ERGONOMIC ANALYSIS OF MOTOR VEHICLES

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INTRODUCTION

Design of motor vehicles had not initially focused around humans [2]. Vehicles were merely designed to perform basic mechanical tasks. Only later designers took into account the human element, even though, in the beginning, ergonomic principles were often introduced as an interventional option at the end of the design process. The aim of ergonomics was mainly introducing further qualities, which were often perceived as accessories or part of the brand image. Only in the past decades, vehicle occupant packaging became a necessary design phase [3].

The primary focus in occupant packaging is the driver's workstation, that is the location and adjustment ranges of the steering wheel and seat with respect to the pedals, the physical location of controls and displays with which the driver interacts, the analysis of interior and exterior driver visual areas, both direct and through mirrors.

The objective of packaging is usually stated in terms of percentage accommodation on particular measures. Accommodation is quantified as the fraction of the driver population achieving some target level of fit or comfort [7].

Beginning in the late 1950's, the Society of Automotive Engineers (SAE International) started considering standardized tools and procedures for packaging [23]. SAE Recommended Practices, first approved in 1962, defined a weighted three-dimensional manikin for measuring seats, known as the H-point machine. The manikin defines and measures the location of the H-point, a reference point that approximates the hip. In the early 1960s, the first percentile accommodation model, known as the eyellipse, was introduced. The eyellipse is a graphical construction that describes the expected distribution of driver eye locations. In the late 1990s, the model was upgraded to take into account the effect of steering wheel position on eye location. Other important statistical models include the seating accommodation model and the driver head clearance contour. In each case, the model provides a geometric design guide that represents a specified percentage of the relevant measure from the population of drivers [15].

An increasing common approach to occupant packaging employs manikins to represent driver requirements. Use of three-dimensional computer graphic models has followed the development of low cost computers. Early human modelling software programs such as Sammie have been followed by Ramis, Jack and Safework among others. These digital human models (DHM) are now widely used for vehicle interior design and have often replaced SAE packaging tools.

Manikins are fundamentally population models, in that they describe percentiles of a population, not the behaviour of any individual within the population. A panel of manikins would be needed to attain good estimates of population characteristics. In the attempt to reduce the number of computer analyses that must be performed, designers select the extremes that span a large percentage of the range of body dimensions in the target population [4,10].

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The five elements to be considered in the ergonomics of motor vehicles are: habitability, accessibility, reachability, internal and external visibility, and seating comfort. The elements are briefly described hereafter.

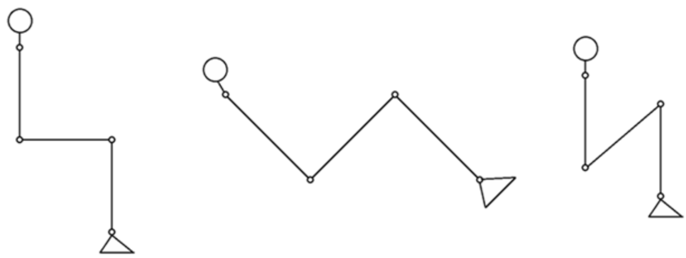
Habitability

Habitability is generally defined as the ability of the vehicle to accommodate the user; it comprises postural comfort, spaciousness and perceived habitability. In the study of a new vehicle, or in a benchmark analysis, the habitability study is often considered as the starting point.

Habitability study consists in positioning the virtual mannequin inside the vehicle so that it reflects natural human body physical angles [18].

Depending on the vehicle segments, designers decide between three basic positions: sit, reclined and cramped. These three positions have advantages and disadvantages (Table 1), related to the vehicle package and to the human body physiology.

Table 1 The three basic positions: main advantages and disadvantages



	SIT POSITION	**RECLINED POSITION**	**CRAMPED POSITION**
PROS	longitudinal size	vertical size	vertical size
	control reach	load on backbone	longitudinal size
	visibility		
CONS	load on backbone	longitudinal size	control reach
	vibration and fatigue	accessibility	vibration and fatigue
	vertical size	visibility	accessibility
			visibility

In most cars, the reclined position is used for the driver and the front passenger, while the cramped position is considered for the rear passengers. This choice guarantees a good comfort level for the driver and reduces the longitudinal size of the front and back seats, allowing to reserve a good trunk space [24].

Sit position is the best suitable for trucks. It guarantees a good front visibility on road, allows an easy reach of the dashboard controls with a reduced longitudinal driver size.

