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ERGONOMIC DESIGN AND EVALUATION OF COMMERCIAL MOTOR VEHICLES

Summary. The number and consequences of traffic accidents and work accidents in road transport represent a burden for individuals and society, as well as a substantial economic burden for transport companies, while also affecting their competitiveness. Research in the area of transport and road vehicle ergonomics can contribute to ensuring conditions for a more secure and efficient operation of commercial road vehicles, thereby reducing the risk of road accidents. The safety of vehicle operation and road transport depends in large part on good comportment between ergonomic vehicle design and human capabilities and limitations. Eventual ergonomic incongruity between these elements may have negative safety implications. The article presents an approach to ergonomic design of commercial road vehicles and their ergonomic evaluation, which occurs in two stages, the design of the vehicle and its exploitation.

PROJEKT ERGONOMICZNY I OCENA KOMERCYJNYCH POJAZDÓW SAMOCHODOWYCH

Streszczenie. Liczba i konsekwencja wypadków drogowych oraz wypadków przy pracy w transporcie drogowym reprezentujące obciążenie dla osób i społeczeństwa, tak jak znaczne obciążenie ekonomiczne dla firm transportowych, co również ma wpływ na ich konkurencyjność. Badanie w sferze ergonomii transportu i ergonomii pojazdów drogowych może przyczynić się do zapewnienia warunków dla bardziej bezpiecznej i efektywnej eksploatacji komercyjnych pojazdów drogowych zmniejszając tym samym ryzyko wypadków drogowych. Bezpieczeństwo działania pojazdów i transportu drogowego zależy od konsekwencji pomiędzy ergonomicznym projektowaniem pojazdów, a ludzkimi możliwościami i ograniczeniami. Ostatecznie ergonomiczna bezsensowność pomiędzy tymi elementami może mieć negatywne konsekwencje dla bezpieczeństwa. Artykuł prezentuje podejście do ergonomicznego projektowania komercyjnych pojazdów drogowych i ich ergonomiczną ewolucję, która występuję w dwóch etapach, projekt pojazdu oraz jego eksploatacja.

1. INTRODUCTION

More than 1 million people die each year as a consequence of traffic accidents. Despite the efforts of engineers, researchers, and politicians relative to the prevention of near misses, accidents and fatalities, their occurrence remains at an unacceptably high level [1]. Unacceptably high incidence of

deaths in the workplace is also a problem: according to the International Labour Organization (ILO), there are around 337 million work accidents and 160 million occupational diseases each year, with 2.3 million workers dying as a consequence [2]. The costs related to occupational safety and health problems represent a significant economic burden, influencing the competitiveness of individual companies and society. Ergonomic problems in the workplace and inadequate organization of work represent risk factors for occupational safety and health problems in all economic areas, including transport, the key affected elements being environmental factors, inadequate posture, inadequate movements, mental and physical burden, and dissatisfaction with work [3].

Given the high incidence of fatalities, traffic safety represents an important aspect of ergonomic research [1]. Commitment to this cause and the importance of this approach are supported by the findings of numerous ergonomic studies published in scientific journals [1, 4], and also by the focus of technical committees of the International Ergonomics Association (IEA).

Research in the area of transport ergonomics and road vehicle ergonomics developed from early research into the human-machine system during the Second World War. These studies proved to be very important, because for the first time the human-operator became a limiting factor for the efficient operation of the operator-vehicle.

Ergonomic design related to the adaptation of road vehicles is a characteristic that is currently often emphasized by vehicle manufacturers. However, often the basic understanding of the ergonomic approach is inadequate for both private and commercial motor vehicles. These vehicles include all vehicles, which are used, according to their construction and technical exploitation characteristics, for public transport in the form of buses, goods vehicles, special purpose vehicles and service vehicles.

