and other machine components were assessed. A record was made of their size, shape and location relative both to the operator and his field of view, and to the control etc to which they referred. Details of the label contents, including the size, type and colour of any script or symbols were also recorded together with a note on the construction materials used and a comment on the general legibility of each label.

(iv) Workspace Layout

The locations of the controls and displays were incorporated into a scale-drawing of the operator's workspace. Where a seat was fitted, its dimensions were also included.

(v) Visual Environment

(a) Machine lighting: Details were recorded of the type, location and condition of any luminaires fitted to the machine. Light levels were measured using a Megatron, type D7, lightmeter. Three sets of measurements were obtained for each headlight or rearlight; (1) before cleaning, (2) after cleaning and (3) 24 hours after cleaning. Each set consisted of five values, one measured at the centre of the beam and one 0.5 m in each direction along the horizontal and vertical axes orthogonal to the light beam. All readings were obtained at a distance of 1 m from the front of the luminaire. Where both red and white bulbs were incorporated into rearlights, readings were made of the light levels produced by each bulb.

(b) Visibility: Data were obtained for the determination of visible and non-visible areas from the operating position using the machine perimeter technique described in Appendix B. The data record was annotated with details of major projections to aid in the subsequent interpretation of the computer drawn sightlines diagrams.

(vi) Thermal Environment

Thermal measurements were obtained using: (1) an Assman Psychrometer for psychrometric wet and dry bulb temperatures, (2) a Kane-May KM2002 electronic thermometer for machine surface temperature measurements, (3) a 38 mm globe thermometer (MacIntyre, 1980), (4) an Abbirko electronic anemometer for general air velocity measurement and (5) a Kata thermometer for situations where the windspeed was below the detection limit of the anemometer. Both electronic instruments were fully certified as intrinsically safe for use in coal mines.

Wet bulb, dry bulb and globe temperature measurements were obtained at chest height at the operator's workspace at the start and end of the shift. Similarly, temperatures were measured at the start and end of the shift from the surfaces of a selection of major machine components (hydraulic reservoirs etc.) together with any other components which the operator or other workmen may come into contact with.

Airflow was recorded at the operator's chest height every 0.5 m across the roadway, both when the machine was idle and, where possible, when the machine was cutting/loading. Supplementary information was also recorded on the clothing worn by machine operators, any other possibly contributory environmental factors (e.g. water sprays) and, where appropriate, the ventilation equipment and system in use.

(vii) Auditory Environment

Noise recordings were obtained using an intrinsically-safe recording system consisting of a Bruel and Kjaer 2206 Sound Level Meter connected to a Tandberg II tape recorder.

The following recordings were made at the operator's ear:

(a) Background noise (no local machinery running);
(b) General noise (conveyors, microdyne fans etc.);
(c) Noise with the machine powered up but stationary;
(d) Noise with the machine tracking;
(e) Noise with the machine drilling/cutting;
(f) Noise with the machine loading out;

(g) Noise with machine cutting and loading (where appropriate).

Where machines were fitted with auditory warning signals, these were recorded both at source and at the location of the likely receiver(s) ear.

2.3.2 Observation of operational activities : Task analysis

Task analysis information was collected during representative working cycles of all aspects of machine operation including its use in arch setting or powering ancillary equipment. The task recording was divided between two observers with the records synchronised by noting the onset of selected task elements. The task analysis data recording sheets are shown in Appendix A.

(a) Observer 1: Recorded the frequency and sequence of control usage including simultaneous use of controls.

(b) Observer 2: Recorded the sequence of operator postures and the apparent reason for each posture categorized as: (1) to aid visibility, (2) to aid communication, (3) for control use. Observer 2 also noted the parts of the working area which the operator needed to see for safe and efficient work (visual attention areas) and the nature and mode of communications together with any limiting factors. For example, where an operator cannot see the floor in front of the machine, he may require a second person (spotter) to guide him in order to cut a good floor line. Communication between the operator and this guide may be hampered by machine noise and/or dust.

2.3.3 Interviews with the workforce

A questionnaire, shown in Appendix A, was designed and used as the basis of structured interviews with the machine driver, spotter, arch-setting team, fitter and deputy (supervisor). The questionnaire covered all aspects of machine operation and maintenance to complement and supplement the measurements made on the machine and its environment, thus providing a means whereby existing criteria could be verified. Where criteria did not exist or needed refining, the data could facilitate the development of new criteria.

A standard data collection package, containing the techniques and methodologies outlined above, was used for each machine study. The duration of each study typically ranged from two to five shifts and covered a minimum of three complete operational cycles of cutting or drilling, loading and arch-setting.

3. SUMMARY OF RESULTS

3.1 Introduction

The underground studies of the three families of development machines generated results on an extensive range of ergonomic issues relating to machine design. The following section contains only a summary of these results. In order to appreciate fully the significance of these results, the operators' tasks for the three families of machine are briefly outlined, preceding each section of results. The mining systems and environments in which the machines operate have previously been described in Tables 2, 3 and 4.

For readers who are involved or have specific interest in the detailed design of development machines, the results are comprehensively reported in Chan(a) (in preparation), Collier (in preparation) and Pethick(a) (in preparation) for roadheaders, continuous-miners and drill-loaders respectively.

3.2 Continuous Miners

3.2.1 Introduction

Ergonomic aspects of the design of a sample of six continuous-miners were assessed in underground operational environments using methods described in section 2. One machine model was studied at three different locations in different collieries. This section reports the ergonomic limitations found in the continuous-miners studied.

3.2.2 Description of continuous-miners operation

Continuous-miners (CMs) are designed primarily to cut coal and medium-hard stone. They are applied in several mining situations, including development of coalfaces, rectangular roadway drivages and pillar and stall mining. Machines in this family are fitted with cutting jibs (see

Figure 1) which provide a continuous cutting and loading action. Some machines are fitted with canopies.

The debris is generally discharged through a central conveyor to the rear of the machine which feeds directly into a loading belt or onto shuttle cars. The machines have non-slewing cutting jibs so they are required to manoeuvre (by tracking) close to roadway sides in order to minimise dirt clearance and cutting by manual means. Good dirt clearance at these areas is necessary to allow proper setting of roof supports.

Some ancillary tasks are performed much more rapidly compared with the other machine families. For instance, supports can be erected from ground level because of the smaller size of the roadway. Tasks such as advancing ancillary equipment also take less time. These produce different ergonomic requirements to achieve safe and efficient machine operation.

3.2.3 Summary of results

There were several ergonomic limitations identified with control designs. Apart from the predominance of ball-headed levers and operator-in-position pedals, there was no standardized allocation and design of controls for particular functions. This was most apparent for the control operating stereotypes. For instance, in the case of track boost and gathering arms controls, there was a different relationship between the control's direction of movement and the associated machine response for every machine on which data were collected. Many controls required excessive operating forces; some electrical controls required up to 10 times the maximum operating force that is normally recommended. Controls were however, generally satisfactory with respect to ranges of movement, dimensions and durability. An important exception was the return spring on an operator-in-position pedal on one machine which had failed, thereby defeating its purpose. Pedals with an exposed return spring underneath may not be suitable for this application. Many controls (100% on one machine) were positioned outside the operator's

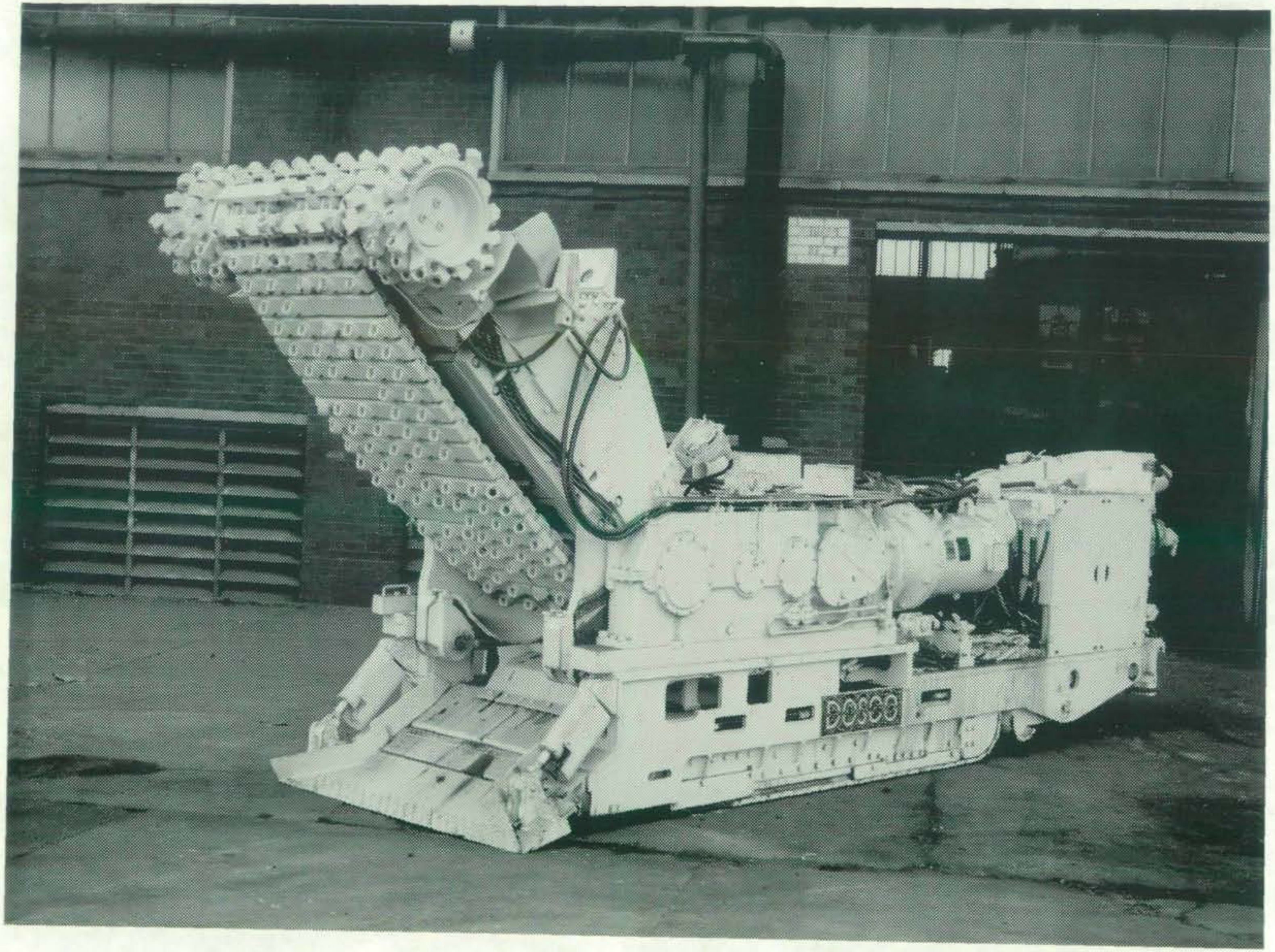


FIGURE 1. An Example of Continous-Miners

normal reach limit. As a result, poor working postures were adopted for a significant proportion of the work cycle. Approximately one third of controls had inadequate clearances around them, and were reported to have led to inadvertent control activiation by operators.

Assessment of the visual displays indicates that gauges located in the operator's workspace were potentially helpful, rather than essential to the machine's operation. Most gauges displayed information more relevant to the fitter than to the operator. Additionally, they lacked markings for normal operating ranges and so the operator would need to remember all the critical values if the displays were to be of use during cutting and loading. This may, in part, explain why they were largely ignored by operators according to task analyses and results of operator questionnaires.

Lines of sight on CMs were generally very restricted because of the design requirements to keep a low machine profile, and because the operator's workspace was located at one side of the machine. Between 50% and 90% of bad operator postures were adopted because of poor sightlines. On one machine, the operator's eye position was below a substantial part of the machine's forward profile, thereby making it difficult to see visual attention areas on one side of the machine. This increased the amount of manual work required in preparation for arch-setting at that side of the roadway. By analysis of the operator's visual attention areas and consideration of other factors such as driver positioning and personnel around the machine, design guidelines have been provided for improved lines of sight which take into consideration the overall design constraints (Collier et al, in preparation). Where fitted, aids such as jib position indicators were useful to help overcome problems caused by poor sightlines.

Seating was provided on four of the six machines studied, though all seats with PVC covered padding had been damaged. None gave sufficient isolation from machine jolting and vibration; all but one operator out of six commented that the speed of machine operation had to be reduced sometimes because of the discomfort caused by vibration. Reported discomfort was exacerbated by the operator's caplamp battery and self-rescuer pressing against the backrest of the seat.

Noise measurements taken at the operator's ear during working periods ranged from 93 dB(A) to 99 dB(A).

Verbal communication was significantly impaired, or in some cases rendered impossible by machine noise, making hand signals between the spotter and the operator the usual mode of communication. In normal circumstances with a driver and spotter team who have worked together for some time, this may be adequate. In other circumstances, for instance, when the spotter or driver is temporarily replaced, hand-signalling will not be understood fully or will be inadequate to communicate novel information.

The heat generated by the CMs had no noticeable effect on the ambient temperature in the headings throughout a shift. However, the direct radiant heat from some components may cause discomfort to operators. On four of the machines studied, the hydraulic tank and oil filters were located within 1 m of the operator. The highest surface temperature recorded within the operator's workspace was 49^{o}C at the hydraulic motors.

Lighting by headlights was generally poor due to the design of the fittings which prevented easy maintenance and cleaning. The positions of headlights allowed dust and debris to accumulate over the lens surface, reducing effective light output by up to 84%. Workers in ancillary tasks such as arch-setting felt that a floodlight would also be useful, provided that it could be turned on whilst the machine was otherwise electrically off.

Most of the maintenance problems were concerned with poor access. Also, the lack of fault-finding displays or diagnostic systems caused problems. One machine even lacked a hydraulic fluid level indicator.

Arch-setting crews commented that lifting aids for handling and erecting large roof supports significantly reduced the physical effort and the operational cycle. However, such aids were provided on only two machines. Often, the support brackets provided by manufacturers were inadequate for the purpose. Similar comments apply to means of helping to advance supplies and ancillary equipment. A winch at the rear of the machine independently operable by support teams would be useful. Rollers on the CM for manoeuvring arch-members onto erection devices also provide useful assistance and could reduce the risk of muscular strains and injuries, especially in wet ground conditions such as those found at three of the study sites.

The main ergonomic limitations on the CMs and the likely adverse consequence of these limitations which were derived from the task analysis are summarised in Table 5.

3.3 Roadheaders

3.3.1 Introduction

This section outlines the results of the underground studies of 13 roadheaders. The mining systems and environments in which the machines operate have previously been described in Table 3.

3.3.2 Description of roadheader operations

Roadheaders have been increasingly used during the past decade, the current number in use in NCB mines being approximately 800 (National Coal Board, 1984). The sizes of roadheaders vary considerably depending on their designed applications. The weights of roadheaders studied, for example, ranged from 20 tonnes to over 70 tonnes. Figures 2(a) and 2(b) show examples of the machines covered in the studies.

The primary tasks of roadheader operators are to exacavate roadways (usually to an arch profile using electrically-powered boom mounted cutters) and to load out the subsequent cut debris. A number of smaller roadheaders developed for face-end ripping operations are hydraulically

TABLE 5.

Implications of Ergonomic Limitations on Continuous-Miners

Ergonomic Limitations	Number of Studies	Number with Significant Limitations	LIKELY ADVERSE CONSEQUENCES.			
			Posture/ Comfort	Safety	Delays	Accuracy
Machine Operations:						
Inadequate lines of sight	6	6	✓	✓	✓	✓
Seating inappropriate or absent	6	6	✓			✓
Poor access to workspace	6	6			✓	
No protective canopy	6	5		✓		
Incorrect control type	6	0			✓	✓
Incorrect control stereotypes	6	6		✓	✓	✓
Excessive control operating forces	6	2	✓			
Unacceptable control movement range	6	0				✓
Inappropriate control dimensions	6	0	✓			✓
Poor control durability	6	1		✓		
Poor control positioning	6	6	✓		✓	✓
Inappropriate control clearances	6	3			✓	✓
Poor control layout/grouping	6	6			✓	
Poor display design	6	6			✓	
Poor display labelling	6	6			✓	
Poor display location and layout	6	6			✓	
Machine too noisy	5	2	✓	✓		
Interference of noise with communication	5	5		✓	✓	
Too high ambient temperature	6	0	✓			

TABLE 5.

Implications of Ergonomic Limitations on Continuous-Miners Continued

Ergonomic Limitations	Number of Studies	Number with Significant Limitations	LIKELY ADVERSE CONSEQUENCES			
			Posture/ Comfort	Safety	Delays	Accuracy
Inadequate lighting	6	6		✓	✓	✓
Too much vibration	6	5	✓		✓	✓
<u>Maintenance</u>:						
Poor access	6	5	✓	✓	✓	
Inadequate tools	6	1	✓	✓	✓	
Poor job aids	6	1			✓	
<u>Ancillary Tasks</u>:						
Lack of arch-lifting aids	6	3	✓	✓	✓	
Inadequate pulling/lifting/manoeuvring aids	6	6	✓	✓	✓	

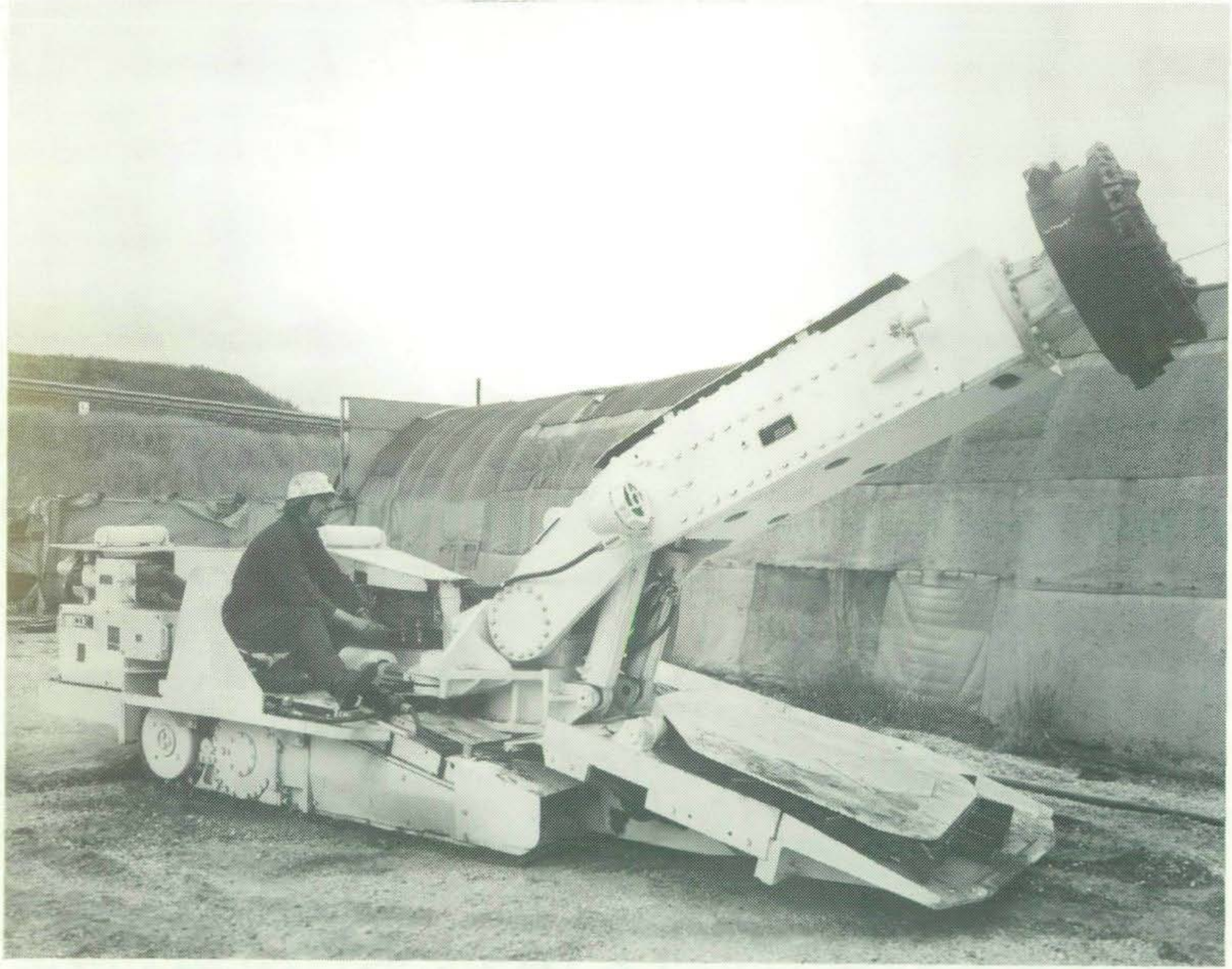


FIGURE 2a. An Example of Roadheaders with Conveyor Loading

FIGURE 2b. An Example of Roadheaders with Gathering Arm Loading

powered. Loading out debris can be performed simultaneously with cutting on most machines, although this operation is normally continued after cutting is completed. The debris is discharged onto a conveyor or into tubs at the rear of the machine. A small number of roadheaders are designed to feed the debris into pack-holes by means of either a side discharge conveyor or by feeding the debris into a stower system.

Cutting and loading operations demand accurate control of the cutter-boom and track controls. Inaccurate control of the machine has economic as well as potential safety consequences. Over-cutting or under-cutting the heading profile, for example, can significantly increase the workload for the arch-setting team, which effectively increases the overall cycle time of the heading operation.

Roadheaders are mainly deployed for major roadway development, and therefore are used in conditions with more headroom than CMs. Because of their size however, lateral clearances are frequently restricted to approximately 1.0 m.

Heading operations are carried out by a team whose tasks cover operating the machine and other duties such as supporting and lagging the roadway after exacavation, as well as advancing ancillary equipment and roof support materials. The necessity for other members of the team to work in the vicinity of the machine presents additional requirements for the machine driver. The design of roadheaders must therefore reflect these requirements to facilitate safe and efficient heading operations.

3.3.3 Summary of results

The study of 13 machines identified a range of operational problems associated with ergonomic limitations of roadheader design. The most critical related to restricted lines of sight where operators' visual attention areas such as arch legs and men around some part of the machine. This was found on 85% of roadheaders. The use of spotters to overcome sightline related problems has health, safety and performance implications (Chan, 1983a). For example, spotters adopted positions often at areas of higher dust concentration and close to the unsupported roof/rip as well as being vulnerable to inadvertent machine movements. Since the spotter was typically required for 30% of a shift, then approximately 5% of the total available manpower of a typical six-man heading team was effectively lost in compensating for a design limitation. In addition, task observation indicated that 54% of those operator's working postures which were likely to aggravate or precipitate back pain problems were adopted purely to overcome sightline limitations. Figure 3 illustrates a typical stooping posture to improve forward visibility when cutting or loading near the arches at the sides of roadways.

Similar postural problems also resulted from poor workspace layout. Over 70% of controls were outside the static reach of some operators, and this necessitated gross postural movements during machine operation.

Sixty-two percent of the machine sample had the driver's workspace positioned to one side of the machine. This type of arrangement could be disadvantageous in headings where the position of the ventilation ducting may prevent the machine from manoeuvring close to the roadway sides owing to lack of overhead clearances for the operator (Chan and Collier, 1983). Additionally, cutting and loading close to the arch legs at the 'blind' side also presented difficulties.

None of the seats fitted on roadheaders had provisions to accommodate the seated operator's caplamp and self-rescuer, and poor seat backrest design were also factors reported to have exacerbated poor postures. The layout of controls did not facilitate sequential or simultaneous control operation, nor were controls grouped according to functions for ease of identification and for fast and reliable control selection. Insufficient clearance around 51% of controls was reported to have caused inadvertent control operation. This mainly resulted from operator's clothing (sleeves) snagging on adjacent controls. Emergency stop controls on five machines were partially obstructed.

The speed and accuracy of machine operation were reduced by three

FIGURE 3. Operator Adopting a Stoop Posture to Improve Vision

aspects of control design in particular. Firstly, the lack of visual differentiation between control shapes and sizes made selection more difficult. Secondly, high operating forces (> 100 N) associated with 14% of controls affected the precision with which the machine could be operated. Finally, a third of controls had movement-response relationships which contradicted operators' expectations. This was shown to increase hesitation in control operation, as well as to increase unintentional machine movements. The latter has obvious safety implications for mineworkers (e.g. spotters) in the vicinity of the machine. The lack of standardisation of control-response relationships between machines would also create confusion for operators who were occasionally required to work on different machines.

Where fitted, displays indicating hydraulic fluid level, temperature and pressure were monitored by operators, and were assessed to be useful job aids. However, 46% of machines did not have temperature or pressure gauges fitted at the operator's workspace.

Labelling of controls although useful, especially for non-regular operators such as fitters, were not provided or had become detached on 54% of the machines studied.

Investigation of the operator's physical environment indicate that 23% of the workspaces had ETA values exceeding 29 °C, and 85% of operators commented that their workspaces became uncomfortably hot during machine operation. On 62% of the machines, the hydraulic tank was located less than 0.5 m from the operator's seat and this was identified as the most likely significant factor contributing to the operator's thermal discomfort.

On 62% of the machines, hydraulic hoses/pipings within the operator's workplace were not shielded and should a hose burst, hot hydraulic fluids could spill onto the driver (Chan and Graveling, 1983).

During cutting, 85% of operators indicated that vibration affected their ability to activate controls accurately. Two operators commented that vibration levels made it difficult for them to keep their foot on the operator-in-position pedals. Ninety-two percent of operators also reported that vibration caused postural instability and fatigue especially on machines without seats.

Recorded noise levels at the operator's workspace exceeded 90 dB(A) on all machines when cutting and loading in medium to hard strata conditions. In coal headings, the noise level of 25% of machines were below 90 dB(A).

In all cases, noise levels during machine operation impaired oral communications, and operators sometimes had to stop the machines to discuss cutting or loading strategies with other members of the heading team. Analysis of the Preferred Speech Interference Level (PSIL) values suggests that reliable oral communication was possible at a maximum distance of 0.5 m between speakers and receivers. Distances between workmen were however, typically 2 to 3 m. Hand and caplamp signals were reported to be less reliable than oral communication.

The provision of headlights on 92% of roadheaders was assessed by operators to have improved their performance. Of the five different designs of light units studied, those light fittings which produce spot-beam illumination characteristics were found to be most effective in roadheader operational conditions. Accumulation of dust and dirt on the headlamp lenses reduced the effective output by as much as 90%. However, the protective-grill on four of the light units did not allow easy and effective cleaning. In addition, many headlamps were mounted where they failed to illuminate important visual attention areas such as the edges of the apron, and 33% of operators indicated that headlamps presented glare problems for the arch setting team.

Approximately 25% of all reported problems connected with routine maintenance and repair tasks were attributable to the inaccessibility of components. Removing inspection covers (up to 30 kg) on some machines was extremely difficult for a single person to carry out. Frequently, fasteners on these covers were difficult to align. Restricted clearances also exacerbated manual handling problems connected with repairs of heavy components such as track or cutter motors. Thirty-eight percent of fitters found their standard tool-kit inadequate for some repair tasks, and only 15% of fitters were provided with maintenance manuals although all fitters thought that these could reduce the time taken for fault diagnosis and repair.

All of the roadheaders studied were used to assist with arch-setting operations. Most operators considered the arch-setting platforms too small for two men to work safely. In addition, the standing surface on 50% of the platforms allowed water and debris to accumulate thus making secure footing difficult. A range of design features was identified for assisting the ancillary tasks such as advancing supplies and stage loaders. Examples of these include powered winches, specifically designed tow-bars and non-slip surfaces on the machines for advancing monorails or ventilation ducts.

Table 6 summarises the health, safety and operational implications of the main ergonomic limitations on the roadheaders studied.

TABLE 6.