After the basic position of the driver has been chosen, a suitable driving limb position during driving is considered. Obviously the stature of the driver has a significant impact on the driving position and therefore on the room left for the rear passengers. Studies on different percentile combinations for driver and rear passenger are usually carried out, also in relation to the car segment and main car usage.

Spaciousness must be considered for the driver and the front and rear passengers. Spaciousness is to be evaluated in the transverse, vertical and longitudinal directions. Designers have to take into account both true geometrical dimensions and clearances, as well as the perception of space. Perceived habitability plays a key role in terms of marketing and value of the vehicle and must be considered carefully.

The spaciousness required by the upper body refers to restrictions of the trunk and arms and their movement; The spaciousness required by the lower body refers to the restrictions of the legs and their movement. Obviously, the requirement of spaciousness becomes more and more stringent as the size of the driver and passengers increases. Also age and state of health of driver and passengers are important parameters, as well as what is likely to be the main usage for the vehicle (city car vs. family car).

The perception of space is a determining factor in the sensation of comfort. It is provided by a complex relation of the physical dimensions of the inside of the vehicle to the ease of movements inside the vehicle, and to perceiving of the external world through the windows and the windshield.

It is worthwhile noticing that there are several targets to achieve to ensure habitability and that often target’s achievement cannot be optimal for all tasks; in fact, the true difficulty for the designer consists in setting all these issues together to find the best solution possible. Needless to say that the car segment, and therefore the intended user and usage of the car, are important factors in determining the constraints to the optimization problem.

The posture of the driver is conditioned by several constraints imposed by the act of driving: awareness of the road, awareness of the dashboards and the displays, operating the steering wheel and other controls, operating the pedals. Some aspects, such as the front visibility, are car parameters subject to homologation.

For passengers, both in the front and in the back, body posture may be quite different with respect to that of the driver and it is only slightly constrained by the criteria of safety norms and regulations (i.e. the use of safety belts).

In habitability studies, there are some relevant dimensions to consider, which are coded according to SAE standards (Figure 1). These dimensions are relative both to the vehicle and to the future occupants.

Car manufacturers have always looked at the design solutions of competitors; historically, the only way to retrieve the information was to purchase the different vehicles and, through reverse engineering, obtain the measures of interest. At the end of 1980, different manufactures decided to set up the GCIE LIST (i.e. European Car Manufacturers Information Exchange Group). Through registration and payment of membership fees, the different vehicle manufacturers share data in a coded format and accessible to others.

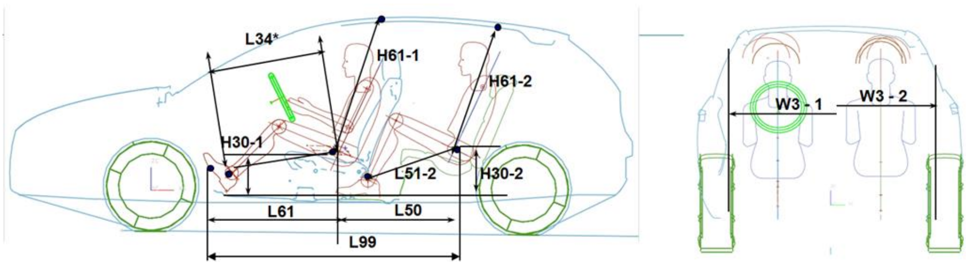


Figure 1 An example of vehicle and occupants' dimensions considered in habitability studies

ACCESSIBILITY

Accessibility refers to the absence of restrictions of movement in entering and exiting the vehicle. The ease of getting into and out of passenger cars and light trucks is a critical component of customer acceptance and product differentiation. A minimum of postural change and the maximum possible naturalness are searched for. For the upper body, freedom of movement may be conditioned by the thickness of clothes, by the mobility they allow, and by the presence of objects being carried (bags, umbrellas,...), while for the lower body, freedom of movement is mainly influenced by the clothes and shoes being worn.

In commercial vehicles, the health and safety of drivers is affected by the design of the steps and handholds they use to get into and out of the cabin. Ingress/egress assessment is often approached through digital human models (Figure 2). Digital modelling is difficult due to the complexity of the design space and the range of possible biomechanical and subjective measures of interest, which often require large-scale subject testing with physical mock-ups. Motion strategies are composite and strongly affected by the geometrical constraints and driver's characteristics, posing great challenges in creating meaningful simulations [23]. Subjects with different physical characteristic are generally tested in a wide range of vehicle conditions. Subjective responses are gathered along with motion measurements. Several people can choose, usually in an unconscious way, different strategies: the virtual path is created by choosing the most common among the different strategies. The primary advantage of this approach to simulation is that the resulting motion can have a very realistic appearance. A principal limitation is that the effects of important occupant covariates, such as stature, body weight, age, and gender, are not modeled explicitly [23].

