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# Advanced Cabin Design

How to Improve Comfort and Performance  
by Progressive Cabin Design

TNO Arbeid, Hoofddorp



\*TN0129044\*

Robin E. Bronkhorst  
Michiel P. de Looze

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## *Editors*

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*Cover photo:*

In co-operation with the public transport enterprise RET in Rotterdam and the manufacturer of the tram, TNO developed a cabin that provides all drivers with a safe and comfortable working environment. This could only be achieved by designing the tram from scratch. The adjustments involve more than just the adjustment of the chair and the range of the controls.

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## Editorial

### *Comfort, the buzzword*

In the automotive industry comfort has become an important issue. In the last decade, the word has entered the world of professional equipment builders like earthmoving machines (wheel loaders, excavators), forklift trucks, cranes, trucks, busses, etcetera.

Comfort nowadays is the buzzword in all those industries where vehicles and cabins are manufactured. Manufacturers became more user oriented focussing on the people working in cabins for prolonged periods of time. Manufacturers aim at optimizing the extra feel of well-being with these users.

Equipment builders are also aware of the fact that comfort increasingly affects purchase decisions with new machines. Comfort has become a sales item in the professional world, emphasized in many brochures. Especially those people with a prolonged exposure in the cab may profit as their daily working conditions improve.

On the other hand, we all know comfort to be a subjective entity. What is it really? In the literature the subject is well addressed. With regard to its definition, scientists agree on three points: comfort is subjective, it is determined by various factors, and it is product or environmental related (De Looze et al., 2003). Moreover, the comfort group of TNO agrees with various scientists (e.g. Helander and Zhang, 1997) that comfort is not on the same scale as discomfort: comfort, i.e. the general feeling of well-being, is a different entity than discomfort, i.e. the physical experience. Within this concept, the strategy is first to eliminate discomfort or reduce it to a minimum, only then to create comfort (Paul et al., 1997). Whereas the traditional design practice focussed merely on the reduction of physical pain, upcoming design practice focuses also on increasing the general feeling of comfort as a positive emotional experience (see Figure 1).

Nowadays, it does not suffice to stop any development process at minimizing the discomfort level. Having reached this level, we are only half way there. We have to continue and look for those extras that create comfort.

In this book various examples are offered of how to create comfort through extra space, improved posture, a different steering system, a better view and so on.



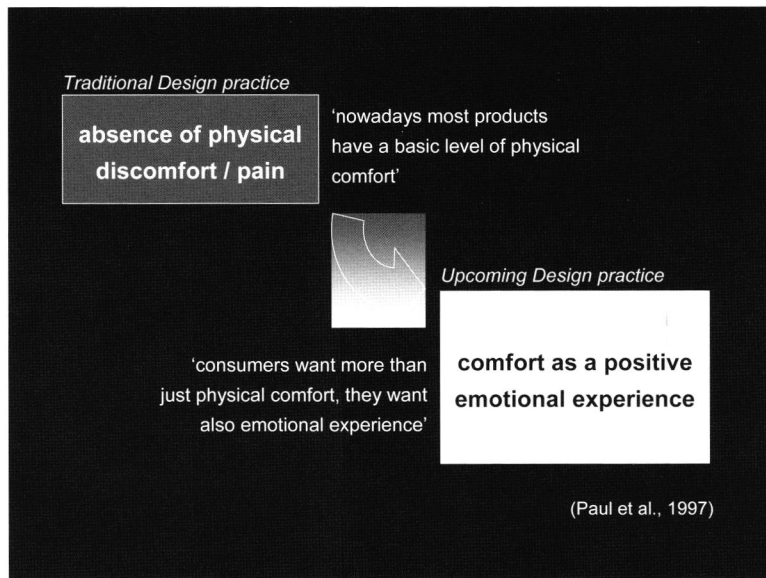


Figure 1

For more than 10 years, TNO has been active in the field of comfort, illustrating our progress through numerous scientific publications and presenting interesting cases to the industry. Because of the many positive reactions on these books, we intend to continue this tradition of sharing our knowledge.

Our present issue, *The Advanced Cabin Design* book, starts with a general introduction on the health risks in relation to current cab design. In this first chapter, we introduce the strategy to aim for alternative postures as a means to create comfort. In the following chapters new challenges are addressed with regard to the design of forklift trucks (Chapter 2), the design of tram drivers' cabins (Chapter 3), the design of quay crane cabins (Chapter 4) and a short introduction into the design of compact sweeping machines (Chapter 5).

Chapter 6 is a typical example of our participatory ergonomic approach to improve the cabs of current equipment.

Chapter 7 focuses on the future of controls. In explorative studies we looked at the possible improvements with regard to the way of steering and the form of the joystick. We made an interesting comparison on the 'control of speed' versus the 'control of position'.

Through these innovative ideas, each in their own way, we aim to contribute to the crystallisation of the buzzword 'comfort'.

Robin E. Bronkhorst, M.Sc.

Michiel P. de Looze, Ph.D.

Editors

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# 1 Major Challenges in Cab Design

Liesbeth Groenesteijn, Michiel P. de Looze

*This chapter addresses the current problems in cab design. Although a lot has improved over the past years, operators still recognize a number of aspects that need further improvement. In addition, the currently available health figures are clear: operators of various vehicles are at increased risk for developing back and neck pain. Specifically, the machines where operation requires a near vertical view (cranes, sweepers, straddle carriers) form a major problem area. Here, the finding of a comfortable and healthy body posture is the major challenge for cab designers. Some new ideas for future cab design are presented in this chapter.*

## 1.1 Current cabin design and comfort

Over the recent years, the design of cabins of all kinds of vehicles has strongly developed. Not only forms and dimensions of the cabins have evolved, also the seat comfort and the climate control, for example, have improved in the past few years. Comparing 'less than four years old' to 'more than four years old' wheel loaders and excavators Kuijt-Evers et al. (2003) found that the general opinion of operators about the comfort of the cabin was clearly higher in the newer machines.

However, the same study indicates that operators can easily think of a number of aspects that need further improvement. An important aspect that is mentioned by wheel loader operators, is the comfort of the seat. Excavator operators specifically consider the cabin dimensions, the outside view, the reliability of the machine and the climate control as factors to improve.

A main question in this respect is: do we need further improvement? Is it a luxury or is it an unambiguous necessity to make comfort improvements?

Obviously, people are currently used to a high level of comfort, not only at work but also at home, in their private cars and so on. As developments in related branches are on-going, comfort is a relative understanding, but it is obvious that expectation levels with regard to cabin comfort are continuously increasing.

It can also be argued that comfort would improve the operators' performance. A comfortable cabin is a cabin where (among other issues) the seat can be optimally adjusted to the driver, where handles, joysticks, pedals are always within

reach, where the inside view (on panels) and the outside view are not obstructed and don't require awkward body postures (trunk twisting, neck extension, and so on) and where the climate can be optimally controlled. It is likely that all these features may directly or indirectly, i.e. by an improved operator's motivation, increase the working speed.

Finally, a comfortable cabin is likely to promote health. Comfortable cabin design should be aimed at the reduction or elimination of risk factors for work-related health complaints like neck and shoulder pain and low back disorders. In the next paragraph the currently known, hard figures about the health of the operators of various machines are presented.

For now, the conclusion is that comfort is a necessity. This is underlined by the increasing numbers of cabin manufacturers recognizing comfort as an important selling factor.

## **1.2 Health of vehicle operators**

In the past, a lot of studies about the physical conditions of the operators in their cabins have been conducted all over the world. The results from these studies are described below and summarized in Figure 1.1.

Zimmerman et al. (1997) gathered the numbers of operators reporting neck/shoulder and back pain for various machines, namely bulldozers, forklifts, power shovels and earth moving machines. More than half of the involved bulldozer operators reported neck and shoulder pain, while over one third of these operators reported an episode of low back pain over the last year (see Figure 1.1). For forklift truck drivers the extent of the health problems is even higher and for the power shovel operators quite similar to the bulldozer operators. The back problems for the operators of earth moving machinery seem even worse: two third reported low back pain over the past year.

In another study (Burdorff et al., 1993) the occurrence of back problems among crane and straddle carrier drivers was studied. The percentages of drivers reporting the occurrence of back problems over the past year were 50% and 44%, respectively. Massaccesi (2003) found high numbers of neck and back pain for street cleaning machine drivers: about 80% of the questioned operators report pain in the neck and back. Other papers show the scores of low back pain for truck drivers, namely 50% (Miyamoto et al., 2000), and neck/shoulder pain for logging machine operators, namely 60% (Axelsson and Pontèn, 1990).

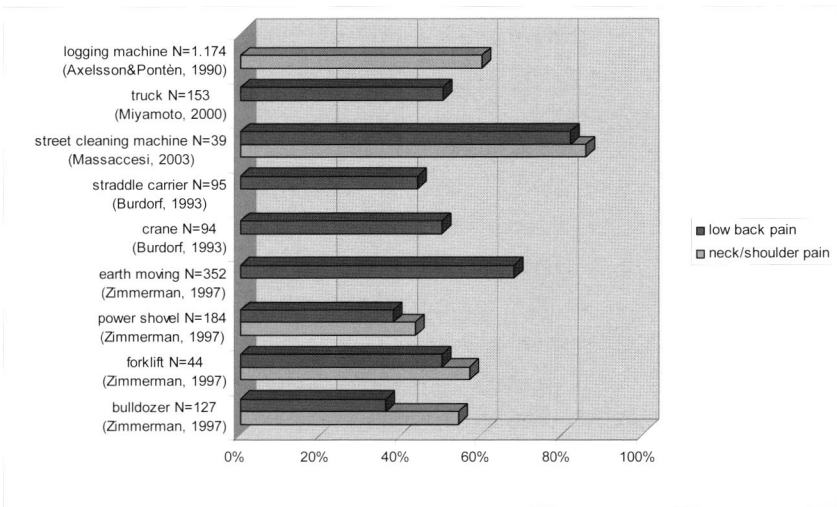


Figure 1.1 The percentages of cabin operators reporting the occurrence of an episode of neck/shoulder and back pain over the past year for various kinds of machinery. N reflects the total number of people for each kind of machine that were involved in this study. When there is just one bar it means that either back or neck problems were recorded and not both

Although the above studies are not exactly comparable because of different subject numbers of different populations and because they don't use exactly the same definitions for health disorders, they all indicate health problems for operators in cabins. Figure 1.1 shows that many operators suffer from health problems in the back and neck/shoulder regions. An important question in this respect is how the observed rates of health problems among cabin operators relate to the rates of other working populations. The health problems of cabin drivers can only be defined as 'work-related', in case the rates of health problems of cab drivers are significantly higher compared to other workers.

Table 1.1 Odds ratios for back and neck pain for the operators of various machines

operators of machinery type	back pain	neck/shoulder pain
cranes	2.7 <sup>1</sup> -3.6 <sup>2</sup>	3.3 <sup>1</sup>
straddle carriers	2.5 <sup>3</sup>	
forestry		3.4 <sup>4</sup>
trucks	2.0-2.4 <sup>5</sup>	
forklift trucks	2.3 <sup>6</sup>	

<sup>1</sup> Piccinni et al., 1992.

<sup>2</sup> Burdorf and Zondervan, 1990.

<sup>3</sup> Burdorf et al., 1993.

<sup>4</sup> Hagen et al., 1998

<sup>5</sup> Miyamoto et al., 2000.

<sup>6</sup> Zimmerman et al., 1997.

Table 1.1 shows the odds ratios (OR) for the operators of various machines. The OR indicate the odds for the occurrence of back or neck/shoulder pain in relation to a reference group. The reference groups vary from blue collar workers in the same company without cabin operator tasks to administrative/office workers, also known as white collar workers.

The risk for vehicle operators of getting back or neck/shoulder pain is sometimes more than three times higher than for the reference group (Burdorff et al., 1990; Piccini et al., 1992; Hagen et al., 1998). All the studies in the table show an OR of at least two or more. That means that the chance of getting back or neck problems is at least double for operators of these machines in relation to the control group. The average is even two point five to three times higher. This shows that the problems of cabin operators are work-related. The direct work environment is one of the aspects which can influence the operators' health. So cabin design potentially helps to reduce back and neck complaints and must be improved.

### **1.3 Main factors in cabin design**

Having said that cabin design may well reduce the health problems among operators, the question is: what aspects should be specifically addressed? Hereto, we need to know the major risk factors of neck/shoulder and back pain.

Ariëns (2001) systematically reviewed the general scientific literature on the work-related risk factors for neck pain. From this review the following factors could be unambiguously defined as increasing the risk for neck pain: (fixed) sedentary postures, twisting and bending of the trunk, neck flexion, high arm force, fixed arm posture, hand-arm vibrations, long duration of sitting and bad workplace design. Another review (Hoogendoorn, 2001) established the main risk factors for back problems. These are: twisting and bending of the trunk, sedentary postures and vibrations.

In general, many of the above risk factors are present in the work of machine operators. In order to prevent the back and neck/shoulder problems, which may even lead to permanent disability to work, it is clear that the above factors are the ones to address in the design of future cabins.

Table 1.2 The specific risk factors for health complaints for the operators of sweeping machines, forklift trucks, tractors and cranes

sweeping machines (Massaccessi, 2003)	forklift trucks (Brendstrup, 1987; Boshuizen, 1992)	tractors (Kondo, 1986)	cranes and straddle carriers (Piccinni, 1992; Burdorf, 1993)
<ul style="list-style-type: none"> <li>• neck flexion</li> <li>• neck torsion</li> <li>• trunk flexion</li> <li>• trunk torsion</li> <li>• non-adjustable chair</li> </ul>	<ul style="list-style-type: none"> <li>• sitting a lot</li> <li>• sitting during long periods without interruption</li> <li>• looking back frequently</li> <li>• many working years</li> </ul>	<ul style="list-style-type: none"> <li>• vibrations</li> <li>• sitting posture</li> <li>• frequent pedal operations</li> <li>• poorly arranged working environment</li> </ul>	<ul style="list-style-type: none"> <li>• monotonous and static posture</li> <li>• vibrations</li> <li>• sitting posture</li> <li>• static posture</li> <li>• neck flexion</li> <li>• bended or rotated postures</li> <li>• uncomfortable chairs</li> <li>• uncomfortable controls</li> </ul>

Various studies on risk factors have been less extensive, but also more specific, addressing the specific risk factors in specific machines. Table 1.2 presents the results of these studies in terms of risk factors for sweeping machines, forklift trucks, tractors and cranes.