Implications on Ergonomic Limitations on Existing Roadheaders

Ergonomic Limitations on Machines	% of Sample with Limitations	IMPLICATIONS ON			
		Working Postures	Safety	Delays	Accuracy
Restricted vision	85	✓	✓	✓	✓
Restricted access to driver's workstation	62	✓	✓		
Inadequate body clearances	46	✓	✓		
Inappropriate seat design	100	✓			✓
Controls out of normal reach	92	✓	✓	✓	✓
Excessive control operating force	85		✓	✓	✓
Incorrect control stereotypes	85		✓	✓	
Insufficient control clearances	77		✓		
Poor control labelling	85		✓	✓	
Inappropriate control layout	92	✓	✓	✓	
Noise limiting effective auditory communication	100		✓	✓	✓
Adverse thermal environment	23	✓	✓		
Whole body vibration (during cutting operation)	85		✓		✓
Inappropriate headlight provisions	75	✓	✓	✓	✓
<u>Maintenability Limitations</u>:					
(a) Poor access to components	100	✓	✓	✓	
(b) Excessive manual force required	85	✓	✓	✓	
(c) Lack of lifting facilities	92	✓	✓	✓	
(d) Inadequate job aid provision	85		✓	✓	

3.4 Drill-Loaders

3.4.1 Introduction

Six machines with combined drilling and loading out functions were studied in this machine family. Five underground studies were conducted and one machine was examined in a surface simulation. Figures 4(a) and 4(b) show two of the drill-loaders studied. The findings demonstrate many ergonomic limitations to machine operation, and are summarised in Table 7. The most frequent are described in this section. More detailed description of the results can be found in Pethick(a) (in preparation)

3.4.2 Description of drill-loader operation

Drill-loaders are used in hard strata where explosives provide the most cost effective solution to drivage problems and where mechanised loading out can be combined with mechanised drilling.

The drill boom is used to provide a pattern of shot holes which should produce a well profiled roadway which does not require extra trimming (i.e. undersized) or excessive packing (i.e. oversized). The new surface produced should be smooth enough to permit the next sequence of drilling to be started with a minimum of preparation. The locations of the shot holes should produce waste material small enough to be handled by loading out devices and outbye conveyors (or be large enough for packing). Typically, the drivers claimed they required an accuracy of hole drilling of 50 mm for position and 5° for angle of entry.

Drilling equipment consisted of hydraulically powered rotary drills and rotary/percussive drills mounted on articulated booms. Four of the machines were equipped with single drills and two were twin drill rigs.

Loading out was either by bucket onto a stage loader (four machines) or using an apron with gathering arms feeding to a conveyor system through the machine (two machines).

FIGURE 4a. An Example of Single-Drill Bucket Loaders

FIGURE 4b. An Example of Twin-Drill Gathering Loaders

TABLE 7.

Implications on Ergonomic Limitations on Existing Drill-Loaders

Ergonomic Limitations Observed During Studies	% of Sample with Limitations	PROBABLE/OBSERVED CONSEQUENCES FOR			
		Operator Posture	Safety	Delays	Accuracy
Workspace position	83	✓	✓	✓	
Operator clearances	100	✓	✓		
Operator protection	83	✓	✓	✓	
Operator visual communications	83	✓	✓	✓	
Operator visual machine monitoring	100	✓		✓	
Operator visual safety information	100	✓	✓		
Operator seating	100	✓	✓		✓
Operator posture	50	✓			✓
Operator access to workspace	100		✓		
Control types	100		✓	✓	✓
Control operating forces	67				✓
Control-response stereotypes	100		✓	✓	✓
Safety controls	100		✓		
Control dynamics	100			✓	✓
Control location	100	✓	✓	✓	✓
Control layout	100	✓	✓	✓	✓
Control clearances	100		✓		✓
Control protection	50		✓	✓	✓
Visual displays	100			✓	

TABLE 7.

Implications of Ergonomic Limitations on Existing Drill-Loaders Continued

Ergonomic Limitations Observed During Studies	% of Sample with Limitations	PROBABLE/OBSERVED CONSEQUENCES FOR			
		Operator Posture	Safety	Delays	Accuracy
Auditory warnings	100	✓	✓		
Location and layout displays	83	✓		✓	
Control and display labelling	67		✓		✓
Noise and auditory communications	N/A		✓	✓	✓
Thermal environment	100			✓	✓
Lighting and visual environment	100		✓	✓	✓
Vibratory environment	N/A				✓

3.4.3 Summary of Results

The results of the six drill-loader studies indicate that all of the machines could have benefited from incorporating ergonomic considerations. These would have led to substantial improvements to the health, safety and efficiency of the operators.

Operator workspaces had several limitations. The workspace were positioned asymetrically on the machines and as a result, features such as access and visibility were noticeably better on one side than on the other. In some development headings and face-ends, this can disadvantage the operator if the main visual attention areas (such as the stage loader) occur on the 'blind' side of the machine, or if the access route into the workspace is on the side which generally has the least clearance.

Workspace positioning gave rise to two problems: (1) if near the front, the operator was close to the boom which can slew close to the operator when it was being parked and also visibility to the rear was greatly reduced; and (2) if near the rear, visibility to the front was reduced.

Clearances around the operator from the moving boom and fixed bulkheads were insufficient for the range of operator sizes typical of the mineworker population. On the majority of machines, the operator was positioned at or near the side of the machine with inadequate clearance to the roadway sides when manoeuvring. One machine was equipped with a protective bar to help minimise the problem, but the bar affected manoeuvrability and obstructed operator movement.

Lines of sight were regarded as unsuitable by most operators as a result of inadequate workspace position or machine components acting as obstructions. Items that needed to be seen, especially during drilling, were sufficiently obscured as to require the use of spotters to make observations and relay the information (usually by hand signal) to the operator. However on the larger machines, there was nowhere that spotters could stand and be seen by the operator whilst being capable of observing the drill boom. On smaller machines used in smaller roadways, the spotter was frequently in a position sufficiently close to the drill boom to be at risk from inadvertent or erroneous control operation giving rise to unexpected boom movements in his direction. A safe spotter's location was further restricted by the hazard of machine movement when tracking.

Flexible hoses on the boom required continuous visual monitoring by operators and spotters during drilling manoeuvres, as the hoses were proned to damage. This led to increases in drill positioning time. The drill shaft was also monitored by operators to check for stalling or jamming. Illumination of hoses and drill shafts was generally by cap-lamp alone and this was inadequate for the types of visual task involved.

When communicating with the driver, spotters did not use any standard set of hand signals and visual signalling was made more difficult as men could not always be seen near the perimeter of the machine for a large portion of its length on both sides and at the rear.

Seating was provided on all machines but none was satisfactory for the operators or their tasks. The major limitations were the lack of provision for equipment which must be worn on the mineworker's belt and instability of the seats. Materials used for seat construction were either too hard for comfort, vibration absorption and support (steel and wood) or too fragile for shot-fired headings (damage to PVC and foam was common). The end result of all of these limitations was inadequate postural support.

Provided that visibility was adequate, sitting was the predominant posture of drill-loader operators (74% of all postures). Standing was adopted on three machines to overcome visibility problems. Substantial bending and leaning were also required to overcome control location problems (30% of all seated postures deviated by more than 30° from the normal erect posture). Postures such as these give rise to concern about the possibility of long term musculoskeletal problems. In the short term, it is possible that postural instability may lead to increased control errors or to operators falling from the machine.

Access to the workspaces was made difficult and potentially unsafe. One machine had no access corridor at all, five had no access aids (steps, handholds etc). One machine had ladders fixed to the track base. The workspace was on a sliding top to the machine which had to be moved forwards for drilling, thus rendering the ladders useless for a substantial part of the drilling cycle. There was a potential for operators to slip and fall during access manoeuvres and the use of controls as handholds could lead to inadvertent control operation. Jumping down for egress because of the lack of hand or footholds (from workspaces up to 2 m high) also raises safety issues.

The operator interface with the machine via controls and displays, demonstrated many incompatabilities between the operational requirements and the operator's ability. These incompatabilities could limit efficient and safe machine operation. Controls were difficult to identify as they were mostly identical ball-headed levers, not laid out on the basis of function or sequence of operation. Control locations were also problematic, 68% of hand controls located beyond the operator's reach envelopes for satisfactory working postures. Control motion-machine response relationships were also problematic; 43% of hand controls did not follow correct stereotype relationships.

Some controls designed as safety features - operator-in-position pedals, divertor valves, interlocks etc were found to be problematic. Access to emergency stop controls was often restricted. None of the operator-in-position pedals functioned correctly and control interlock devices were found to be broken or inoperative. The design of divertor valves also limited the machine operation in one instance where power was selected between the tracks, and the bucket boom assembly during loading out. This prevented simultaneous use of the bucket and tracks, and extended the operating cycle time significantly.

Operators reported that they never used any displays (and were never seen to do so). Displays on drill-loaders were sometimes located where they could not be seen. Details of display design also made them difficult to read under the prevailing illumination.

Labelling of controls and displays was often absent of illegible. This exacerbated the control selection problems which appeared to have led to modification of controls on some machines to aid identification. Control motion-machine response information which could have minimised the stereotype problems was generally absent from control labels.

Noise levels during drilling and tracking (up to 94 dB(A)) could be sufficiently high as to prevent successful speech communications between the driver and spotter. The operator was wholly dependant upon visual communications (and therefore lines of sight).

The thermal environment gave rise to Effective Temperatures from 15.5 to 29.5 ^{o}C, in the upper range of which operators reported problems of discomfort. These temperatures produced a high heat load on the men, which can be further exacerbated by the performance of heavy manual tasks such as arch-setting, packing etc which the development team must carry out (Nicholl et al, 1984). Environmental measures showed that the machine also produced a high radiant heat load on the machine driver. This suggests that advantages could be derived if machines were more thermally efficient, and that active cooling of the operator may be beneficial.

The operator's caplamp was inadequate for some of the visual tasks he must perform. Machine headlighting was absent on two drill-loaders, not functioning on two and of the remainder one had lights positioned where they rapidly accumulated dirt rendering them ineffective while the other had 'spot' headlights attached to each of its booms and one to the main chassis. These, however, did not illuminate visual tasks such as drill tips, clearance of the sides of the drill masts etc, and caused deep shadows (the worst example being around the drill tip).

Operators were also subject to machine vibration, notably jolting during tracking. This was a particular problem on those machines with unstable seating or where the operator had to adopt awkward bending or leaning postures to operate controls. Mis-operation of controls was likely to arise from jolting.

Maintenance of drill-loaders was hampered by problems of poor access, inadequate information, poor diagnostic facilities and the tendency of drill booms to trap and damage their hoses unless carefully monitored. Illumination problems, especially for peripheral visual tasks minimised the effectiveness of this monitoring. Damage to hoses and consequent down-time were frequent. Replacement hoses and other parts were sometimes unavailable. As a result, the drill-loader was often operated without repair or with improvised repair. The repair was often complicated by poor access. This also caused problems with routine maintenance, in some cases preventing routine tasks from being conducted, e.g. filter changing and cleaning.

Support setting was largely a manual task because drill-loader booms were not suitable for lifting arch components or as working platforms. This gave rise to diverse manual handling problems and high physical workload (especially in the prevailing thermal conditions). Other tasks, such as shot loading and development preparation were also largely unaided by the machine. Advancing supplies and equipment was identified as a potential area for machine assistance that was usually conducted manually or by use of man power through winches etc. There was also a potential for using the machine as a source of power for hand tools which could help overcome some of the more strenuous tasks involved in the development.

The machine itself was sometimes used as a working platform for advancing roof fixtures, but none of the machines had surfaces suitable for such tasks or access provisions for these purposes.

4. DISCUSSION OF UNDERGROUND STUDIES

4.1 Implications of Ergonomic Limitations

The overall results of studies of the three families of machines clearly demonstrate that there are many aspects of machine design where ergonomic improvements can be beneficial in terms of health and safety, as well as productivity. An analysis of the operational problems showed that many are common to all three families of machines. For example, all machines had operational and postural problems associated with the workspaces and operator's interface design, 85% of machines required spotters owing to poor lines of sight, and there was often no standardisation on many of the ergonomic design features within and across the three machine families.

Many of these problems result from a lack of application of ergonomic criteria at the design stage. This was clearly demonstrated in the design of operators' workspaces. For example, although in all machines there were controls that some operators would have been unable to reach, our analyses showed that all the important controls could have been sited more conveniently. Had this been the case there would have been consequential improvements in speed and precision of operation which in turn could have led to improved safety of workers together with increased efficiency of machine usage; indeed our calculations suggest that a reduction of 3% in the overall operational time could have been achieved. Furthermore, there would also have been benefits in terms of reduction in operator fatigue and risk of back injury.

Moreover, in designing the machine, consideration of where to site the operator in terms of his ability to have a good view of his operations could make significant improvements to the safety and efficiency of development machines. It was estimated that by improving the lines of sight to a level where a spotter is no longer necessary to guide the operator, the efficiency of the heading team could be increased by as much as 5%. At current costs, this may represent a saving of as much as £8 million per annum.

In UK mines, machine operators may be required to operate a number of different types of machine; for example, an experienced roadheader operator may be deployed to operate a different type of roadheader if the regular operator of the latter machine was absent from work. Standardisation of important features of machine design could clearly improve operational safety and efficiency by minimising error or hesitation in control operation. In addition, where control operation stereotypes and the layout of important controls on machines are standardised, the operator's skills on one machine will be more readily transferable to a different type of machine, and the familiarisation or learning times to reach maximum efficiency will be shortened considerably. One important safety implication of standardising details which often occurs when drivers change between machines of different control layouts and design characteristics is that control operation errors when responding to emergency situations will be minimised.

4.2 Differences in Ergonomic Limitations Between Machine Families

Although many of the ergonomic limitations and operational difficulties which resulted are similar across the machine families, detailed analysis suggests that the ergonomic criteria to overcome these limitations are different in many instances. For example, visibility related problems could be reduced by providing operators with lines of sight which enable them to see critical visual attention areas (VAAs). As such, the operator's VAAs form the basis of the criteria for acceptable lines of sight. A comparison of the VAAs recorded for each of the three families of machines (see Table 8) however, shows that there is no agreement between the three sets of VAAs. It follows that sightline criteria based on VAAs must therefore be different for each machine family.

Similarly, two of the main criteria for establishing optimum location and layout of controls are based on the frequency and sequence of

TABLE 8

Differences in Operator's Major Visual Attention Areas

Visual Attention Area	Cutter-Loader %	Continuous-Miner %	Drill-Loader %
Cutting Boom	32	19	-
Spotters	12	9	11
Controls	12	9	30
Apron/Bucket	9	-	7
Arches/Girders	8	-	-
Scraper Conveyor	7	12	-
Men Behind Machine	5	-	-
Rip/Heading	5	27	2
Drill-Carriage	-	-	37
Breaker-Bar	-	5	-
Stage-Loader	-	-	2
Others	10	19	11

control usage. Comparing the frequency of use of similar controls (see Table 9) however, showed that there are differences between the three machine families. This is not surprising since operational strategies for extracting the strata are different for the three machine families. Consequently, control layouts which satisfy operational requirements for each machine family are likely to differ considerably.

Lighting requirements also differ between machine families. Roadheaders, for example, require headlight units which illuminate the cutter and boom, often in dusty conditions. Intense spot lights, attached to each side of the boom, which therefore meet this requirement. It would also provide visual cues for operators to assess the position of the cutter in conditions where direct vision is obscured by dust. Operators on drill-loaders, on the other hand, have many fine acuity tasks and peripheral visual tasks which require a broad beam which can be of a lower overall intensity than roadheaders since dust is not a common problem.

The final example highlights the influence of operational differences between machine families in constraining ergonomic solutions. Continuous-miners are generally low profile machines designed to work in in-seam conditions with limited overhead clearances. In such conditions, a canopy is often necessary to provide operators with minimum head clearance and protection. These requirements in turn, impose restrictions on the overall height of the operator's cab. In order to meet physiological comfort criteria and to satisfy task and safety requirements within a limited cab height, a more reclined working posture is necessary. The consequences of such working postures dictate the design of ingress/egress apertures, the operator's seat and control, and display layout. Roadheaders and drill-loaders, on the other hand, are seldom subjected to such headroom restrictions. For these two families of machines, more upright working postures can be recommended for reasons of visibility, speed of egress and ease of posture changes for communications with other mineworkers.

There are many other task differences between the three machine families

TABLE 9

Differences in Frequencies of Control Usage (%)

CONTINUOUS-MINERS	%	ROADHEADERS	%	DRILL-LOADERS	%
Cutter Boom Raise/Lower	25	Cutter Boom Raise/Lower Slew	36	Drill Boom and Carriage Raise/Lower/Slew	19
Tracks	33	Tracks	25	Tracks	20
Gathering Arms/Apron for Loading	5	Gathering Arms/Apron for Loading	16	Bucket Crowd Raise/ Lower/Tip	25
Main Motor On/Off	5	Main Motor On/Off	4	Main Motor On/Off	4
Cutter Motor On/Off	0.3	Cutter Motor On/Off	3.4	Drill Rotation	2
Track Boost	7	Track Boost	11	Track Boost	0
Machine Jacks	5	Machine Jacks	0.5	Machine Jacks	0
Others	19.7	Others	4.1	Others	30

(e.g. maintenance and ancillary tasks) which would necessitate different ergonomic criteria to meet their requirements.

4.3 Limitations of Existing Ergonomic Information

Machine designers who wish to incorporate ergonomic considerations into their designs will find that there is no ergonomic information in the industry's design standards or purchasing policies for development machines which would enable them to overcome the limitations described. Through interviews with machine designers, it is apparent that their existing ergonomic information was generally unsuitable for the design of mining machines. For example, some designers used an anthropometric data set which consistently underestimated the dimensions appropriate for the mining population (Ashby, 1976). In addition, recommended design dimensions often appeared to be based on the 50th percentile dimensions, for example, clearance dimensions specified according to the recommendation would be too small for operators larger than the 'average' man.

Outside the mining industry, there is an abundance of ergonomic recommendations for equipment designers (e.g. Van Cott and Kincade, 1972; Shackel, 1976; Murrell, 1965; Clarke and Corlett, 1984; MRC, 1971; McCormick and Sanders, 1983 etc). However, these sources were seldom known to mining machine designers. More importantly, much of the ergonomic information in the literature is unsuitable for mining equipment design. For example, an investigation of control location criteria showed that the differences in anthropometric dimensions of the mineworker population were sufficiently different from other populations to require new control location envelopes to be developed to be suitable for mining machines. Mining tasks and protective clothing requirements also dictated changes to the recommendations in the quoted ergonomic literature.

Many of the existing recommendations were often contradictory. An example is the recommendations for the direction of control movement to raise/lower a machine element. The BSI (1967) recommends lifting the control upwards to raise the machine element, whereas the opposite direction is recommended by the ISO (1976).

Similarly, there are many instances where the literature provides no guidance at all, for example, the control stereotype relationships for drilling-mast assemblies.

4.4 Designers' Ergonomic Requirements

There is sufficient evidence, from the comparisons already described, to suggest that one set of ergonomic criteria or design recommendations would not meet the task and operational requirements of all three machine families.

It is also apparent that to promote ergonomic improvements in the design of development machines, the ergonomic design criteria must firstly be tailored to suit requirements of mining tasks and conditions as well as the practical constraints of the industry. Secondly, any ergonomic criteria should be translated into design specifications and guidelines which are readily usable by machine designers without further interpretations by specialists. Since a large number of criteria are different for each machine family, the recommendations for each machine family are incorporated into individual design handbooks, thereby ensuring that only the relevant information is presented to designers of each type of machine. Finally, ergonomic improvements would be cost-effectively implemented and controlled by incorporating the ergonomic guidelines and specifications as an integral part of the NCB's design standards and purchasing policies. This is currently being considered by the NCB and close liaison with HQ Mining Department has been established over the development of ergonomic guidelines, and specifications to ensure their engineering and economic validity.

A number of subsidiary studies were necessary to obtain new ergonomic criteria which are tailored for the design of development machines. These new criteria, which have been derived either from experimentation or from underground study results taking full consideration of operators' tasks, mining conditions and mineworker population characteristics are reported in Section 5.

5. SUBSIDIARY STUDIES

5.1 Development of Criteria for Lines of Sight Standards

5.1.1 Introduction

During studies of different types of development machines, visibility from these machines was shown to be the most consistent limitation. These studies have shown that over 60% of the poor driver postures recorded arose directly from the need to adopt awkward postures to gain better vision whilst still being capable of operating the controls. Poor sightlines also create safety risks to men working close to such machines as reflected in the Mines Inspectorate report (HSE, 1982) which suggests that in over 50% of major injuries caused by mobile machinery, the driver did not detect the presence of the victims. Performance also suffers from poor sightlines. The studies summarised in Section 4 have shown that drivers on 85% of the roadheaders required guidance from a second man for about 30% of the shift. This not only required mineworkers to be taken off other mining tasks, but this also meant that communication difficulties between the driver and the second man often reduced the accuracy of the profile being cut. Improvements in machine sightlines could therefore clearly have significant benefits in health, safety and efficiency.

5.1.2 Limitation of existing criteria

A review of the literature shows that guidelines on sightline requirement on mobile machines which are currently available are not immediately relevant to mining tasks. In addition, there are no sightline standards which exist within the mining industry other than general statements such as that "operators should have adequate visibility". As a result, mining machinery designers often need to adopt arbitrary criteria.

Of the sightline standards available for other industrial equipment and motor vehicles (e.g. Hemmings, 1974; SAE, 1977; SAE, 1981), there is little agreement between procedures prescribed for deriving ergonomic criteria. Also, there is an apparent lack of quantitative criteria in existing sightline standards to allow designers some flexibility in making trade-offs between ergonomic requirements and other design decisions. There is, therefore, a need for procedures to be established which can be used directly to produce a set of practical sightline criteria for designers of underground mobile machinery.

5.1.3 The measurement of sightlines

Central to the development of practical sightline criteria, for use during the design process or during prototype evaluation, is the ability to reliably measure the operator's sightlines. Published sightline recording techniques (e.g. Penn and Davis, 1973; Sell, 1958) have limited utility to the assessment of sightlines in underground machinery.

The suitability of any sightline measurement technique depends on the nature of the investigation. For example, a technique designed solely for a one-off assessment of a production or prototype machine during an investigation of an accident may not be very effective, if used to predict the benefits to sightlines from locating the workplace at different locations on a machine.

In addition, the suitability of any sightline technique will also depend on the stage in the design process or the availability of a production machine. Suitable techniques therefore need to cope with the following conditions of machine availability:

(a) General arrangement drawings only (GA's);
(b) Scale models;
(c) Full-scale machine on open ground;
(d) Full-scale machine in a surface simulation of a heading (space constraints);

(e) Machine in use underground (space constraints, time constraints and Intrinsic Safety requirements of measuring equipment).

Therefore, in order to reliably, quickly and safely measure machine sightlines, a suite of 11 techniques were developed by the Institute of Occupational Medicine (Mason et al, 1980). The technique used for sightline assessment during the underground studies is given in Appendix B.

These sightline techniques establish the operator's sightline limits, which if compared with a set of minimum visual attention areas (VAAs) necessary for safety and performance considerations, would enable a design engineer to identify any engineering modifications necessary to achieve good operator sightlines. In practice, any machine can be used in a variety of underground situations each possessing unique VAAs. Therefore to ensure safe and efficient roadheading operations, a set of VAAs appropriate for the range of potential applications was needed before practical sightline standards could be developed. These have been derived from studies of 25 machines working in a wide range of face-end configurations and in a representative range of geological and environmental situations.

Table 10 shows the typical VAAs for the three families of development machines obtained from underground studies.

TABLE 10

Operators' Main Visual Attention Areas on Three Families of Development Machines

Continuous-miners	Roadheaders	Drill-loaders
Cutter Jib	Cutter Drum	Drill-Bit
Breaker Bar	Cutter Boom	Drill Carriage
Men at Sides of Machines	Men at Front/Sides	Men at Front/Sides
Girders/Props	Men Behind Machine	Men Behind Machine
Rear Discharge Conveyor	Loading Apron/Conveyor	Loading Apron/Conveyor
Heading Profile	Hand Controls	Hand Controls
	Arches/Girders	Stage-loader

5.1.4 Development of practical sightline standards for roadheaders based on safety and performance considerations

The ergonomic sightline standards for roadheading machines are described; however the procedure is applicable to all three families of development machines.

Any ergonomic sightline standard will be heavily influenced by engineering feasibility and the safety policies of the industry. The standards were therefore derived with cooperation of the NCB HQ Engineering functions and although they may not correspond with ideal ergonomics, they do represent what the industry considers to be the best currently achievable.

For example, the size of hydraulic tanks, motors etc prevent total vision of the floor immediately adjacent to roadheading machines. Some sightlines therefore must be more restricted than others, and the standard must ensure that those areas of prime importance in terms of safety and machine performance have the best possible sightline, even at the expense of more restricted sightlines being accepted elsewhere around the machine.

(i) Safety Considerations

The underground study results indicated that 25% of drivers had difficulty in seeing men working near the front sides of the machine, whilst 54% of drivers reported that men working behind the machine were sometimes difficult to see. Stooped postures were often adopted by men working around the machines and therefore this needed to be taken into consideration when specifying the minimum sightline standard.

Criteria related to men working around these machines are based on the potential risk to men at different locations around the machine, and also on the conspicuity of men under low illumination levels for various working postures. The highest risks are at the corners as rapid slewing can trap men to the sides of the roadways. The corners therefore are treated as 'Primary Safety Zones' where sightline criteria need to enable very high rates of detection of mineworkers. Other areas around the machine can be subject to a less strict criteria, although still adequate in terms of safety, as mineworkers are under less immediate safety threat. These are termed the 'Secondary Safety Zones', as shown in Figure 5.