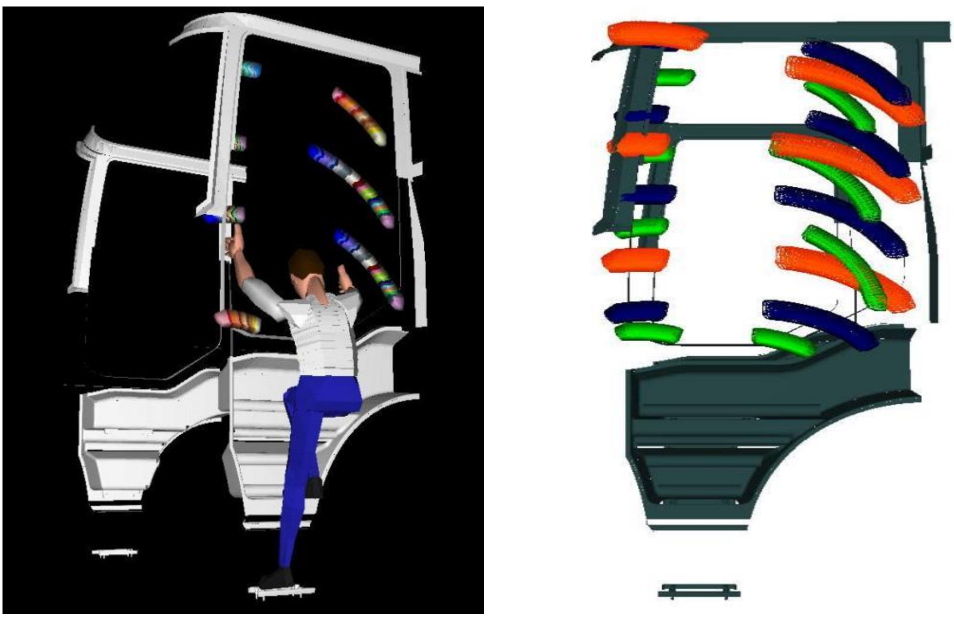


Figure 2 Different areas of reachability of the handles from each step for various percentiles, (5th percentile: green; 50th percentile: blue; 95th percentile: orange)

REACHABILITY

Check on the level of reachability of the different controls and devices on the dashboard, as well as of vehicle compartments, is also part of an ergonomic analysis of the motor vehicle. Reaching in postural comfort must be possible for different percentiles of users, that is, regardless of the driver's size, the joint angles for the different body segments and for the torso must be kept within comfortable bounds. Also no physical interference between the arms and the steering wheel or other cabin parts must prevent correct reachability.

In unrestrained positions, reachability generally represents a bigger issue for small individuals (Figure 3). However, this is not necessary the case for the driver of a vehicle, since bigger individuals, due to the longer legs, must position the car seat further away from the pedals, and are therefore more distant from the steering wheel and the different parts of the dashboard (Figure 4).

Assessment of reaching capabilities using human models is commonly performed by evaluating each joint of the kinematic chain, terminating in the hand, through the associated ranges of motion [21]. The result is a reach envelope determined entirely by the segment lengths, joint degrees of freedom and joint ranges of motion.