It appears from this table, that nearly all factors got to do, one way or the other, with body posture and movement. It may concern the static and sedentary character of body posture or the repetitive, monotonous character of body movements, or the frequent occurrence of awkward body postures like a twisted trunk and a flexed neck, or cab features like uncomfortable chairs and controls leading to uncomfortable postures and movements. In other words: body posture is crucial in the design of comfortable and healthy cabs.

This is illustrated by the model in Figure 1.2, showing the determinants and effects of the operator's body posture.

Roughly, the operator posture is determined by the cabin design (specifically the seat, but also layout of controls, mirrors and monitors), the task demands (object that must be kept in sight, manoeuvres, around sight and accuracy) and the individual operator properties (like anthropometrics and preferred posture). Further the operator orientation determines the position and movement variation of individual body parts (for instance the degree of neck flexion or trunk torsion), the pressure distribution at the man-machine contact area, the direction of affective forces (shocks, vibrations), the way of operating, the ease of operating of pedals, joysticks and suchlike and the operator's sight. By these factors there is



the effect on physical load , discomfort/comfort, emotional perception, performance and health.

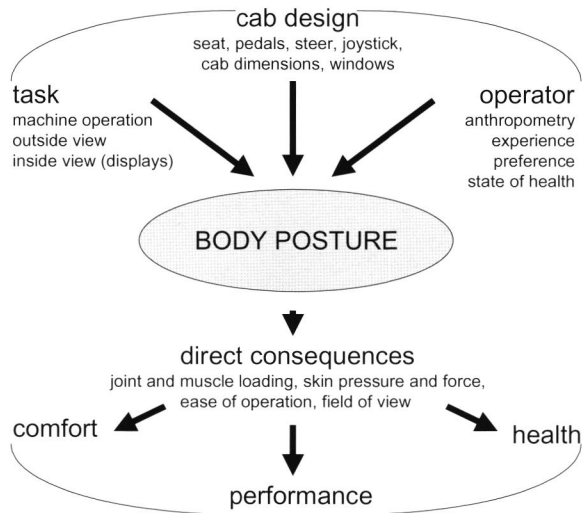


Figure 1.2 The crucial issue of body posture in the design of comfortable, productive and healthy cabins

The crucial role of body posture in comfortable cabin design becomes very clear when considering machines where operators need to look in a near vertical direction. This is the case in sweeping machines, cranes, straddle carriers (see Figure 1.3). Working in these machines mean: static or highly frequent, awkward body postures for long periods of time in combination with frequent body vibrations and shocks in variable directions! Not surprisingly, the rates of injury are high among the operators of these machines, as illustrated before. Optimal solutions, specifically addressing the above problem, do not yet exist. Several ideas are presented in the final paragraph.



Figure 1.3 The body postures in sweeping machines, cranes, straddle carriers, which is forced by the required (near-vertical) viewing direction

#### 1.4 Future challenges

How can we create a healthy posture or, preferably, a number of alternating healthy postures for the crane, straddle carrier and sweeping machine driver. Two solution directions can be distinguished.

First, one may change the required viewing direction. Hereto, mirrors and camera systems might be implemented. In some cases this might work. In Chapter 4 addressing the design of compact sweeping machines gives a good example of the potential power to improve the body posture by implementing a camera-monitor system on a sweeping machine.

The second kind of solution direction might concern a fundamental modification of the standard body posture. Here, we can learn from the experiences with re-

spect to other workplaces where workers adopt for some reason a body posture which is different from normal.

The figures below (Figures 1.4-1.6) show examples of alternative body postures in various industries for a better upward and downward view.



Figure 1.4 Example of an alternative body posture in the assembling industry



Figure 1.5 Workplace of an operator of a fuel airplane. The operator lays on his ventral side with the chin resting on the small pillow and looks through the small window for refuelling a plane in the air

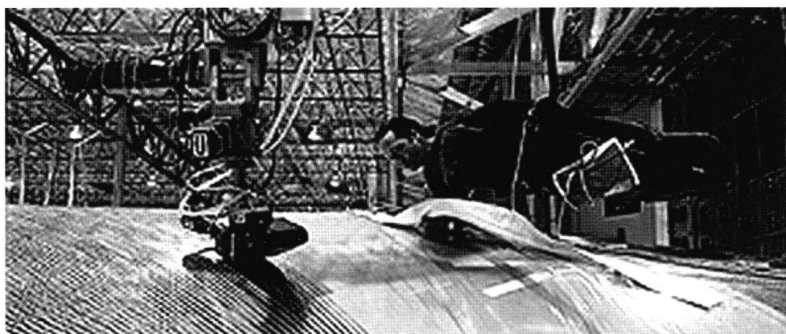


Figure 1.6 Example of an alternative body posture in the sail industry. The person in the photograph is repairing sails

Concepts for new operator body postures for shovel cabins were developed earlier in cooperation between TNO and the University of Delft in the Netherlands. Figure 1.7 shows an example. The shown operator orientation provides the advantages of a better sight, elimination of unfavourable joint postures, an opportunity for variation in posture, less tiredness, more comfort and (through all this) and improved performance.

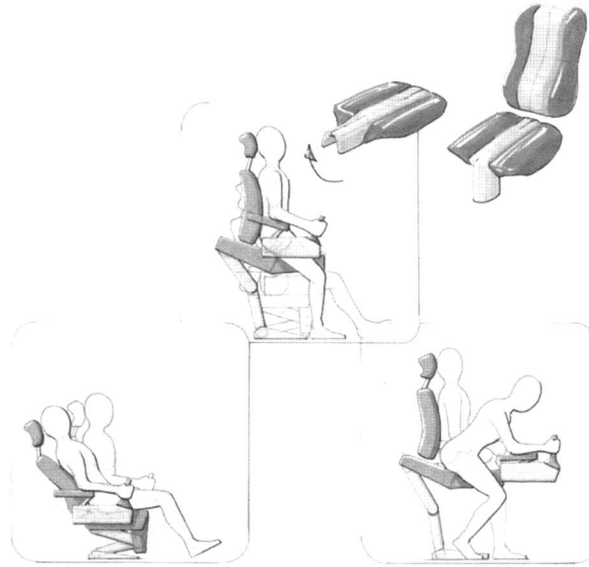


Figure 1.7 An example of alternative operator orientations in a shovel cabin. Particularly the picture on the bottom right shows how the operator could choose to vary between sitting straight up and in 'motorcycle position'

Figure 1.8 shows a good example of an innovative cabin, facilitating a new working posture. The cabin is designed for cranes and harbour facilities. The design of the cabin, the seat and the instruments was specifically aimed to create a comfortably bent forward body posture (like the motor position in Figure 1.7) for the operator who needs to look down in a near vertical direction. Special arm-rests were designed for upper body support. Chapter 4 in this book pays specific attention to this interesting cabin.

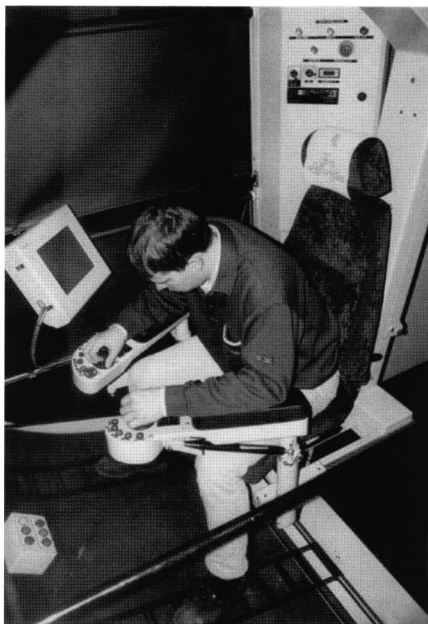


Figure 1.8 Merford's ceiling suspended Ergo-seat specifically aims at supplying more support to the crane operator for a more comfortably bent forward body posture

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## 2 Integral Design of Small Forklift Trucks

*Lottie F.M. Kuijt-Evers, Robin E. Bronkhorst*

*Neck and back pain are common health problems among forklift truck drivers. In order to reduce these problems manufacturers and designers have paid much attention to the separate elements of the forklift truck, like the driver's seat, the suspension mechanism and the cab dimensions. Some of these efforts are described in literature. Although, a comfortable driver's seat, reduced body vibration and optimal cab dimensions are basic requirements for a comfortable forklift truck, optimisation of the separate parts does not automatically lead to more comfort for the truck driver. In this chapter we propose some ideas of a more integral design of forklift trucks.*

### 2.1 Small contra-balanced forklift trucks (1.25 to 2.5 t)

Forklift trucks are designed for the internal transport of materials in auction halls, storehouses and other buildings. They are specifically used to move pallets from one place to the other by means of their forks which are in front of the truck. Forklift trucks can be divided into different groups based on the weight of the load they can lift. In this chapter we focus on the small contra-balanced forklift trucks which can lift up to 2.5 ton. They are designed to operate in narrow spaces. Therefore, they are very compact which in the past years has frequently resulted in an ergonomically poor construction of the driver's seat (Brendstrup and Biering-Sørensen, 1987). This illustrates that ergonomics became secondary to technical requirements in design of forklift trucks in the past.

Nowadays, in forklift truck design more attention is paid to providing a comfortable working environment for the drivers. How manufacturers attend to comfort and ergonomics in their trucks, can be observed on the various manufacturer's websites that are accessible on the Internet. Several aspects of forklift truck design are currently accounted for, like a spacious operator compartment, easy access to the machine, control levers, introduction of power steering, a low noise level, the suspension, a comfortable seat, an adjustable tilt of the steering column, and ergonomically well-designed floor mounted pedals. Although these separate elements of the truck have been improved, the question presents itself

whether these improvements really resulted in a more comfortable working environment and did solve the forklift truck drivers' problems.

## 2.2 Problems of forklift truck drivers

The odds ratio (OR) indicates the odds for the occurrence of back pain in relation to a reference group (Zimmerman et al., 1997). The OR for forklift truck drivers is 2.3, which means that the chance of getting back problems is more than double in relation to the control group with general workers.

Forklift truck drivers may suffer from physical complaints like back and neck/shoulder pain because of several reasons. Three main reasons are mentioned in the literature:

1. static load during prolonged sitting with hands and feet held steady on handles en pedals;
2. awkward postures (i.e., twisting the spine during looking backwards and extending the neck during looking upwards (up to 11 meters);
3. whole body vibrations (Brendstrup and Biering-Sørensen, 1987; Boshuizen et al., 1992; Donati and Patel, 1999).

To get more grip on these problems of forklift truck drivers we conducted a case study in a Dutch auction hall, where the forklift truck drivers transport pallets with vegetables and fruit from the auction hall to the trucks and vice versa. In this study we collected the opinions of thirteen forklift truck drivers.

### *Static load during prolonged sitting*

Static load during prolonged sitting was one of the problems of forklift truck drivers mentioned in literature. Our case study in the auction hall confirmed that forklift truck drivers are exposed to prolonged sitting. Figure 2.1 shows that a large majority of the drivers sit in their truck for more than six hours a day.

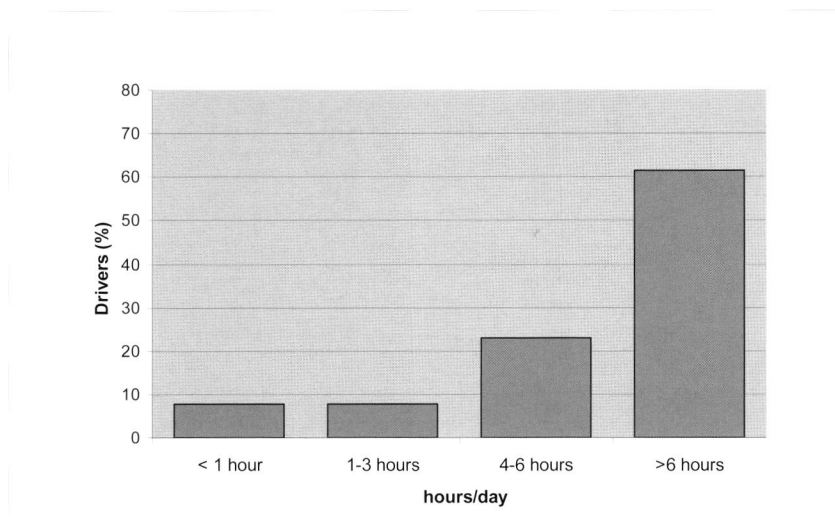


Figure 2.1 Forklift truck drivers are exposed to prolonged sitting during work. A large majority is sitting for more than 6 hours a day in their truck

#### *Awkward postures during looking backwards and upwards*

As described in literature, another problem of the forklift truck drivers are awkward postures when driving backwards and looking upwards. Awkward postures during driving backwards were also confirmed by the forklift truck drivers. 46% of them reported that they drive backwards about half their working time and 14% even reported to drive backwards up to 75% of their working time (Figure 2.2). The reason for driving backwards is that their visibility in front of the truck is blocked or reduced by the load. Driving backwards is very often accompanied by looking backwards. Most of the drivers reported that when heavy traffic occurs, they are looking backwards constantly or very often (Figure 2.3). When looking backwards the neck and (sometimes) the trunk are twisted, resulting in awkward postures.