Just as it would be impractical to design a car with perfect vision all round, there are practical constraints on the maximum sightlines around roadheading machines. Studies of Beith and Sanders (1982) have shown that detection rates of approximately 96% are possible under low illumination levels if the head and upper body are visible, and 78% when the head only is visible. Both figures are for subjects wearing retroflective strips which are not regularly used in the UK mines. Engineers consider that the maximum feasible sightline appropriate for an industry standard would be to see the head and chest of a 5th percentile mineworker adopting a stooped posture (1.0 m). This condition, which

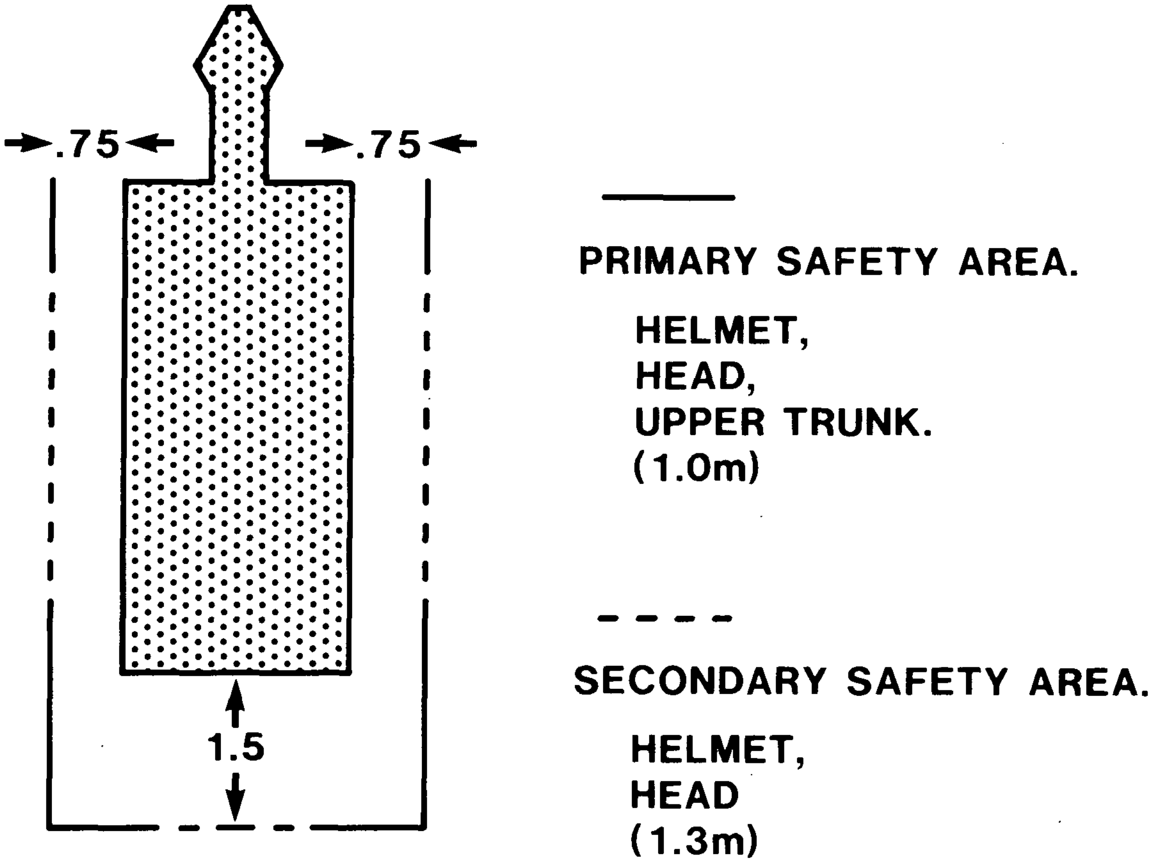


FIGURE 5. Safety Criteria for the Sightline Standard on Roadheader

corresponds to the higher conspicuity described above, was therefore adopted as the most stringent practical minimum standard for those areas in the primary safety zones. Where this criterion could not be met in the secondary safety zones, a less critical sightline requirement of a 5th percentile driver being able to see the head and helmet of a stooped 5th percentile mineworker (1.3 m) was accepted as achievable in engineering terms and adequate in safety terms, since a mineworker in these areas would be under no immediate risk. These criteria apply to areas being visible at distances of 1.5 m behind and 0.75 m to the sides of the machines respectively. Figure 5 summarizes the safety criteria for the proposed sightline standard.

It is also necessary to allow sufficient time for men to move to safety should the machine reverse and the driver not be aware of men behind the machine. Even though there may be no sightline problem in highly repetitive machine cycles where men rarely work near the machine, drivers have been observed to reverse over short distances without turning to see behind. It is therefore necessary to ensure that any mineworker near the machine has sufficient time to move from a working posture behind the machine to a safe position on the roadway side. Such times have been derived from various postures (e.g. kneeling on both knees) using pre-determined motion time systems (MTM-1). Ideally, the acceleration period of the vehicle should be allowed for, in addition to its maximum speeds; however it may be appropriate only to use maximum speed in any calculations as this adds to the safety factor. For example, MTM-1 predicts a mineworker kneeling and facing a machine would require 3.03 seconds to move to a safer location should the machine reverse. If the maximum machine speed was 1.0 ms^{-1}, then in this time the machine would have reversed a distance of 3 m. Therefore, if men work closer to the machine than this distance and the driver fails to see them, then under certain conditions an accident would result. If restricting reverse speeds was not desirable or practical, the likelihood of an accident must then be prevented by adopting working practices which eliminate the need for men working at such close proximity to the machines. For roadheaders, since the highest tracking speeds of existing machines are approximately 0.2 ms^{-1}, the minimum "escape" distance from the periphery of the machine is therefore calculated at 0.6 m. As this is considerably less than the 0.75 m and 1.5 m specified by this standard, no further addition to the standard was necessary.

(ii) Performance Consideration

Peformance considerations are generally easier to incorporate into a sightline standard as they relate to VAAs. Direct observational techniques to derive VAAs must however be supplemented by questionnaires to elicit those VAAs which would be beneficial to the task, but which could not be seen because of the sightlines of the individual machines studied. The performance related VAAs for roadheading machine relate to being able to see around the cutting drum and the sides of the loading apron at the front.

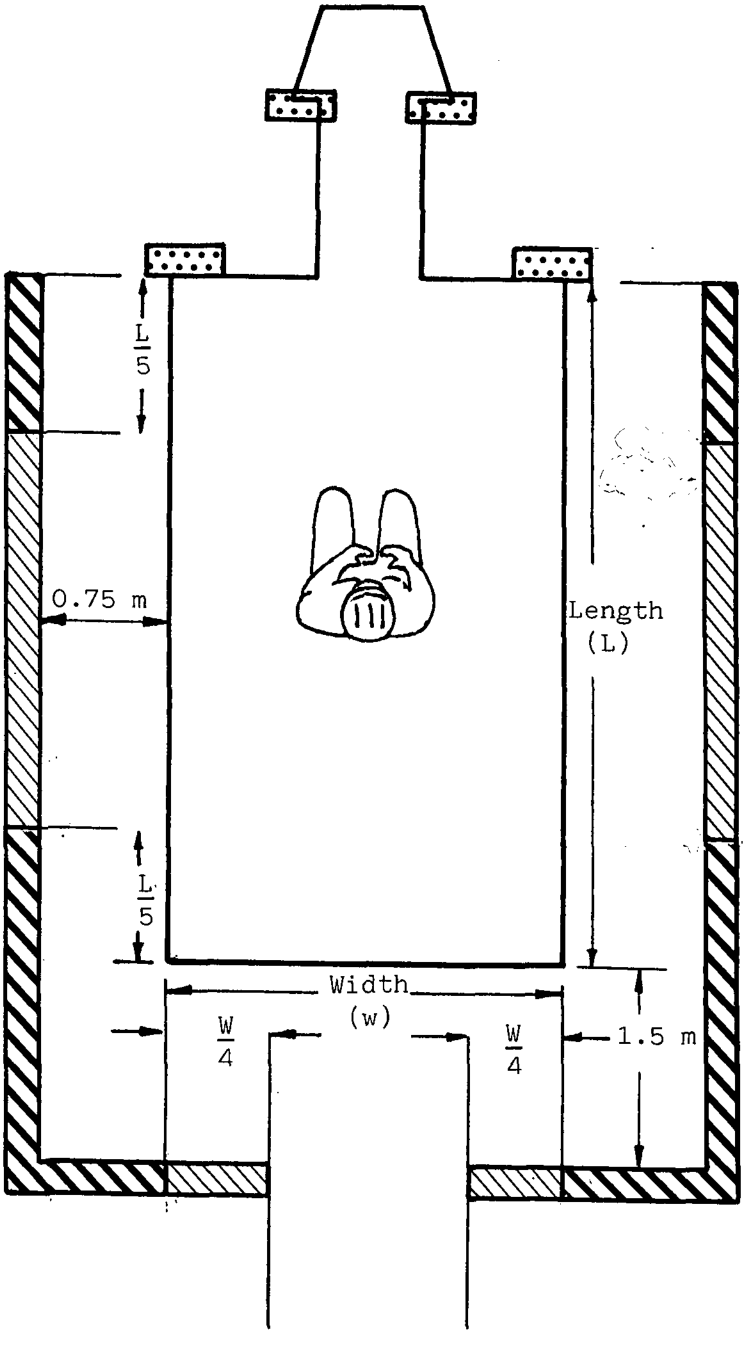
Figure 6 shows both the performance and safety criteria for the sightline standard on roadheaders.

5.1.5 Design procedures for the implementation of sightline criteria

The implementation of sightline criteria essentially depends on the design options open to a manufacturer. In cases where the design and construction of the main 'modules' have already been determined, then the implementation will largely involve identification of the minimum driver eye-height. Only if this derived eye-height cannot be achieved, will the need arise to consider modifications to the seating position or machine profile. The detailed procedures for both conditions are described in Appendix C.

To demonstrate the utility of the above procedure, a recent prototype roadheader (see Figure 7) was assessed (Coleman, 1985) to determine the minimum eye-height which would meet this ergonomic sightline standard.

(Note: Criteria based on a 5th percentile seated operator with an eye - seat squab distance of 660 mm).



KEY:

▧ Primary Safety Area - Helmet, head and upper trunk of stooped 5th percentile miner visible (1.0 m)

▨ Secondary Safety Area - Helmet and head of stooped 5th percentile miner visible (1.3 m)

⠿ Performance related criteria

FIGURE 6. Performance and Safety Criteria for the Sightline Standard on Roadheaders

FIGURE 7. A Prototype Roadheader Shown in a Simulated Heading

(i) The Derivation of the Overall Mininum Eye-Height

Following the procedure, the machine is divided into nine zones as shown in Figure 8. The coordinates of the highest obstruction xr, xl, yf, yr and hp at the machine periphery were recorded, and entered into the equations shown in Figure 8. The overall minimum operator eye-height to satisfy the sightline standard is therefore the highest value of the minimum eye-height for the nine zones. In this case, it was 2.15 m above ground level.

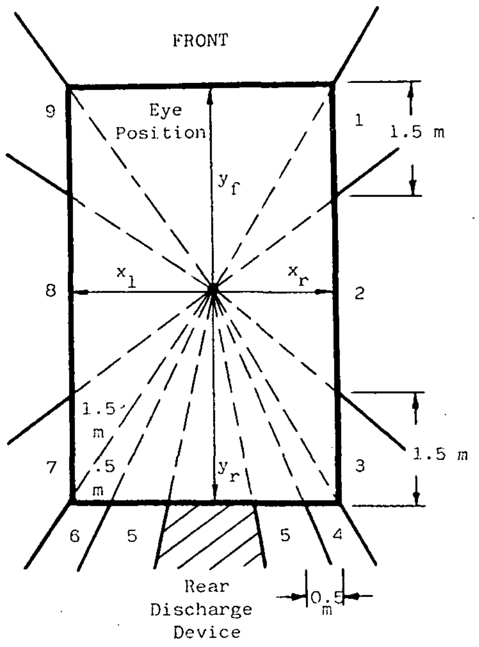
To assess whether the operator's sightline meets the safety criteria proposed in the ergonomic sightline standard, the minimum eye-height at each zone is compared witht the existing eye-height (i.e. 1.66 m above ground level). The comparison shows that operator's lines of sight at zones 1, 3, 4, 6, 7 and 9 failed to meet the standard, since the existing operator eye-height is less than the minimum eye-heights required.

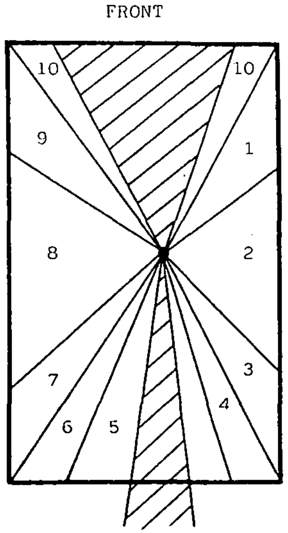
To demonstrate these findings graphically, the sightline limits of a small (5th percentile) operator on the machine is superimposed on the minimum sightline limits to satisfy safety criteria (see Figure 9). Clearly, there are areas around the machine where men/objects at the heights stipulated by the sightline standard will not be seen by the driver.

The result of the minimum eye-height assessment allowed the machine designer to identify that a 500 mm increase in the 5th percentile eye-height (i.e. from 1.66 m to 2.15 m) would meet the sightline standard. This is illustrated graphically in Figure 10. With such an increase, a tall mineworker's (97.5th percentile) head-height, when seated, would be 500 mm below the centre of the roof of the smallest roadway (3.66 m x 3.05 m) in which the machine was designed to operate.

(ii) Derivation of Maximum Machine Profile

In most situations of machine design, the minimum working roadway





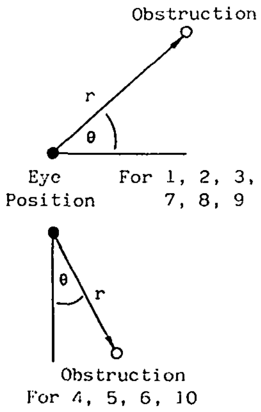


FIGURE 8. Derivation of Minimum Operator Eye-Heights

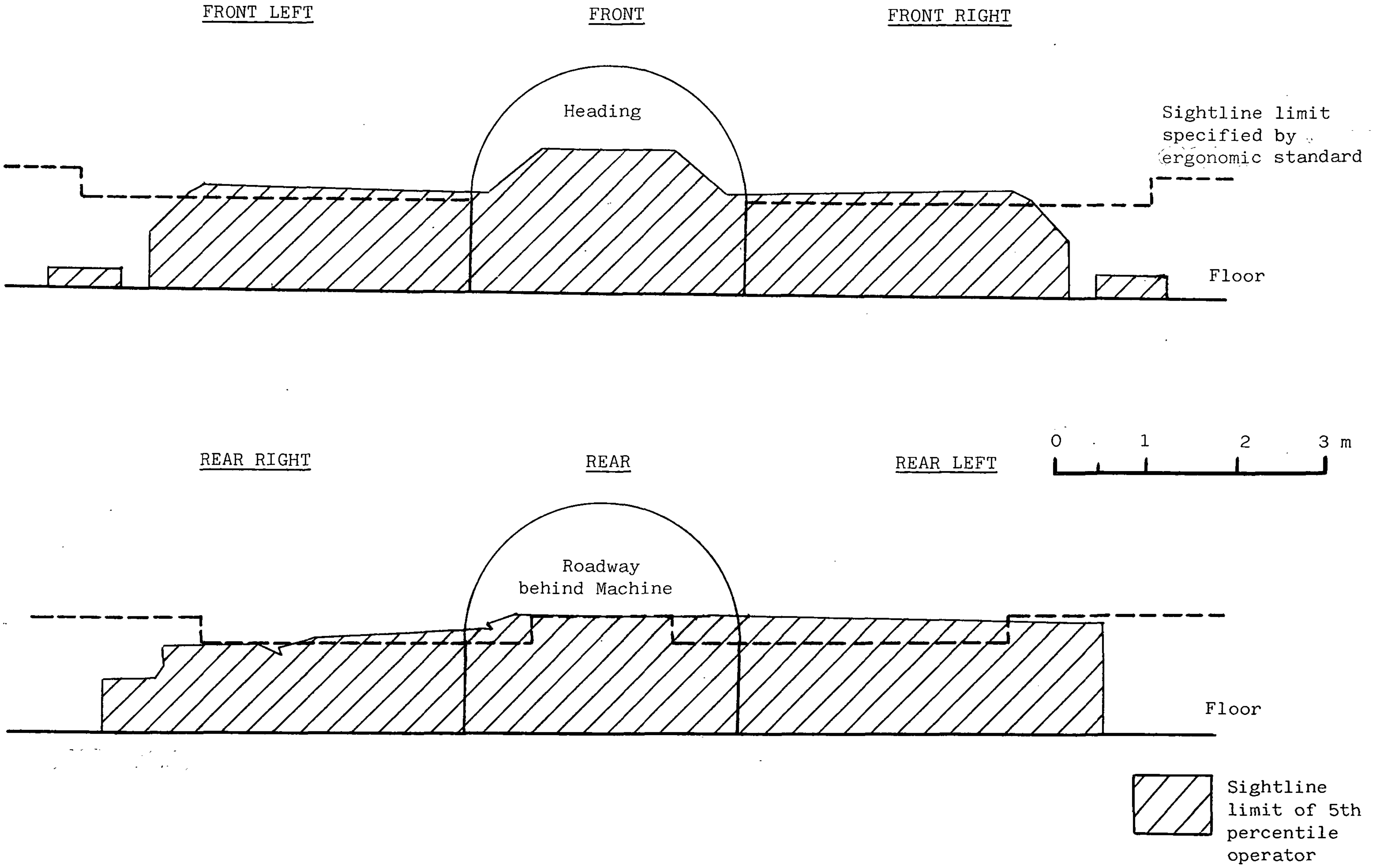
(a) Peripheral Obstructions Existing 5th percentile eye-height = 1.66 m

ZONE	MAXIMUM PERIPHERAL HEIGHT hp (m)	CALCULATION FOR MINIMUM EYE HEIGHT he	he (m)
1	1.41	$(hp - 1) \times (1.33\, x_r + 1.0) + 1.0$	1.84
2	1.36	$(hp - 1.30) \times (1.33\, x_r + 1.0) + 1.30$	1.40
3	1.34	$(hp - 1) \times (1.33\, x_r + 1.0) + 1.0$	1.70
4	1.41	$(hp - 1) \times (0.66\, y_r + 1.0) + 1.0$	2.15
5	1.41	$(hp - 1.30) \times (0.66\, y_r + 1.0) + 1.30$	1.47
6	1.41	$(hp - 1) \times (0.66\, y_r + 1.0) + 1.0$	2.15
7	1.41	$(hp - 1) \times (1.3\, x_l + 1.0) + 1.0$	1.84
8	1.41	$(hp - 1.30) \times (1.33\, x_l + 1.0) + 1.30$	1.53
9	1.41	$(hp - 1) \times (1.33\, x_l + 1.0) + 1.0$	1.84

(b) Obstructions Inside Machine Boundary

ZONE	DETAILS OF OBSTRUCTION				CALCULATION FOR MINIMUM EYE HEIGHT he	he
	Name	Height hp	r	Cos		
1					$\frac{r.\ \cos\theta.\ (hp - 1)}{x_r + .75 - r.\ \cos\theta} + hp$	
2					$\frac{r.\ \cos\theta.\ (hp - 1.30)}{x_r + .75 - r.\ \cos\theta} + hp$	
3					$\frac{r.\ \cos\theta.\ (hp - 1)}{x_r + .75 - r.\ \cos\theta} + hp$	
4					$\frac{r.\ \cos\theta.\ (hp - 1)}{y_r + .75 - r.\ \cos\theta} + hp$	
5					$\frac{r.\ \cos\theta.\ (hp - 1.30)}{y_r + 1.5 - r.\ \cos\theta} + hp$	
6					$\frac{r.\ \cos\theta.\ (hp - 1)}{y_r + .75 - r.\ \cos\theta} + hp$	
7					$\frac{r.\ \cos\theta.\ (hp - 1)}{x_l + .75 - r.\ \cos\theta} + hp$	
8					$\frac{r.\ \cos\theta.\ (hp - 1)}{x_l + .75 - r.\ \cos\theta} + hp$	
9					$\frac{r.\ \cos\theta.\ (hp - 1)}{x_l + .75 - r.\ \cos\theta} + hp$	
10					$\frac{hp.\ yf}{yf - r.\ \cos\theta}$	

FIGURE 9. Sightline Limits of a Seated 5th Percentile Operator (eye-height 1.66 m above ground)



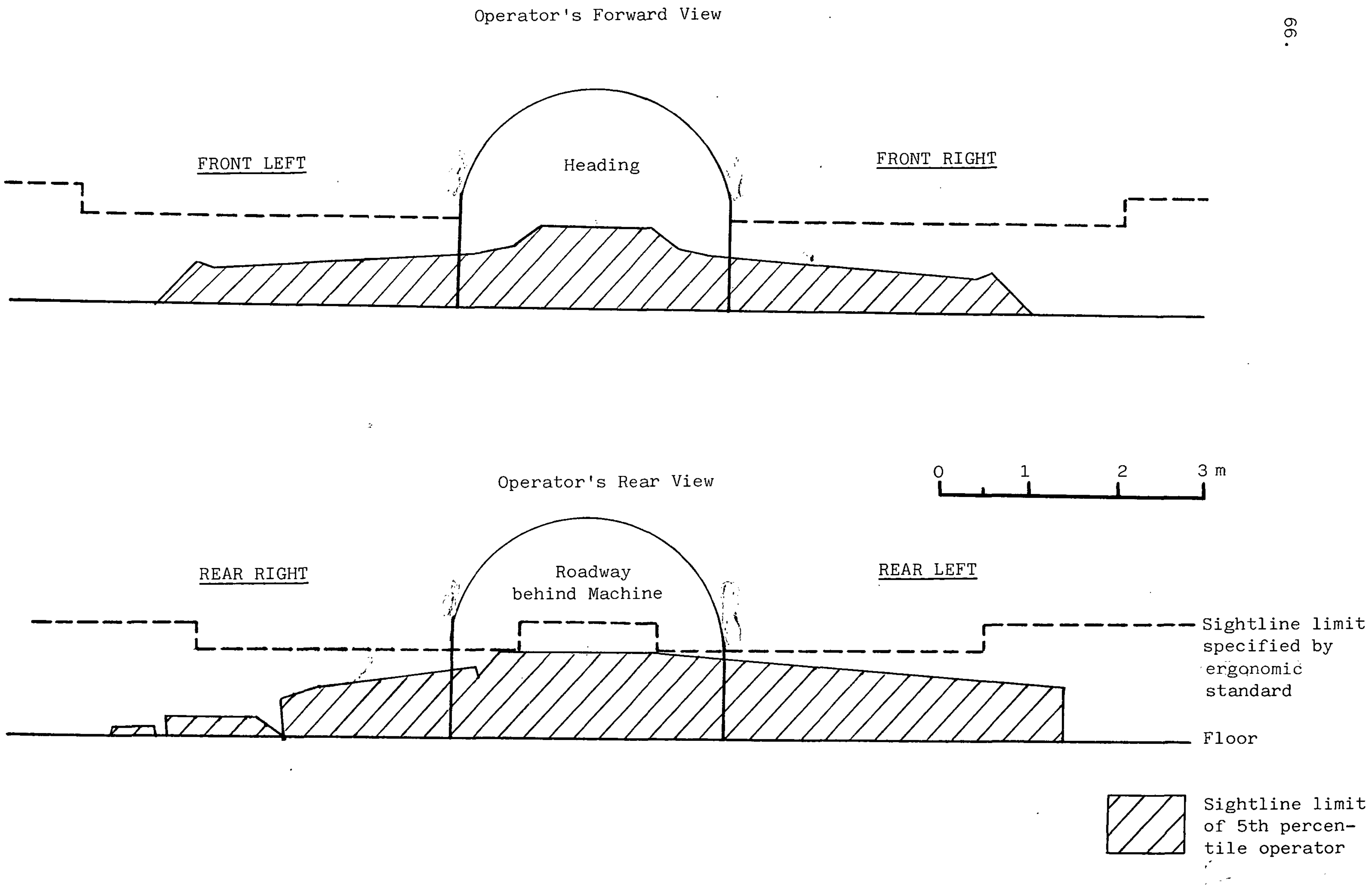


FIGURE 10. Sightline Limits of a Seated 5th Percentile Operator (eye-height of 2.15 m above ground)

dimensions govern the specification of the maximum operator eye-height as well as the maximum external dimensions of the machine. The following example illustrates the procedure to enable designers to identify the maximum height of the external machine to meet the sightline standard, given that a maximum operator eye-height is already specified.

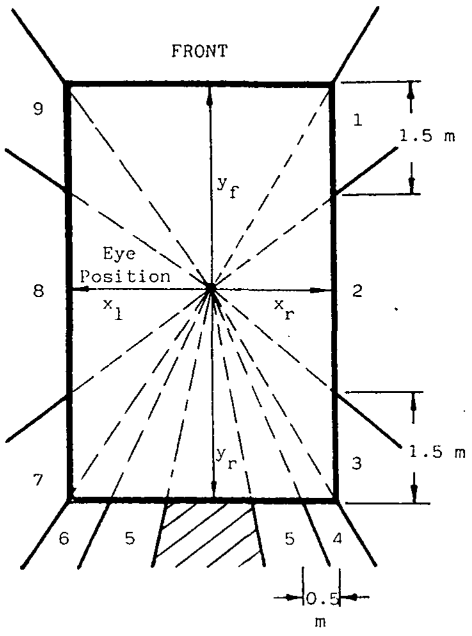
Using the same prototype roadheader as an example, and assuming that the designer had no scope of altering the operator's eye-height (at 1.66 m above ground) to obtain the maximum height of the machine periphery, the machine is divided into nine zones as before. Using the same values for xr, xl, yf and yr. The maximum machine periphery heights which meet the sightline standard are calculated as shown in Figure 11.

A comparison of the calculated maximum machine periphery heights with the existing periphery heights showed that machine super-structures in zones 1, 3, 4, 6, 7 and 9 obstruct operators' critical vision. This information allows the designer to identify the "offending" structure or component, and to formulate options for manipulating the arrangements and/or the shapes of machine components to achieve the sightline standard (see Figure 12).

5.1.6 Conclusions

The criteria described in this section are specific to roadheading machines and are currently being used by the IOM to assess prototype machines. However, the procedure could be equally valid for establishing sightline criteria on continuous-miners and drill-loaders as well as many other types of mobile machinery. The techniques can be carried out manually as described, or adapted for computer graphics application to allow designers of machines to assess correct sightlines of prototype machines at the drawing board stages where changes are relatively less costly, and also to allow the NCB to assess the sightlines of new roadheading machines entering the industry.

Although designers readily agree that sightlines are important for both



he = 1.66 m
x_r = 0.8 m
x_l = 0.8 m
y_r = 2.8 m
y_f = 2.73 m

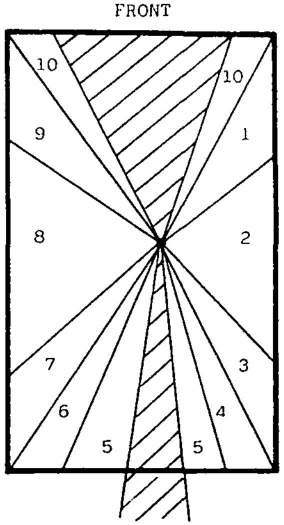
(a) Profile Limits Around the Machine Periphery

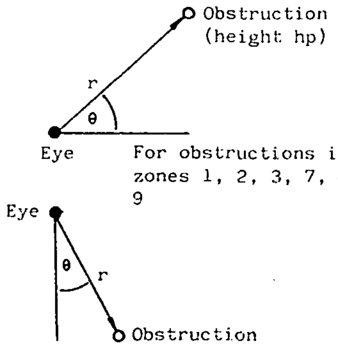
ZONE	MAXIMUM HEIGHT OF MACHINE PERIPHERY (hp) (m)	hp (m)	*
1	$\frac{.75\,(he - 1)}{x_r + .75} + 1 =$	1.31	(1.41)
2	$\frac{.75\,(he - 1.3)}{x_r + .75)} + 1.3 =$	1.47	(1.36)
3	$\frac{.75\,(he - 1)}{x_r + .75)} + 1 =$	1.32	(1.34)
4	$\frac{.75\,(he - 1)}{y_r + .75} + 1 =$	1.07	(1.41)
5	$\frac{1.5\,(he - 1.3)}{y_r + 1.5} + 1.3 =$	1.45	(1.41)
6	$\frac{.75\,(he - 1)}{y_r + .75} + 1 =$	1.07	(1.41)
7	$\frac{.75\,(he - 1)}{x_l + .75} + 1 =$	1.32	(1.41)
8	$\frac{.75\,(he - 1.3)}{x_l + .75} + 1.3 =$	1.47	(1.41)
9	$\frac{.75\,(he - 1)}{x_l + .75} + 1 =$	1.31	(1.41)

* Figures in brackets are maximum periphery or heights on existing machine.