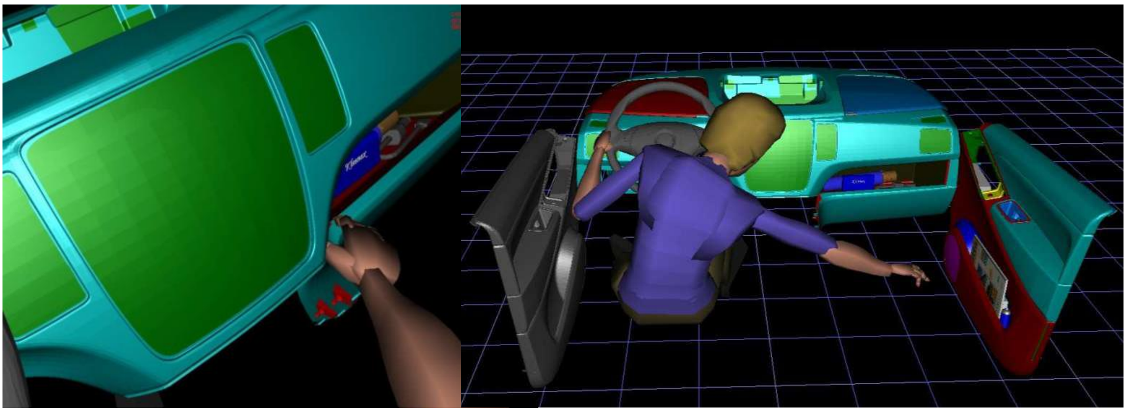


Figure 3 Reachability check of internal compartments. 5th percentile female

Software tools provide the ergonomist with the ability to simulate the vehicle occupant reaching to controls or other targets, by articulating the joints of a virtual human. For many vehicle interior analyses, computer simulations with manikins are used instead of statistical reach models. In typical applications, the range within which an occupant can reach is obtained by iterating through its range of motion each joint of the upper extremity, from the shoulder joint to the wrist. Analytical methods have also been developed to calculate the surfaces defining the reach envelope [1]. Earlier studies have examined the validity of reachability simulations for pilots with fixed-length torso restraints [9].

Belt restraints in modern road vehicles are commonly equipped with emergency locking retractors. With this type of belt system, the belt does not substantially restrain the occupant's torso during normal reaching activities. Hence, a vehicle occupant's reach envelope is determined by torso mobility in addition to upper extremity dimensions and range of motion. However, most designers currently use the reach envelopes obtained with fixed length, highly restrictive torso belts. Experience has shown that controls located within the more restrictive envelops approximate, comfortable reach for less restrictive conditions [17,23].

The ongoing increase in the number of in-vehicle controls, particularly in commercial vehicles, is exposing the problems of this type of approach. With a large number of controls to be placed and a limited area within the traditional design curves or within the reach envelopes generated using human models, it is unavoidable that some controls are placed in zones that are considered "unreachable" [5,6].

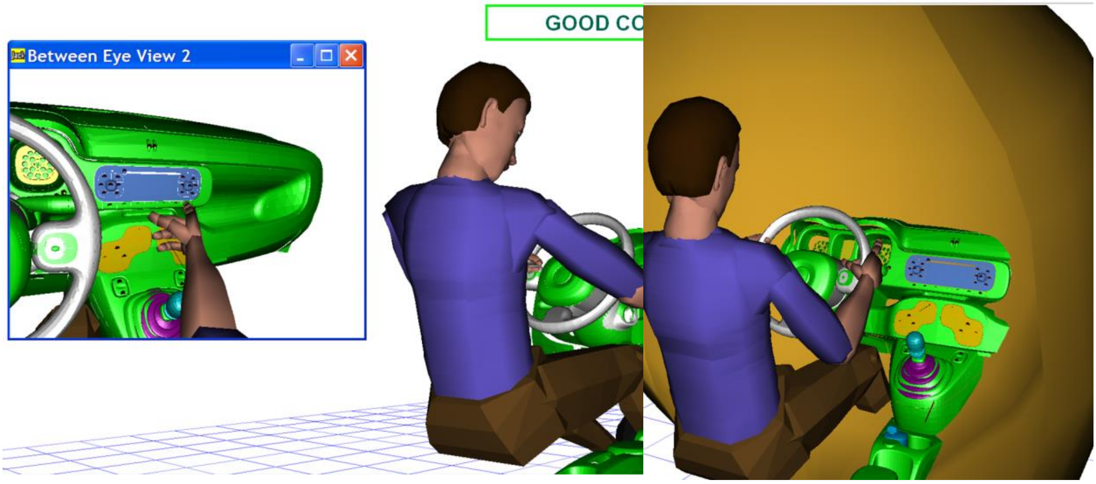


Figure 4 Reachability check for a 95th percentile male.

The reach envelope on the right allows to verify which parts of the dashboard fall within driver's reach

INTERNAL AND EXTERNAL VISIBILITY

Visibility is one of the most important vehicle performance. To guarantee good external visibility does not simply represent an ergonomics target to achieve, but an homologation parameter. The main visibility parameters are the SAE and the European regulations. In any case, it's possible for single countries to require vehicles to meet additional national requirements.

There are also other issues concerning visibility. In particular, designers also have to ensure that the interior devices and controls are visible for all percentiles of users.

In visibility checks, experimental testing as well as virtual analyses are performed. Experimental testing is usually carried out with expert users who perform a specific task. Movements are observed and registered in order to be analyzed and for defining strategies to be implemented in the simulation. Virtual analyses include virtual reality tools as well as simulation through software packages such as Jack and Ramsis. In virtual reality tools, users can perform a specific task interfacing with a mock-up of the vehicle interior, which is part physical and part digital. A realistic reproduction of external scenarios is also projected.