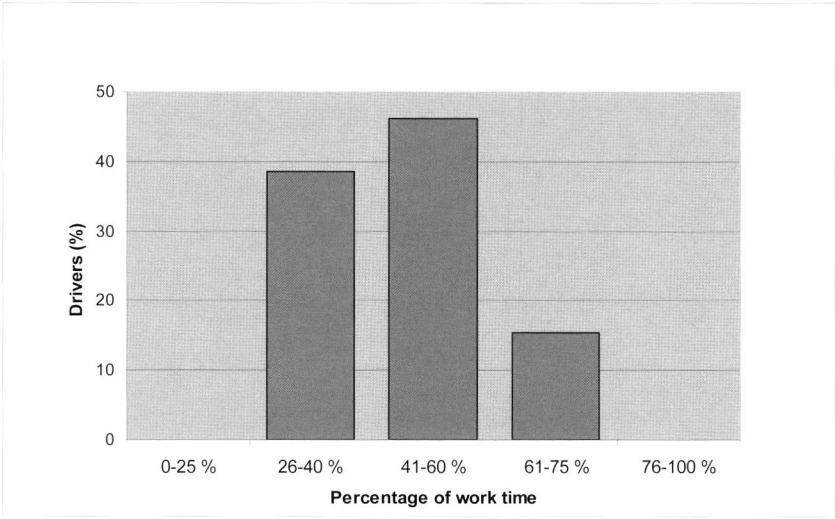


Figure 2.2 A majority of the operators reported to drive backwards about almost half of their working time or more

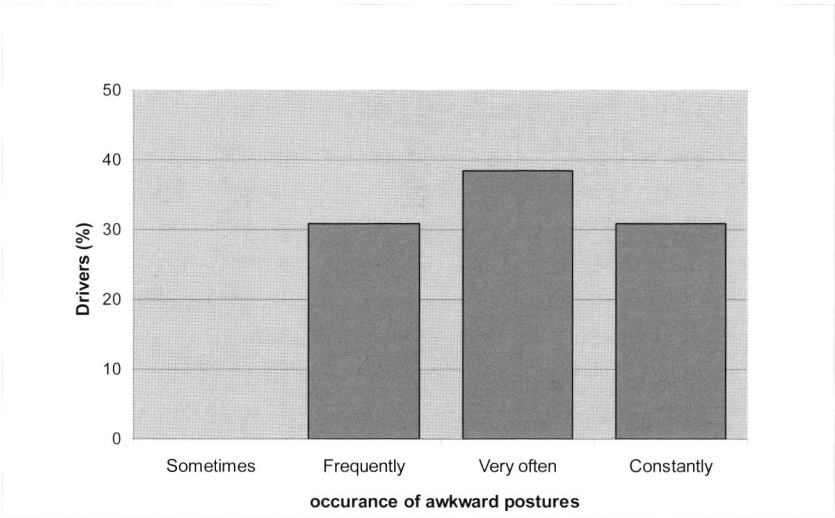


Figure 2.3 The occurrence of looking backwards during heavy traffic

In an experiment we investigated how the postures during looking backwards and upwards correspond to comfort guidelines as described in literature (Kee and Karwowski, 2001) and health guidelines (Arbouw, 2001). We would like to measure the buttocks, trunk and neck rotation during driving backwards and the

head inclination when looking upwards. As the experiment took place in the auction hall, we were not able to use sophisticated laboratorial measurement techniques. Additionally, it was not possible to measure body part rotation and inclination when the drivers were performing their job. However, we used an even simple as effective method. The forklift truck drivers were asked to sit in a stationary truck. We asked them to look at a target five meters right behind the truck rotating their neck and trunk as they were used to do. Digital photos were made from above. In order to recognize body parts and anatomical structures markers were placed on the head, chest and pelvis (Figure 2.4). These markers were used to measure the rotation of the separate body parts. The neck and trunk rotation (Figure 2.5) were measured from the photos.

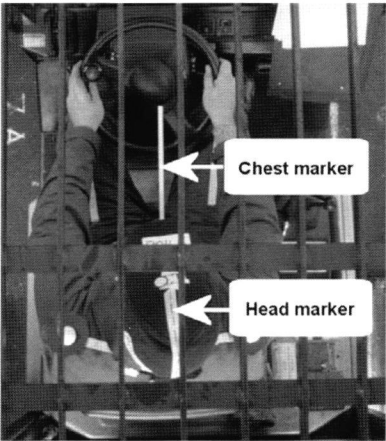


Figure 2.4 Head and chest marker to measure neck and trunk rotation

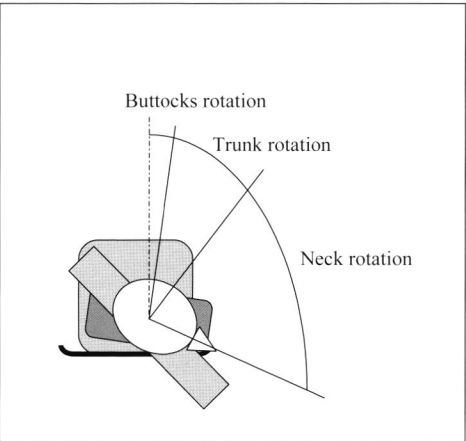


Figure 2.5 Neck, trunk and buttocks rotation

The results confirm that the neck and trunk rotation are a real problem. Table 2.1 shows comfort guidelines for neck and trunk rotation. The comfort levels are shown as a percentage of the maximal active rotation. To compare our results with these guidelines the neck and trunk rotation are calculated relative to the maximal rotation. The relative neck and trunk rotation both exceed the marginal comfort level. The relative neck rotation was 98%. The relative trunk rotation was 108%, which even exceeded the maximal active trunk rotation. This means that the drivers rotated their trunk even more than can be achieved by active trunk muscle contraction, which can be explained by the use of arm and hand to

pull the trunk further rotated (Figure 2.6). In fact, this is an awkward posture that can lead to musculoskeletal complaints.



Figure 2.6 The driver puts his arm around the backrest and pulls his trunk in a further rotation than he can achieve by active trunk muscle contraction

Table 2.1 The relative neck and trunk rotation exceed the comfort levels (marginal index and good index) in sitting posture (from: Kee and Karwowski, 2001)

	comfort level (% of maximal rotation/inclination)		
	relative rotation	marginal index	good index
neck rotation	98	96	57
trunk rotation	108	65	25

The neck and trunk rotation do not only exceed the comfort levels, but also the health guidelines (Arbouw, 2001). The health guidelines of TNO contain guidelines for static load and repetitive movements combined with awkward postures. In the previous section it was seen that awkward postures during looking backwards are maintained for a long time during a working day. Consequently, forklift truck drivers are exposed to static load (according to the health guidelines) in combination with awkward postures, which can lead to musculoskeletal complaints. The results of this part of the case study show that looking backwards is a real problem in forklift truck driving.

In this auction hall, looking upwards was a minor problem. The drivers stacked the pallets up to 6 meters, which is not too high compared to the situation in many other locations. During the experiment we also measured the head inclination (Figure 2.7) when looking upwards at the fork in highest position, using the same methods as in looking backwards. The results show that the head inclination was 68% of the maximum. As seen from table 2.2, the head inclination exceeds the marginal comfort level.

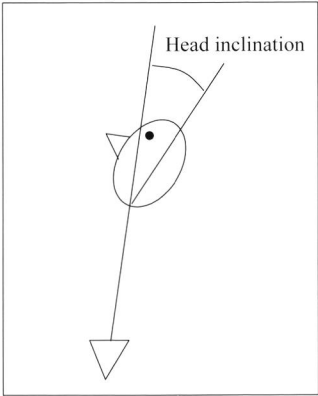


Figure 2.7 Head inclination

Table 2.2 The relative head inclination exceeds the marginal comfort level of head inclination (Kee and Karwowski, 2001)

	comfort level (% of maximal rotation/inclination)		
	relative inclination	marginal index	good index
head inclination	68	56	20

As the drivers do not have to look upwards that high, looking upwards takes just a few seconds. So, the exposure time to static neck loading is quite low. Additionally, the act of looking upwards did not occur frequently. Consequently, health guidelines of static and repetitive neck loading due to looking upwards are not exceeded in the auction hall. However, in other environments (like storage houses) where the pallets are stacked up to 11 meters, looking upwards can be a real problem: on the one hand the forklift truck drivers' head inclination will be enlarged by looking upwards that high, on the other hand the endurance time of head inclination - that exceeds the marginal comfort index - during a day will be enlarged as lifting the pallets up to 11 m will take more time than lifting pallets up to 6 m.

*Whole body vibration*

The third problem of forklift truck drivers which was described in the literature was whole body vibration. In this case study, the forklift truck drivers did not mention whole body vibration as a problem during their work. The relation between whole body vibration and physical complaints was not clear in this situation.

### 2.3 A new seat design: a solution for forklift truck drivers?

From the previous section it is seen that awkward postures during driving backwards should be avoided such that the drivers need less neck and trunk rotation in order to look behind the truck.

A seat manufacturer wanted to improve the driver's seat in such a way that neck and trunk rotation when looking backwards can be avoided. A straight solution should be a rotatable seat. When the seat is rotated, less trunk and neck rotation is needed to look behind the truck. However, feet and hands can not reach the pedals and control levers anymore when the seat is rotated. Therefore, the seat manufacturer proposed another possible solution: a flattened seat pan in comparison to the more traditional curved seat pan (Figure 2.8). As it is easy to shove with the buttocks on a flat seat pan, they expected that drivers would sit a little rotated on the seat. When the buttocks with respect to the seat are a little rotated already, less trunk and neck rotation is needed to look behind the truck. The seat manufacturer wondered if flattening the seat pan could reduce awkward postures when driving backwards or that rotation on the seat was obstructed by pedals and control levers. TNO was asked to test the effect of the flattened seat pan on body posture.

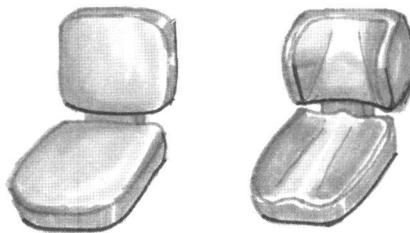


Figure 2.8 Flattened seat pan (left) against curved seat pan (right)

To answer the question of the manufacturer, we conducted a study in which we compared two seats with each other. The seats with different seat pans were mounted on two forklift trucks of the same kind. One seat had a seat pan with curvature and the other seat was flat with no curved parts. The drivers were asked to look backwards as described before and the neck, trunk and buttocks rotation were measured. We observed no difference in neck and trunk rotation between the flattened seat pan and the curved seat pan (Figure 2.9). The rotation

of the buttocks was also the same for both seats. Flattening the seat pan does not effect more rotation of the buttocks on the seat, as hands and feet are fixed to the steering wheel and pedals.

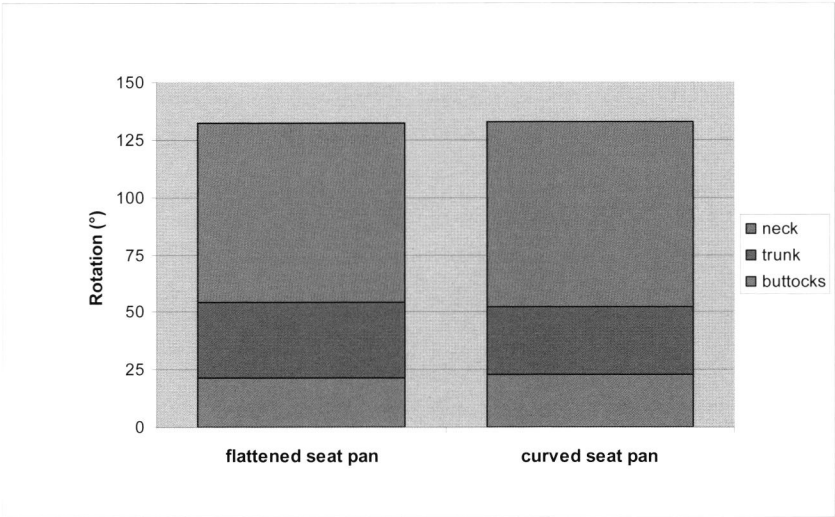


Figure 2.9 Rotation of neck, trunk and buttocks for both seats

This experiment showed that awkward postures during driving backwards can not be solved by just a rotatable seat or flattening the seat pan, as the rest of the cabin is not suited to the new situation.

## 2.4 Integral design: the solution for forklift drivers!

Although a well-designed seat can provide a comfortable posture to the forklift truck driver, it should be seen in its context: the forklift truck, the environment and the tasks.

The task which the driver performs, recommends that the driver uses the pedals for gas and brake, uses the steering wheel and control levers/joysticks and has a good visibility on the environment (traffic and load handling). All these elements have to be considered together, when solving the problems of forklift truck drivers, such as driving backwards. That is what is meant with integral design: taking into account *all* possible influences on the driver's comfort en well-being when driving and operating a forklift truck. This is also the reason why design-

ing a forklift truck is that complicated. Therefore, several experts are needed: engineers, designers, seat manufacturers, joystick/control manufacturers, end users - the experts in operating the forklift trucks -, and ergonomists, who have a holistic view.

However, not all problems of forklift truck drivers which are mentioned in the literature can be solved by integral forklift truck design. For example, prolonged sitting can better be solved by improving the organisation of work.

From the case study it was seen that awkward postures during driving backwards are a major problem of forklift truck drivers. Therefore, the design ideas in the next sections are focussed on solving this problem. Based on the case study, our ergonomic experience and our holistic view we had some ideas of integral design of forklift trucks. Two of them are described in next sections. These are general ideas. The details still have to be worked out by several experts.

#### *Rotatable cabin*

The rotatable cabin is *the* solution for awkward postures during driving backwards. Trunk and neck rotation are not necessary to have a good visibility behind the truck. When the cabin is rotated over 180°, the driver can look straight ahead. His visibility is not reduced by the load anymore (which is now behind him) and he can drive 'forwards' again (Figure 2.10).

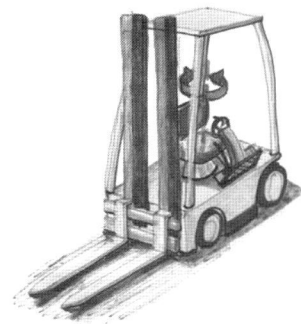


Figure 2.10 The rotatable cabin

The load can be looked after by using mirrors. The rotatable cabin is especially useful for driving 'backwards' over long distances. For driving backwards when manoeuvring it is not advisable to rotate the cabin. The driver should have the opportunity to make his choice whether he rotates the cabin or not, before he starts driving backwards. Further, the cabin has of course to meet the anthropometric and ergonomic standards and it should have a comfortable seat and controls (Bohets et al., 1996).

#### *Rotatable seat*

Another solution is a rotatable seat. When the seat is rotated, less neck and trunk rotation are needed to look behind the truck. However, if the seat is rotated, the driver must still be able to use the gas and brake pedal with his feet. Therefore, we mention two possibilities:

1. the pedals are enlarged and curved, and

2. a second pair of pedals is mounted at the right side of the truck, so these can be used when the seat is rotated.

The joystick is integrated in the armrests, which provides a comfortable posture when using the joystick. The armrests are adjustable in height, so a relaxed working posture can be adopted. Unfortunately, it is not possible to move the steering wheel, so the driver has to reach with his left arm to turn the wheel. But the armrest supports the left arm, when driving backwards (Figure 2.11). The seat should have the possibility to be locked in different degrees of rotation. The construction

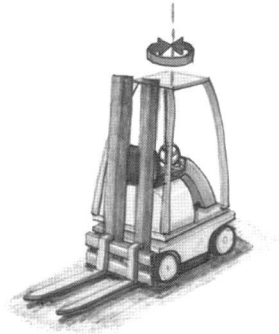


Figure 2.11 The rotatable seat  
of the seat still must be very stable to avoid ‘unsafe’ feelings of the driver. The twistable seat is already studied by Schröder et al. (2003) and it causes a remarkable reduction of neck and trunk rotation.