(b) Profile Limits Inside the Plan Boundary of the Machine

1	$he - \frac{\cos\theta.\ (r.\ he - 1)}{x_r + .75} =$	
2	$he - \frac{\cos\theta.\ (r.\ he - 1.3)}{x + .75}$	
3	$he - \frac{\cos\theta.\ (r.\ he - 1)}{x_r + .75} =$	
4	$he - \frac{\cos\theta.\ (r.\ he - 1)}{y_r + .75} =$	
5	$he - \frac{\cos\theta.\ (r.\ he - 1.3)}{y_r + 1.5} =$	
6	$he - \frac{\cos\theta.\ (r.\ he - 1)}{y_r + .75} =$	
7	$he - \frac{\cos\theta.\ (r.\ he - 1)}{x_l + .75} =$	
8	$he - \frac{\cos\theta.\ (r.\ he - 1.3)}{x_l + .75} =$	
9	$he - \frac{\cos\theta.\ (r.\ he - 1)}{x_l + .75} =$	
10	$he - \frac{r.\ he.\ \cos\theta.}{y_f} =$	





For obstructions in zones 1, 2, 3, 7, 8, 9

For obstructions in zones 4, 5, 6, 10

FIGURE 11. Derivation of Maximum Machine Profiles

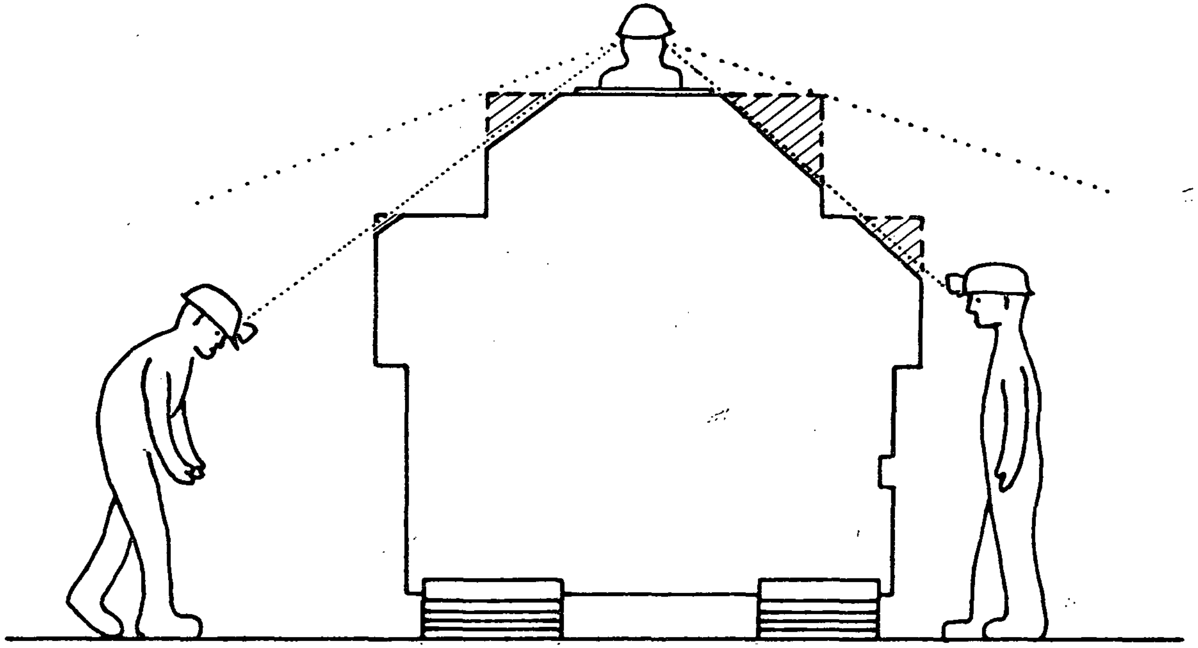


FIGURE 12. Improving Operators' Sightlines by Manipulating the Shape of Machine Components and Structures

the safety and performance of machines, it is only following detailed studies of a wide range of similar machines in their working environment that the true magnitude of the problems become apparent.

Estimates of potential production savings in the order of £8 million per annum have been suggested if all development machines in use by the NCB achieved the sightline criteria described by the research above. As a result of the potential significant performance and safety gains, the NCB is currently assessing the proposed sightline standard for inclusion in its design standards and purchasing specifications, where the long term benefits of ensuring the health and safety of the workforce with attendant performance improvements are most cost effectively made.

5.2 An Investigation of Control Movement-Machine Response Relationships

The relationship between a control movement and the resulting effect on machine response which is expected by most of the population is known as a 'population stereotype' (Fitts, 1951), and control-response relationships (CRRs) which conform to a stereotype are said to be 'compatible'. Development machines, especially drill-loaders, have complex configurations and articulations. The drill-boom, for example, can have four degrees of movement (slew, elevate, rotate, extend). This in turn leads to complex control movement-machine response relationships. Evaluation of a number of such machines (Mason et al, 1982) has identified CRRs which do not follow operators' expectations. In addition, there was a lack of standardisation of CRRs between different machines, and occasionally even on the same machine. Incompatible or non-standardised CRRs lead to hesitation and errors in control operation which have obvious safety and performance implications, as results of the underground studies have shown (see Section 3).

Designers often assumed that CRR compatability is of minor importance as operators will learn to adapt to "unnatural" relationships and there is some evidence to support this (Balentine, 1983). There are, however, at least three disadvantages in relying on operators to adapt to incompatible CRRs. Firstly, it could take substantial periods to adapt to these unexpected relationships during which speed and reliability of control operation are sub-optimal. Secondly, numerous studies (Vince, 1945; Mitchell, 1948; Norris and Spragg, 1953) have shown that with incompatible CRRs, errors in control operation increases with task speed and complexity. Thirdly, it has been shown that under conditions of fatigue or information overload, the operator may forget what he has learnt and revert to his natural stereotypes (Broadbent, 1959; Loveless, 1959).

5.2.1 Limitations of existing population stereotype criteria

Normally where the movement of controls and machine elements are in parallel, there is general agreement from previous research on the optimum CRR. However, there are CRRs which may evoke conflicting mental models in the user population. For instance, a simple logic model would suggest that to raise an element you raise the control; this is reflected for example in the recommendations of BSI (1965), MRC (1971) and Murrell (1965). Alternatively, a more mechanical model may postulate a "see-saw" effect whereby to raise an element, you lower the control as reflected in the recommendation of ISO (1976) and Van Cott and Kincade (1972). Conflicting recommendations of this type have been noted previously by Loveless (1962). Similarly, Ross et al (1955) have shown that the validity of extrapolating results obtained from experiments using simple two-dimensional tasks, to three-dimensional control of machine elements in space, is at least questionable.

In addition, more complex relationships between movements of controls and machine elements such as those for rotating machine elements commonly found on mining machines, are inadequately covered in the literature. It is clear that conflicting recommendations and gaps in the literature would need to be resolved before any standardisation of control-response relationships for mining machines was possible.

In view of the above problems, an experiment was designed to investigate twelve control-response arrangements, frequently found on mining equipment. These relationships included those which were questionable in relation to existing criteria, and those for which there were no criteria in the literature. In order to examine the possible effects of the mental models mentioned above, a comparison of subjects with differing technical backgrounds was also included.

5.2.2 Method

(i) Subjects

One hundred and forty-four subjects, all male NCB employees, took part in the experiment. These subjects were drawn from three groups of workers:

(a) 48 Fitters/industrial workers;
(b) 48 Design engineers;
(c) 48 Administrative and clerical staff.

The subject groups were chosen on the basis of the differences in their work experience and training. The fitters group represents the experienced machine operators who as part of their work, drive and service the machinery. The design engineers group designs the machines, specifies the C/R relationships, but has little machine experience. The third group serves as the 'inexperienced' or control group who have very little or no experience. Subjects' length of employment at the NCB ranged from three months to over thirty years.

(ii) Apparatus

To minimise problems identified by Ross et al (1955), the control-response a 1/10th scaled wooden model of a drill-loading machines was used for the purpose of the experiment. The model incorporates the full range of articulations of the machine elements to allow three-dimensional simulation of the controlled movements. The control used was a ball-headed lever which could be operated in the horizontal and vertical plane. There were no linkages between the lever control and the machine elements. A photograph of the model is shown in Figure 13.

(iii) Experimental Procedures

Twelve control-reponse arrangements were selected for this experiment as detailed in Table 11. The experiment employed the single response procedure. This requires that each of the three subject groups be divided into two equal sub-groups, in order that both directions of machine response movements may be studied. It cannot safely be assumed that the operator's expectations are 'reversible'. Thus, the twelve control-response arrangements were split into 24 C/R relationships, although each subject responded only to twelve relationships.

TABLE 11

The Twelve Control-Response Arrangements Under Investigation

Machine Response	Control-Motion
Bucket Rolled Backward/Forward	Up/Down
Bucket Side-Discharge ACW/CW	Fore/Aft
Main Boom Lowered/Raised	Up/Down
Main Boom Lowered/Raised	Fore/Aft
Main Boom Slew to Right/Left	Fore/Aft
Drill-Tip Raise/Lower	Up/Down
Drill-Tip Raise/Lower	Fore/Aft
Drill Carriage Slew to Left/Right	Fore/Aft
Drill Carriage Slew to Left/Right	Left/Right
Bucket Rolled Forward/Backward	Fore/Aft
Bucket Side-Discharged ACW/CW	Left/Right
Main Boom Rotate CW/ACW	Fore/Aft

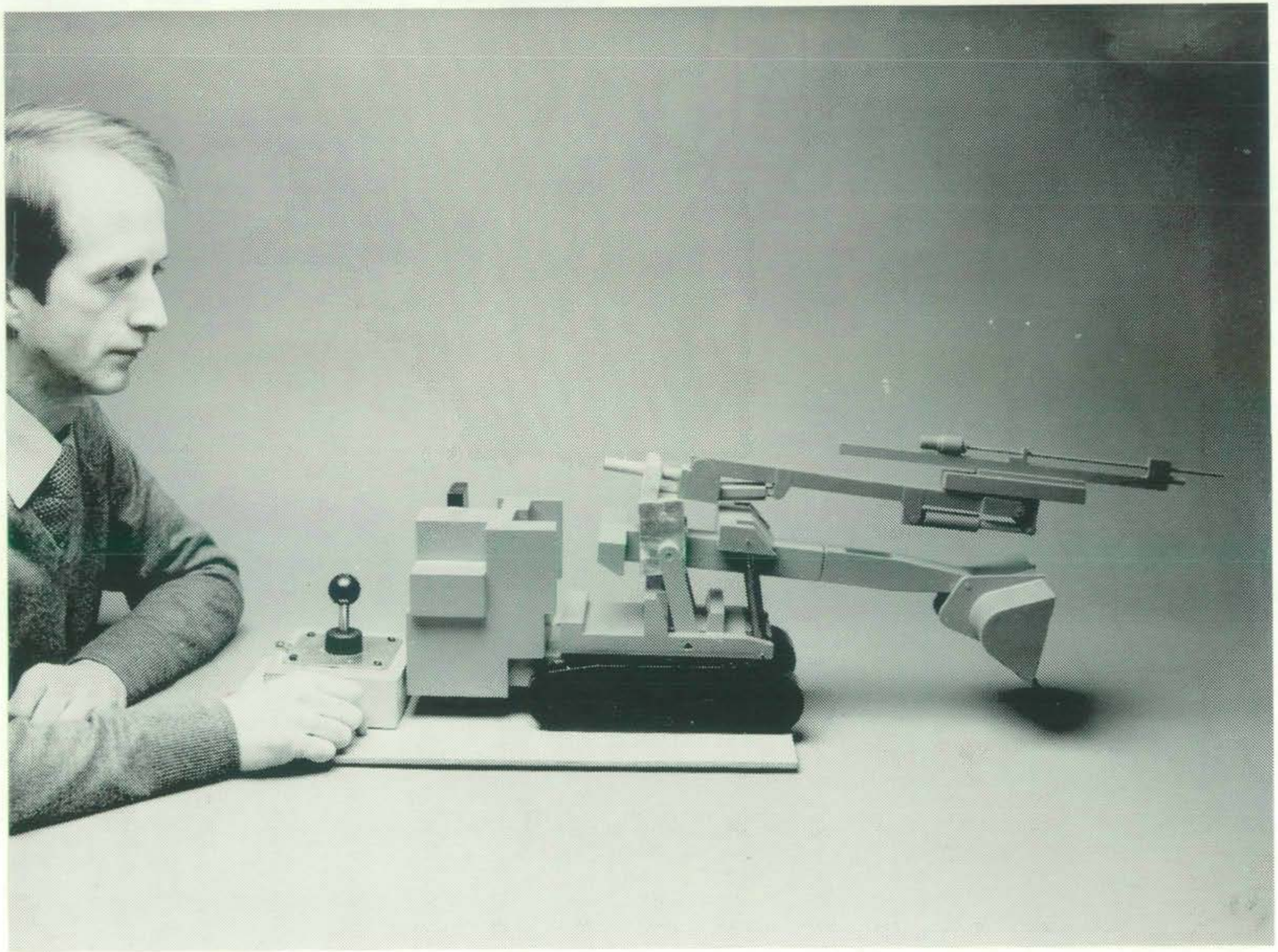


FIGURE 13. Scale-Model Used in the Control-Motion Stereotype Experiment

The procedure of the experiment was as follows:-

(a) The wooden model was placed in front of the seated subject;

(b) The subject was given verbal instructions regarding what he was required to do during the experiment;

(c) The subject was told that there are twelve functions on the machine, each function is controlled by a two-dimensional valve lever control, i.e. the lever can move in one of two specified directions.

(d) For each of the twelve C/R relationships specified in Table 11, the subject was first informed of the two possible directions of control motion. The experimenter then demonstrated the machine response movement to the subject using the model. The subject was required to respond, as quickly as possible, using his preferred hand by moving the control lever in the direction that he considered most appropriate for the machine movement. In most cases, responses were made in not more than three seconds. All machine movements were made from the 'null' position.

(e) Biographical data relating to work experience, training and hobbies were collected from the subject at the end of the experiment.

5.2.3 Results and discussions

(i) Treatment of Data

Analysis of the overall responses, and responses from between and within the three subject groups were undertaken using the chi-square one sample and independent sample tests. Where chi-square analysis was inappropriate, as in cases of small number of subjects' responses, binominal and Fisher's exact probability tests have been used (Siegal, 1956). The influence of factors such as work experience and training, experience in machine operation, hobbies and handedness was examined. For uniformity, the 0.05 level of significance was adopted throughout the statistical analysis.

The major results of significance are discussed in the sections below. Detailed discussion of the results in reported in Chan(b) (in preparation).

(ii) Overall Responses

The levels of statistical significance of overall responses are given in Table 12. The results show that 17 of the 24 CRRs have a significance level of < 0.05, indicating that there are stereotypes in the perception of these relationships.

A number of the results were seen to contradict existing recommendations used in the UK (e.g. BS 3904, 1965; Murrell, 1965; Shackel, 1976; MRC, 1971). Examples of this are the Up/Down and Fore/Aft movements to raise/lower machine elements. There are a number of factors which could explain the differences. Firstly, that existing criteria are mostly derived from experimental tasks involving small visual displays or paper and pencil tests. Subjects in those experiments are therefore unlikely to perceive any mechanical linkage between the control and machine element. In practice, however, as in the three-dimensional task used in this experiment, the subject is able to see the pivot about which the boom or drill components raise or lower. He was, therefore, likely to identify this with a 'mechanical' model, and therefore more likely to perceive a 'see-saw' effect. Additionally, the three-dimensional experimental task allowed subjects to see the pivot points of both the control lever and the machine element, therefore, the arcing movements of the control and the machine element may not be seen as parallel motion-response relationships. Instead, the control lever may be perceived as an extension of the machine element separated by a pivot, thus reinforcing a 'see-saw' interpretation.

To investigate the differences between results of two-dimensional and

TABLE 12.

Level of Significance (α) of Overall Responses

Machine Response	Control Motion Relative to Operator Body	Percentage of Subjects Preferred this Arrangement	Level of Significance (α)
Bucket Side-Discharge CW	Right	100	.001
Bucket Side-Discharge ACW	Left	98.5	.001
Bucket Rolled Backward	Aft	96	.001
Bucket Boom Lowered	Fore	96	.001
Bucket Boom Raised	Aft	93	.001
Drill-Tip Lowered	Fore	92	.001
Drill-Tip Raised	Aft	92	.001
Drill-Carriage Slew Right	Right	92	.001
Bucket Rolled Forward	Fore	86	.001
Drill-Carriage Slew Left	Left	88	.001
Bucket Rolled Backward	Down	85	.001
Bucket Rolled Forward	Up	82	.001
Drill-Tip Lowered	Up	76	.001
Drill-Carriage Slew Left	Fore	69	.001
Bucket Boom Raised	Down	67	.01
Drill-Tip Raised	Down	64	.02
Bucket Boom Lowered	Up	63	.05
Bucket Side-Discharge ACW	Fore	61	.10
Bucket Boom Slew Left	Fore	61	.10
Bucket Boom Slew Right	Aft	58	.20
Bucket Boom Rotate ACW	Fore	58	.20
Bucket-Side Discharge CW	Fore	57	.30
Bucket Boom Rotate CW	Fore	54	.40
Drill-Carriage Slew Right	Fore	51	.50

three-dimensional experimental tasks, results from this experiment were compared with compatible results of a recent experiment by Hotta (1979). Hotta's CRRs were selected as the linear indicator-lever control task on which the experiment was based, can be considered the two-dimensional equivalent of the three-dimensional control tasks on mining machines.

Of ten similar CRRs compared, significant differences were (< 0.05) observed on six relationships. These differences were particularly marked on relationships where the control moves either Fore/Aft or Up/Down. Where the control moves in the Left/Right direction, the two sets of results were in agreement. The implication of this finding is important to designers in that it suggests that some of the existing criteria are not suitable for generalisation to three-dimensional machine control design.

(iii) Experience in Machine Operation and Job Training

It has been frequently reported in past experiments (e.g. Astley, 1973) that the 'experienced and trained' operators' perception of certain CRRs differ from those of 'inexperienced' operators. To investigate whether such differences exist in the NCB population, the results were analysed according to the subject's experience in machine operation (e.g. experienced fitters and designers vs. inexperienced clerical) and also according to their occupations, i.e. fitters vs. designers, vs. clerical groups.

Comparison of responses from 'experienced' and 'inexperienced' machine operators indicate no significant differences between these two groups of subjects on any of the 24 relationships. Similarly, no significant differences were observed for the comparison between the three occupational groups. However, both the fitters and the designer groups showed a marginally stronger preference to Up to Lower and Down to Raise relationship than the clerical group.

These results apparently contradict past findings, and could be explained by one or a combination of the following factors:

(a) that all NCB employees are exposed to industrial working environment and therefore the 'inexperienced' group are not totally "naive" of machine operation in the true sense;

(b) that owing to social, technical and cultural changes in the last three decades, it is conceivable that the populations' perception/mental models of control-machine response relationships have altered by increased everyday contact with machines. Consequently, the gap between 'inexperienced' and 'experienced' operators has reduced;

(c) that the perception of the 24 CRRs investigated in this experiment are not significantly affected by experience in machine operation;

(d) that the effects of experience in machine operations on the perception of CRRs are significantly less on three-dimensional experimental tasks than on two-dimensional tasks.

It is impossible however from this particular study to suggest which if any, of the above suggestions has the major influence. The overall results however, do suggest that the distinction made previously between naive and experienced users may be less important than imagined. This could be of value in that it reduces one element of uncertainty in the provision of recommendations.

Investigation of hobbies, for subjects with leisure activities which could be described as involving "engineering aptitudes" showed that such a comparison had little effect on the perception of the CRRs.

(iv) Handedness

Of the 144 subjects taking part in the experiment, thirteen were left-handed. Comparison of responses from left and right-handed subjects showed that the preference of one of the 24 CRRs, i.e. Fore/Aft for slew to Right is significantly affected by handedness of the subjects. There was also a slight preference for left-handed subjects to slew the drill to the right by pushing forward the control lever.

Results of this experiment are therefore consistent with Holding (1957) and Chapanis and Groper (1967) who found no differences between left and right-handed subjects for 'well-established' CRRs.

5.2.4 Conclusions and recommendations

The experiment has established the following:

(a) Population stereotypes exist on the perception of 17 of the 24 CRRs investigated;

(b) Stereotypes do not exist in Fore/Aft control motion for rotary machine responses relationship;

(c) A number of the findings conflict with current ergonomic criteria recommended for use in the UK, most notable of which are the Up to Lower, Down to Raise, Forward to Lower and Backward to Raise relationships.

(d) 'See-saw' effects are evident on control-response relationships on the vertical plane but not on the horizontal plane;

(e) The differences between responses from the experienced and inexperienced machine operators groups are not significant;

(f) Where control-response relationships (associated with Fore/Aft controls) evoke ambiguity, results indicate a tendency for people to initiate Forward control movements irrespective of the machine responses;

(g) That control response relationships which are weak or ambiguous appeared more susceptible to effects of work experience and handedness.

Based on results of the experiment, recommendations for the standardisation of those CRRs most commonly found on development machines were prepared. These are shown in Table 13.

5.3 Effects of Vibration on Machine Users

5.3.1 Introduction

Vibration is an environmental condition which occurs to some extent with all mobile plant and vehicles. Vibration from development machines underground arises primarily from the cutting or drilling action of the machine, particularly when driving into hard strata. A less important contribution to the vibration dose received by the machine operator arises from the tracked movement of the machine.

Whole-body vibration received by being seated or stood on the machine, or hand-arm vibration received by being in contact with controls etc can have comfort, health, safety and job performance implications for machine operators. These effects have been considerably researched and many countries have jointly or separately produced standards advising what levels and types of vibration produce this effects. Even the most widely accepted international standard (ISO 2631, 1974) continues to be controversial however, and the type and degree of vibration produced by underground development machines has not been measured because of the lack of electrically safe recording instrumentation for use underground.

A literature review was carried out (Collier and Chan, in preparation) to draw out the implications for machine design of the effects of vibration on mining machine users. This is summarised here.

5.3.2 Aims

The specific objectives of the review were:

(a) to discuss by examination of research literature, not necessarily directly related to mining, the effects of vibration upon humans;

TABLE 13

Recommended Control Motion-Machine Response Relationships for Mining Machines

Machine Response	Recommended Control Motion (Lever Controls only)	Comments
Drill Carriage/Boom Raised	Downward Backward	BACKWARD is more reliable than Downward and therefore preferred (only for single lever controls).
Drill Carriage/Boom Lowered	Upward Forward	FORWARD control motion is preferred to Upward.
Drill Carriage/Boom Slew Left	Left	Strong stereotype.
Drill Carriage/Boom Slew Right	Right	Strong stereotype.
Drill Carriage/Boom Rotate CW	Right	Very strong stereotype.
Drill Carriage/Boom Rotate ACW	Left	Very strong stereotype.
Bucket Rolled Forward	Forward Upward	FORWARD motion is marginally more reliable than Upward.
Bucket Rolled Backward	Backward Downward	BACKWARD motion is marginally more reliable than Downward.
Bucket Side-Discharge CW	Right	Very strong stereotype.
Bucket Side-Discharge ACW	Left	Very strong stereotype.
Drill Carriage/Boom Extended	Forward	This is the best arrangement.
Drill Carriage/Boom Retract	Backward	No disputes between reference sources.

NB: The above recommendations are primarily based on results from the experimental work with three-dimensional tasks.

(b) to relate these effects to the type and level of vibration generated by non-mining machines so that the practical relevance to mining could be discussed;

(c) to assess the adequacy and applicability of existing whole-body vibration standards;

(d) to suggest ways of recording the effects of whole-body vibration without electrically safe instrumentation, which could be adopted in the underground studies of the three families of machines;

(e) to detail the implications for machine design.

5.3.3 Effects of whole-body vibration

Most vibration research has been confined to the conditions found in normal surface vehicles or transportation: predominantly vertical vibration (called "Z axis" vibration) at frequencies below 20 to 30 Hz. This is caused by the movement of the vehicle over rough surfaces.

Vibration from mining development machines may also arise from movement over rough surfaces, but will probably be less great because of the use of tracks as opposed to wheels; the weight of the machinery (over 30 tonnes) smoothing its own path and the low speed of movement as compared to surface vehicles.

The vibration caused by the machine's other activities can be much greater and different in character. Vibration caused by cutting or drilling (to a lesser extent) into rock is much more multiaxial (not just confined to the Z axis) and is random (unpredictable in level and frequency from moment to moment). Therefore, research which uses sinusoidal vibration or only single axis vibration does not reveal completely the effects of vibration underground.

(i) Physical and Physiological Effects

Transmissibility is a measurement of the extent to which vibration is absorbed by the body it is entering. It is defined as the ratio of the response amplitude of a system to the excitation amplitude. Transmissibility greater than 1 can occur when the system resonates.

Transmissibility of Z axis vibration through the human body is greatest at 4 to 6 Hz when it is around 1.3 to 2 (Coermann, 1970; Coermann et al, 1962) meaning an amplification of the vibration in effect of 30-100%. In the Y axis (sideways) peak transmissibility seems to be at around 1.5 Hz (Woods, 1967). X axis vibration (back-to-chest) transmissibility peaks at 1.5-2 Hz (Goldman, 1961).

Vibration may excite body organs into resonance. This can be painful and injurious (Magid et al, 1960). Fortunately, fairly high acceleration levels of perhaps 20 ms^{-1} or more are needed to produce resonance, though it can have practical significance in some cases, for instance tractor drivers (Coermann, op cit). Z axis vibration (data for other axes was not identified) causes the most sensations due to organ resonances in the frequency band 3 to 9 Hz.

Back pain may be caused mainly by vibration in the 8 to 12 Hz band. The effects begin almost as soon as vibration of sufficient amplitude begins. Other effects and resonant frequencies are given in Magid et al (1960).

(ii) Sensory and Task Performance Effects

(a) Visual performance: Vibration may be transmitted to the head by direct contact of the body with a vibrating surface. Certain combinations of acceleration and frequency may cause significant blurring of vision.

Z axis-only studies suggest that for viewing distances under 1 m, numeral or character displays will remain readable in a vibrating environment if they subtend to at least a quarter of a degree

(Teare and Parks, 1963). At 1 m, this corresponds to a letter or numeral height of about 4.4 mm, though this is under clear and well-lit viewing conditions which are otherwise optimal. Any frequencies above 5 Hz can potentially cause blurring but the acceleration needed to cause blurring at 7 Hz (0.4 ms^{-1} at 1.2 m) is much less than that required at, for example, 15 Hz (1.96 ms^{-1}). Some multi-axis work (Meddick and Griffin, 1976) suggests that where combinations of directions of vibration are the norm, the levels of vibration required to cause blurring will be much less, and possibly the letter size and design needed will be different.

(b) Intellectual Functioning: Cognitive tasks such as mental arithmetic or monitoring for visual or auditory warning signals have received little research attention but generally seem not to be affected by vibration.

Tasks making simple demands such as recognising a pattern (Shoenberger, 1967) or monitoring warning signals (Holland, 1967) are unaffected. Even in tasks where an appropriate response needs to be picked, depending upon the stimulus, choice reaction time is also not affected (Hornick, 1962). Huddleston (1964) found that mental addition and recent memory were affected by vibration, but Shoenberger (1974) attributed this to mechanical interference with the input of information rather than interference with cognitive processes. There is general agreement that vibration has little or no cognitive effects.

(c) Simple Reaction Time: Some research findings as to the effects of vibration on simple reaction time are contradictory (see, e.g. Simons and Schmitz, 1958; Dudek and Clemens, 1965; Shoenberger, 1970; Harris and Shoenberger, 1970). Whereas Holland (1970) found no reaction time effect after six hours random vibration, Shoenberger (1970) and Harris and Shoenberger (1970) found that simple reaction lengthened by typically 0.1 second (but up to 0.5 second) under low frequency vibration.

Usually effects, if they occur, will be practically insignificant in an underground context where fractions of a second saved in reaction time are likely to be unimportant.

(d) Manual Control: Many tasks involve operating a control in response to the operator's perception of the state of what is being controlled. For instance, drivers control the position of a steering wheel in response to their view of the road. This is called "tracking". It is a primary task for pilots and operators of vehicles. Manual tracking experiment in the laboratory might give some indication of how difficult it is in practice to control machinery under vibrating conditions.