External visibility comprises static and dynamic aspects. The static external visibility refers to a stationary vehicle. Usually three aspects are checked: a) rotation of the point of view, b) analysis of wiper/screen printing, c) visibility of a child located outside the vehicle (Figure 5).

The dynamic external visibility is usually checked on four different tasks: a) right turn, b) left turn, c) exiting an underground parking through a ramp, d) reverse parking. For all manoeuvres, external agents (other vehicles, children and pedestrians) that move around the scenario, independently from the driver's choices, are present (Figure 6).

External visibility must also be checked in terms of reflected visibility, that is what the driver sees through the rear view and side mirrors. Usually two manoeuvres are simulated: reverse parking and passing on the motorway. The problem of reflected visibility is highly critical for industrial vehicles.

Internal visibility takes into account possible elements of visual obstruction and what parts of the dashboard drivers of different sizes may see or not see. The dashboard includes controls and displays of key importance, as they are used in the primary task of driving, as well as secondary displays and controls, which may be used for example in controlling the climate inside the car, switching on/off the radio...[6]

Ergonomics software programmes like JACK or Ramsis give designers the possibility to watch the rendered environment from the left, the right eye and from a point that approximates a binocular point of view, called "between eye view". In this way, by changing the point between eye due to the percentile being examined, it's possible to analyze what different percentiles see (Figure 4).

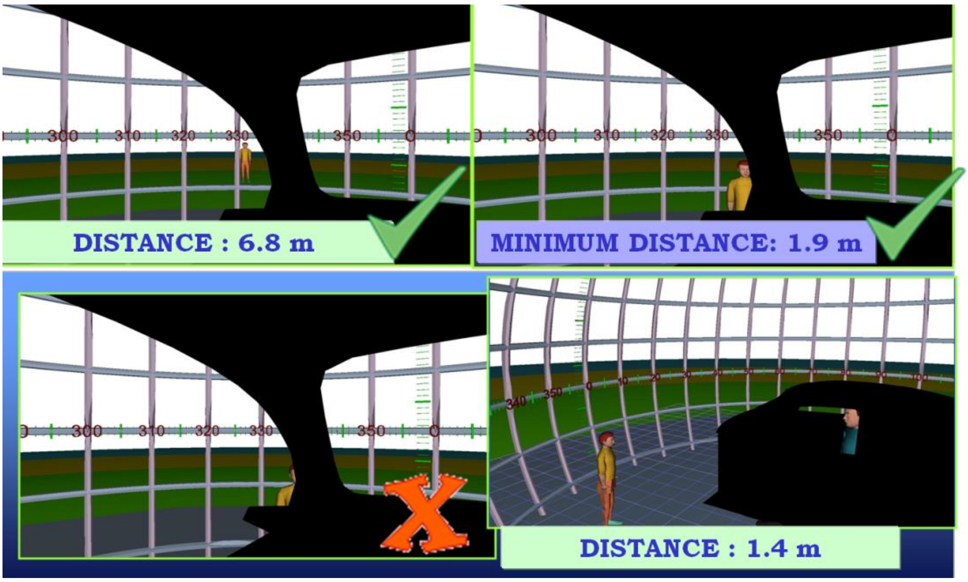


Figure 5 Visibility of a child located outside the vehicle. 50th male; driver's trunk rotation 30°

Reflexes are also important to consider and prevent. Non-homogeneous materials and lights are the main cause for reflected images on the windscreen. Both in a car and a truck, the dashboard upper surface is the most reflected on the windscreen. In particular, the annoyance comes from edges between different surfaces, because physiological perception is focused on discontinuity. Making the dashboard surface as homogeneous as possible decreases the chance of reflections. Sometimes reflexes can appear from illuminated objects. One of the most common examples is the gearlever illuminated by navigator screen and then reflected on windscreen.

Reflexes on cluster are usually created by instrument lights on the interior surface of the cluster's eyelid. This problem can be avoided by choosing a material with no lucid surface finishing. The same material with a rough or embossed surface is known to completely stop reflection.