## 2.5 Epilogue

This chapter showed the problems of the forklift truck drivers. These problems can not be solved by just a comfortable seat or more interior space in the cabin. To avoid for example awkward postures an integral design of the forklift truck is necessary. Two integral design ideas are shown. These ideas need to be worked out in more detail. We argue that seat, joystick and forklift trucks manufacturers and ergonomists should cooperate, in close conjunction with the end user (forklift truck drivers), in order to design a forklift truck that provides a healthy and comfortable working environment.

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### 3 Tram drivers' comfort optimised

Dirk Osinga, Peter Vink, Cor Becker<sup>1</sup>

*The requirements put on trams regarding comfort, safety and capacity are high and numerous at the same time. Trams should be comfortable and safe for passengers and should allow fast getting in and out of the tram. Also, capacity should be enlarged due to the increasing number of passengers. Apart from passengers the driver's cab should meet the driver's needs. The cab should be comfortable for small, long, tender and corpulent drivers, and should stimulate safe driving as well as a good view and clearance. This chapter describes how a Dutch public transport organisation realised all those goals in a new tram design.*

#### 3.1 Driver's cab and passenger cabin requirements

The public transport enterprise of Rotterdam RET (Rotterdamse Elektrische Tram) is confronted with changing demands and therefore pays much attention to the process of designing their new trams. That's why requirements for a new tram were defined and after a European invitation for tenders, Alstom (France) was chosen to deliver the new trams, because their trams not only met most of the requirements, but also because adaptations were still possible.

An important advantage of the Alstom tram was the high passenger capacity, because the tram is relatively wide, which increases capacity. Furthermore, the tram has a low floor, which increases passenger comfort in getting in and out of the tram. Based on the existing Alstom concept the RET specified the outside look and many technical facilities. The requirements of the interior of the cabin were specified together with specialists from TNO regarding vehicle interior design. The process of the driver's cab specification is the focus of this chapter.

#### 3.2 Reasons to optimise the driver's cab for a better performance

It is essential to adapt a driver's cab to human behaviour to enable optimal human performance. Nowadays, many software packages are available to support an ergonomic design, which is needed to check whether the various drivers fit in

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the seat, if their view isn't obstructed and if the controls are within reach. These software packages are especially useful in an early stage of development. However, it is impossible to predict both human behaviour and the feeling of comfort. Therefore, in a later stage of design, participation of various drivers will always be needed to test the handling, view and comfort.

Participation of real drivers is essential, because:

- one of the requirements of the RET is that the driver should at least be able to see an object of one meter high located at one meter of the tram, in order for the driver to have a good sight on the traffic in front, left and right of the tram;
- real users should test controls and displays, because they know the driver's work best;
- only real drivers can judge the comfort of the cabin.

A healthy environment will prevent drivers from becoming ill or enable them to start working again after illness. Comfort will enable the driver to stay more alert during their shift without being diverted or becoming tired. Furthermore, nowadays drivers are used to the high comfort standards in their private cars or at home and therefore also expect high comfort at work.

### **3.3 The 5 steps design process**

Ultimately, the driver's cab should be a workplace that enables an optimal driver's performance. Therefore, in the process of developing the new tram the driver played an important role. In this project a stepwise approach used in a train interior design process was used (Bronkhorst et al., 2002). Explicit attention was given to the communication in the process between designers of Alstom, drivers of the RET and researchers of TNO, among other things we tried to make the drivers and designers owners of the solutions (Wilson, 1995).

In each step of five successive steps the three groups met. A project group guided this process. The project group consisted of a 'manager tram' of the RET, a representative of the union of the RET, a number of drivers, an instructor of the drivers' training department and a specialist concerning work research. This project group guided the process of the optimal cab design through the five crucial steps.

At a few points in the process the project group had to report their progress to a steering group, that arranged the coordination with other project groups concerning technology, exploitation and passenger interior of the new tram. During

the process Alstom delivered a number of mock-ups to evaluate the design and communicate about possible changes. TNO added an expert opinion and analysed the tests done by the drivers and converted these into redesign proposals.

#### *Step 1: test first design*

In the first step designers of Alstom made drawings of the cab interior based on the requirements. At the end of this step these designs were discussed, which resulted in some changes. Climate control was hardly possible in the proposed interior, because of the large dashboard. The dashboard was a large horizontal plane from close to the driver to the coach-work, which makes ventilation hardly possible, because the air flow is hindered. Also, and probably more important, by drawing sight lines in the design it was shown that the sight was reduced, because of the large dashboards. Smaller drivers were not able to have a good view of the traffic. The position of displays and controls could also be improved.

#### *Step 2: test first mock-up*

Based on the results of step 1 the project group decided to make a new design based on other for this tram available designs. This design consisted of adapted controls and displays and a more round surface of the dashboard enabling a better sight. Another adaptation was the addition of height adjustable pedals (see Figure 3.1) next to the height adjustable seats.



Figure 3.1 In height adjustable pedals

This is relatively new in trams. To enable good traffic sight for drivers of different lengths, height adjustable seats are often found and sometimes even height adjustable dashboards. Height adjustable pedals are not often found. The advantage of height adjustable pedals is that the sight lines of the persons relative to the dashboard and the coach-work can be fixed independent of the anthropometrics of the driver.

This design was shown in a mock-up (see Figure 3.2), which was evaluated by 8 drivers in 4 sessions using a protocol set-up by TNO. To test the adjustability drivers with extreme body characteristics were used. Tall and short drivers as well as tender and corpulent drivers participated in the test. Three seats that were chosen



Figure 3.2 The mock-up used in the test

based on previous tests (two new seats and one used in the current tram) were tested in the mock-up. The height adjustability of seats and pedals were evaluated as positive. Traffic close to the tram could be observed during a simulation. All three seats were evaluated positively. Drivers mentioned during the test that in fact a dynamic test is needed to choose a seat, because the vertical vibration is not always damped effectively with a seat. It was decided to do a dynamic test in a comparable tram. New problems were also discovered during the test.

One new problem was the knee space. Knee space was theoretically (and in software) enough, but the real driver's behaviour showed that knee space was too small. Based on the discussion of the results of the test it was decided to make the dashboard more U-shaped to create space in front of the driver. Another problem discovered, was the fact that for precision handling and steering an armrest was preferable, which was now not sufficient. It was decided to add an adjustable arm support for the right arm and a fixed wrist support for the left hand (see Figure 3.3).



Figure 3.3 Armrests supporting precise handling

It was decided to add an adjustable arm support for the right arm and a fixed wrist support for the left hand (see Figure 3.3).

### *Step 3: test improved mock-up and emergency handle*

In the third step six drivers evaluated the U-shaped mock-up and it was decided to choose this design. Now further refinements were made, like the positioning of the controls and displays, the instructor's seat for the instructor tram and a sunblind.

In this step the emergency-break was also tested. Alstom could deliver a new emergency brake integrated in the drive-stop handle (see Figure 3.4). In existing RET trams drivers have to press a pedal continuously. Loosening this pedal creates an immediate stop. In the new tram the integrated handle could be used. Loosening the handle creates the emergency stop. In this way the hand cannot leave the handle. Drivers tested the new system in an existing tram. Based on the test the old system was preferred by drivers as well as by the experts, because of the armload. Therefore the old system will be built in the new tram.



Figure 3.4 Emergency-stop, integrated in the drive-stop handle

#### *Step 4: dynamic test of seats*

The next step was the dynamic evaluation of three seats in an existing comparable tram. All three seats were tested by drivers according to a fixed protocol and objective tests were done regarding vibration and pressure distribution. Analysis of these tests showed that one seat was not appropriate for the tram in the Rotterdam area. The seat didn't provide enough support in lateral direction and didn't damp the vibration enough. One seat was best, but improvements were needed, like adjustment of the armrests to give more support, a more flat front of the seat and a better pressure distribution characteristic.

Other recommendations concerned technical aspects to improve stability and maintenance. The supplier was satisfied with the specific research based comments and was willing to adapt the seat.

#### *Final evaluation*

In the last step a complete mock-up was evaluated consisting of a part of the passenger cabin and the chosen colours, light, pictograms of displays and tested completely. Some details were adapted, but the total was evaluated positively.



Figure 3.5 The prototype to examine all parts of the interior and exterior design



Figure 3.6 Reality has no surprises anymore

### 3.4 Conclusions

Because of the active involvement of several drivers and because of the research based redesign approach, all knowledge available in designers, drivers and experts is used.

Also, new knowledge came available in doing the tests. The final cabin interior of Alstom is optimally adapted to the needs of the drivers, because the designers of Alstom were made aware of the needs and were creative enough to adapt their design on the new demands.

The new tram is now a couple of months in service and the tram drivers experience the cab as comfortable. What is of more importance, because drivers have a good view on the traffic, the cab is more safe.

A couple of years ago RET designed their subway cab in a comparable way and this resulted also in a comfortable and safe workplace for the drivers and other participants in traffic. The 5 steps design process with a participatory approach is a successful formula.

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## 4 An Advanced Cab and Seat Design for a Quay Crane

Frank Krause, Michiel P. de Looze

*In many types of cranes work requires the operators to look downwards almost continuously. Such a viewing angle forces the neck and back in an unfavourable, flexed posture. Consequently, many crane drivers suffer from neck and back complaints. Can this problem be solved by a progressive crane seat design? This chapter describes this problem and discusses the potential advantages of a new design of a quay crane cabin and seat.*

### 4.1 The quay crane and its driver

With the expanding global market increasing amounts of containers and goods are shipped all over the world. For the handling of these materials cranes are crucial. There are many types of cranes. In ports we may see: quay cranes, ship cranes, rubber tired gantry cranes (RTGs), rail mounted gantry cranes (RMGs), and straddle carriers. These various cranes are used for different purposes. For instance, a quay crane is used to load container vessels from dry land to the ship or vice versa; a ship crane moves containers on the ship itself from one location to another; straddle carriers and mobile cranes, like RTGs or RMGs, are used to handle containers on dry land.

In this chapter our focus is on the quay crane, which is also called a ship-to-shore crane (see Figure 4.1). The driver's cabin is positioned at a height of 30 meter on a trolley that runs to and from the quayside along the boom. Also part of the trolley, right in front of the cab, is the hoisting mechanism to which the hoist is connected. The hoist is part of the equipment that together with the spreaders connects to the containers. Because of the cabs position relative to the hoist the viewing angle is almost vertical (see Figure 4.2).





Figure 4.1 Quay crane or ship-to-shore crane at Thamesport, UK

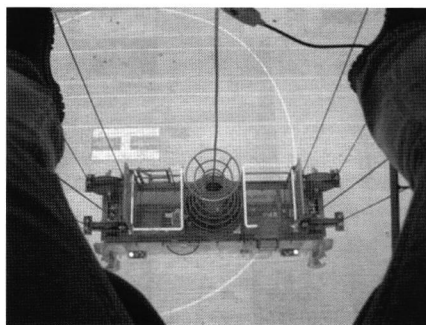


Figure 4.2 Crane driver's view on hoist and spreaders

The main job of the quay crane driver is to load and unload each container ship as fast as possible. The crane driver is located high in the crane to have a good view on his work. With joysticks he not only carefully controls the vertical and horizontal position of the container, he often also needs to control the swaying of the load. Because of the dangers and the required speed of work the job has a high mental load.

Usually, crane drivers also perform other tasks involved in container handling. If so, this may give some variation in the physical and mental loading for the crane driver, offering the opportunities to recover from the postural and mental stresses during crane driving.

## 4.2 Activities, postures and problems

The crane driver performs several activities. The viewing demands of some of these activities more or less dictate the crane driver's working posture. A lot of time is spent looking downwards while positioning the spreader on top of the container or positioning the container. Figure 4.3 shows typical examples of the working posture operators adopt. Typically the trunk does not remain straight and does not flex forward in the hip joint as sometimes depicted by simple manikins (see Figure 4.4-I). The hip angle remains around  $90^\circ$  and the trunk is flexed to a C-form (see Figure 4.4-II). The backrest can hardly be used. Because of this slumped posture the neck flexion is only moderate ( $20\text{--}30^\circ$  from neutral). The legs are spread to be able to view downwards.



Figure 4.3 Typical crane driver's posture

For short periods of time extreme variants of this posture sometimes occur. This can be when the crane driver wants to look over a container, thus not having to use a stevedore helping him handle a container out of sight (see Figure 4.5) or when he wants to see what is below and behind him while moving from ship to shore. He then sometimes may even lean with a hand on the floor, depending on the maximum viewing angle the cab allows.

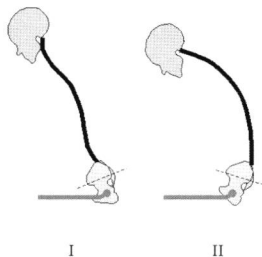


Figure 4.4 I Bending forward in the hip joint  
II Bending forward by flexing the spine to a C-form



Figure 4.5 Crane driver operating the crane in extreme posture

During crane movements toward the ship the viewing direction can be less vertical. The crane driver may take this opportunity to sit up straight for a short moment or stretch his back over the back rest which is often kept in its most an-

gled position. This is also the case when the crane driver needs to wait, for instance for a truck to unload the container on.

As illustrated above the crane driver's working posture involves slight to extreme back and neck flexion for prolonged periods of time. Prolonged bending of the neck and prolonged bending of the trunk are known as risk factors for the development of neck pain (Ariëns et al., 2000) and back pain (Hoogendoorn, 2001). In addition to the posture problems, the shocks of the cabin are an aggravating factor, therefore it is not surprising that many drivers have complaints. A study of Zondervan et al. (1989) mentioned that 64% of the crane drivers are suffering from back complaints and 42% of them from neck complaints, while Burdorf and Zondervan (1989) found a prevalence of back problems over the past year among crane drivers of 50% (see also Chapter 1).

Another point of concern is the mental load on the cabin driver, which may result from the pressure of responsibility, high demands on the pace of loading and unloading, and the severe safety instructions.

Other complaints that can be heard from crane drivers are bad climate conditions, noise and visibility.

### 4.3 A progressive new cab design

The question is whether a new design of the crane driver's seat and cab could solve the main problems. A promising attempt has been made by Merford, a Dutch manufacturer of quay crane cabs and other cabs.