Tracking errors increase in proportion to the amplitude of vibration and are also dependent on the frequency. The greatest effects are in the frequency range 3-6 Hz where an acceleration of 4 ms^{-1} (Z axis) can produce as much disruption as acceleration at 20 ms^{-1} at 20 Hz (Chaney and Parks, 1964; Harris and Shoenberger, 1966; Weisz et al, 1965). X axis vibration has the most effect at 1 to 5 Hz and Y axis at 1 to 3 Hz (Hornick, 1962; Shoenberger, 1970). Effects are greatest when the axis of movement of the control coincides with the vibration axis. They seem to be caused not only by mechanical interference but also by disruption of the nervous information that tells the brain the exact positions of the limbs and muscles (Lewis and Griffin, 1976).

Effects of disruption of manual control by vibration can be reduced by introducing stiffness into the control (Lewis and Griffin, 1976) or by careful selection of the axis of control movement.

(e) Subjective Responses: Studies of intensities and frequencies of vibration that can be tolerated voluntarily for a short time (reviewed in Shoenberger, 1972) suggest that the least tolerated frequency is 5 to 6 Hz, at which about 15 ms^{-1} Z-axis acceleration can be tolerated. Tolerance increases as frequency departs from 5 to 6 Hz in all axes, but X and Y axis vibration tolerance does not increase as much as Z axis below 5 Hz. The precise levels and shapes for tolerance curves are not exactly known because of procedural and experimental difficulties. It is also difficult to extrapolate to the field because multi-axis studies have been insufficient.

5.3.4 Whole-body vibration standards

A draft International Standard (ISO 2631, 1974) was released for whole-body vibration by the ISO. This was also published as a draft for development by the BSI in the same year. Other standards have been released by several countries, such as Czechoslovakia, Japan and the USSR but the most widely accepted standard so far is that by the ISO, though it has controversial aspects (Sandover, 1979).

The Standard suggests that the body is most sensitive to vibration in the frequency range 4-8 Hz with tolerance increasing by 3 dB/octave at lower frequencies and increasing at 6 dB/octave at higher frequencies. Similar shaped curves, but at different levels, are offered for 'fatigue decreased proficiency', 'reduced comfort' boundaries and an exposure limit, for all three axes. Only the frequency range 1-80 Hz is considered.

The Standard admits that the effect of whole-body vibration is very variable and that some tasks (it does not suggest what kind) will be more disrupted than others. Therefore, the guidelines can only indicate the general area in which problems may occur. In addition, some of the assumptions and methods of measurement in the Standard have been called into question (Sandover 1979). Until the Standard is revised or withdrawn, it is recommended that it should be used as a guideline for the assessment of whole body vibration, given the lack of suitable internationally agreed alternatives.

5.3.5 Alternative vibration assessment methods

The International Standard, ISO 2631 offers guidelines on the vibration and exposure times which should not be exceeded. Vibration levels and exposure times should be assessed against this Standard and against the knowledge of levels required to produce the effects summarized above, if the exact consequences of vibration in the mining context are to be known. However, at present, it is not permissible to measure vibration from a machine whilst it is being operated underground due to the lack of suitable intrinsically safe equipment. Therefore, it is not possible to assess vibration exposure from mining machines against the international standards unless underground conditions can be realistically simulated.

To identify the likely importance of whole-body vibration on the development machines studied by the project, an alternative assessment method was necessary. The literature review identified many possible effects or symptoms of whole-body vibration. In the absence of direct measures, many of these effects could be elicited through questioning the operators of the development machines on topics such as:

(a) <u>Effects on vision</u>:
  - Vibration can cause blurred vision.
  - Labels can be more difficult to read when a machine is being operated.

(b) <u>Efficient use of controls</u>:
  - vibration can interfere with the use of controls.
  - The orientation of controls can affect the ease with which they can be used under vibration conditions.

(c) <u>Effects on posture</u>:
  - The operator may need to adopt a certain posture specifically to minimise the effects of vibration outlined above.
  - Seating can increase the effects of vibration.
  - Vibration may constrain the operator from adopting certain postures (e.g. leaning out to improve visibility).

A questionnaire was therefore developed which allow machine drivers to volunteer any effects of vibration which they have experienced under the above general headings. This questionnaire is given in Appendix A, (section 7) and was used for all 25 machines studied.

The results show that operators on roadheaders and continuous-miner were affected more by machine vibrations than operators on drill-loaders. Table 14 summarises these results.

TABLE 14

Percentage of Operators' Responses to Effects of Vibration on Development Machines

Main Effects of Vibration	Continuous-Miners	Roadheaders	Drill-Loaders
General discomfort	33%	100%	86%
Causing inaccurate control movements	33	85	0
Causing unstable postures	16	92	57
Causing tiredness	50	85	43
Impairing vision	0	8	14
Necessitating reduction in speed of operation	33	100	86

Analysis of the above results in conjuntion with other task data suggests that consideration of the following guidelines could minimise effects of machine vibration.

(a) Seats should be designed to attenuate vibration and that their mounting should be sufficiently stiff not to resonate appreciably. Padding of the seat may provide some attenuation, particularly of X and Y axis movement if there is sufficient thickness. Vertical (Z) axis vibration is difficult to attenuate by paddinig, a shock-absorbing mounting may be more appropriate.

(b) Labels or gauges which are to be read around 1 m distance should have scripts/letters at least 5 mm high. If vibration could be limited to one axis mainly, the effect upon ability to read labels would reduce.

(c) Where lever controls are to be used in vibration conditions known to affect control operation accuracy (e.g. cutting hard strata), the controls are best mounted so that their direction of operation is perpendicular to the major (usually the vertical) vibration axis. Controls should not have so loose or light action that their operation is easily disrupted by vibration. A degree of stiffness (between 30 N and 40 N) helps to reduce the effects of vibration on control accuracy.

These recommendations, along with other ergonomic recommendations, are presented in separate design reports for each machine family (Chan et al, in preparation; Pethick et al, in preparation; Collier et al, in preparation).

5.4 Determination of Control Location Envelopes

Control location envelopes are a simple graphic aid used to represent human biomechanical and anatomical constraints when assessing whether an operator can reach hand or foot controls on scaled-drawings of machines. Envelopes can be used either to evaluate existing machinery or to aid designers in the location of controls on new machines. Control location envelopes have been used extensively in the UK coal mining industry (e.g. Kingsley et al, 1980) for the evaluation and design of underground locomotives and free-steered vehicles, and have been established as successful means of communicating ergonomic criteria to machine designers.

This section describes the more general issues relating to control location envelopes for development machines. The operator's body is represented by straight line links between points representing simplified joints in the skeleton, similar to the body-link method of Dempster (1955). The spine and pelvis are regarded as a single rigid structure (no bending, leaning or twisting) whilst the shoulder girdle is permitted to articulate, allowing the shoulder joint some forwards movement. Arm and leg joints are articulated within the optimum and maximum joint ranges. The extremes of the population range are used to draw up the reach and body space limits, at the extremes of the seat adjustment (or from the same seat position for the fixed seat envelopes). The volumes which are between the lines drawn for the extremes, or are wholly within both limits, are the control location envelopes.

Experience with locomotives and free-steered vehicles has shown that two types of envelopes were required. Firstly, general evaluative envelopes, for use during the project, in assessing control locations on the development machines in the study samples. Secondly, design envelopes, for use after the project, incorporating ergonomic criteria derived from the studies, pertinent to individual development machine families. The latter envelopes include all of the ergonomic trade-offs between conflicting requirements (e.g. ease of reach of controls and ingress/egress clearances) that have been identified in the field studies.

5.4.1 The development of general evaluative control location envelopes

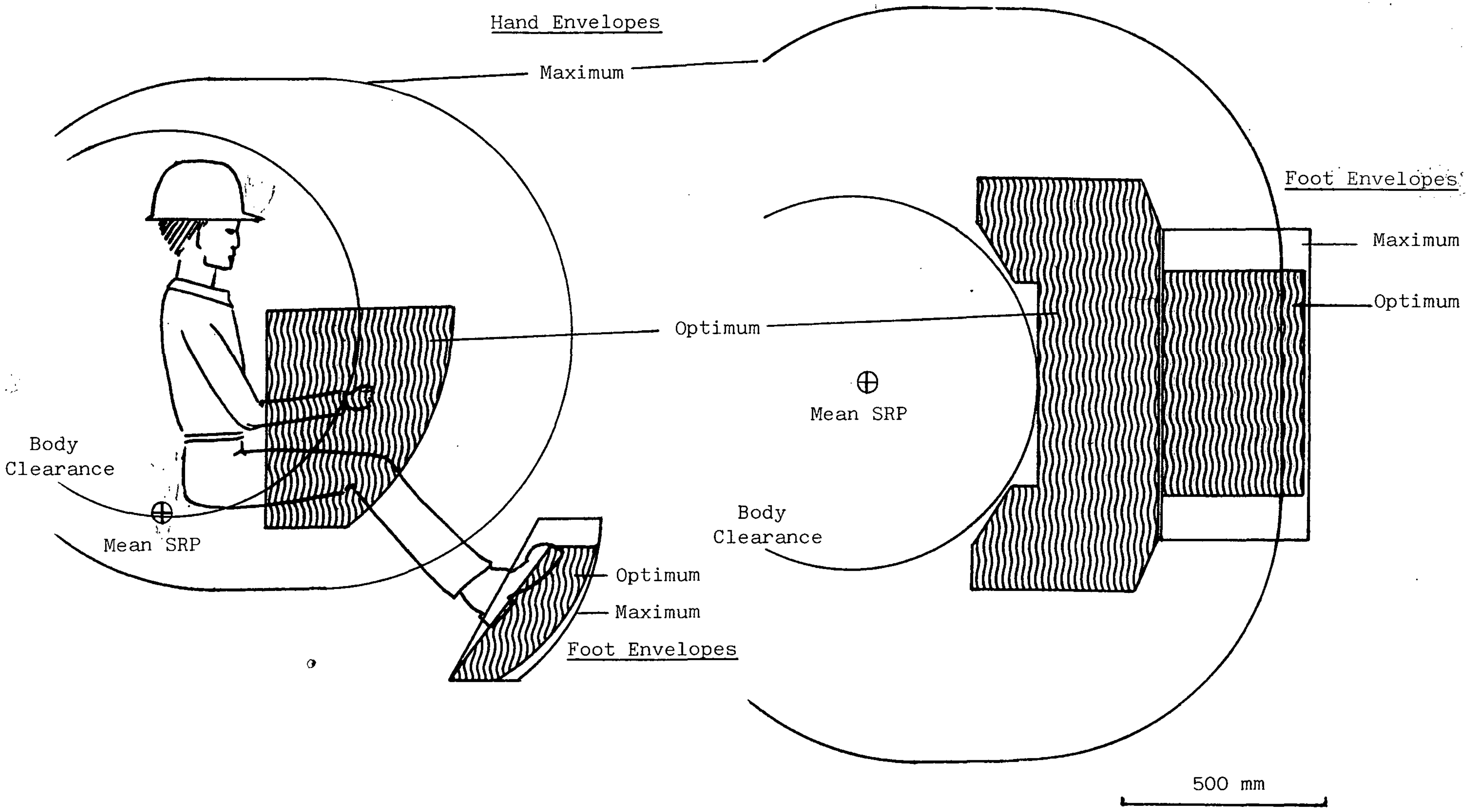
(i) Selection of Initial Criteria

The initial criteria should reflect the anatomical and biomechanical characteristics of the UK mineworker population. Previous investigations (Ashby, 1976) have established that the UK mineworker population is closely approximated by an industrial group which has been extensively surveyed (GEGB, 1977). This has obviated the need for a survey of mineworkers and provides a reliable body of anthropometric data. Considerable research in the literature on human joint movement capabilities has led to the adapting of criteria for European civilians, performing sustained driving tasks (Rebiffe, 1967). The majority of available criteria on joint movement have been rejected as they were not only for young, selected, military personnel but also included some forced movement of the limbs, and were therefore highly unsuitable for use as sustained voluntary postural limits. The 5th and 97.5th percentile range of mineworkers was chosen (rather than the conventional 5th to 95th percentiles) to minimise the consequences of confined spaces on emergency egress from the machine by the upper percentile group of mineworkers. Other safety issues were also taken into consideration, for example, the need to minimise accidental control operation caused by jolting which can be prominent when an operator is required to bend, lean or twist his trunk to reach a control. Jolting can then lead to inadvertent or incorrect control operation as the extent of unwanted body motion that jolting can cause becomes greater as the operator's posture becomes less stable. These postures also reduce the operator's forward vision and preventing them aids both safety and performance. Leaning, bending or twisting are not incorporated in the design of evaluative envelopes. A restriction on hand controls higher than the 5th percentile shoulder was made as sustaining raised arms reduces control operating precision. Foot controls were similarly restricted above seat reference point level, the seat reference point (SRP) being the intersection of the compressed seat backrest and squab, at the level of and slightly behind the buttocks.

(ii) Investigation of existing control location envelopes

Two sets of location envelopes were found for construction and earth moving machinery. These may have been suitable for general evaluative envelopes as development machines are fairly similar. Each of these was evaluated against the initial criteria for suitability.

(a) ISO 6682 Earth Moving Machinery - Zones of comfort and reach for controls, (side elevation and plan drawings are shown in Figure 14).



N.B. Seat design is specified ± 74 mm horizontal adjustment

FIGURE 14. ISO 6682 Earthmoving Machinery - Control Location Envelopes

This standard was rejected on the basis that:

1. the foot envelopes were beyond the reach of the required mineworker population range;

2. that the maximum hand envelope required the operator to lean to either side and to the front;

3. that the optimum hand envelope involved the maximum reach of the operator including forward shoulder flexion; and

4. that the standard was for an excessive population range (stature range from 1537 to 1854 mm, as compared with the UK mining criteria of 1617 to 1834 mm).

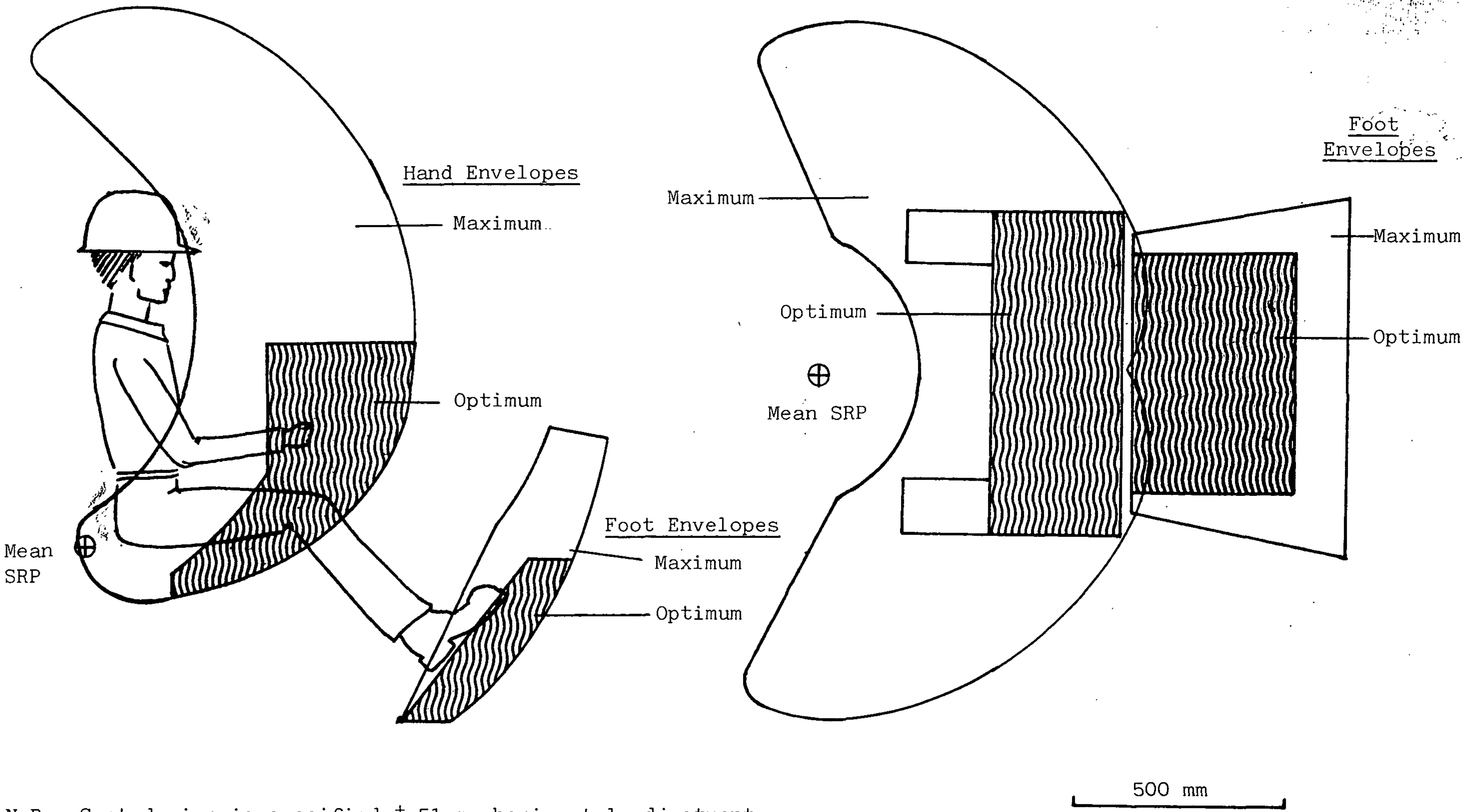
The consequences of these factors were demonstrated by comparison with subjective responses from previous studies on locomotive operation, where of seven hand controls that operators regarded as out of reach, ISO 6682 indicated that five were within reach. The adverse consequences of adopting ISO 6682 would have been (1) to accept substantial operator postural changes, incompatible with stable posture and control operating accuracy, (2) to permit controls requiring high accuracy of use to be located where they could not be used and (3) to locate hand and foot controls where they could not satisfactorily be operated under mining conditions by mineworkers.

The substantial proportion of the hand envelope above shoulder height and behind the operator indicates the major differences between these envelopes and our initial criteria.

(b) SAE - J898 APR 80 - Construction and Industrial Equipment Design (see Figure 15).

This standard has the same major problems as the ISO. It allows overhead reach and hand controls behind the operator. Foot

FIGURE 15. SAE J898* - Construction and Industrial Machinery Control Location Envelopes



N.B. Seat design is specified ± 51 mm horizontal adjustment

> controls can be located further away than can be reached and there is little distinction made between optimum and maximum reach for control operational accuracy. It is, however, closer to the initial criteria in that it does not allow body leaning and the anthropometric range is similar (SAE range of stature 1616 to 1849 mm, UK mineworker range 1617 to 1834 mm).

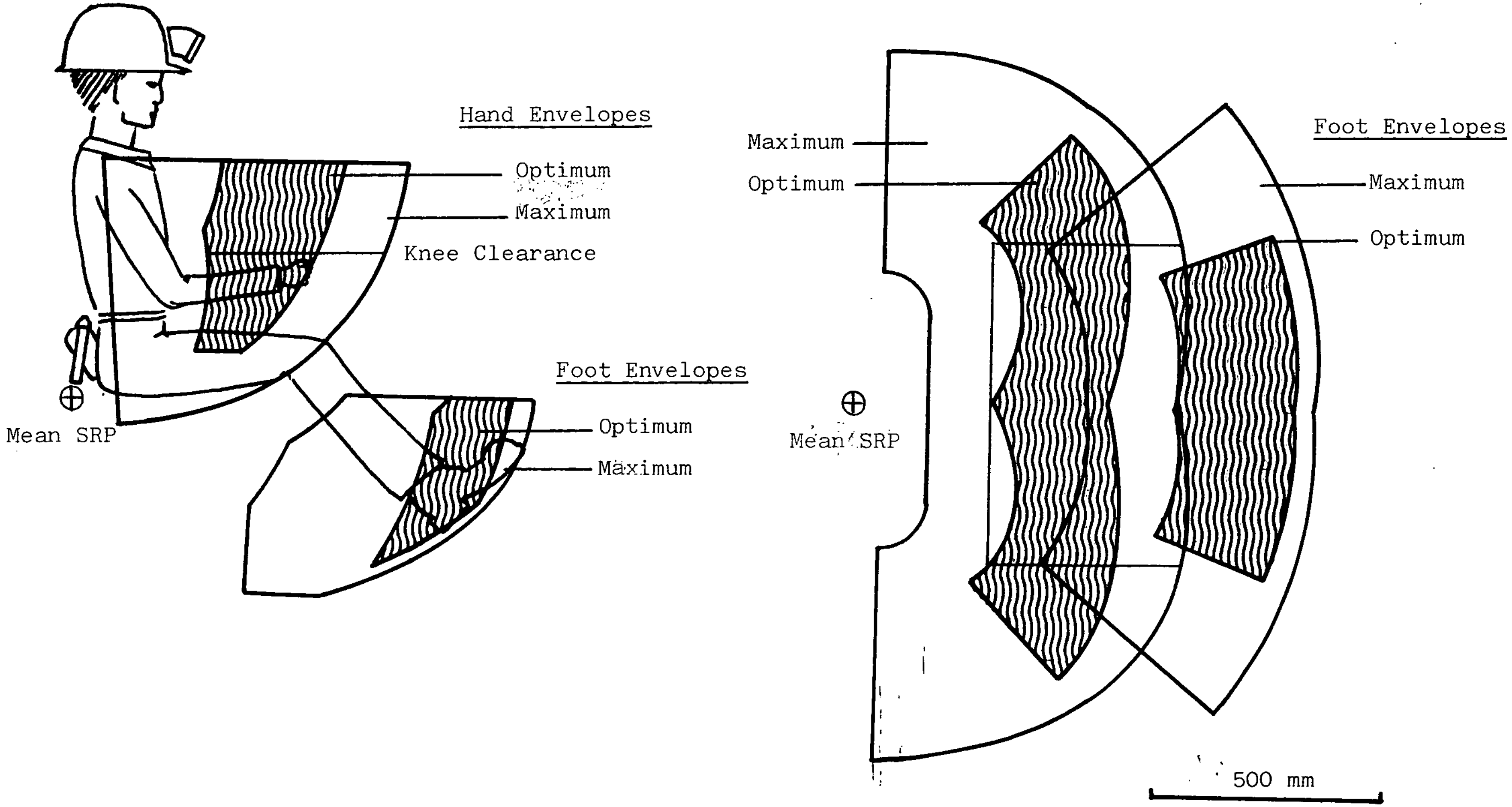
One common limitation was that ISO and SAE envelopes were based on a seat adjustment range of 150 mm, as this is optimal for design. In evaluating development machines, there is a requirement for fixed seats to be included, on the basis that adjustable and fixed seats are in use. Given that neither ISO nor SAE fully met the initial criteria, two sets of general evaluative envelopes were produced using the method summarised earlier.

These envelopes incorporated all of the initial criteria of mineworker anthropometry, joint movement capabilities, postural constraints and seating design variants. Additional modifications to suit mining conditions involved reducing ankle movement to that allowed by rubber calf boots and restricting the height of pedals. Figures 16 and 17 show the general evaluative envelopes.

5.4.2 The development of design control location envelopes for each machine family

The results of the field studies (see sections 3 and 4), showed that there was a considerable need for control location envelopes specific to each machine family. The relative merits of ergonomic features change with the task demands of the different machine families, although the anatomical and biomechanical limits are constant. It is therefore advantageous for design envelopes to incorporate not only anthropometric and biomechanical data, but also interacting features such as: seat design, control design (especially pedals), operator access, body movement clearances, force applications, eye position constraints and body posture constraints which differ between families. Three examples of these design envelopes are shown in Figures 18, 19 and 20. Each of

FIGURE 16. General Evaluative Control Location Envelopes
(± 75 mm horizontal seat adjustment)



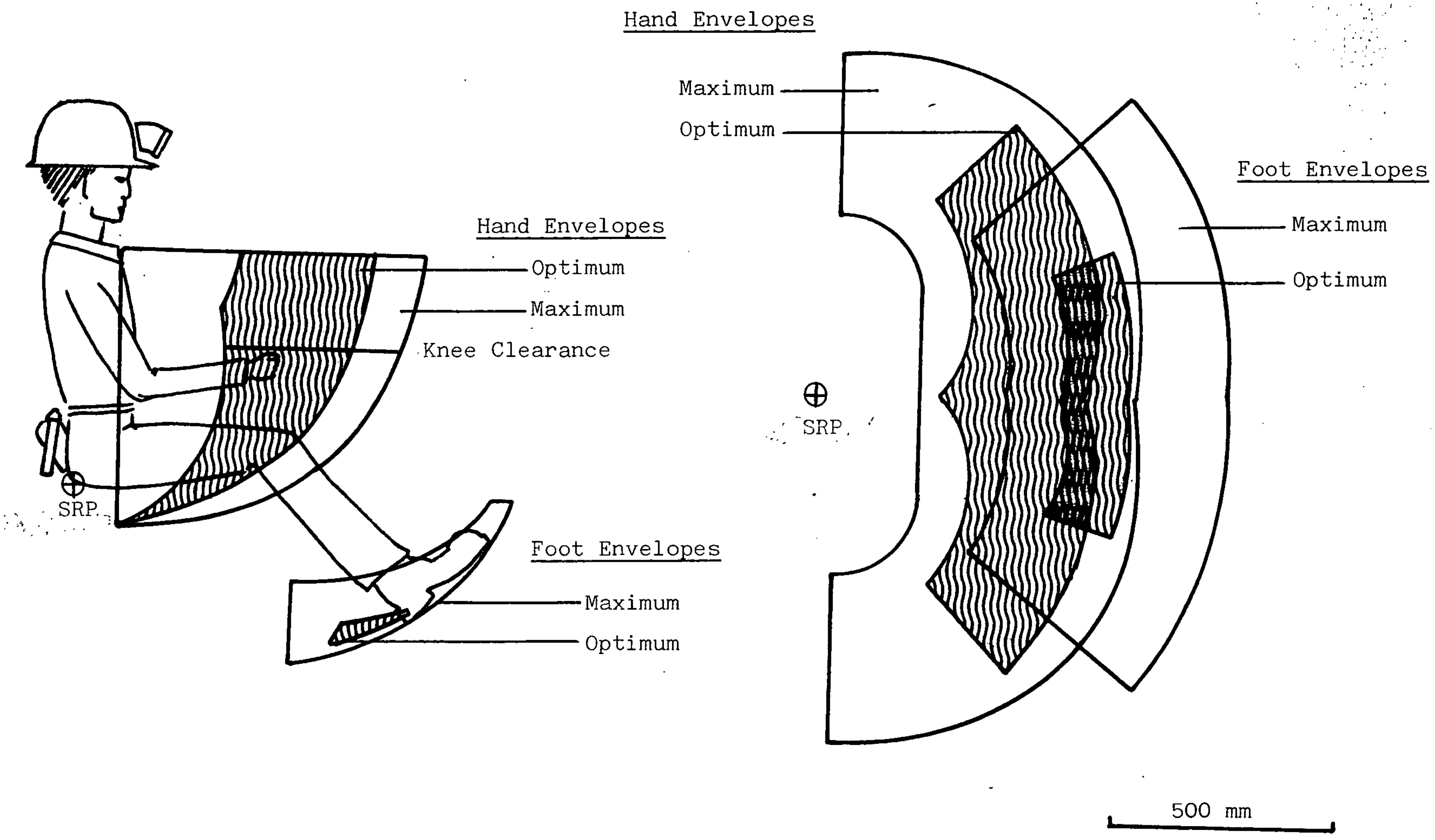
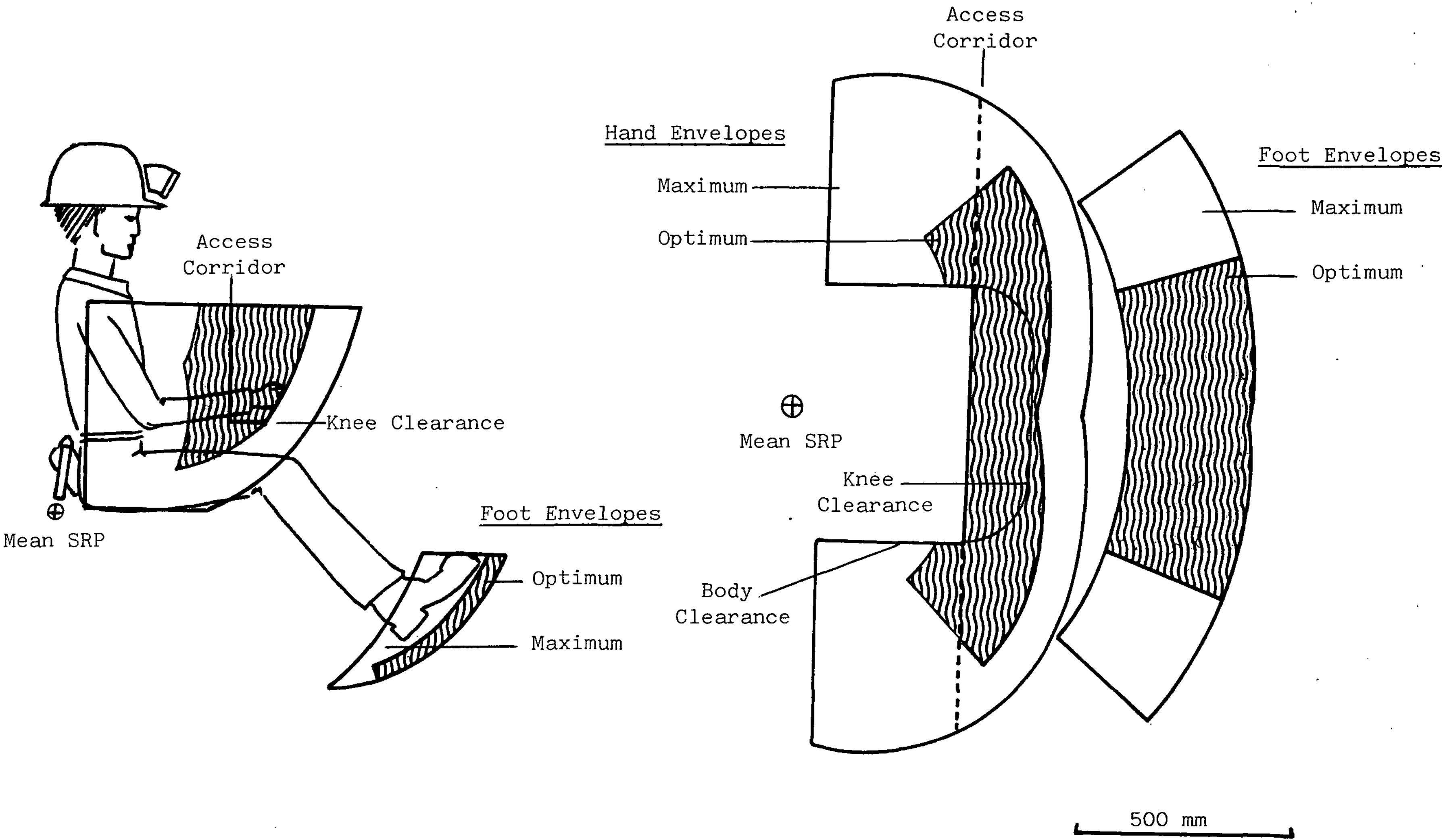