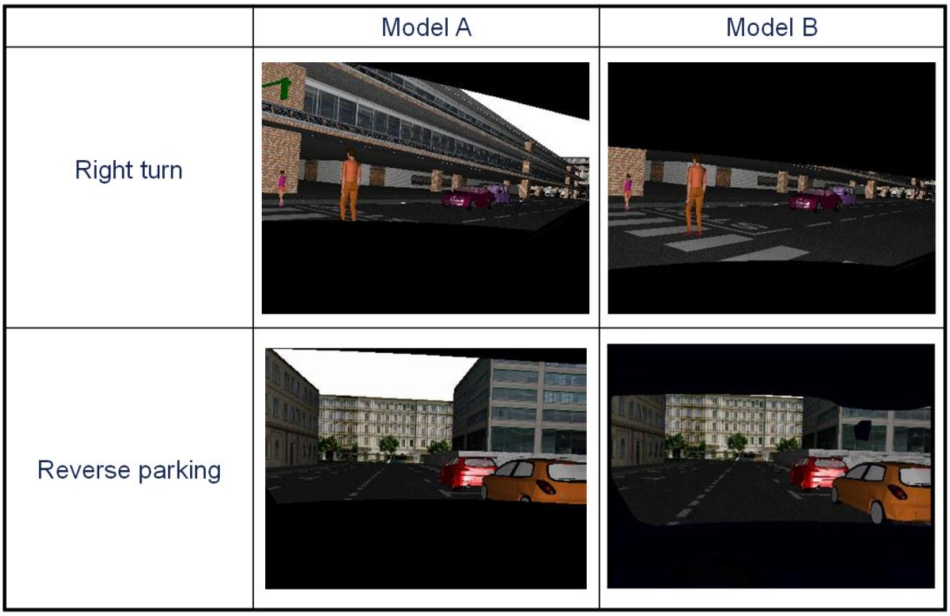


Figure 6 A comparison between two car models in different standardized manoeuvres

Before software analyses on reflexes were possible, the reflex issue was checked in the dark room requiring a prototype with almost final surface finishing. This wasn't possible in the first project phase and neither when materials where decided, but only after prototypes arrived and were mounted. The evolution of rendering software programmes made it possible for a highly realistic rendering of surfaces and a virtual representation of the dashboard as it will look like in reality.

COMFORT AND SEAT DESIGN

Comfort is the general state of well-being that derives from the reduction or absence of perceived disturbances. It is a passive and sensorial concept that is also linked to sensorial pleasantness. Sensorial pleasantness cannot be measured as it is an active and cognitive aspect that responds to customer expectation.

Comfort comprises quite different aspects: vibration, acoustic, thermal, tactile, vision and smell. The last three aspects are now considered important factors, but they have generally been studied in less detail.

Vibration comfort is related to the effects of the mechanical vibrations induced by the motor and the road profile, and transmitted through the suspension system.

Acoustic comfort depends on the effects produced by the mechanical parts and the noise induced by air turbulence and road surface. It is influenced by the mechanical characteristics of the vehicle and by the degree of sound proofing of the vehicle interior.

Thermal comfort is related to the quality of the microclimate and the thermal sensation of the contact surfaces.

Seat design is an important aspect for postural comfort as well as for reachability and visibility issues [14,16].

Today car manufacturers have to consider drivers of very different sizes. Stature range is constantly increasing, requiring seats to be moveable for almost 30 centimeters. While the steering wheel can be adjusted axially, the dashboard cannot move along with it. Thus, optimizing an interior design is to find the best compromise for the variety of possible drivers, while maintaining the corporate identity in interior design.

Since not all combinations can be evaluated with real test persons and physical mock-ups, virtual humans become more and more present. By placing a virtual human in different virtual scenarios, a much broader set of alternatives can be investigated in early stages of the design.

Most of the research findings concerning industrial and office chair design can be applied to car seats. However, there are several important considerations, unique to the mobile environment, that should influence design recommendations. In particular, the control locations and line of sight requirements serve to constrain postures to a greater extent than in most other seated environments. Safety concerns dictate that the driver be alert and continually responding to changing road conditions, and be positioned in such a way that the occupant restraint systems offer maximal protection in a crash. Passenger cars generally require a more extended knee posture than it is necessary in other types of seating. This has important implications with regards to the orientation of the pelvis and the lumbar spine. Additionally, vibrations impose tissue stresses that are not generally present in a stationary environment.

When attempting to specify design characteristics of a comfortable seat, it is important to bear in mind a functional definition of comfort as it applies to seating. Research has pointed out that it is unreasonable to assume that comfort extends in a continuum from unbearable pain to extreme feelings of well-being. Since a seat is not likely to convey a positive physical feeling, the continuum of interest reaches from indifference to extreme discomfort. The best a seat can do is to cause no discomfort. This definition is useful, not only in the design of subjective assessment tools such as questionnaires, but also in consideration of strategies to improve comfort. The aim of car seats should be to reduce or eliminate factors causing discomfort, rather than to elicit feelings of well-being.