Merford invented a new concept aiming at reducing the loads on the back and neck muscles and at the same time improving the outside view. The operator's bent forward posture is made easier by giving a new way of support. Within this concept, called Ergoseat (see Figure 4.6a), the support of the upper body is provided by the installation of two armrests with integrated controls, one on each side of the driver. These armrests are fully adjustable, which means that they can be adjusted in height, in a fore-aft direction and they can pivot towards each other. Thus, the driver is able to bend over with his body while leaning on his forearms. In addition, in the new concept the seat is no longer positioned on the cab's floor, but is suspended from the ceiling. This construction together with the armrest mounted controls allows for more glass in the cab's floor. The main viewing window can be extended underneath the operator and extra viewing

windows can be created to the left and right of the operator for viewing backwards. This idea was first elaborated in the Ergocab2000 (see Figure 4.6b).

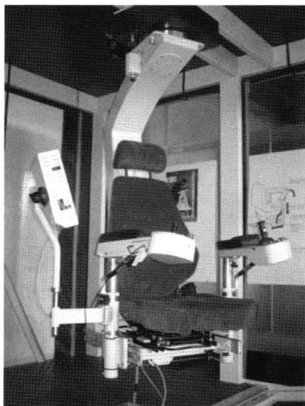


Figure 4.6a Ergoseat



Figure 4.6b Ergocab2000

To find out about the quantitative advantages of the Ergocab/Ergoseat compared to the more traditional cabins and seats for quay cranes, Merford asked TNO to make an objective comparison. Below are the results from a biomechanical analysis and a practical study performed at Thamesport in the UK.

#### 4.4 Biomechanical evaluation

Figure 4.7 illustrates the biomechanical context of the traditional working posture of a crane driver and of the new posture that he can adopt on the Ergoseat. The figure shows that differences in neck and trunk posture between the Ergoseat and a conventional seat are only minor. In the traditional seat the low back is under significant stress since the back muscles need to generate muscle forces to counteract the forward torque of the upper body. However in the Ergoseat a significant part of the weight of the trunk, head, arms and hands is carried at the armrests. The mechanical loading on the low back is thereby reduced.

On the basis of the total body mass of the operators, the body segment lengths, the orientation of the body segments and the measured pressure at the armrests we quantified this reduction. It appeared that the Ergoseat is capable of reducing the loading on the low back by more than 50%, compared to the traditional situation. (The torque at low back level was 58 Nm and 27 Nm in the traditional seat and the Ergoseat, respectively.)

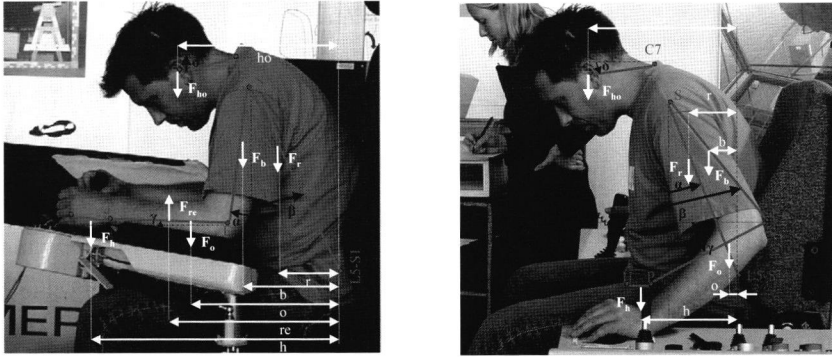


Figure 4.7 Ergoseat and traditional seat. Biomechanical context: forces and lever arms applied to operator in Ergoseat (left) and traditional seat (right)

With regard to the neck we did not find any significant difference between both types of sitting. Regarding the shoulder load the differences between seats are not clear. In the Ergoseat with arm support the stabilizing forces at shoulder level would be lower (e.g. Attebrant et al., 1997). However, this decrease in internal shoulder load might be counterbalanced by the muscle activity that is required at shoulder level when leaning on the armrests with 30-40 N per side as measured. Nevertheless, a clear advantage of the Ergoseat is the potential variation in shoulder load over the day: the crane operators may vary the load on their shoulders (and low back) by varying the extent to which they lean on the arm support (ranging from total support to none). In contrast, in the traditional situation the loading on shoulder and low back level while operating the crane is constant and continuous!

#### 4.5 Practical evaluation

To find out about the experiences with the Ergocab in real life, TNO conducted a comparative study at Thamesport in the United Kingdom. Quite an ideal research situation was found, as the container terminal had six quay cranes in operation, two of which were equipped with an Ergocab. Operators were used to operating both type of cranes and regularly switched between cranes. Hence, we could make a clear comparison between the work in the Ergocab and the work in a traditional cab. For this comparison, we observed nine operators during a two hour shift in both the Ergocab and the traditional cab. During this shift the op-

erators were observed, they were interviewed, they filled in a questionnaire and they were recorded by video. Table 4.1 shows the results of several questions in which the operators were asked about their cab preference with respect to several aspects.

Tabel 4.1 Number of operators preferring the traditional cab or the Ergocab (or no preference) with regard to general cabin aspects, the seat and the operation of joysticks

	traditional	Ergoseat	equal
<b>Cabin in general</b>			
Which cab offers the best view for your work?	1	8	0
Which cab offers the best climate conditions on hot and sunny days?	0	9	0
Which cab offers the best climate conditions in winter time?	0	7	1
Which cab do you prefer regarding noise and sound?	0	6	3
Which cab do you prefer regarding vibration and shock absorption?	0	9	0
Which cab do you prefer regarding sense of space?	7	1	1
All in all, which cab do you prefer?	3	5	1
<b>Seat</b>			
Which seat offers the best adjustment?	2	6	1
Which seat offers the most comfort?	3	5	1
Which seat has the best shock absorption?	0	9	0
<b>Joystick operation</b>			
Which joystick controls allow you to work most precisely?	4	4	1
Which joystick controls allow you to work the fastest?	5	4	0
Which operating station offers the most comfort?	4	5	0
Which operating station lets you control and position the spreader the best?	4	3	2
Which operating station is easiest to operate the flippers?	7	2	0
Which operating station lets you pick up a container faster?	3	4	2
Which operating station lets you pick up a container easier?	2	4	3
Which operating station lets you control a swinging container the best?	3	2	4
All in all, which operating station do you prefer?	4	4	1

Concerning the general cabin aspects, the Ergocab is preferred above the traditional cab. The outside view, the climate control (in heat and in cold), the noise insulation, and the suspension are all considered to be better in the Ergocab/Ergoseat. The only aspect they find not to be improved in the Ergocab compared to the traditional cabin is the 'sense of space'. This is quite clear since the

tested Ergocab was narrower than the traditional cab. The Ergoseat is also used in cabs with a more traditional appearance.

With regard to the seats one could say that the Ergoseat is preferred above the traditional seat, mainly because of its suspension characteristics and its larger adjustability. Those who prefer the traditional seat do this mainly because the back of the seat can be set back further. Operators left it in this position and stretched their back whenever they could. A feature of the Ergoseat that was widely appreciated was a wedge in the front part of the cushion. Not only does the seat no longer obstruct the view, leg support is also maintained while sitting with legs spread.

When asked about preference for joystick operation, the results are not clear. Some prefer the traditional, while others prefer the new situation. This result might be explained by the fact that the Ergoseats under investigation were equipped with joysticks that were somewhat too long. The larger for-aft travel of these joysticks and the use of armrests do not go well together. In fact, to some extent the armrests may even hamper the control of the joysticks. The latter would not have been the case, had smaller (mini) joysticks been used. Originally, the Ergoseat is specifically designed for application of finger operated mini-joysticks.

## 4.6 Conclusions

The Ergoseat is a good example of an attempt to improve posture, comfort and view by use of an advanced cab and seat design. The main conclusions from the evaluation are:

- the Ergoseat reduces the static loading on the low back by more than 50%;
- the Ergoseat provides the possibility for the crane operator to vary his body posture and, thereby, vary the load between the shoulders, upper back and lower back. Hence, internal structures in the back and shoulder can recover during work! Fatigue can be postponed;
- the armrests of the Ergoseat stabilize the trunk, which may further reduce the back load in case of shocks or vibrations. Though not tested it is quite likely that the armrests in combination with the seat's ceiling mounted suspension also reduce the influence of shocks and vibrations on stability of control because of the integral suspension of the seat and armrest mounted controls. This is different from most traditional seats in which only the seat is suspended and the controls are not;

- the outside view in the Ergocab is improved. Crucial in this respect are the seat's suspension from the cab ceiling and the armrest mounted controls. This eliminates any view obstructions by the seat and traditional control consoles. It also creates the possibility to improve outside view by extending the floor window pane underneath the seat and add windows to the seat's side. Also of importance are the reduced sill dimensions of the front and side windows and the introduction of a wedge in the seat pan;
- the Ergoseat is considered comfortable and is appreciated for its features;
- it is not unlikely that the Ergocab/Ergoseat will improve performance. A better view, less discomfort, less physical loading and less fatigue are all factors that may well increase task efficiency. Furthermore, it can be assumed that the armrests will provide more stability, which is specifically needed for high precision tasks. (In an additional comparative study on the performance at a computer-simulated crane task we found that the Ergoseat with small joystick grips scored slightly better compared to a traditional seat with no arm support and larger joystick grips);
- the Ergoseat may have a positive effect on health as two main risk factors are clearly reduced. First, the magnitude of the load on the low back is reduced by more than 50%. Secondly, the operators may vary between body positions, thereby breaking the monotony of the load and offering the chance on recovery to body structures.

The present study also provided some other issues that need to be stressed here.

- It has become clear that the armrests on the Ergoseat are less suitable for application of larger joystick handles. Therefore, the Ergoseat is recommended particularly in combination with mini-joysticks.
- Within the current design of the Ergoseat it is quite difficult to stretch the back during micro breaks in the cab. This aspect may be improved in the near future.
- A traditional seat requires a larger cabin compared to the Ergoseat. This might be advantageous in that a smaller cab can be applied. However, one should be aware of a potential drawback on the operator's 'sense of space'.
- The Ergoseat with its large variety of adjustment possibilities and its mini-joysticks requires a good introduction and some time to get used to as this differs from what most crane drivers are used to.



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## 5 Cabin ergonomics and comfort of compact sweeping machines

*Annemieke Leegwater*

*Current developments bring new challenges for the design of compact sweeping machines. In general, there is a growing attention for a healthy working environment. In addition, the operator has more demands with regard to his comfort and the ease of operation of the machine. These demands increasingly affect purchase decisions for new machines. To find opportunities for the future generation of sweeping machines TNO and a main producer of sweeping machines performed a project, addressing the issues of health, comfort and ease of operation. This chapter presents the outcome.*

### 3.1 Present design

Compact sweeping machines are primarily made for the mechanical cleaning of alleys, paths, gutters, streets, market squares and road maintenance. A sweeping machine is in fact a large driving vacuum cleaner: two brushes spinning towards each other collect the muck off the street and move it towards the nozzle of a vacuum unit in the middle front of the machine, under the cabin floor. With great power the street dirt is vacuumed up into a build-in container. On board there is also a water tank from which nozzles spray a water film, to prevent dust getting blown up by the wind, and to bind the dirt in the container. The removed muck contains mainly plastic, paper garbage, leaves, grid, sand and water. An increasing amount of machines are equipped with a third brush, which is mounted in front of the machine. This third brush can be moved sideways and is exceedingly suitable to remove weeds between the pavement, to reach corners and to clean wide paths.

The main task of the machinist is to drive the machine safely, and simultaneously to operate the brushes and vacuum unit. The machinist has to concentrate on the traffic and public movements and on the work that has to be done properly. The tasks of the machinist are complex and demand substantial mental and physical effort. On top of that, the work includes environmental stresses on the machinist when dealing with aggravating circumstances as rain, coldness, (extreme) warmth and darkness.

The driver seat is at the right side in right-driving countries, so they have a good view on the right hand brush when cleaning the gutter at that side of the road and can easily move around the parking cars. For driving, this seat position is on the other side of the vehicle than usual.

Roughly, there are two types of sweeping machines, namely the big truck mounted machine and the compact machine (see Figure 5.1).

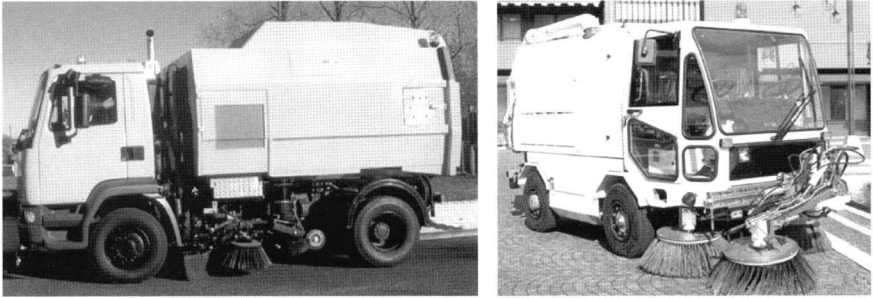


Figure 3.1 Truck mounted versus compact sweeping machines

The first is mainly used in the outskirts of cities who have a large scattered working area. The truck has more speed potential than most compact sweepers and is therefore appropriate for long distance driving. The cabin is spacious and is comfortable, dependent on the type of trucks. The container has, generally speaking, a larger capacity than the compact sweeping machine, which is mainly used in the urban areas.

The compact machine is designed mainly for the cleaning of small lanes, public footpaths, gutters, market squares and driving under porches and underpasses. In this machine the machinist has a better view on the working area, the brushes and the environment, and the machine is more manoeuvrable compared to the bigger truck mounted machine. Therefore, the work can be done more accurately, while the risk for any traffic accident is less. For a good view on the right brush, which is mounted just in front of the front wheels, a mirror is installed. By the windows in the front, the door and the cabin floor the operator can have a direct view on the right brush, on the third brush (in front of the machine), on the dirt on the street, and on the vacuum nozzle. Because of its compactness the cabin's inner space is restricted.

This project was aimed at the improvement of the design of the cabin of the compact machine.

## 5.2 Bottlenecks in present design

What can be improved in the design of the compact machine? How can we create more comfort and a good outside view on the tasks and the traffic within the restricted space within the cabin? To find answers we needed a basic investigation into the bottlenecks of the current design. This investigation comprised:

- a study of the documents about the layout of the present concept;
- a demonstration of the compact machine's functions by an instructor;
- interviews with staff members of the manufacturer about their ideas of improvement;
- observations of and interviews with five experienced operators during work (each for several hours) to analyse their working actions and to obtain their experiences and ideas about the functioning and ergonomics of the machine;
- interviews with supervisors of the machine operators and with ergonomic experts/advisors about their ideas of design improvement;
- a categorization of the results into ten main bottlenecks.