The first edition of the scientific journal Ergonomics (Volume 1, Issue 1, 1957) included a number of ergonomic papers related to this issue, one of which clearly highlighted the need for a close connection between biological and psychological characteristics of the driver and the physical design of the motor vehicle [5]. This link should be realized by designing the vehicle in a manner to assign the most important role to human, which would confirm the need to focus on the human operator when designing a vehicle. The driver-vehicle system would enable greater efficiency and safety, a lower incidence of errors, and also a lesser need for a subsequent redesign of equipment.

The safety of vehicle operation and transportation depends on the ergonomic consistency between the vehicle design and the human factor [6]. An ergonomic mismatch between the vehicle design and the driver can have safety related consequences. These can be the result of reduced efficiency when driving, operating the vehicle, or resting in the vehicle, and can lead to traffic accidents. The consequences of traffic accidents of commercial vehicles are usually severe, especially because of vehicle dimensions and weight. The consequences of inconsistencies are more problematic with drivers who operate vehicles in difficult conditions such as long driving time, tight schedules for the implementation of transport, and overnight stays in the vehicle.

Despite the ongoing and intensive research in the field of ergonomics over the past six decades, some commercial motor vehicles are characterized by non-compliance with the rules and the particularities of ergonomic design.

2. ERGONOMICS IN COMMERCIAL MOTOR VEHICLES

Commercial motor vehicles are operated and controlled by a human. The vehicle and the driver together form a typical human-machine system, in which each of the components of the system performs different functions. The driver-vehicle system can meet the quantitative and qualitative objectives set if the vehicle is adequately designed, while at the same time the driver has to meet the necessary requirements in the form of mental and physical characteristics as well as professional qualifications, to perform the duties planned. There is also a third requirement - the interface between the driver and the vehicle and the working conditions must be designed in a manner to comply with the needs, limitations and capabilities of the human operator.

Inadequate ergonomic design of commercial vehicles usually includes all areas of ergonomic design, the most notable being the neglect of anthropometry: the design of operating elements and

meters is often subjected to the influence of industrial standards, which are often inadequate from the point of view of ergonomic criteria for motor vehicles; inadequate visibility from the vehicle cab and of the sides, lighting of the interior and immediate surroundings of the vehicle, microclimate, noise, and vibrations [7].

Non-compliance with ergonomic principles or their neglect during the design of commercial vehicles leads to a number of consequences both for the operator and for the entire driver-vehicle system. The most important consequences for operators include a reduction of the work safety and efficiency, an increased level of risk for injuries and health, and decreased comfort and motivation. Some health problems include musculo-skeletal disorders and pain, and symptoms of stress, which, together with headaches and sleeping problems, represent a prevailing problem among European workers [8]. Typical consequences at the operator- vehicle system level are reflected in the reduction of the total system efficiency, which is accompanied, by a reduction of productivity and quality of work performed.

Professional drivers of commercial vehicles represent a population of motor vehicle drivers with a high risk of musculo-skeletal disorders, especially spine, shoulder and joint problems [9, 10]. These drivers are characterized by a high level of morbidity and a relatively low retirement age [11]. The job of a professional driver includes environmental conditions in the vehicle cab, exposure to changing climate conditions, noise and vibrations, and the position and posture of the driver during work, which represents factors of burden and stress for the driver at work. These are factors that need to be taken into consideration during the ergonomic design of a commercial vehicle.

Some researchers believe there are strong links between musculo-skeletal disorders of drivers and stress at work, and dissatisfaction at work as psychosocial risk factors [12, 11]. The position of the driver in the vehicle cab during work is directly connected to the dimensions of the driver's job. The driver's seat, which represents an important element of the latter, is often found to be inadequately designed, for example for short and/or heavy drivers [11]. The driver's current mental and physical condition, which is influenced by the factors of the working environment and the work itself and is the subject of ergonomic design, emerges as one of the dynamic factors that influence the driver's behavior [4]. Appropriate ergonomic design of the working environment is thus one of the potential workplace interventions capable of reducing the risk factors for employees' musculo-skeletal and mental disorders [13]. An ergonomically well-designed workplace not only has a positive effect on the reduction of risk factors that influence the individual worker, which is most often the case, but also positively influences competitiveness and work productivity [13].