Most virtual models used in ergonomic analyses provide postural comfort ratings based on joint angles, through a single whole body comfort score or on a joint-by-joint basis (Figure 7). The source data for these ratings is generally derived from laboratory studies that link posture to subjective ratings. What is lacking in many of these models is a thorough treatment of the distribution of ratings in the population of users. Information about rating distributions is necessary to make cost-effective tradeoffs when design changes affect subjective responses.

VIRTUAL DESIGN AND USE OF ANTHROPOMETRIC PERCENTILES

From a physical point of view, the biggest issue in designing a product for people is considering the variability of the target population through the use of percentiles. In first production age, craftsmen fulfilled the buyers' needs building around them the car as a tailor creates a suit. Following the industrial production age, business was based on mass production. No longer the case buyers "pull" the productive engine, the production chain is "pushed" to create a product that may suit the largest possible number of users [16].

Designers incorporate scientific data on human size into the design of systems and equipments through the use of anthropometric percentiles (Figure 8). The population is divided into 100 percentage categories, ranked from minimum to maximum dimensions, so that for example, when referring to stature. the 5th percentile is a value whereby 5% of the population is shorter and 95% is taller, the 50th percentile is the median stature and the 95th percentile is a value whereby 95% of the population is shorter and 5% is taller.

The same concept applies to different body segments as well as to weight and strength of the population. Manikin weight can be important as bigger transverse dimensions of the body can determine a reduced range of movement, posing problems of accessibility and reachability.

Parameter	Recommendation
Pressure Distribution	
• Seat cushion patterns	Peaks should be located only in the areas of the ischial tuberosities. No other local maxima should be found.
• Backrest patterns	Peaks should be located only in lumbar area. No local maxima should be found in the shoulder area.
• Peak levels	Peak levels should be determined by subjective comfort testing with target populations. Large differences in pressure distributions and sensitivity among individuals make specifying a quantitative "optimal pressure distribution" difficult.
Surface Shear	Surface shear on the seat cushion should be minimized by increasing the cushion angle and/or by contouring the cushion to achieve the same effect.
Temperature and Humidity	The seat covering should allow heat transfer of at least 75 W/m^2 by conduction and diffusion of water vapor. Foam should not be compressed to more than 80% to allow for maximum vapor diffusion.
Vibration	The seat should minimize the transmission of frequencies between 4 and 8 Hz.

Figure 7 Recommendation on pressure distribution patterns [23] and optimal pressure levels [25]

Since the late 1970's there have been many surveys, large and small, to obtain anthropometric data on a variety of subjects . Traditionally, the largest number of data have been taken on military personnel and the most noticeable survey belongs to U. S. Army. The army anthropometry databases are widely used because of the large number of measurements and the rigorous methodology [8]. Some other surveys dealt with smaller samples of factory workers. One large document covering the results of many surveys, Adult Data, was prepared by Nottingham University and published in 1998 by the Department of Trade and Industry of the United Kingdom.