One of the main bottlenecks found concerns the static and awkward body postures that are adopted during the work. These postures comprise lateral and forward bending and rotation of the head and trunk. Hence, it is not surprising that the literature mentions neck and back pain as the predominant health problems for operators of sweeping machines (Massaccesi et al., 2003).

The observations showed us a remarkable variation in body posture across the five operators. The adoption of body posture seems to depend largely on individual strategy to perform the job and on individual preferences. For instance, some operators use the mirror to look at the right brush, while others prefer a direct view on the right brush through the window, which has a significant impact on the upper body posture. One of the operators had even an extra mirror fitted to see the right brush, to reduce bending of the neck. Another source of variation is the varying stature of the operators. Finally, the lack of support for the left arm, inviting some of the operators to lean on the steering wheel, leads to variation in posture.

During the interviews the drivers surprisingly did not mention their awkward body postures although clearly occurring frequently and for long periods of time. From all observations and interviews we categorised the obtained bottlenecks, which resulted in a list of issues. Generally speaking, cabins in this kind of machines are too small in relation to the required tasks performed. There are definitely possibilities and requirements to improve the cabin but this will lead to

contradictions. To name one is more height required in the cabin but the total height of the machine is already at the maximum and lowering the cabin floor is impossible because of the structure and the vacuum equipment.

Examples of the issues leading to unwanted postures are shown in Figure 5.2 and 5.3.



Figure 5.2 A preferred view on the right underbrush leads to an awkward body posture



Figure 5.3 The armrest with operating system dictates the operator in a fixed position

### 5.3 Future design

On the basis of the investigation results, TNO experts and manufacturers held a brainstorm session. The purpose was to address the main issues to be improved in a new to design compact sweeping machine.

It appeared that the ideas that were discussed could be clustered into two themes 'sight and view' and 'space, sitting position and layout operating system':

- to improve the view capabilities particular sensory aids are mentioned, for example lane keeping system, camera systems and pop-up displays, acoustic signal system, robotics and sonar aid;
- to improve sitting positions some options were mentioned and must be investigated to increase the space in the cabin and to modify the operating elements in relation to the seat.

## 5.4 Conclusions

The main challenges for cabin innovation in sweeping machines are to improve the basic body posture of operators (of varying stature) by changing the cabin size, optimising the body fixation points and using the aid of detection systems, to reduce the risk of injury by both robotizing regular sweeping functions and improving the positions of the controls and their way of handling, and finally, to improve the physical environment and to prevent fogging windows by optimising the climate control system.

By improving the ergonomic layout of the cabin we expect to promote comfort, to improve performance and to reduce the health problems as neck and back pain.

Based on expert view (and following the ergonomic standard for lorry cabins), the cabin of the compact sweeping machine can be considerably improved by applying modern technology such as sensory aids, lane keeping system, robotics, camera monitor systems and further automation of the manual task.

The left brush is sometimes used to clean the left gutter of the road. This task requires improvement in order to eliminate the unfavourable working posture (rotation of trunk and neck) as well as losing all view on the environment.

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## 6 Improving Earth Moving Machines: Mind the Details!

Frank Krause, Maarten P. van der Grinten

*This chapter addresses the final results of the Eurocabin project in which three medium sized companies together with TNO explored how their machinery could be improved. The focus was on how to further innovate and optimise the cabins of the machines.*

*The improvements were based on the problems spotted by experts and mentioned by end-users. Those improvements are in fact details. However, the details solve problems and in the re-test the end-users mention that most details have a positive effect on comfort and even on work output. They did create a changed cab.*

### 6.1 Keeping up with large competitors

When we interviewed over 300 operators of construction machinery (Kuijt-Evers et al., 2003), one thing became clear: they wanted power! This is actually quite logical because the operator wants to perform the job and cannot do this if insufficient power is available. Of course if the operator has a boss, he too will be satisfied mostly by the operator's output.

However, this doesn't mean that no attention needs to be paid to the operator's comfort. On the contrary. If you want to get the most out of the machine's power over a long period of time, the operator must be able to perform in an optimal manner. Therefore the machine must be optimally attuned to the operator. Especially in those cabs where operators spend eight hours or more in the cab, you would want the cab to be comfortable.

Large OEMs<sup>2</sup> are expected to have large resources available for research and development in this field. Also the large production numbers make it more profitable to apply materials in rounded forms, thus giving machinery a modern car-like interior and exterior. Small and medium sized enterprises (SMEs) could be at risk to fall behind and lose competitiveness. To further innovate their machinery and thus try to secure a competitive position, three medium sized manufacturers formed a consortium and founded the Eurocabin project together with TNO as R&D partner. The project was partly funded by the European Union. The companies concerned were Maschinenfabrik Paus GmbH from Germany, Van Vliet b.v.

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<sup>2</sup> OEM - original equipment manufacturer.



(manufacturing ETEC machines) from the Netherlands and Kaiser AG from Liechtenstein (see Figure 6.1).

The goal of this project was to further innovate and optimise the cabins of the machines.



Figure 6.1 The companies concerned and their machines

For one thing it became clear that with these SMEs their size was also their strength. Because of their size all involved departments of the company (service, design, sales) stand close to their customer. Furthermore they are able to adapt faster to their customers' needs, even if individual. Nevertheless expert support was valued to progress in the field of comfort and ergonomics.

This chapter describes the changes that were made to two of the three machines to improve comfort. Characteristically, no very expensive and impressive changes were needed to improve the operator's comfort, most improvements lie in the detail.

## 6.2 How to give the operator what he wants

It is our strong opinion that designing the best machine possible requires the involvement of experts and end-users as will become clear when reading this chapter.

For this project we took the following steps to secure that the end-product would appeal to all users (Vink and Kompier, 1997; Noro and Imada, 1991).

Step 1: getting to know what the machine does and what is done with the machine

This served as a first orientation on the type of work and machinery and was very important in order to be able to ask the right questions to the operators.

**Step 2: end-user's opinion**

Gaining access to the opinion of large numbers of operators is difficult in this type of machinery, due to the fact that you will seldom find large numbers of the same machine within a close range. Notwithstanding its time consumption we tried to visit as many operators as



Figure 6.2 Discussions with end-users

possible to observe their work and interview them (see Figure 6.2). Extra information was gathered from questionnaires sent by the manufacturer to specific operators. Sometime phone calls were made to clarify answers. The information we got from interviewing more than 300 operators at the Bauma regarding comfort aspects (Kuijt-Evers et al., 2003) was used as background information.

**Step 3: expert opinion**

A group of experts studied the machines, sometimes with specific evaluation methods to study the fit (with ergomix) or to study vibration or noise.

**Step 4: adaptation proposals**

Based on the end-user opinion and expert evaluations the main problems on the specific machines were described and improvement proposals were defined.

**Step 5: first redesigned machines**

Based on the advice some machines were redesigned and were tested by end-users again.

**Step 6: implementation in the new production process**

In this step the companies decided which changes would be standard in the new machines, which ones could be bought as an additional feature and which would not be implemented.

### 6.3 The changes that improved comfort of the Paus machine

#### *Ingress-egress*

From the previous steps it was known that ingress-egress often takes place between 20 and 50 times a day. Each time the height difference between the ground and the cabin (approximately 1.2 m) needs to be mastered. Therefore improving ingress-egress was considered to be important, with respect to both ease and safety.

To do so the climbing aid's grip diameter was increased to 25 mm and the hand clearance between climbing aid and cabin was increased to 65 mm, thus improving the feel of the grip and the ease with which the grip can be grabbed, even with gloves. The steps were also modified: all step heights are now more or less equal and a third strip was added to each step. This increases step depth to improve the stability for the foot (see Figure 6.3).



Figure 6.3 The step modification: left the old situation, right the new situation

Operators were mostly satisfied with the offered ingress-egress helps (steps and grips). All operators find the new grips more comfortable, yet all state that they still require the same amount of strength for ingress-egress. This can be explained by the fact that the height difference between ground and cabin is still the same. They find the new steps more comfortable and safer though it requires getting used to because of the changed step height.

### *Seat*

The seat height adjustment range was lowered 30 mm to improve seating, especially for smaller persons. This was achieved by modifying the seat pedestal. A necessary elevation of the seat can be effected by means of spacer blocks.

The lowered seat height was mostly appreciated. Surprisingly one small operator was not pleased with the new height. He liked to use the seat in the highest position to be able to have a good view on the ground and the shovel, because he had less 'feel' of the machine. This can be explained by the fact that more than one driver often uses this type of machine for generally short periods of time. For drivers it is harder to acquire the same feel of the machine as an experienced driver.

### *Steering column*

A steering column being adjustable in height and inclination was installed (see Figure 6.4). At the same time changes were made to the dashboard support, the support structure in the cabin floor and the cabin matting. This was done to reduce rattle, an annoying feature of the older cabin.

The new adjustable steering column is very much appreciated. All operators found that they could now find a better seating position in the cab. Additionally, operators all agreed that ease of ingress-egress had improved because the steering wheel folds away with one easy lever movement increasing the space for the body movements.



Figure 6.4 The new adjustable steering column

### *Dashboard*

The instrument board was changed completely according to TNO's design suggestions (Figure 6.5). This implied constructing a new casing, re-grouping gauges, control lamps and switches, changing electric wiring and building a new steel support for the casing. In the redesign process and in the manufacturing careful attention was paid to avoid rattle and squeak of the new dashboard.

Other aspects that were considered in the design were avoiding reflections and making the machine easy to maintain. The latter was done because Eastern Europe is a target market and the owner mostly does servicing is mostly done by the owner.



Figure 6.5 Dashboard improvements

The operators evaluate the new dashboard as equal to the former model. They do not notice the improved layout of gauges and switches, most likely because the amount of time spent looking at the dashboard is very small. Also, the quality and speed of work are not affected by the way the dashboard is laid out. They do find the new dashboard more appealing to the eye than the previous model.

### *Controls*

The possibilities to adjust the joystick relative to the driver are now limited, due to the design of the control console. Adjusting the seat for optimal viewing and operation of pedals could result in a sub-optimal joystick position. Therefore an increase in adjustment of the joystick or control console was proposed. Grammer, a large manufacturer of operator seats, cooperated in the project and came up with a new and important prototype seat with a multi-adjustable armrest to which the joysticks can be attached. Such a system is preferred because a seat adjustment does not lead to a changed position relative to the joystick. Further, the adjustability of the joystick relative to the driver is increased and the seat offers good arm support. Unfortunately it could not yet be built in the test machine and therefore was not tested.

### *Climate*

In the Paus machine as in the other tested machines climate was a point often mentioned by operators. Due to large glass surfaces, heat build up can easily take place on sunny days. Therefore many would appreciate having air-conditioning in their cab. However, installing air-conditioning is not necessarily a solution to the problem as operators prefer to work with the door or window open, for reasons of outside view, communications and sense of space. The desire for air-conditioning is also likely to be connected to the fact that their luxury cars often have air-conditioning as a standard feature. In most machines air-conditioning is already optional.

Installing air-conditioning as a standard feature was economically not feasible. A simple and feasible measure to at least reduce blinding by the sun was attaching a sun protection foil (green) to the upper part of the windows.

Besides this basic problem, another problem was the insufficient defrosting of the windows. For defrosting and defogging new air routing systems were built in the machine. Together with the new instrument the defrosting unit was changed. The purpose was to create more vents. Two additional vents aimed at the side panels of the front window were especially needed to defrost this window (see circled part in Figure 6.6).

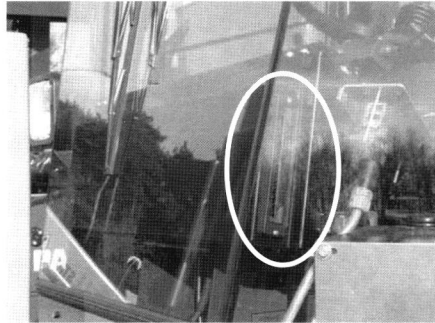


Figure 6.6 Improvements in the defrosting and defogging vents

### *Mirrors*

The mirror suspension was a problem in the old machine. The inflexible part of the suspension protruded too far from the cab and the flexible part was too small (see Figure 6.7 left). Often mirrors and mirror suspension got damaged. The improvement is shown in Figure 6.7 to the right. Operators all find the new mirror suspension an improvement compared to the older machine. The risk of damaging cab structures when the mirrors collide with a tree or similar protruding object, has become a lot smaller. The view through the mirrors remained equal.

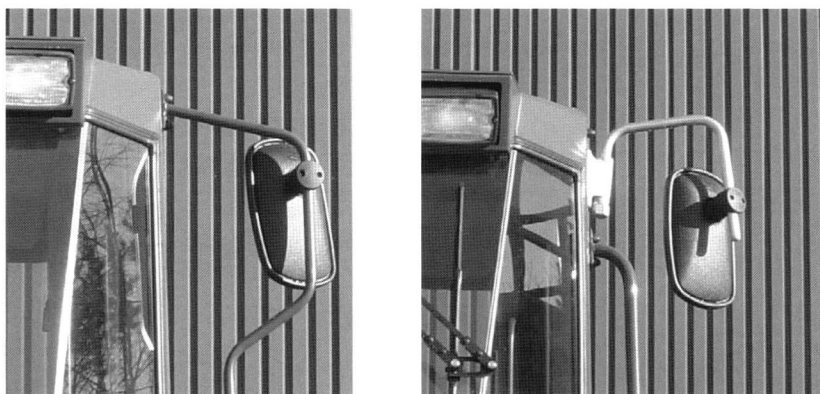


Figure 6.7 Mirror suspension: left the old inflexible situation, right the new flexible situation

### *Noise*

To reduce interior noise the following measures have been taken:

- the flexible sealing which was used to connect the three windows that form the front and rear window, was replaced by a stiffer glue to reduce resonance at idle engine revs;
- steering column and instrument casing were designed and mounted paying careful attention to the avoidance of rattle and squeak;
- insulating material under the cabin bottom plate was thickened (from 15 to 30 mm);
- openings around the engine were closed and damping measures were taken for the engine air intake and engine cooling. Careful attention was paid not to disturb the engine's heat balance.

The measures that were taken to reduce interior noise in the cabin, have had effect according to the operators. They all find that the sound level is lower and more pleasant in the new machines.