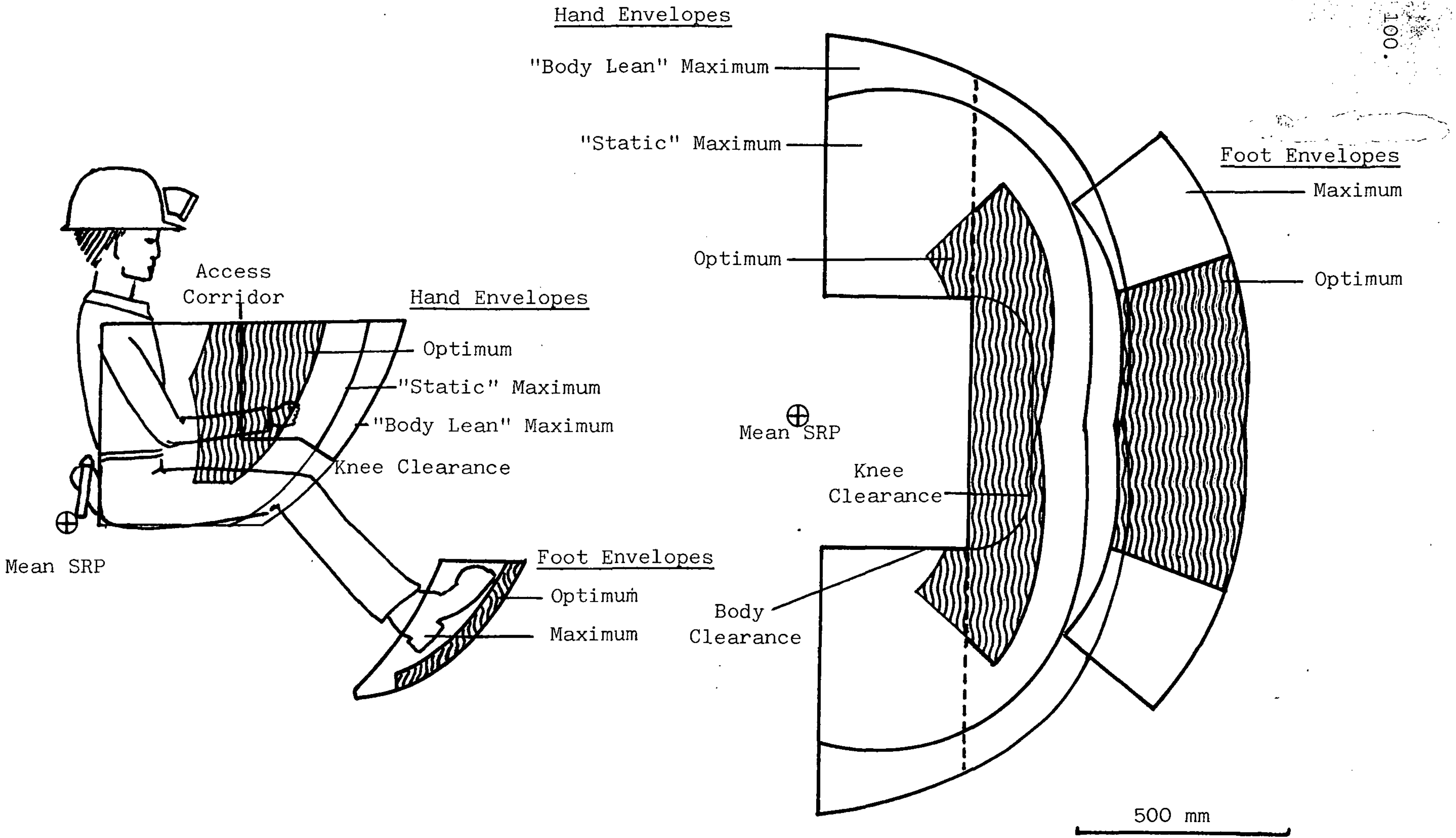
FIGURE 17. General Evaluative Control Location Envelopes (no seat adjustment)

FIGURE 18. Control Location Envelopes for Roadheader Design



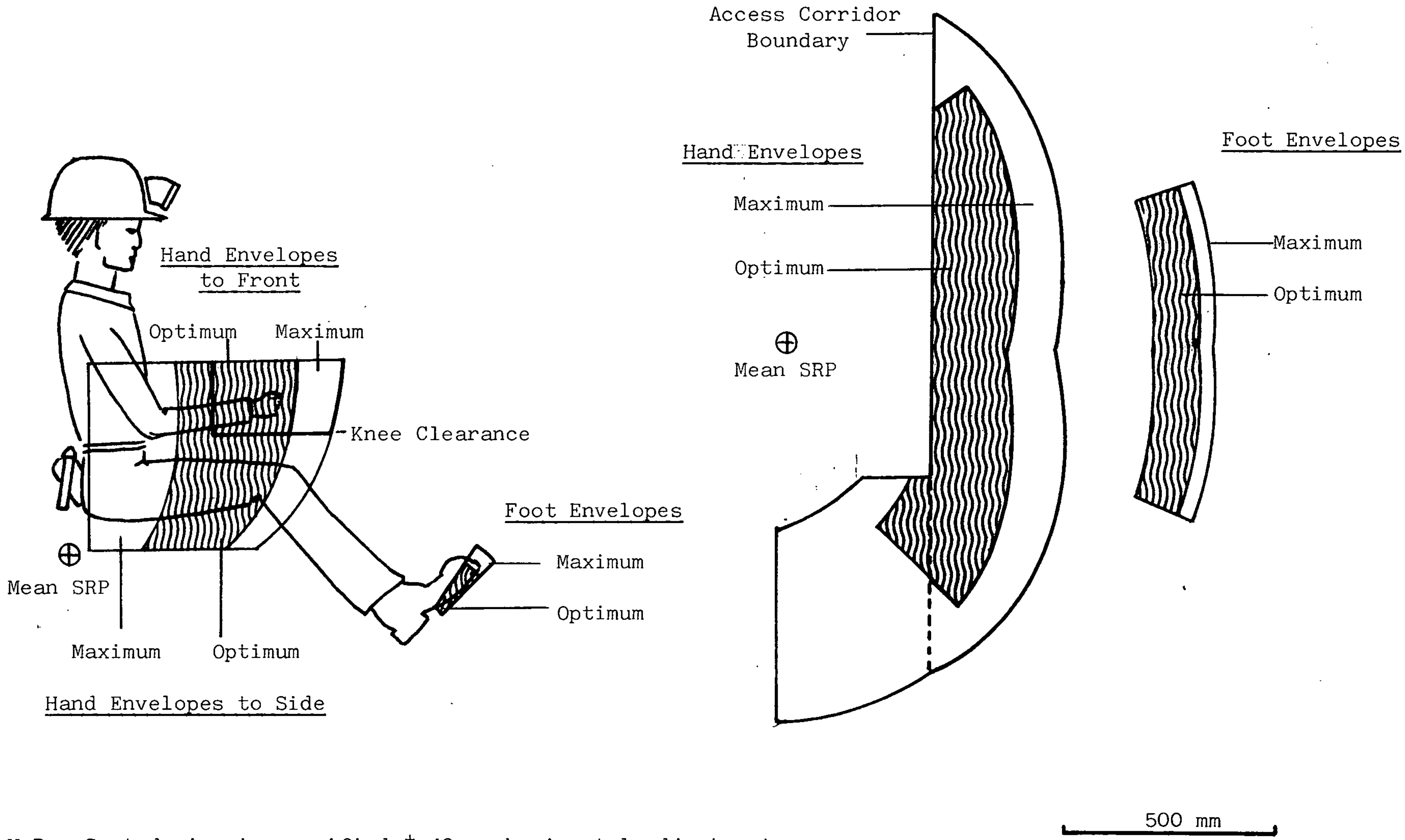
N.B. Seat design is specified ± 75 mm horizontal adjustment

FIGURE 19. Control Location Envelopes for Drill-Loader Design



N.B. Seat design is specified ± 75 mm horizontal adjustment

FIGURE 20. Control Location Envelopes for Continuous-Miner Design



N.B. Seat design is specified ± 40 mm horizontal adjustment
± 60 mm vertical adjustment

these sets of envelopes has been derived on the basis of the optimum ergonomic configuration for different variants of machine family (e.g. very low height, no height constraint, canopies or sightline constraints).

In addition, Figure 21 shows hand control operating forces attainable in each part of envelope. The biomechanical configuration leading to maximum force is a straight arm, which is moved by the body acting through the shoulder girdle. This does not provide optimum accuracy, and therefore care should be exercised when this figure is used for controls which were seen to require sensitive or accurate movement (e.g. drill mast controls). The posture for optimum accuracy involves a bent elbow, which does not allow maximum reach or force.

For the optimum ergonomic configurations, interacting ergonomic features must be included to attain the best implementation of ergonomics for the health, safety and efficiency of development machine operators. The design envelopes for each machine family incorporate such features and are constructed to enable ergonomic requirements to be easily implemented by designers.

5.5 Experimental Headlight Assessment

5.5.1 Introduction

The field studies of development machines showed that machine lighting had an important contribution to the operator's performance and that suitable design data were required for manufacturers to provide adequate machine lighting.

During a previous ECSC funded project investigating haulage and transport equipment (Kingsley et al, 1980) controlled evaluation of several types of headlight, which are also found on development machines, was conducted. Since those tests, new and revised designs of headlights, were obtained and evaluated to add to the existing database of headlight performance.

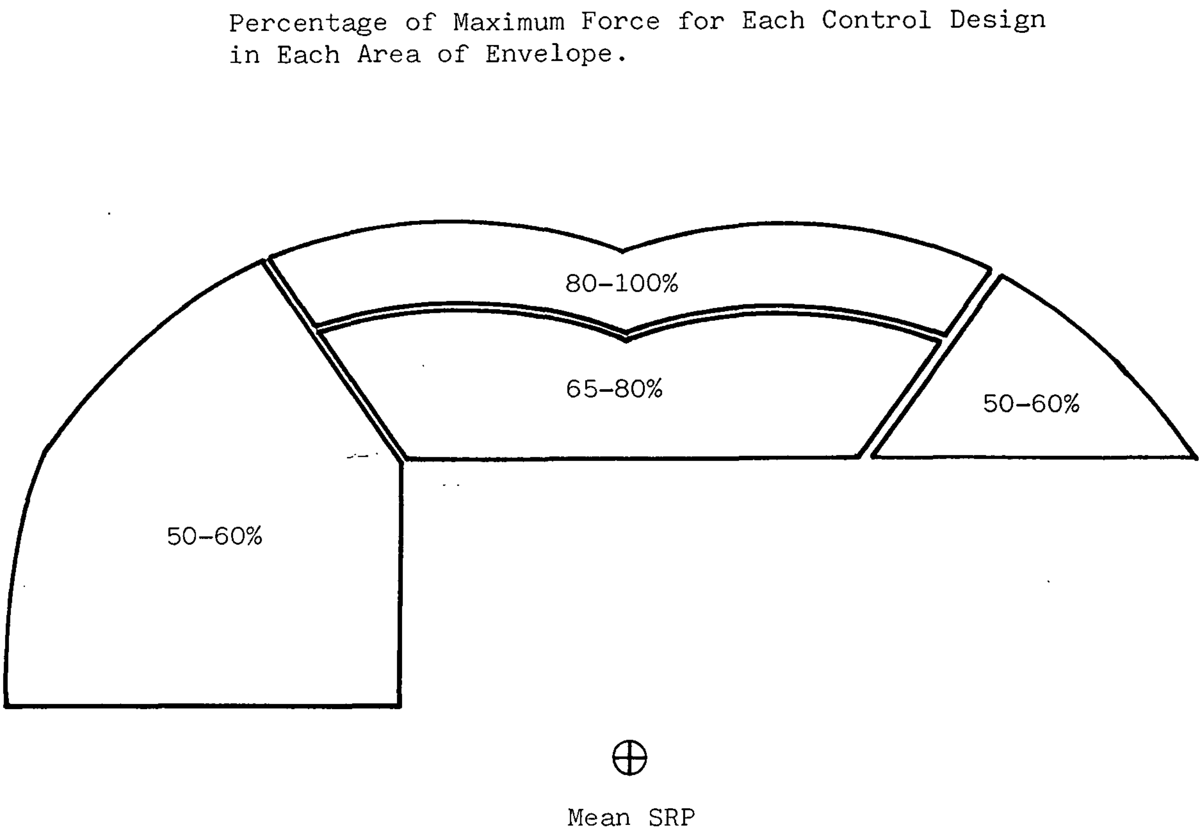


FIGURE 21. Operator Control Force Application Superimposed Onto Hand Control Location Envelopes for Roadheaders

5.5.2 Method

Headlights were tested in a disused surface tunnel. Measurements were taken using an Hagner SD1 Universal Photometer. The headlights were held in a specially constructed stand and supplied with a controlled voltage according to the manufacturers recommendations. The headlights were orientated such that the beam centres were horizontal. Preliminary investigations showed that the headlight output was roughly concentrically symmetrical, and it was decided that measurement on the horizontal diameter through the centre of the beam would provide an adequate description of each headlight's output distribution. Measurements were taken 2 m from the front surface of the headlight casing, over a 100° angle (at 2° intervals at angles greater than 10° from the beam centre and at 1° intervals in the central 20° of the beam) giving 62 measurement points for each headlight.

5.5.3 Results and discussions

The photometric results were entered into a computer data base of headlight performance. Graphs representing the incident light levels can be produced using the inverse square rule for the most appropriate headlight to task distance. The results are described for a distance of 5 m as this represents a typical working distance for development machines.

Examples of the light distribution curves at 5 m from the headlight are shown in Figures 22 to 25. (It should be noted that the Victor 36 L/C and Victor 36 LE were specially designed as low intensity rear lights for development machines). The size of the central, intense, portion of the spot beams at 5 m was approximately 0.5 m in diameter. The overall diameter of measurable light output was approximately 4 m for spot and 8 m for flood headlights although incident light levels generally outside of 4 m diameter were too low in flood headlights and outside 1.75 m in spotlights to be considered effective for illumination of visual attention areas.

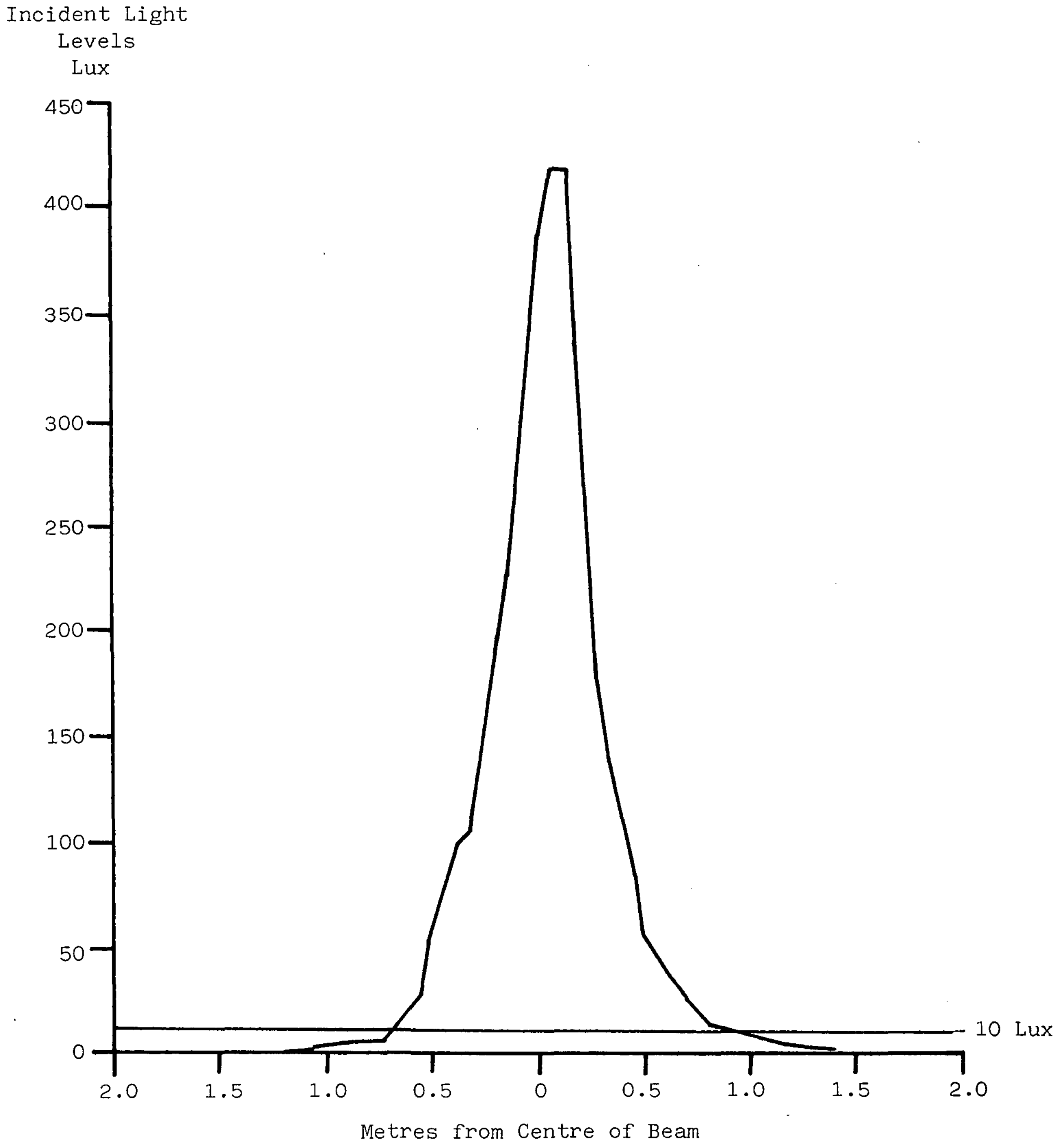


FIGURE 22. Incident Light Levels at 5 m From the FRS1 70 W H1 Spot Headlight

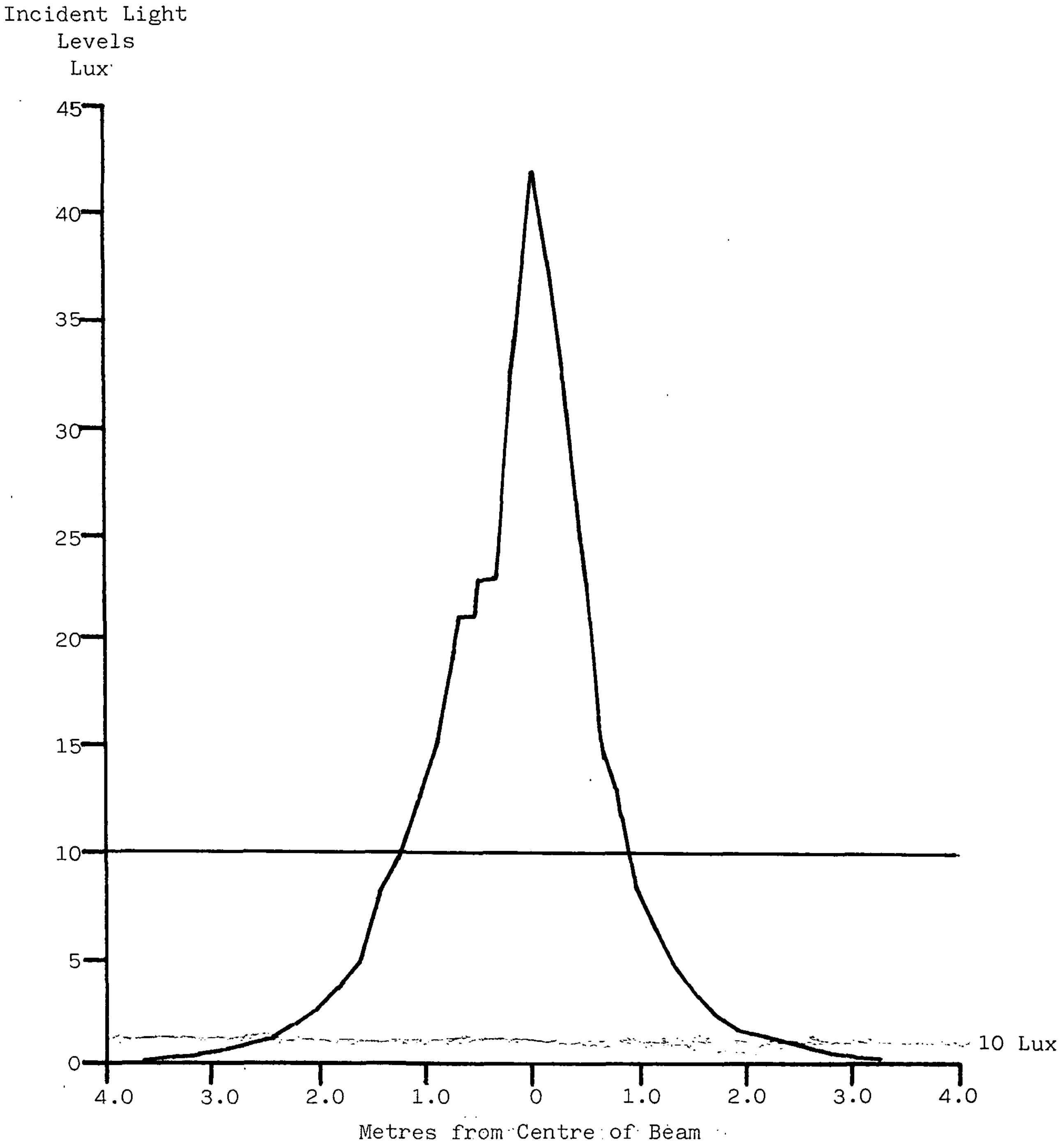


FIGURE 23. Incident Light Levels at 5 m From the FRS1 55 W H1 Flood Headlight

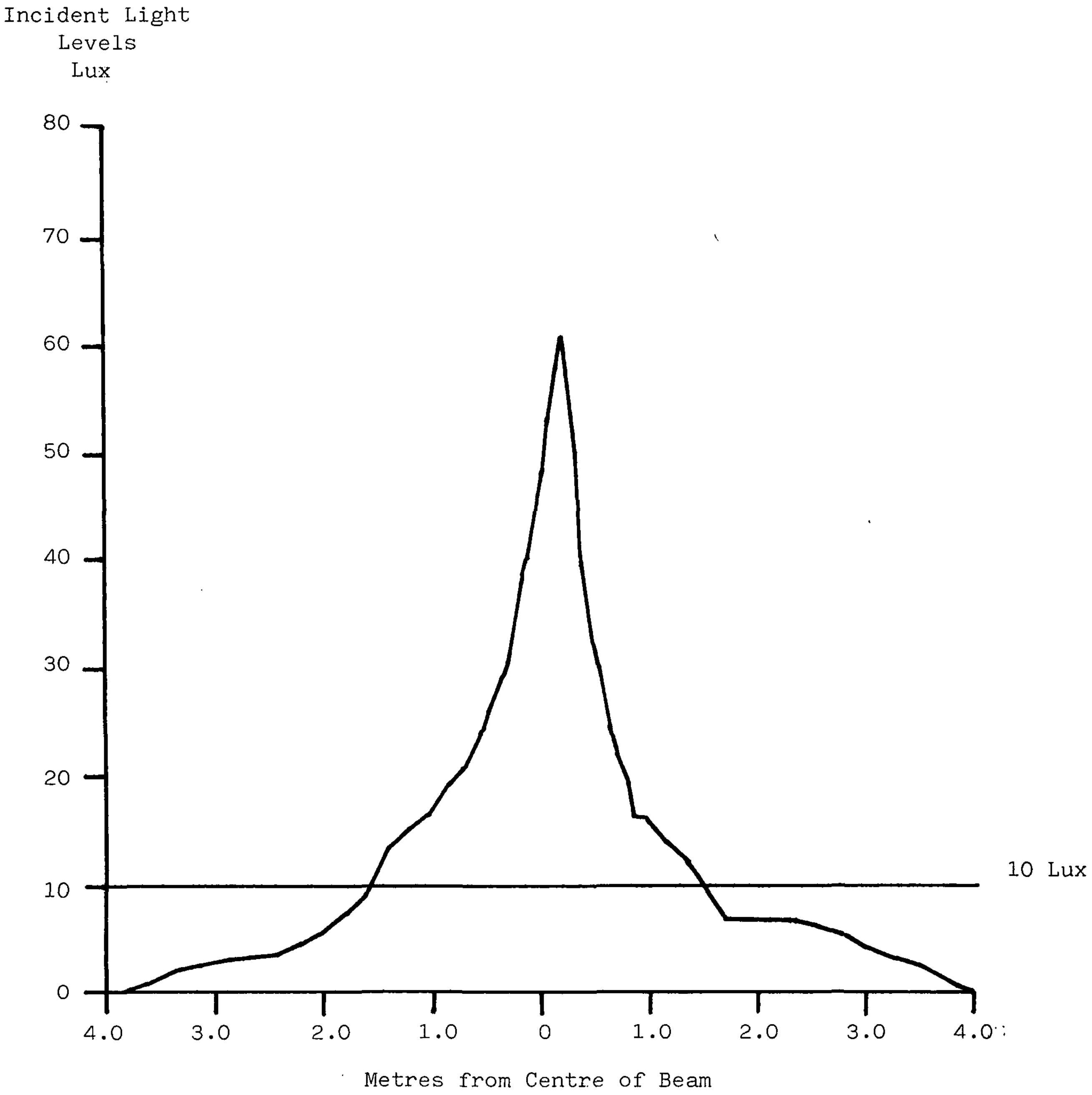


FIGURE 24. Incident Light Levels at 5 m From the Victor 37 L/B 70 W H3 Flood Headlight