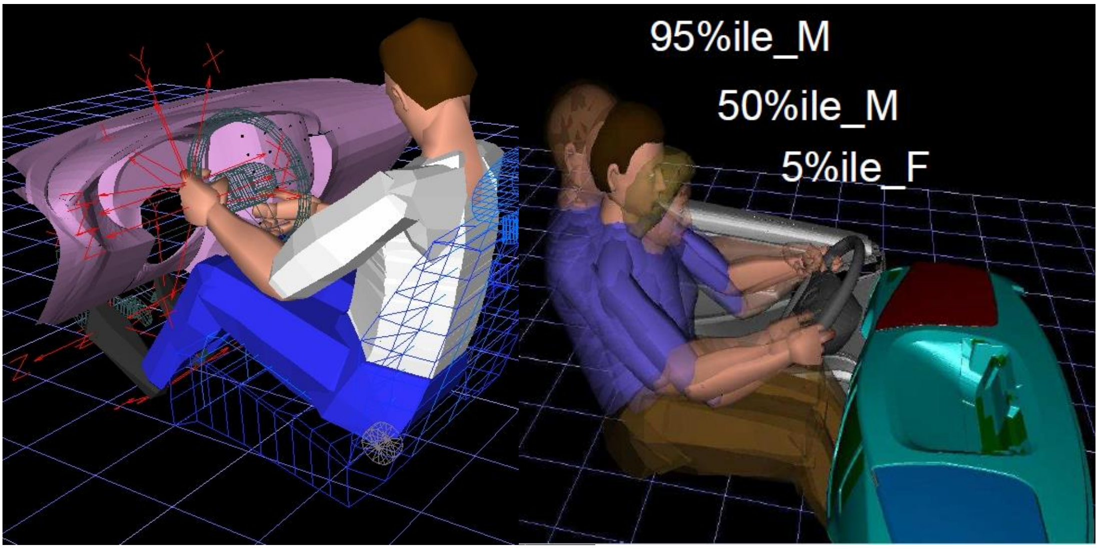


Figure 8 A virtual simulation in Jack through the use of different manikin sizes

In 2008, the International Organization for Standardization (ISO) released the Technical Report 7250-2, "Basic human body measurements for technological design - Part 2: Statistical summaries of body measurements from individual ISO populations." This technical report contains summary statistics for a number of anthropometric dimensions from various countries around the world. Available anthropometric data from a variety of countries are presented in a single source. Informative annexes contain information specific to Asia and Europe, so that designers of products to be marketed in those regions can use appropriate dimensional criteria.

The strategies for applying anthropometric data in design include:

- find the relevant data for the intended occupants with respect to their origin, occupation, age, gender, disability;
- make any necessary allowance for secular growth and clothing;
- determine the design limits. Traditionally these have been stated as the 5th percentile female value and the 95th percentile male value. Some authors [10] consider these limits somewhat out-of-date, given the concern for life quality and safety, and recommend using the 1st percentile female to the 99th percentile male values whenever possible. This wider range is particularly important when several dimensions are critical for accommodation or when safety is of concern;
- design for extreme individuals when appropriate. Clearance dimensions that must accommodate or allow the passage of the body or parts of the body shall be based upon the 95th percentile of the male distribution data. On the contrary, when reachability is an issue, generally it is the 5th percentile of the female distribution data that must be considered;
- design for the adjustable range when minimum fatigue, optimum performance, comfort and safety is required (e.g. vehicle seats, steering wheels, seat belt mountings);
- design for the ‘average’ person when adjustability is not feasible, but never use median values for clearance, reach or strength. The ‘average value’ should be used only when it is likely to cause less inconvenience and difficulties to the user population than a larger or smaller value would do.

Even though some general guidelines can be given, designers shall be aware that, even if the concept of percentile is easy to understand, fallacy arises because it is assumed that application of percentile data is equally easy. The first trap is referring to mythical people such as a 5th percentile female or a 95th percentile male. Anthropometric dimensions are poorly correlated, which means that people of the same stature can have markedly different leg and arm lengths, weight, torso breadth and so on. Percentiles are univariate and only refer to one dimension at a time. A percentile value should never be used without obtaining details of the age range, nationality and occupational groups included in the original survey data. The date of the survey is important too, due to the secular growth issue.

A common mistake is to assume that designing from 5th percentile female to 95th percentile male dimensions will accommodate 95% of people. This is true if only one dimension is relevant to the design solution (i.e. univariate accommodation, such as standing headroom). However, vehicle interior design is likely to require simultaneous accommodation on a large number of dimensions (i.e. multivariate accommodation). Since correlation between body dimensions is poor, it follows that those males who are designed out because of limited headroom (5% of males in theory for a large random sample) will not necessarily be the same 5% who are designed out for having arms that are too long or the 5% with legs too long, hips too broad and so on. Similarly, those females who are designed out because they have legs, arms, sitting eye height, etc. that are too small will not constitute just 5% of the females. Several literature studies demonstrated the complexity and seriousness of the anthropometric mismatch problem [10] that shall never be underestimated.

CONCLUSIONS

Habitability, accessibility, reachability, internal and external visibility, and seating comfort are the five elements in the ergonomics of motor vehicles, that are directly linked to the dimensional relationship between man and vehicle. The objective of the ergonomic analysis is usually stated in terms of the percentage accommodation on particular measures, where accommodation is quantified as the fraction of the population achieving some target level of fit, reachability or comfort.

Today digital human models are widely used for vehicle interior design and have often replaced SAE packaging tools. A panel of manikins is needed to attain good estimates of population accommodation. However, in the attempt to reduce the number of computer simulations, analysts often select the percentile extremes.

In percentile selection, designers shall be well aware that while percentiles are univariate, vehicle interior design is likely to require multivariate accommodation. Poor correlation between body dimensions, together with the increasing need of common platforms in a globalized market, pose a great challenge to design for all.

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