## **6.4 The changes that improved comfort of the Kaiser machine**

### *Seat*

The choice of seat suppliers is limited. There are only a few major players in the market. From questioning the operators it became clear that operators in general rated the seat itself as fairly comfortable. Improvements were desired with respect to the following aspects:

- armrests: they were considered to be very important. The seat offered sub-standard armrest adjustability and comfort. Some seats come without armrests in which cases armrests are often fitted onto the joystick console (see Figure 6.8). Operators often complain about the width, hardness and improper height of armrests;
- adjustability: adjustment levers are often not easy to reach and require too much pressure to be operated. Also, it is often unclear what the lever's function is. Weight adjustment of seats with mechanical springs is difficult. As a result, the adjustment is often not done;
- suspension: seat suspension can still be improved. Several operators complain about the seat bottoming out, which leads to peak forces on the lower back. Also the damping characteristics of the air suspended seats change with the chosen seat height.



Figure 6.8 A console mounted armrest has poor adjustment qualities (here mounted in a wheelloader)

Obtaining these improvements was not possible inside the project. Buying a more expensive seat from the seat supplier would not necessarily solve the problems and in the market, being as competitive as it is, construction companies are not willing to pay for many extras.

However, one improvement could be made. The seat's adjustment range was larger than needed. By restricting the range extra storage space was created in the very confined space of an excavator cab.

#### *Ingress-egress*

Also, with the Kaiser machine the grips were improved. This was expected to be an improvement as operators step in and out of the machine 20-50 times a day. The grips were extended downwards to be able to catch them standing on the ground or climbing up one of the legs in steep terrain. In general the extended grip is appreciated by all but one test operators. This operator finds the grip equal to the older type. Surprisingly the questionnaires show no increase in safety experienced by the operators due to the new grip. This may be caused by the fact that the prototype was hardly tested in very steep terrain, in which the new grip would show its qualities best. The retest further revealed a new operator wish that was not recognized in the first testing. The test operators also



wanted to have a grip on the left inside of the door opening. This is further investigated.

### *Pedals*

This type of excavator is designed to work in very difficult terrain (see Figure 6.9). Foot rests were added to improve operator support possibilities while working with the machine in a tilted position. Also, the outer pedals were turned 10 degrees to enable a more neutral position of the leg and foot (see Figure 6.10). A foot switch requiring frequent pushing and 90 degree turning, was removed and its function allocated in a joystick switch.



Figure 6.9 The Kaiser machine of this study

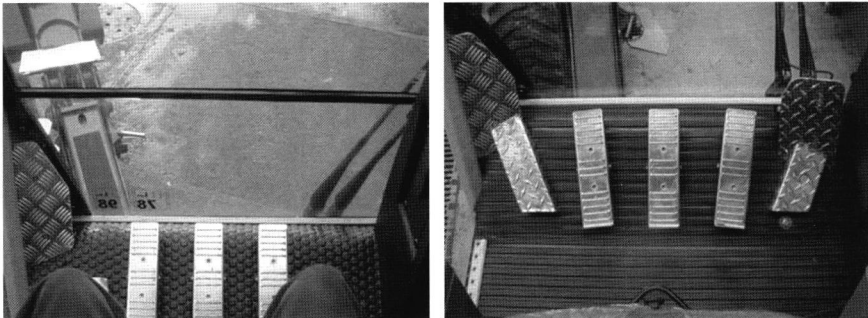


Figure 6.10 The position of the pedals: left the old configuration, right the new one

Though corresponding with a more natural foot position operators did not find the changed position of the pedals better than the parallel position. Neither did they find them worse.

Operators appreciate the fact that they no longer have to operate the switch with the foot. The operators had different opinions about the new footrest to the right. Some said it was not needed. However, as it hardly obstructs the operator's view, they agree that it should be left in place. The new footrests in front of the tilted foot rests are appreciated by the shorter operators, though they should be extended a bit toward the operator. As one operators stated: he likes the seat

up high so the air suspension in the seat works properly. With the new footrests it is easier to reach the floor.

### *Joysticks*

A thumb-operated switch on the joystick that, when used, needed frequent depressing during longer periods of time, was replaced by a switch operated by the index finger (see Figure 6.11 left and middle) thus improving its position. By doing so the above mentioned foot switch could be replaced by a joystick switch to improve handling and reduce leg load. This switch had approximately the same position as the first mentioned thumb-operated switch, only higher up on the joystick to improve thumb position (see Figure 6.11 right).



Figure 6.11 The frequently used thumb-operated switch on the joystick (left) was replaced by an index finger operated switch (middle). The foot switch was replaced by a joystick switch (right: lower middle switch)

In a meeting with six experienced operators their opinion was asked and an expert checked whether different hand sizes could operate the switches safely. With respect to joysticks operator preferences vary greatly. A consensus was reached that the joystick would definitely need getting used to. However, it was better than the existing one. The switches have a better position, the joystick is lighter, therefore the operating force can be reduced and it fits to more hands than the older type.

### *Front window*

The opening mechanism was improved, thus significantly reducing the load on the operator's shoulders and back. The standard pane was replaced by special heat reflecting glass reducing heat build-up from radiation in the cabin. Half of

the test operators finds the changed window sliding system easier to operate, the other half finds it equal to the older type. One operator finds it easier, but he also believes that one has less control over the closing of the window when the cab is tilted forward. The effect of the heat reflecting glass could not yet be evaluated.

#### *Heat regulation*

The position and design of the air vent near the feet was changed in order to prevent inadvertently closing the vent with the foot. Also, heat regulation in the cab was difficult because of a hard to control regulation switch. The regulation switch was replaced by a better one. All operators find the new position of the air vent better. They also found that the new switch enabled them to adjust the temperature better than before.

#### *Noise*

Several measures were taken to reduce the noise among which the padding of the cab's outside floor and side panels (see Figure 6.12). Though measurements reveal a decreased interior sound level of 5 dB inside the cab, most operators had not noticed this due to the fact that they mostly work with either the front window or the door open. Measurements had been made with both door and window closed. Surprisingly the retest brought another fact to the light that had not been noticed previously. One operator experienced an increase in cab noise while working with an opened front window compared to a closed window. This may well be caused by the reflecting of noise against the window. In open condition the window covers the padded cab ceiling. This certainly deserves attention in the future.

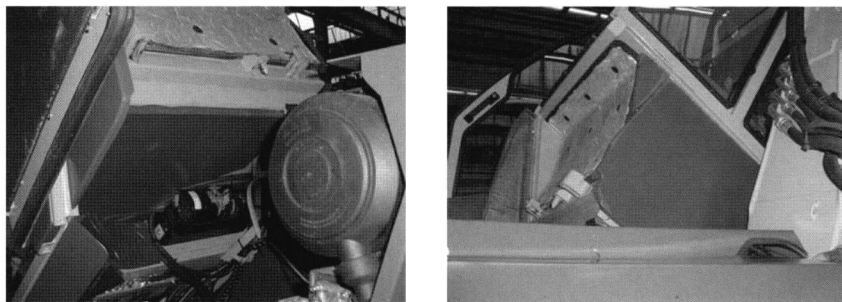


Figure 6.12 The padding of the cab's outside floor (left) and side (right) panels with sound insulating material

## 6.5 Conclusion: it pays to mind the details

The above mentioned improvements are in fact details. However, the details solve problems mentioned by end-users and in the retest end-users mention that most details have a positive effect on comfort and even on work output.

The retests showed that as a whole the prototypes have better cab comfort than their predecessors, due to the various small improvements in the seat, controls, climate, view and noise. An important step in work related musculoskeletal risk reduction in the arm was taken together with seat manufacturer Grammer who designed a multi adjustable armrest on their seat to which a joystick can be mounted. This was the first seat-control system for earth moving machinery where armrests and joysticks are adjusted together and therefore are easier to adjust by the operator and offer a better positioning of the controls relative to the operator.

In the final meeting of this project the companies mentioned that they considered the retest to be a very important part of the project. Through this the effects of improvements were explicitly known by the manufacturers. Although the improvements were based on the problems mentioned by end-users, they did create a changed cab. Only retesting by end-users could reveal whether the right adjustments to the cab were made. With this information manufacturers are better capable of making plans for their future products. This is very important considering the competition in this market sector.

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## 7 Controls in Future Earth Moving Machines

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*The last 25 years the application of joysticks has increased. The use of the joystick in computer gaming is nothing special anymore. Nowadays, joysticks are also applied for professional use. For example, in the latest earth moving machines these joystick controls are almost standard. They are used for instance to steer the boom or the bucket. In other vehicles the application of joysticks is increasing as well. Even experiments are done with joystick steering in passenger cars. In this chapter we explore whether a new way of steering has positive effects. We also compare controlling the speed of a movement versus the position of a movement.*

### 7.1 Introduction

Whether designed for fingers or palms, or combined with buttons for extra functions, there are many different forms of joysticks (see Figure 7.1). There are also different ways for their movements to influence functions; for example, forward-backward movement could influence the position or the speed of the shovel. No empirical scientific studies provide criteria for choosing the best joystick for a specific task.



Figure 7.1 Some examples of joysticks

In this study it is explored what the disadvantages and advantages are of the use of different joysticks. Three main themes are addressed:

1. orthogonal steering

In 'orthogonal steering' movements along straight horizontal and vertical

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lines are controlled. In this theme the issue is whether this is favourable compared to the traditional way of steering the machine cylindrically;

2. form of the joystick

This theme questions what the advantages are of a new developed joystick;

3. speed or position

This theme regards the advantages and disadvantages of controlling the speed of a movement versus the position of a movement.

## 7.2 Current design

As is seen in Figure 7.1 the current joysticks used in earth moving machines look like joysticks used in computer gaming. Some ten years ago large lever controls were replaced by these joysticks in earth moving machines. As a consequence large forceful movements are replaced by small localized movements (Krause, 2003). Another type of joystick is the finger joystick, which is controlled by one or two fingers. This finger joystick localises the muscle efforts even more. In discussions with drivers of earth moving machines they mention that for precision tasks the finger joystick works better. The selection of a joystick is now mostly made by the manufacturer and it is based on common sense and experience. There is no firm knowledge base to support the decisions concerned.

## 7.3 Current problems

As is mentioned above a major problem in designing a new earth moving machine control system is that criteria are missing based on empirical data. One criterion has some empirical support: joysticks could lead to end-user complaints. At least 20% of the operators of earth moving machines indicate that joysticks need to be improved (Kuijt-Evers et al., 2003). Also, in the wood industry problems with joysticks are mentioned. In a cross-sectional study among 1,174 wood-industry operators, half of the operators reported neck/shoulder complaints (Pontén, 1988). One third of the operators ascribed this to the joystick.

Research among 300 operators of earth moving machines showed that the change from the large lever controls to joysticks is seen as an improvement (Kuijt-Evers et al., 2003). So, the joystick will probably be introduced on a large scale the coming years. However, the same study shows that 20% of the opera-

tors are still not satisfied with the applied joysticks. Sometimes the joysticks are fixed to the console and have little or no adjustability. Sometimes the armrests cannot be adjusted to give the lower arm support while the hand is on the joystick. Often if the operator adjusts his seat to get a proper seat height, the joystick does not follow. In general, solutions for these problems are available. In fact, the solution is to make the joystick position adjustable. However, it is also important to reduce the static load. So, freedom in body movement is also needed.

Apart from the health problems it is important that joysticks facilitate high quality of work and speed of the job with limited time requested for learning how to use the joystick. However, an ideal design is still unknown. This study explores the three themes to stimulate a better performance.

## **7.4 Possible solutions**

In the future drive by wire will be introduced in earth moving machines. According to some manufacturers this will be available in 5 years from now. This makes it possible to introduce new control techniques based on the possibility to manipulate the electronic signal with microcomputers and software. Hereby the freedom for choosing the steering system increases and knowledge for making the right choices is needed.

### *7.4.1 Orthogonal steering*

Traditionally, a joystick controls a cylinder that rotates a part of a machine. This means that movements in circles are directly steered (see Figure 7.2, at the left). Wallersteiner et al. (1993) described another steering principle for log loaders in the wood industry: the orthogonal principle. We applied this to an excavator. This means that a forward-backward movement of a joystick controls a horizontal forward-backward movement of the shovel and the forward-backward movement of the other joystick controls a vertical movement (see Figure 7.2, at the right).



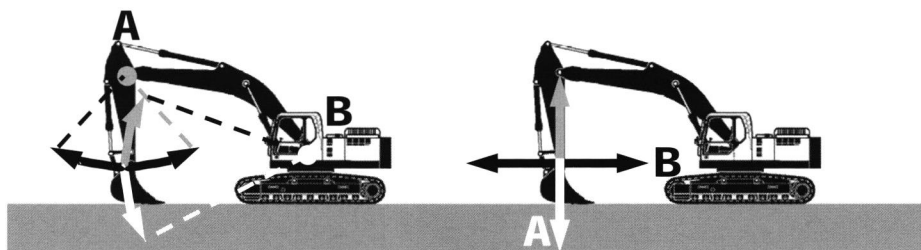


Figure 7.2 Left side: the traditional way of steering. The joystick movements control the rotation of different parts of the shovel  
Right side: the orthogonal steering principle. The joystick movements control a horizontal or vertical movement of the shovel

To test orthogonal versus traditional steering a scale model was made of an earth moving machine (1:10) and tested by seven subjects. This machine was controlled by joysticks attached in the front of the armrest of a seat. Four subjects started working with the orthogonal technique, which means that a forward movement of the joystick resulted in a forward movement of the shovel. After a break they worked with the traditional method, where cylinders were steered. The other three subjects first worked traditionally and then orthogonally. Four tasks had to be completed:

- moving along horizontal lines (simulating levelling);
- moving along slope lines (simulating talus work);
- touching several points (simulating earth moving);
- touching points close to each other (simulating digging between cables).

The number of movements (indication for efficiency and musculoskeletal load) was significantly lower in all tasks for orthogonal steering. In general the orthogonal steering principle was preferred by all seven subjects. For specific tasks some differences are shown. In moving orthogonal steering was preferred by all subjects. For the last two tasks (touching) three subjects mentioned no difference and three preferred orthogonal steering. One subject saw no difference in touching several points, but preferred the traditional way with points close to each other.

We conclude that there is an indication that orthogonal steering is preferable.

### 7.4.2 Form of the joystick

To study the effect of the form of the joystick a new design was developed as a more logical connection to the task. The new design was compared with a traditional joystick to learn more about the effect of the form.