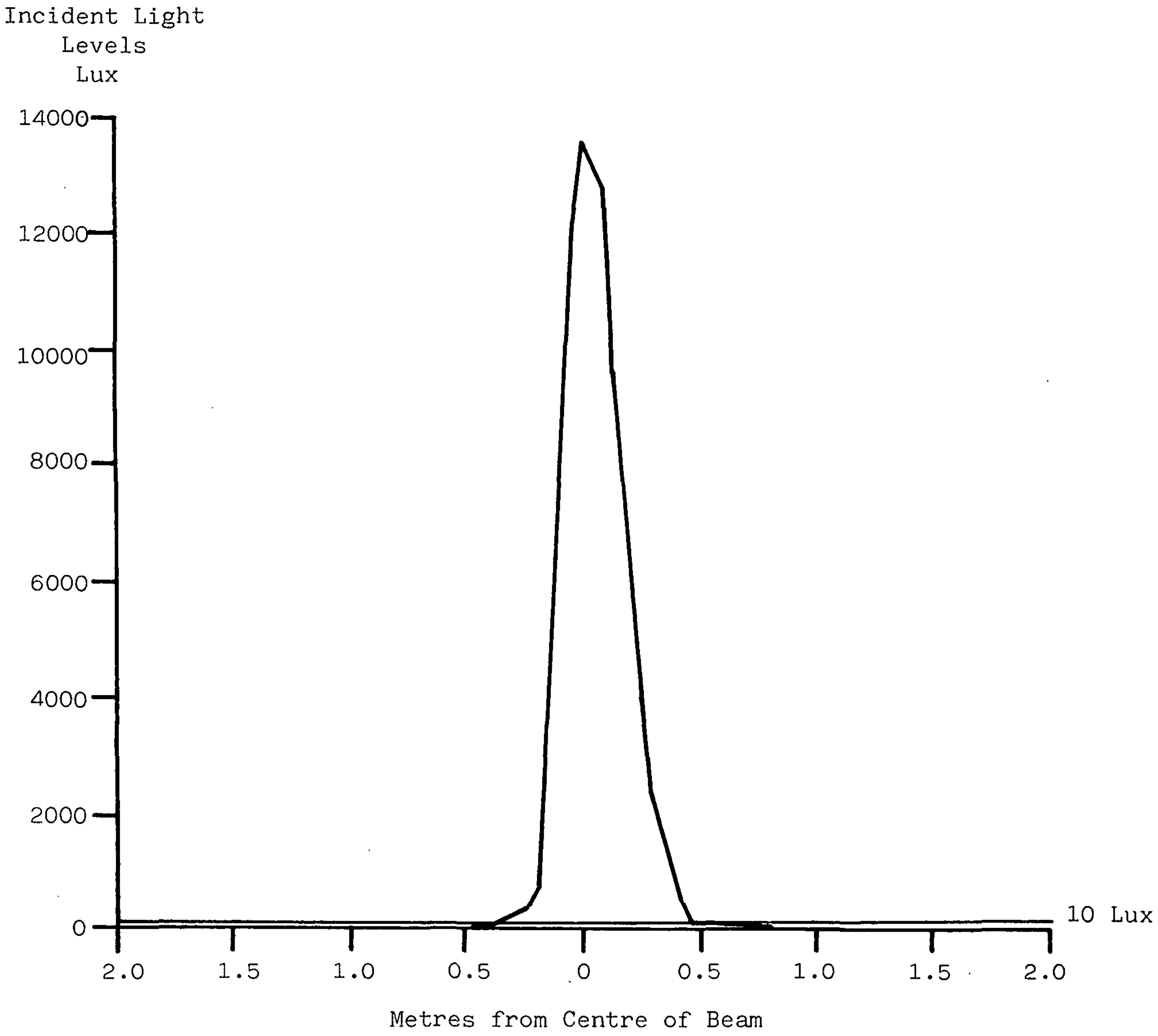


FIGURE 25. Incident Light Levels at 5 m From the Victor 36 L/B 70 W H3 Spot Headlight

There was considerable variation in the maximum incident light levels produced by headlights using similar bulbs. This results from variations in reflector design and protective grill designs on different types of headlight. For example, using the same H1 55 W bulb, the peak incident light levels ranged from 75 to 620 lux for spot headlights. Table 15 shows the effective reduction in light from headlights due to the protective grill. Grill design is also associated with ease of cleaning dirt from the glass cover of the headlight, a factor of great importance to development machine headlights (see Section 3.3).

TABLE 15

The Effective Reduction of Light Output Caused by Protective Grills on Headlights

Headlight	Parts	% Reduction in Light Output
Ashfield Main	Grill and outer glass	63
Ashfield A2	Grill and outer glass	20
Cedav	Grill and outer glass	90
Heyes	Grill and outer glass	48
Victor	Polycarbonate disc and outer glass	11
Westair	Grills and outer glasses	65

5.5.4 Conclusions

The environment of development machine operation is unsuitable for accurate measurement of headlight output as dirt, power supplies and extraneous light present problems.

The experimental headlight assessment under controlled conditions, allowed an accurate evaluation of the relative performance of different headlight designs. Results of the experiment generated four main findings:

(a) There were significant differences in light output of different headlights using similar bulbs;

(b) Variations in the design of the reflectors significantly affected the pattern of light distribution;

(c) The use of different designs of grill/cover to protect the lens of the headlamps resulted in reductions of effective light output, ranging from 11% to 90%;

(d) Generally those grill designs which caused significant reduction in effective light output also increased the difficulty of cleaning the lens.

6. IMPACT OF ELECTRONIC TECHNOLOGY ON DEVELOPMENT MACHINE OPERATION

Development programmes for the remote control and automation of coal production have been in existence in the NCB for approximately two decades (Tregelles, 1980). The rapid advancement in micro-electronic technology over the last decade has led to an expansion of these programmes to cover many other mining activities, including development operations. Over the last three years, much effort has been directed towards automating certain aspects of roadheading machinery tasks (Morris, 1981).

Current NCB automation programmes being developed include remote control and automatic sequencing of drilling machines (Colliery Guardian, 1984; Edmunds, 1979; Bounackoff, 1983), automatic profile cutting on roadheaders and continuous mining machines (Weber, 1983; Olaf, 1979; NCB Annual Report, 1984).

Since the objective of these systems are to improve safety and performance (Glasby, 1982; Hunter, 1983), it is possible that some of the guidelines produced by the project will be less important to future machine design. The main ergonomic implications of such systems are therefore discussed.

6.1 Remote-Control Systems

The systems currently available relate to control of machinery by wire-link or radio-link to a portable controller. This has been applied to drilling machines (Edmunds, 1979) and to continuous-miners (Fox, 1982).

A drilling machine fitted with a prototype of this system was studied simulated underground conditions (Chan, 1983a; Colliery Guardian, 1984). The operator stood to the sides of the machine whilst operating the drill boom controls. The operator's 'mobile' positions enable improved visibility to align the drill, and therefore minimise the necessity for a spotter to guide him. To attain improved visibility however, the study showed that the driver may have to adopt positions close to unsupported roofs (see Figure 26). Additionally, an operator standing to one side of the machine will be restricted in vision for movements of mineworkers at the other side of the machine. Similar limitations were also concluded by Sigal (1983) from his work in remotely-controlled roadheaders in the French mining industry.

Another ergonomic factor was the effect of operators' change of orientation with respect to the machine elements on control operation stereotypes. Allowing the operator to re-orient himself and the control box relative to the machine may cause confusion and control operating errors. Operational efficiency could also be adversely affected as a result of operators loosing direct sensory feedback of vibration and cutting resistance in the remote control system (Fox, 1982).

Since one of the main advantages of remote-control systems was the mobility of the control unit, it was concluded that the following ergonomic factors need to be considered when designing such portable consoles:

(a) portability (e.g. weight, size, shape and harness design);
(b) stereotype compatability of control movements;
(c) control sensitivity;
(d) layout of the panel to maximise operational reliability.

Sigal's work (1983) on hydraulically operated mobile control panel showed that operators are unlikely to utilise control units which were too heavy or unwiedly to manoeuvre.

6.2 Automated Systems

Automated systems applicable to development machines relate to automatic sequencing on drilling machines and automatic profile sensing on boom-type roadheaders.

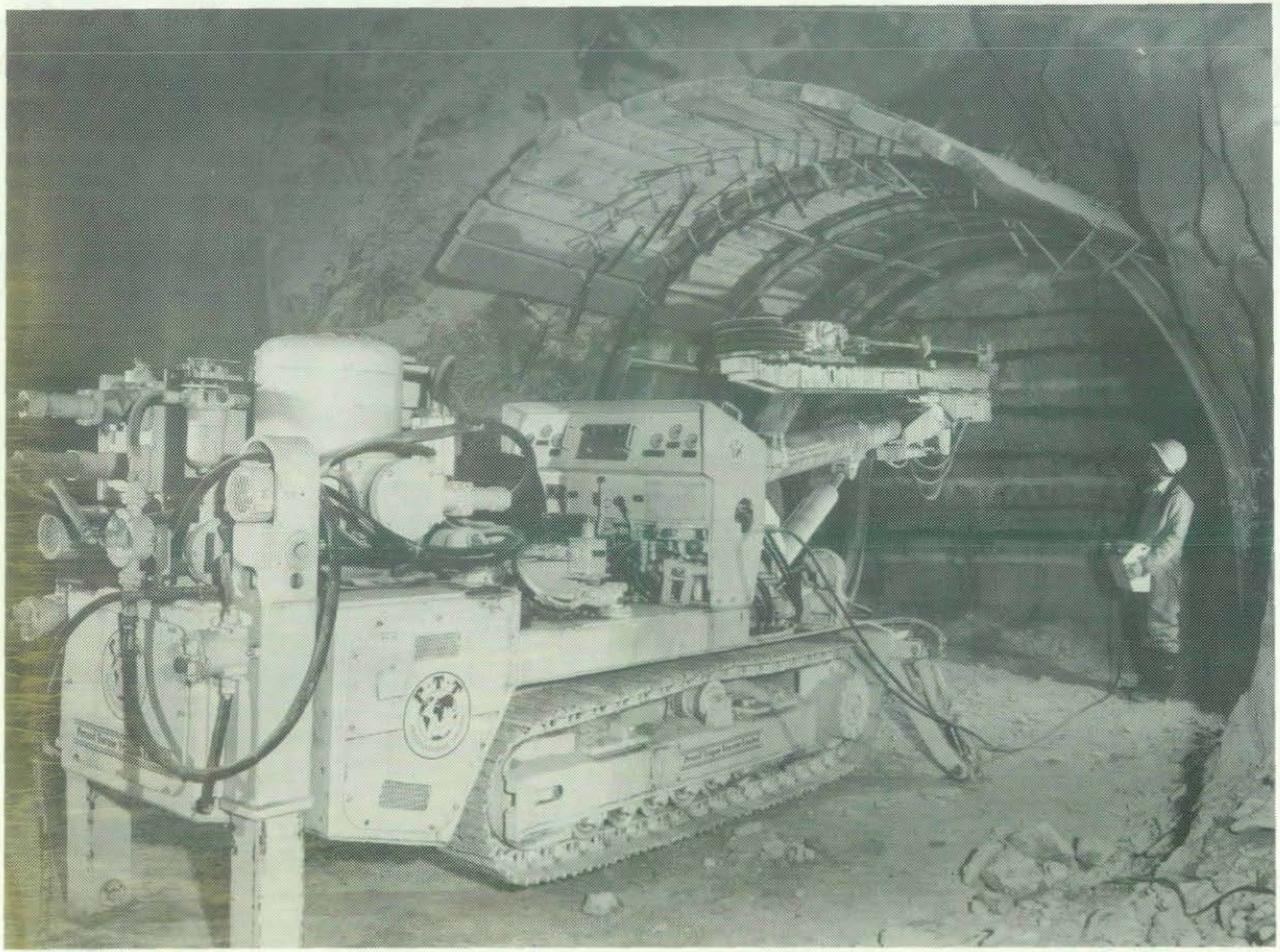


FIGURE 26. Operator Adopting Potentially High Risk Positions to Operate a Drilling Machine by Remote-Control

6.2.1 Drilling

A typical example of automatic drilling is the French Moutabert device which has twin drill booms (Bounackoff, 1983). The operator is provided with the facility to switch to manual control, although his main task is to monitor for unexpected occurrences.

In comparatively homogeneous strata, automated systems appeared to perform satisfactorily. However, in NCB mines, it is rare that two successive drill patterns are the same (NCB, 1975) and much of this advantage may be lost.

Although the manoeuvring of the drill boom no longer required good visibility from the operating position, the checking of clearances of hoses and for mineworkers in the vicinity are still dependent on good visibility. In effect, the safety regulating system is still the man. It could be said that because the machine movements are programmed, the operator must anticipate boom movements, visually check before starting, and countermand the system if a potential problem exists. Bearing these factors in mind, the response lag in the automatic systems may become critical in certain events requiring emergency stops.

6.2.2 Profile sensing on roadheaders

The automation of profile sensing on roadheaders is described by Weber (1983) and by Tregelles and Morris (1983). The need for a spotter is eliminated because the cutting sequence is automatic. The underground studies of roadheader tasks has shown that in non-homogeneous strata, cutting strategies are often selected or changed based on the operator's previously accumulated experience, so that the risk of damage to the machine, or cutting over areas already 'fallen-out' is minimised. In such strata, it is possible that an experienced driver could equal, or exceed, the performance of an automated system.

With the automated roadheader systems, the tracks are linked to the remote-control desk/panel. As with conventional machines, it is therefore equally important for the operator to be able to detect other mineworkers in the vicinity of the machine (Sigal, 1983).

Current automation systems on development machines also monitor the "machine health", as well as incorporating fault diagnosis facilities. In some situations, this information has been shown not to be compatible with the fitter's training and skills, or with available maintenance manuals.

6.3 Conclusions

Of the remote-control and automation systems currently available for development operations, it is apparent that many of the operational problems identified from the studies of conventional machines, such as awkward postures, poor visibility and exposure to vibration etc could be reduced or minimised by the applications of such systems. Job aids such as profile-sensing display if properly designed could enhance the operator's skills and improve operational efficiency, especially in dusty conditions. However, there are many potential safety and performance limitations inherent with current remote-control and automated systems. Such limitations include increased risks of operators adopting positions at the front of the machine where they are exposed to greater risk of roof-falls and increased dust dosage, and are also less likely to detect the presence of mineworkers behind and at the 'blind' side of the machine. These limitations have already led some researchers (e.g. Sigal, 1983) to abandon 'mobile' remote control systems in favour of fixed control workstations on the machine. In non-homogeneous strata, it is possible that automated systems may loose their advantage to the more flexible manual operation by a skilled operator. Facilities which allow the intervention of the operator, may therefore be a desirable feature on automated machines.

Maintenance tasks will change because of computerised diagnostics and machine health monitoring information. Unless diagnostic job aids are improved to supplement this information, new skills will have to be acquired for interrogation of the diagnosis system.

7. CONCLUSIONS

Studies of 25 development machines in use at NCB collieries have consistently shown that health, safety and system costs have been introduced through ergonomic design limitations. One of the most critical limitations was poor driver sightlines. Over half of the poor working postures which were recorded became necessary simply through the need to gain better vision whilst still being capable of operating controls. Despite such attempts to overcome the poor visibility inherent with these machines, a second person (known as a spotter) was required on 85% of those machines studied for approximately 30% of the shift working time. Since the NCB currently operates approximately 1,250 development machines, around 220,000 man-shifts per annum are being spent simply to overcome the limitations of poor sightlines. These limitations also increase the accident potential; over 50% of major injuries associated with mobile machinery underground have been linked with a failure of the driver to detect the presence of people around the vehicle.

Numerous design limitations were found in the operator's workstations: console layout, control stereotypes, control identification, display design, seating, workspace and the access/egress facilities. Apart from many of these limitations increasing the likelihood of control selection or operating errors with their resulting safety implications, a reduction in overall machine performance occurs. The extra hand movement and control selection time caused by poor control layout has been estimated to typically add 3% to the cycle times for development machines. Poor control layout was also the cause of around 30% of the poor working postures which were recorded.

The exact cost of back pain to the NCB is not known in detail; however in one Area, on average 4.03 days per man per year were lost due to back problems. Detailed studies by insurance companies have consistently shown that designing equipment ergonomically is considerable more effective than either medical screening or training in reducing lost time back problems. It is therefore clear that improvements to sightlines and the drivers' workstations alone could produce considerable gains in health, safety and operational efficiency.

Other significant ergonomic limitations were found with:

(a) noise levels severely restricting efficient verbal communication as well as masking warning signals;

(b) headlights which were generally ineffective and unreliable;

(c) the thermal environment on some machines worsened by heat radiated from the machine itself;

(d) whole body vibration at a level which caused discomfort for the drivers.

In addition to these limitations which primarily affect the driver, ancillary tasks of arch setting, advancing supplies and supports would be made easier and quicker if appropriate powered devices were provided on all development machines.

Many maintenance tasks were seen or reported to be hindered by poor accessibility to components, fasteners and lubrication points. As a result of the excessive time demands for the correct servicing of these machines which has been created by poor access, aspects of routine maintenance could be neglected.

Many of the ergonomic limitations of machine design could be overcome with little or no additional cost using existing techniques, if suitable ergonomic design criteria and standards were applied within the UK mining industry.

Changing the design of machinery at the prototype or operational stages can be prohibitively costly. It is therefore most cost-effective, in the long term, to influence machine design at the drawing board stage.

To facilitate this, separate ergonomic design handbooks have been produced for designers of continuous-miners, roadheaders and drill-loading machines. It was necessary to produce separate handbooks for each type of machine because significant differences exist in the ergonomic requirements between each type of machine. Where existing criteria were unsuitable or contradictory, a series of studies generated new criteria. This approach ensures that the designers are provided with detailed guidelines which have been tailored exactly to the individual requirements of that type of machine. Discussions with the NCB Mining Department have ensured that the ergonomic specifications contained in the handbooks are viable in both engineering and economic terms. The handbooks have been produced in a form which, if the industry dictates, could become part of the design audit procedures or a purchasing specification thereby ensuring that the full benefits at a little or no additional cost to the manufacturers or the NCB.

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Littleton Colliery
Parkside Colliery
Point of Ayr Colliery
Silverdale Colliery

South Midlands Area:

Birch Coppice Colliery
Whitwick Colliery

South Nottinghamshire Area:

Babbington Colliery
Bentinck Colliery

North Nottinghamshire Area:

Blidworth Colliery
Harworth Colliery
Thoresby Colliery

South Yorkshire Area:

Brookhouse Colliery
Manton Colliery
Silverwood Colliery

North East Area:

East Hetton Colliery
Ellington Colliery

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APPENDIX A

DATA COLLECTION PACKAGE

Project 04 Underground Study No. ..... Colliery ....

Investigator .... Liaison ....

Date of Study ....

MACHINE IDENTIFICATION

Manufacturer's Name ....

Model ....

Serial No. ....

Age (if known) ....

Date of Last Overhaul ....

HEADING TEAM

Number in Team ....

Responsibility/Deployment ....

Number in Team Qualified to Operate Machine ....

ANY OTHER COMMENTS:

....

....

Type of Heading ....

Geology ....

Roadway Dimensions/Gradients ....

Environmental Conditions ....

Type & Method of Roof Support ....

Method of Materials Supplies ....

Type of Drilling Pattern ....

No. of Holes Drilled ....

Expected Rate of Advance/Shift ....

CONTROL CHARACTERISTICS

Machine ....

Colliery .... Study Date ....

Function ....

Type ....

Dimensions ....

Force ....

Motion (relative to operator) ....

Machine Response (relative to operator) ....

Range of Motions (from neutral) ....

Control Response Dynamics ....

State of Control ....

Detent ....

Detachable ....

Safety Interlock ....

Control Label ....

A4.

LABELS

Machine ....

Colliery .... Study Date ....

Type/Function ....

Materials/Construction ....

Plate Dimensions ....

Script Type ....

Script Size ....

Legends/Content ....

Symbols/Pictogram ....

Legibility State ....

Vertically/Horizontally Mounted ....

Position (relative to operator and control display) ....

ARTIFICIAL DISPLAYS

(a) Type of Display ....

(b) Function of Display ....

(c) Labelling/Pictogram ....

(d) Range of Markings ....

(e) Colour of Script ....

(f) Colour of Background ....

(g) Colour of Pointer ....

(h) Colour of Bezel ....

(i) State of Display (damage/wear) ....

(j) Cause (if damaged) ....

(k) Position of Display Relative to Operator's Normal Position ....

(l) Is it Obscured from Operator's Direct View ....

Drawing of Display (with dimensions):

SEATING DESIGN

From Platform Surface:

(a) Squab Height ....

Squab Depth ....

Squab Width ....

Squab Thickness ....

Squab Angle ....

(b) Range of Adjustability ....

(c) Means of Adjustment ....

(d) Materials & Construction ....

(e) Current State (damage/wear) ....

(f) Cause (if damaged) ....

(a) Backrest Height (above SRP) ....

Backrest Thickness ....

Backrest Angle ....

(b) Range of Adjustability ....

(c) Means of Adjustment ....

(d) Materials & Construction ....

(e) Current State (damage/wear) ....

(f) Cause (if damaged) ....

Sketch of Seat:

AUDITORY ENVIRONMENT

(a) General Noise Level (at operator's ear level) ....

(b) Background Noise (without machine) ....

Machine Noise: (at operator's ear level)

(c) Tracking ....

(d) Stationary ....

(e) Loading ....

(f) Drilling/Cutting ....

(g) Drill/Cutting & Loading ....

WARNING SIGNALS

(a) Type of Signal ....

(b) Functions ....

(c) Source of Signal (Location) ....

Record:

(d) Signal at Source ....

(e) Signal at Receiver's Ear Level ....

(f) Background Noise at Receiver ....

(d) Receiver's Task Description ....

....

....

....

....

AUDITORY ENVIRONMENT

(a) Tape recordings (dB(Lin)) of machine operation noise levels.

(b) Record dB(A) levels of machine noise in various modes of operation.

Modes of Operation	dB(A)
Idling	....
Tracking	....
Cutting (coal)	....
Cutting (dirt)	....
Cutting (hard)	....
Cutting & Loading (soft)	....
Cutting & Loading (hard)	....
Loading (empty)	....
Loading (full)	....
Ambient	....

	Distance (m)
Driver - Spotter (normal position) =	
Driver - Rear Belt Man =	

VISUAL ENVIRONMENT

Machine Lighting: Headlamp(s)/Rearlights

(a) Type ....

(b) Wattage ....

(c) Fittings ....

(d) Direction of Beam ....

(e) Mounting Position ....

(f) Adjustability ....

(g) Interlocks ....

(h) State of Lamp (damage/wear) ....

(i) Cause (if damaged) ....

Other Comments: ....

....

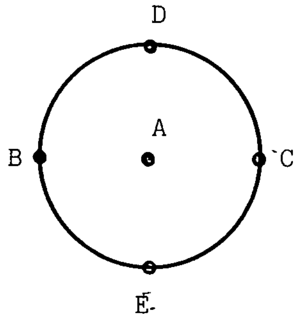
....

....

Sketch of Lamp:

A10.

MACHINE LIGHTING



looking towards heading inbye

1 m from Lens	LEFT LIGHT					RIGHT LIGHT				
	Type of Light:					Type of Light:				
	A	B	C	D	E	A	B	C	D	E
Before Cleaning										
After Cleaning										
After 24 hours										
% Increase after Cleaning										
% decrease after 24 hours										

THERMAL ENVIRONMENT: SURFACE TEMPERATURES

Component Surface	Location Relative to Driver	Temperature °C Recorded
....	....	....
....	....	....
....	....	....
....	....	....

Machine Operator Clothing:
(tick as appropriate)

Donkey jacket ☐
Shirt ☐
Bare-top ☐
Shorts ☐

Overall ☐
Vest ☐
Trousers ☐

Environmental Factors:

		Stationary	Tracking	Drill	Cut	Load
Dust	: YES/NO					
Waterspray	: YES/NO					
Others	: YES/NO					
	: YES/NO					

VENTILATION EQUIPMENT

Type ....

Capacity ....

Location ....

A12.

THERMAL ENVIRONMENT

Record climatic conditions at operator chest position.

	Date:		Date:	
	Time: Operation:	Time: Operation:	Time: Operation:	Time: Operation:
Dry Bulb °C				
Wet Bulb °C				
Relative Humidity %				
Globe Temperature °C				
Air Velocity ms^{-1}				
Effective Temperature				
Ambient Temperature at Roadway °C				

SIGHTLINE MEASUREMENTS: PERIPHERAL METHOD/TECHNIQUE

Machine ....

Site .... Roadway Dimensions ....

Investigator ....

Driver's Eye Height Above Ground Level ....

Driver (SRP) to Front of Machine ....

Driver (SRP) to Rear of Machine ....

Driver (SRP) to Left Side of Machine ....

Driver (SRP) to Right Side of Machine ....

Boom Position ....

Record coordinates of sightline cut-off points.

X	Y	Z	Prominent Part of Machine
....	....	....	....
....	....	....	....
....	....	....	....
....	....	....	....

Observations of Control Usage

OBSERVER 1

Task Element ....

....

Visual Search for Controls ....

....

Control Operation:

(a) Left hand ....

(b) Right hand ....

Control Operation Hesitancy ....

....

Comments ....

....

....

....

Observation of Machine Operator's Tasks OBSERVER 2

Task Elements Ingress/Egress ....

....

Operator Posture ....

....

Reasons ....

....

Visual Attention Areas Tasks ....

....

Communications:

(a) Type ....

(b) Links ....

(c) Why? ....

Activities and Movements around Machine of Other Personnel ....

....

Comments ....

....

POSTURE CODING (to be used by Observer 1)

N/F = Normal forward facing - upright

Side L = Body and feet facing LHS
Side R = Body and feet facing RHS
Rear = Body and feet facing rear

LFs = Small lean forward up to 30°
LFl = Large lean forward 30° to 60°
BF = Bending forward 60° +
LLs = Lean to LHS up to 30°
LLl = Lean to RHS 30° to 60°
BL = Bending to LHS 60° +
LRs = Lean to RHS up to 30°
LRl = Lean to RHS up to 60°
BR = Bending to RHS 60° +

TLs = Turn to left (head and body) up to 30°
TLl = Turn to left (head and body) 30° to 60°
TLr = Turn to left (head and body) 60° +
TRs = Turn to right (head and body) up to 30°
TRl = Turn to right (head and body) 30° to 60°
TRr = Turn to right (head and body) 60° +

MACHINE EVALUATION QUESTIONNAIRE

Colliery/Site ....

Date ....

Machine Type ....

Location ....

Type of Heading ....

Operator's Height ....

Operator's Weight ....

Experience on this Machine ....

....

Experience on other Machines ....

....