#### *The design process*

Based on the new possibility of 'drive by wire' and on the preference for orthogonal steering the designing of the new control started with ideas. Some of these ideas were materialized and tested by subjects. Based on discussions with experts in the field of ergonomics (to prevent health problems and increase the job quality and speed) and by tests of preliminary controls with subjects, three concepts were further developed. The three concepts were presented and discussed with experts in the field of ergonomics. This gave input for the final designs for the new controls to be referred to as: 'ball', 'unfixed' and 'wheel'.

In the concept 'ball' (see Figure 7.3) two functions are separated and controlled by two different muscle groups. Positioning the handle forward and backward generates the front-backward movement. Rotating the ball clockwise and counter-clockwise controls the sideward movements. The theoretical advantage should be that the two movements can be steered separately.

The concept 'unfixed' (Figure 7.4) is in fact a bar with two balls approxi-

mately the size of a tennis ball. Changing the distance between the balls steers the left-right motion of the shovel. Hand pads can support the hands.

The third concept 'wheel' (Figure 7.5) is close to the current joystick. However, two joysticks are connected together to form a kind of a large steering wheel. Pushing the left side downwards results in an upward movement of the right handle. The two hands support each other. With the steering movement of the complete steering wheel an extra function is created for an additional function.

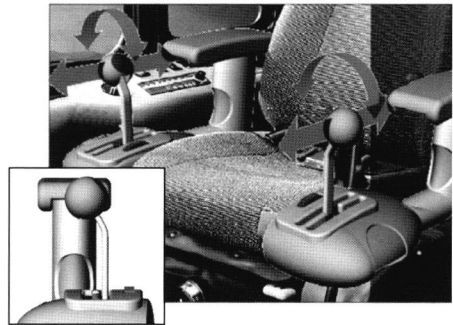


Figure 7.3 Concept 'Ball': this joystick can rotate left-right and translate forward-backward. An extra function for talus is the knob in the console

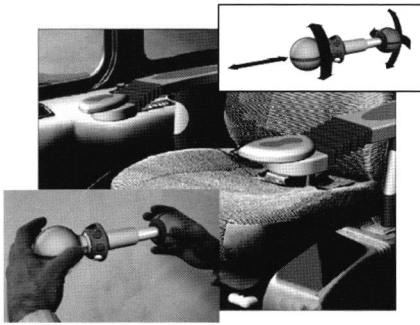


Figure 7.4 Concept 'Unfixed': two hands can be positioned in various ways to control the machine. Pads support the hands

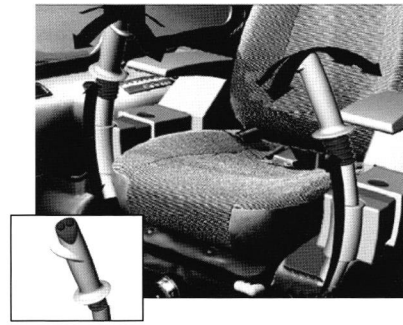


Figure 7.5 Concept 'Wheel': two traditional joysticks are coupled and can be moved as a steering wheel. This creates extra steering functions with a good support

### *The final design*

For all three concepts end-users and experts mentioned disadvantages and advantages. These were listed and gave the input for the final design of the new control. In fact it was an optimisation of concept 'ball'. The anatomically natural position of the hand is with the palm downwards, but more with the palm facing laterally. This means that the stick under the ball had to be bended. In levelling ground this control is easy to handle. A forward movement of the control results in a horizontal forward movement of the shovel. A sideward rotation results in a horizontal left-right movement (orthogonal). In case of a talus, the knob next to the control can adjust the slope.

### *An experiment*

To test whether the new design has effects experienced by end-users, an experiment was set up. It was tested whether the new control would be more simple and would lead to less mistakes and a more efficient task performance. The effect is studied by the indicators: the number of mistakes (errors), the efficiency of the task (speed) and the experience of subjects.

The difference between the new designed control and a traditional joystick was measured in four conditions:

- task 1: speed-controlled, drawing of a square (10 times);
- task 2: speed-controlled, drawing of a 45 degrees rotated square (10 times);
- task 3: position controlled, drawing of a square (10 times);

- task 4: position controlled, drawing of a 45 degrees rotated square (10 times).

#### *Subjects and experimental set-up*

Eight students with no experience in joystick control participated in the test. These participants were right-handed. The experimental setting consisted of a seat with a joystick (changeable between current or new) situated at the right side. The joystick was linked to two electronic servos, each for one direction, capable of switching between speed and position control. In the speed control mode the servo speed is analogous with the deflection of the joystick (when there is no deflection the servos will not move, when there is full deflection the servo will move at top speed). In the position control mode the position of the servo is analogous to the position of the joystick (the servo returns to the origin when the joystick returns to its origin). The servos are orthogonally aligned, thus enabling a controllable X-Y axis system.

The servo powered, mechanical construction moves a Wacom tablet pen over a tablet. The movements are input for the mouse pointer of a personal computer. On the computer, software was installed that shows two squares (or rhombus when the table and monitor are rotated 45 degrees). The software recorded the track of the mouse pointer, the time a task takes and the amount of errors during a task. An error is counted by the software when the mouse pointer is moved outside the path between the squares (see Figure 7.6).

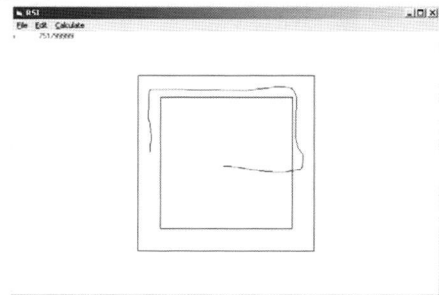


Figure 7.6 Screen dump of the interface. A line has to be drawn between the two squares. Outside the squares is defined as an error

The software recorded the track of the mouse pointer, the time a task takes and the amount of errors during a task. An error is counted by the software when the mouse pointer is moved outside the path between the squares (see Figure 7.6).

#### *Protocol*

The experiment was performed in two different series of tasks, each with one of the two joysticks. Each series consisted of four tasks that have been repeated once in the same order. After the second series subjects were interviewed with regard to the experience with joystick controls and they had to rank the tasks in difficulty from 1 (easy) to 4 (hard).

So, there are eight possibilities in task-joystick order of the experiment (four tasks and two joysticks). Each participant had a different order.

Participants were asked to start from the centre point and follow the path of the squares. They were asked to draw the figure ten times. Whenever they would get outside the borders of the figure they should correct themselves, but they didn't need to go back to the point where they crossed the border. There was no indication given whether they should focus on speed or precision. The four tasks were repeated once and only the second series were analysed.

*Results of the experiment*

It appeared that all subjects preferred the traditional joystick. The main reason the subjects mentioned, was that the new joystick didn't function good enough. The force needed to steer the control was experienced as high compared with the traditional joystick.

Figure 7.7 and Figure 7.8 show that for task 4 the performance indicated by errors and speed is significantly ( $p < 0.05$ , t-test for paired comparison) better with the current joystick. These results resemble the preferences of the subjects (see Figure 7.9).

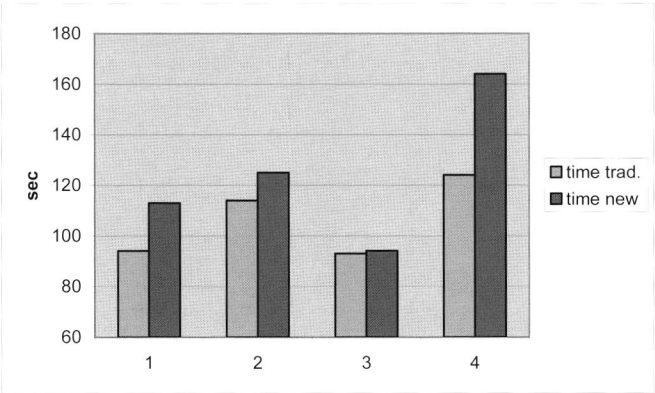


Figure 7.7 The time the different tasks (1-4) consume for the traditional joystick (time trad.) and the new control (time new) in seconds averaged over 10 trials and 8 subjects

Most errors were found in task 4; consequently task 4 consumed most time. This task was experienced as most difficult. Task 2 was experienced as the second most difficult, which again corresponds with the time needed and the errors made. These observations were highly correlated ( $r$  (Pearson) = 0.90 and 0.92 between experienced difficulty and time for the new control and the traditional

joystick respectively; 0.95 and 0.99 between experienced difficulty and number of errors for the new control and the traditional joystick respectively).

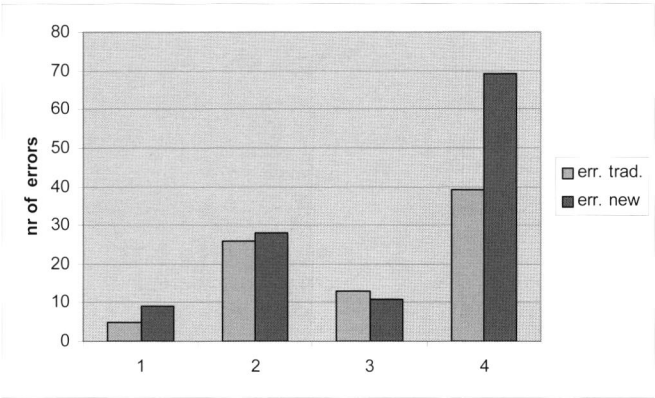


Figure 7.8 The number of errors (number of crossing the lines of the squares) for the different tasks (1-4) using the traditional joystick (err. trad.) and the new time control (err. new) over 10 trials and 8 subjects

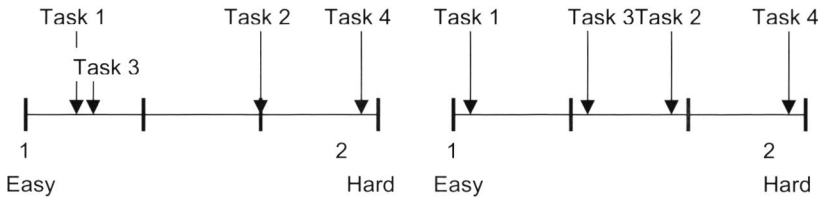


Figure 7.9 Assessment of the difficulty of the task: 1 is Easy, 2 is Hard; left scale for the traditional joystick, right scale for the new control/joystick

Considering that the new control needs more force and is less comfortable, it would seem arguable that this control is more suited for task 3: drawing a position controlled square.

The video recordings showed that subjects varied their position more with the traditional joystick. Some positioned their fingers at the top, some at the bottom of the joystick (see Figure 7.10), others had a full grip. In the new design everyone held the control in approximately the same way. From the interviews no uniform reason was found for the changing of the height. Some end-users reported that for precision tasks finger grip was more accurate.

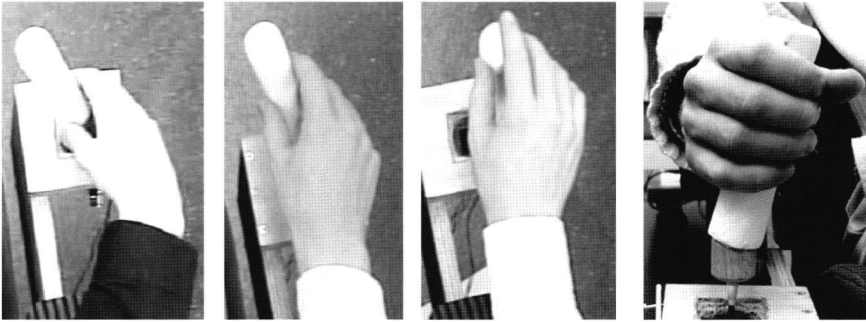


Figure 7.10 Different finger and hand positions observed in the operation of the joystick

We conclude that in this study the new control didn't have a better performance. However, this could be due to the fact that the new design didn't function well enough, which resulted in high control forces. It seems reasonable to suggest that the new control fits better to task 3 (positioning in a square). This would mean that the best form of the joystick is task-dependent. Regarding the inter-individual differences the traditional joystick also has the advantage of allowing variation in posture.

#### 7.4.3 *Speed versus position*

##### *The experiment*

In interviews with drivers of earth moving machines it appeared that most joysticks control the speed and not the position of the shovel or bucket. This means that a more forward position of the joystick in most cases results in a higher speed of the object. Since both systems (speed and position) are found in practice, it is interesting to find out which system is preferable. In the study mentioned above we also studied this issue. It is presumed (hypothesis) that the task where two directions need to be controlled simultaneously by speed (task 2) is more complex than all the other tasks. The reason for this presumption is that controlling the position is directly linked with the joystick position and the position of the shovel.

### *The results*

Figures 7.7, 7.8 and 7.9 indicate that our presumption is false. Task 2 is not experienced as most difficult. In addition, the number of mistakes and time needed is not highest for task 2. Rather task 4 (positioning) is experienced as most difficult. This is found for both types of controls, the new one and the traditional one.

Of course this was a limited laboratory study and further research is needed to study whether the effects are also shown in working in a real earth moving machine.

We conclude that this simulation indicates that speed control is preferable over position control.

## **7.5 Conclusions**

A machine that enables more accurate work and increases productivity is interesting for operators, management and manufacturers. Our explorative studies have generated a number of ideas that could be helpful in designing new controls. The experiments discussed in this chapter indicate that there are possibilities to improve the operator's performance by:

- applying the orthogonal principle in joysticks;
- using the principle of linking the functions in the joystick to the task performed by the machine;
- creating freedom for an operator to position the joystick in the hand;
- implementing speed control instead of position control.

This study is of explorative in nature, which means that further studies in real earth moving machines are still needed to underpin these indicative conclusions.

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## Comfort, the buzzword

In the automotive industry comfort has become an important issue.

In the last decade, the word has entered the world of professional equipment builders like earthmoving machines (wheel loaders, excavators), forklift trucks, cranes, trucks, busses, etcetera.

Comfort nowadays is the buzzword in all those industries where vehicles and cabins are manufactured. Manufacturers became more user oriented focussing on the people working in cabins for prolonged periods of time. Manufacturers aim at optimizing the extra feel of well-being with these users.

Equipment builders are also aware of the fact that comfort increasingly affects purchase decisions with new machines. Comfort has become a sales item in the professional world, emphasized in many brochures. Especially those people with a prolonged exposure in the cab may profit as their daily working conditions improve.

For more than 10 years, TNO has been active in the field of comfort, illustrating our progress through numerous scientific publications and presenting interesting cases to the industry.

In this book various examples are offered of how to create comfort through extra space, improved posture, a different steering system, a better view and so on.

Through these innovative ideas, each in their own way, we aim to contribute to the crystallisation of the buzzword 'comfort'.