PART 1 QUESTIONS FOR MACHINE OPERATOR

1.1 Visibility

1.1.1 List in the following table for cutting/drilling, loading, tracking forward and backward, arch setting and packing operations, the critical and other areas requiring your visual attention. For the critical areas include whether there are any obstructions to vision, how you overcome these obstructions and whether the illumination provided by the machine is useful or not.

Operation	Critical Areas	Visual Obstructions		Is Machine Illumination Useful?	Other Areas
		Items	Solution		
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....
....	....	.....	....	....	.....

1.1.2 Do you need a spotter for the following operations?

Cutting/drilling [Yes] [No]

Loading [Yes] [No]

Tracking Forward [Yes] [No]

Tracking Backward [Yes] [No]

Arch Setting [Yes] [No]

Packing [Yes] [No]

1.1.3 When drilling, do you ever find it difficult to see holes that have already been drilled?

[Yes] [No]

1.1.4 Do you ever have difficulty in seeing the spotter?

[Yes] [No]

Explain when

....

....

....

....

1.1.5 Do you ever have difficulty in seeing men working behind the machine?

[Yes] [No]

1.1.6 Is the machine fitted with lights?

[Yes] [No] Would you prefer that it was?

[Yes] [No]

Do the headlights present any glare or shadow problems for you or any other member of the team?

[Yes] [No]

Would you prefer an alternative choice of beam characteristics?

[Yes] [No]

Describe this choice

....

....

Are the headlights effective in dusty conditions?

[Yes] [No]

Explain what particular
problems are encountered
and how they are overcome

....

....

Do you consider that the headlights are useful?

[Yes] [No]

Do you consider that the headlights are positioned optimally?

[Yes] [No]

What adjustments
would you advocate?

....

....

1.2 Noise and Communication

1.2.1 Do you rely on guidance from other men in the team when operating the machine?

[Yes] [No]

What are the main reasons for communication between you and other men in the team when performing the following operations?

Cutting/Drilling ....

....

Loading ....

....

Tracking Forward ....

....

Tracking Backward ....

....

Arch Setting ....

....

Packing ....

....

1.2.2 Do you ever find that noise in the heading makes it difficult for you to talk to other men in the team when operating the machine?

[Yes] [No]

1.2.3 Does the spotter or other men in the team use hand, caplamp or other non-auditory signals to communicate with you?

[Yes] [No]

Can you easily see and understand these signals?

[Yes] [No]

Do you find hand and caplamp signals adequate?

[Yes] [No]

1.2.4 Do you believe that it would be useful if the machine were fitted with any of the following?

Klaxon	[Yes]	[No]
Tannoy system	[Yes]	[No]
Auditory pre-start warning signal	[Yes]	[No]
A device providing a single auditory warning automatically for any change in direction of machine travel	[Yes]	[No]

1.3 Workspace Layout and Seating

1.3.1 Could any of the controls be re-located so that they are less awkward to reach?

[Yes] [No]

What are these controls and where is the preferred position?

....

....

1.3.2 Are there any aspects of the seat design that you would criticize?

[Yes] [No]

Is the seat comfortable to sit on?

[Yes] [No]

Does the seat squab give you good support?

[Yes] [No] → Why not?

Does the backrest give you good support?

[Yes] [No] → Why not?

....

Does the backrest restrict your turning movement when wearing the battery and self-rescuer?

[Yes] [No]

Describe any other criticisms you may have of the seat:

....

....

....

1.3.3 Is the seat position adjustable?

[Yes] [No]

Do you ever find it necessary to adjust its position?

[Yes] [No] Why not?

For what purpose?

....

....

....

1.4 Machine Controls

1.4.1 Are there any controls which are a little too stiff to operate?

[Yes] [No]

What are these controls?

....

....

1.4.2 Are there any controls which are too sensitive or not sensitive enough for normal operation?

[Yes] [No]

What are these controls?	What problems are caused?
....	....
....	....
....	....

1.4.3 Are there any controls which are situated too close together or too far apart?

[Yes] [No]

What are these controls?	What problems are caused?
....	....
....	....
....	....

1.4.4 (Is this machine a drill-loader)?

[Yes] [No]

When the drill carriage is inverted through 180°, do you find any difficulties in relating direction of control movement to direction of machine movement?

[Yes] [No]

What problems does this cause and how to you get over them?

....

....

....

....

....

1.4.5 Excluding drill carriages, have you ever experienced difficulties in relating direction of control movement to direction of machine movement?

[Yes] [No]

What are these controls?	What do you consider the correct relationship to be?
....	....
....	....
....	....
....	....
....	....

1.4.6 Are there any safety controls fitted to this machine

[Yes] [No]

What are these controls?	Where are they positioned?
1	....
2	....
3	....
4	....

Do you experience any difficulties in using these controls?

[Yes] [No]

Controls	Describe these difficulties
1	....
2	....
3	....
4	....

1.4.7 Are there any safety controls not fitted on this machine that you believe ought to be fitted?

[Yes] [No]

What are these controls?

....

....

....

....

....

1.4.8 Excluding criticisms already described, are any of the controls awkward or tiring to use?

[Yes] [No]

Which are these controls?	Why are they awkward or tiring to use?
....	....
....	....
....	....

1.4.9 Do you have any criticisms on the layout of the controls?

[Yes] [No]

What are these criticims?

....

....

....

....

....

1.5 Machine Displays

1.5.1 Do you regularly monitor any gauges?

[Yes] [No]

What are these gauges?	What are the criticial readings?	How are the critical zones distinguished?
1	....	....
2	....	....
3	....	....
4	....	....

Describe any features on the gauges listed above that you would like to see improved

1 ....

2 ....

3 ....

4 ....

1.5.2 Are there any gauges not fitted on the machine that you feel ought to be?

[Yes] [No]

What are these gauges?

....

....

....

....

1.5.3 Are any of the labels or instruction plates on this machine difficult to read because the scripts are too small or they are covered in dust or for any other reason?

[Yes] [No]

Which are these labels?	Why are they difficult to read?
....	....
....	....
....	....
....	....

1.6 Access to the Workspace

1.6.1 Are there any obstructions preventing easy access to or egress from the machine?

[Yes] [No]

What are these obstructions?

....

....

....

....

1.6.2 Are there any additional mounting aids such as foot or handholds that you would advocate to make access or egress easier?

[Yes] [No]

Describe the nature and
position of these aids

....

....

....

....

1.7 Environment

Vibration

1.7.1 Does the machine vibrate or jolt uncomfortably?

[Yes] [No]

Which particular operations cause this problem?

....

....

....

(Ergonomist to observe postural problems for these operations).

Does the vibration or jolting sometimes make it more difficult to control the machine accurately? [Yes] [No]

Does the vibration or jolting make it more difficult for you to maintain a stable posture? [Yes] [No]

Does the vibration or jolting cause tiredness? [Yes] [No]

Do you ever have to slow-down the machine to reduce the vibration? [Yes] [No]

Does the vibration or jolting impair any important observations that have to be made?

[Yes] [No]

Describe the particular operation and observations that are affected

....

....

....

....

Thermal Effects

1.7.2 Does the machine or the immediate working area become uncomfortably hot?

[Yes] [No]

Which particular operation cause this condition?

....

From where does the heat emanate?

....

Which exposed surfaces become hot to touch?

....

(Ergonomist to measure these)

1.7.3 Does the machine ever cut-out due to the high temperature of the hydraulic fluid?

[Yes] [No]

What particular operation cause this problem?

....

How frequently does this occur?

....

What is involved in re-starting the machine for commencement of work?

....

Dust

1.7.4 Does dust present a major problem?

[Yes] [No]

What particular operation(s) cause this problem?

Cutting/Drilling	[Yes]	[No]
Loading	[Yes]	[No]
Tracking	[Yes]	[No]

What problems does the dust cause?

....

....

What improvements would you advocate to suppress the dust?

....

....

1.8 Other Machine Activities

1.8.1 Does the machine help with packing operations?

[Yes] [No]

Does the packing device ever work too fast or too slow?

[Yes] [No]

Explain what problems this creates

....

....

....

....

....

1.9 Maintenance

1.9.1 Excluding the work carried out by a fitter, do you or any member of the heading team carry out checks or repairs on this machine?

[Yes] [No]

What types of checks or repairs do you carry out?

....

....

What are the most frequent causes of breakdown that you have to repair?

....

....

Do you consider the tools and instructions provided for you are adequate?

[Yes] [No]

What other items do you believe should be provided?

....

....

Is a copy of the operator's service manual available for this machine?

[Yes] [No] [Dont Know]

1.9.2 Have there been any breakdowns when the machine could not be repaired quickly?

[Yes] [No]

Give examples of these breakdowns

....

....

1.10 Training

1.10.1 What types of training did you receive on the operation and maintenance of this machine?

....

....

....

....

1.10.2 Are there any aspects of the training that you believe could be improved?

[Yes] [No]

What are these aspects?

....

....

....

....

1.10.3 Do you have a copy of the operator's manual for this machine?

[Yes] [No]

Have you seen a copy? [Yes] [No]

PART 2 QUESTIONS FOR SPOTTERS

2.1 Do you use any of the following means of communication with the machine operator?

Hand Signals [Yes] [No]
Camplamp Signals [Yes] [No]
Shouting [Yes] [No]

Do you use a pre-arranged series of signals?

[Yes] [No]

Describe these?

....

....

2.2 List in the following table for cutting/drilling, loading and tracking backwards and forwards, where you usually stand. Indicate whether, from these positions, you can easily see what you need to see, what obstructions there are to your view and whether the illumination provided by the machine is useful or not.

Operations	Standing Points	Can You See Adequately?		Visual Obstructions	Is Machine Illumination Useful?	
		Yes	No		Yes	No
....	....	...	..	....	...	..
....	....	...	..	....	...	..
....	....	...	..	....	...	..
....	....	...	..	....	...	..
....	....	...	..	....	...	..

2.3 Can the machine lights be improved in anyway or positioned better for you?

[Yes] [No]

Describe how?

....

....

....

2.4 When cutting, do you ever find it difficult to see clearly where the cutter head is?

[Yes] [No]

Explain why?

....

....

....

2.5 When drilling, do you ever find it difficult to see holes that have already been drilled?

[Yes] [No]

PART 3 QUESTIONS FOR ARCH-SETTING AND MATERIAL SUPPLY CREW

3.1 Do you believe that the machine could be improved to help your job in anyway?

[Yes] [No]

Describe how?

....

....

....

....

....

....

....

....

....

PART 4 QUESTIONS FOR FITTERS

4.1 Are there any features of this machine which make maintenance and repairs difficult?

[Yes] [No]

↓

What are these features
and what remedies would
you advocate?

....

....

4.2 Are there any features of this machine which make maintenance and repairs particularly easy?

[Yes] [No]

↓

What are these
features?

....

....

4.3 What are the most frequent causes of breakdown on this machine?

....

....

4.4 Do you consider the tools and instructions provided for you are adequate?

[Yes] [No]

↓

What other items
do you believe
should be provided?

....

....

4.5 Is there a maintenance/service manual available when you have to carry out repairs on this machine?

[Yes] [No]

4.6 Are commonly replaceable parts stored on the machine?

[Yes] [No]

Are they sufficient for the more common causes of breakdown

[Yes] [No]

Do you believe that they ought to be?

[Yes] [No]

4.7 Are there any problems associated with the availability of spare/replacement parts?

[Yes] [No]

Describe these problems

....

4.8 Have there been any breakdowns when the machine could not be repaired quickly or without undue difficulty?

[Yes] [No]

Describe these breakdowns

....

4.9 Have you effected any modifications to the machine to improve operating conditions or maintainability etc.

[Yes] [No]

Describe these modifications

....

PART 5 QUESTIONS FOR THE DEPUTY

5.1 In addition to cutting/drilling and loading, indicate whether the machine is used to help the following operations and explain how it is used.

Arch-Setting and Lagging	[YES]NO]	....
Packing	[YES]NO]	....
Materials Handling Duties	[YES]NO]	....
Advancing Auxiliary Equipment	[YES]NO]	....

5.2 Are there any features or modifications which could be added to help arch-setting or packing operations?

[Yes] [No]

Describe these features or modifications

....

....

5.3 When preparing for shotfiring, do you ever encountered difficulties in seeing holes that have already been drilled?

[Yes] [No]

What is the cause of these difficulties?

....

....

APPENDIX B

Machine Perimeter Technique for Sightlines Determination

Mason et al (1980) described a ranging pole technique for determining sightlines for machines in restricted spaces (e.g. in underground roadways). However, although the technique was satisfactory on smooth roadways, it was found that uneven roadway surfaces, dirt piles etc. introduced errors which, in some cases, were unacceptably high. Consequently, a new method was developed known as the machine perimeter technique. This technique involves determining the 5th percentile miner's eye height at the driver's normal operating position. From this viewing point, the visual cut off points at the perimeter of the machine are observed, and their locations relative to the seat reference point recorded as a series of x, y and z coordinates. The location of the seat reference point is fixed by recording its distance from the sides, front and back of the machine. In addition, the 5th percentile driver's eye height above ground (track) level is also recorded.

As well as removing the effect of variations in ground level on the accuracy of the sightline calculations, this has the advantage that it can be used by one person, although it is more efficient to have one individual in the observing position and one determining the coordinates.

The data obtained, together with the roadway dimensions, is fed into a computer. The coordinates are then analysed using a computer program which then generates a 360° view from the operating position via a graph plotter, hatching those areas of the machine, roadway sides and ripping profile which cannot be seen. An example of a completed diagram is shown in Figure 9.

Further programs can be used to adjust the position of the driver's eye to examine the effects of seat adjustment and/or different operator heights where the machine profile allows this to be done without affecting the validity of the final diagram. In addition, the effect of the sightlines of a canopy or other potential modifications can be estimated by adding their calculated coordinate data to the machine perimeter data base.

APPENDIX C

Design Procedures for the Implementation of Roadheader Sightline Criteria

1. Derivation of Minimum Eye Height

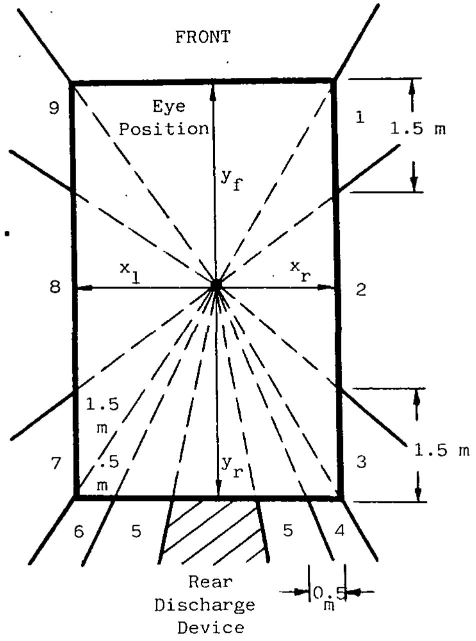
The method shown in Figures C1 and C2 determines a series of minimum eye heights for zones on and around the periheral of the machine which ensured that the sightline criteria were met (see section 5.1.4). The overall minimum eye height, taking into consideration all sightline obstructions, was therefore the maximum of the eye heights of each zone. Should this eye height be considered impracticable then an examination of the individual zone eye heights would identify which was the critical obstruction that determined the overall eye height. The designers can then improve an operator's sightlines by directing his attentions to this critical obstruction. Likewise the individual zone eye heights could be ranked in order to determine the most effective sequence for design attention.

Referring to Figures C1(a) and C1(b), the method would be:

(a) From a plan view of the machine, determine the position of the mid-point between the eyes of a 5th percentile mineworker (i.e. 14 cm forward, and 66 cm above the seat reference point (SRP)) and reference this position to the front, rear and sides of the machine to obtain yf, yr, xl and xr respectively. For this exercise, the overhang to the front caused by the boom can be ignored.

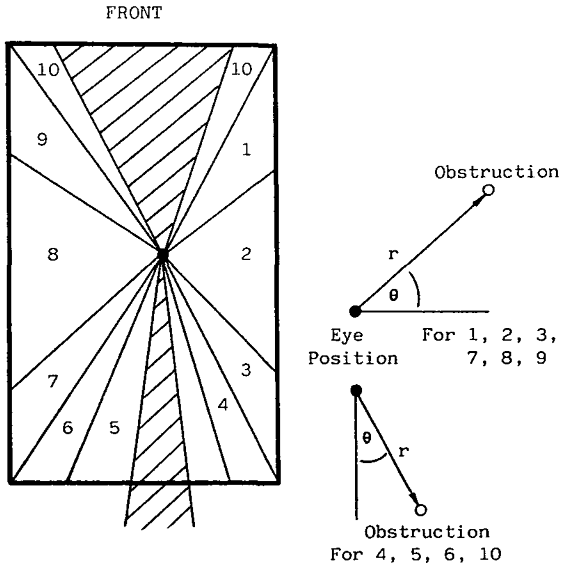
(b) On the same plan view, identify the boundaries of the zones marked 1-9. The boundary of the primary safety zones extend 1.5 m from the corner of the machine along the side and 0.5 m along its width.

C1(a) Derivation of Minimum Eye Height for Peripheral Obstructions



ZONE	MAXIMUM PERIPHERAL HEIGHT hp	CALCULATION FOR MINIMUM EYE HEIGHT he	he
1		$(hp - 1) \times (1.33\, x_r + 1.0) + 1.0$	
2		$(hp - 1.30) \times (1.33\, x_r + 1.0) + 1.30$	
3		$(hp - 1) \times (1.33\, x_r + 1.0) + 1.0$	
4		$(hp - 1) \times (0.66\, y_r + 1.0) + 1.0$	
5		$(hp - 1.30) \times (0.66\, y_r + 1.0) + 1.30$	
6		$(hp - 1) \times (0.66\, y_r + 1.0) + 1.0$	
7		$(hp - 1) \times (1.3\, x_l + 1.0) + 1.0$	
8		$(hp - 1.30) \times (1.33\, x_l + 1.0) + 1.30$	
9		$(hp - 1) \times (1.33\, x_l + 1.0) + 1.0$	

C1(b) Derivation of Minimum Eye Height for Obstructions Inside Machine Boundary



ZONE	DETAILS OF OBSTRUCTION				CALCULATION FOR MINIMUM EYE HEIGHT he	he
	Name	Height hp	r	Cos		
1					$\frac{r.\ \text{Cos}\ \theta.\ (hp - 1)}{x_r + .75 - r.\ \text{Cos}\ \theta} + hp$	
2					$\frac{r.\ \text{Cos}\ \theta.\ (hp - 1.30)}{x_r + .75 - r.\ \text{Cos}\ \theta} + hp$	
3					$\frac{r.\ \text{Cos}\ \theta.\ (hp - 1)}{x_r + .75 - r.\ \text{Cos}\ \theta} + hp$	
4					$\frac{r.\ \text{Cos}\ \theta.\ (hp - 1)}{y_r + .75 - r.\ \text{Cos}\ \theta} + hp$	
5					$\frac{r.\ \text{Cos}\ \theta.\ (hp - 1.30)}{y_r + 1.5 - r.\ \text{Cos}\ \theta} + hp$	
6					$\frac{r.\ \text{Cos}\ \theta.\ (hp - 1)}{y_r + .75 - r.\ \text{Cos}\ \theta} + hp$	
7					$\frac{r.\ \text{Cos}\ \theta.\ (hp - 1)}{x_l + .75 - r.\ \text{Cos}\ \theta} + hp$	
8					$\frac{r.\ \text{Cos}\ \theta.\ (hp - 1)}{x_l + .75 - r.\ \text{Cos}\ \theta} + hp$	
9					$\frac{r.\ \text{Cos}\ \theta.\ (hp - 1)}{x_l + .75 - r.\ \text{Cos}\ \theta} + hp$	
10					$\frac{hp.\ yf}{yf - r.\ \text{Cos}\ \theta}$	

FIGURE C1. Procedures for Derivation of Minimum Eye Height

(c) For each of the zones (1-9), determine the maximum height of any obstruction on the periphery of the machine (hp) and enter these in the column on the table in Figure C1. Note: Small objects on the periphery of the machine which do not cause significant sightline restrictions can be ignored). Using these hp values and the eye position reference dimension from step (1), use the equations given to determine the minimum eye height for each zone (he).

(d) If there are no further limiting obstructions to sightline located inside the plan boundary of the machine, and if the outside 0.3 m of the loading apron are visible, then the minimum overall eye height is the maximum of the individual zone eye heights. If such obstructions are likely to occur then these can be taken into consideration in the following manner, using the table in Figure C1(b) as an aid for calculations.

(e) The zones 1-9 in step (2) are extended onto the machine (Figure C1(b)) and two further zones are constructed to the front of the operator. These extend a distance of 0.3 m from the front corners of the machine.

(f) For each zone, the location of any likely obstruction is determined by its distance from the eye position (r) and its angular displacement (θ) relative to the xl/xr plane for obstructions in zones 1, 2, 3, 7, 8 and 9 and relative to the yf/yr plane for obstructions in the 4, 5, 6 and 10 zones. The height of these obstructions is then determined (hp).

(g) The minimum eye height to satisfy the criteria relevant to any particular zone can then be found using the equation given, for each obstruction in that zone. The most critical obstruction in a zone will be that which requires the largest eye height (he). Repeat this process for all zones.

(h) The minimum driver eye height can now be determined as the largest value calculated in steps (c) and (g).

The seat can now be located 660 mm below this eye position and the SRP established. This datum point is necessary when determining ergonomic workspace and control location envelopes.

2. Deviation of Maximum Machine Profiles

In cases where the maximum eye height is known (i.e. when this is dictated by the minimum roadway size), then the following method can be adopted. This determines the heights of the machine profile in various zones on and around the machine which are necessary to ensure the sightline criteria are met.

Referring to Figure C2(a) and C2(b), the following procedure may be adopted.

(a) From a plan view of the machine, determine the position of the mid-point between the eyes of a 5th percentile mineworker (see Figure C2(a)) and reference this position to the front, rear and sides of the machine to obtain yf, yr, xl, and xr respectively. For this exercise, the overhang to the front caused by the boom can be ignored.

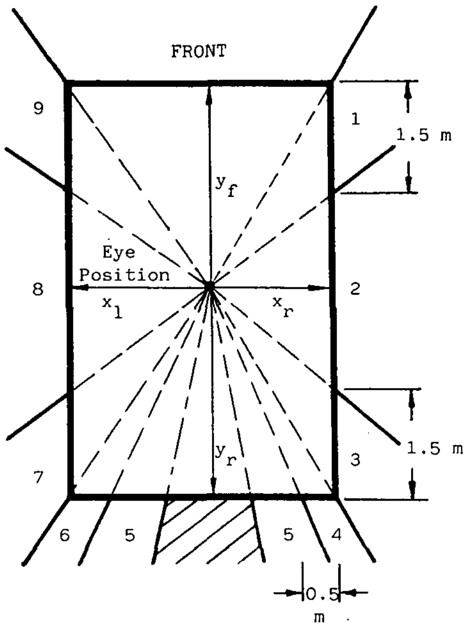
(b) On the same plan view, identify the boundaries of the zone marked 1-9. The boundary of the primary safety zones extend 1.5 m from the corner along each side and 0.5 m along its width.

(c) For each of the zones 1-9, the maximum height of the periphery of the machine can be calculated using the equations given. (Note: Small objects on the periphery of the machine which do not cause significant sightline restrictions can be ignored).

(d) The limitations to the positions and heights of any additional obstructions which lie inside the boundary of the plan view can be determined for each of the ten zones shown in Figure C2(b) using the

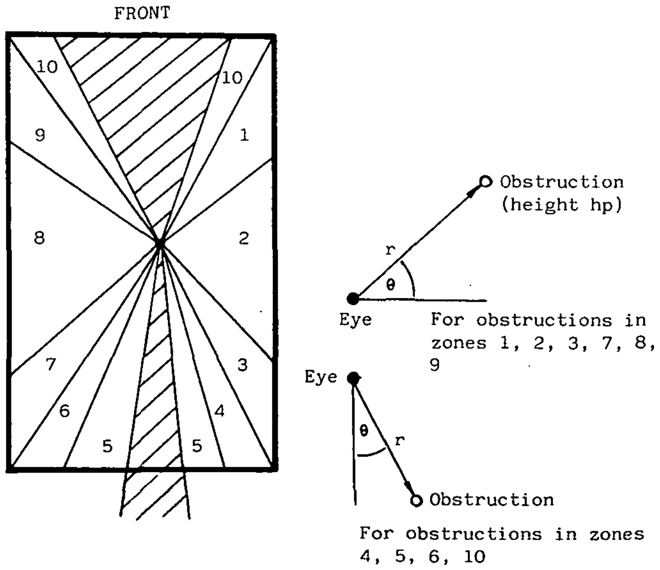
FIGURE C2. Procedures for the Derivation of Maximum Machine Profiles

C2(a) Derivation of Maximum Machine Profile



ZONE	MAXIMUM HEIGHT OF MACHINE PERIPHERY (hp)	hp
1	$\frac{.75\,(he - 1)}{x_r + .75} + 1 =$	
2	$\frac{.75\,(he - 1.3)}{x_r + .75)} + 1.3 =$	
3	$\frac{.75\,(he - 1)}{x_r + .75)} + 1 =$	
4	$\frac{.75\,(he - 1)}{y_r + .75} + 1 =$	
5	$\frac{1.5\,(he - 1.3)}{y_r + 1.5} + 1.3 =$	
6	$\frac{.75\,(he - 1)}{y_r + .75} + 1 =$	
7	$\frac{.75\,(he - 1)}{x_1 + .75} + 1 =$	
8	$\frac{.75\,(he - 1.3)}{x_1 + .75} + 1.3 =$	
9	$\frac{.75\,(he - 1)}{x_1 + .75} + 1 =$	

C2(b) Derivation of Maximum Machine Profile Inside the Plan Boundary of the Machine



1	$he - \frac{\cos\theta.\,(r.\,he - 1)}{x_r + .75} =$	
2	$he - \frac{\cos\theta.\,(r.\,he - 1.3)}{x + .75}$	
3	$he - \frac{\cos\theta.\,(r.\,he - 1)}{x_r + .75} =$	
4	$he - \frac{\cos\theta.\,(r.\,he - 1)}{y_r + .75} =$	
5	$he - \frac{\cos\theta.\,(r.\,he - 1.3)}{y_r + 1.5} =$	
6	$he - \frac{\cos\theta.\,(r.\,he - 1)}{y_r + .75} =$	
7	$he - \frac{\cos\theta.\,(r.\,he - 1)}{x_1 + .75} =$	
8	$he - \frac{\cos\theta.\,(r.\,he - 1.3)}{x_1 + .75} =$	
9	$he - \frac{\cos\theta.\,(r.\,he - 1)}{x_1 + .75} =$	
10	$he - \frac{r.\,he.\,\cos\theta.}{y_f} =$	

equations provided. In each zone, the maximum height of an obstruction is classified by its angular displacement (θ) relative to the x /xr plane for zones 1, 2, 3, 7, 8, 9 and relative to the yf/yr plane for obstructions in the 4, 5, 6 and 10 zones. The horizontal distance of the obstruction from the eye position is measured as Y.

HEAD OFFICE:

Research Avenue North,
Riccarton,
Edinburgh, EH14 4AP,
United Kingdom
Telephone: +44 (0)870 850 5131
Facsimile: +44 (0)870 850 5132

Tapton Park Innovation Centre,
Brimington Road, Tapton,
Chesterfield, Derbyshire, S41 0TZ,
United Kingdom
Telephone: +44 (0)1246 557866
Facsimile: +44 (0)1246 551212

Research House Business Centre,
Fraser Road,
Perivale, Middlesex, UB6 7AQ,
United Kingdom
Telephone: +44 (0)208 537 3491/2
Facsimile: +44 (0)208 537 3493

Brookside Business Park,
Cold Meece,
Stone, Staffs, ST15 0RZ,
United Kingdom
Telephone: +44 (0)1785 764810
Facsimile: +44 (0)1785 764811

Email: iom@iom-world.org