Similar importance in the study of the human driver-vehicle system is attributed to the area where the operator's workplace is located. A correct ergonomic design of the driver's workplace enables a safe, comfortable, economical and efficient operation of the motor vehicle. The most important areas of ergonomic design of the driver's workplace or the microenvironment include: the design and installation of the driver's seat, controlling instruments and meters, viewing angles and microclimate conditions in the vehicle cab, which must be amenable to the characteristics of the population of drivers [14].

3. DESIGN OF COMMERCIAL MOTOR VEHICLE ERGONOMIC MODEL

The process of ergonomic design of commercial motor vehicles begins with the design of the vehicle driver's workplace as the element of the driver-vehicle system, which requires a systematic structuring of all relevant design areas. The process of ergonomic design can be divided into three broad areas:

- anthropotechnic design - anthropometric design, entering/exiting, driver's/passenger's seat, visibility conditions, living area, bed, and trays;
- interface design - connecting elements between the driver and the vehicle, such as gauges, displays and signals, controlling instruments, and communication devices, and

- the design of the driver's working environment, the microenvironment - microclimate, vibrations, noise, and lighting, and the macroenvironment - organizational and technological aspects of the driver's work, type of drive, structure of work organization, and communication with the organization.

The required characteristics of the designed vehicle and its individual aspects such as efficiency, and simple and safe use, can be obtained by following three main principles, which seem simple and easy to understand, yet are often not taken into consideration by designers of certain products [15]:

- an early enough focus on the user, driver or passengers, their duties and procedures;
- the implementation of empirical measurements, and
- iterative modeling.

An early focus on the user and the procedures refers to the acquisition of information about physical and mental capabilities of people for which a certain product or system is designed, with a clear definition of what these users will be doing. If possible, the information should be based on direct observation of people using this or a similar and comparable product. An iterative design is based on the fact that it is not likely, whatever the preliminary planning and accuracy of the obtained specifications, that the ergonomic design of the vehicle or an individual part or system will be successful on the first try. In fact, the quality of an ergonomic model is proportional to the number of iteration loops of the model: design-evaluation/testing-re-design. For a successful iterative design it is important that the model be tested and evaluated early enough in the development cycle.

The production and shape of the ergonomic model are closely linked with the process of the physical design of the product or system. The process of designing a specific physical product, working process or technical/technological structure, is usually based on a systematic approach, which includes all components and limitations of the system, and on a methodical structure of the modeling process during the development and evaluation of the main design solutions. The procedure includes specific phases: definition; concept development; realization; analysis and optimization; evaluation, and application.

Each of the phases of technical design or modeling can include a number of sub-tasks, which defines them more clearly. At the same time, a suitable procedure is attributed to each phase of technical design connected to the ergonomic area of design of the product. This procedure represents an individual phase of the ergonomic modeling. The main phases of technical design and the phases of ergonomic design with individual tasks that are attributed to them are presented in Table 1.

Modeling and designing elements according to different fields such as anthropotechnic design, link between the driver and the vehicle, environmental conditions, is based on ergonomic recommendations which are compiled and designed on the basis of specific literature from the field of motor vehicle ergonomics, general ergonomic recommendations, and literature on ergonomics, as well as available standards and regulations.

The model of ergonomic design provides for the creation of a selected number of areas, which represent structural elements, and constituent parts, or certain functional entities of the vehicle. Individual areas are composed of elements whose number depends on the complexity of the approach to ergonomic modeling and on the choice of elements to be designed this way. Each of the elements is determined by certain features or characteristics such as dimension, shape, selected material, type and quality of treatment of material surface, force of activation, and layout characteristics that determine its operation and use. For each of the features or characteristics there are certain recommendations such as the actual dimensions, recommended forms and colors, the selected position of the element layout, the method of its activation, the value of the force necessary for its activation, and certain limit values for environmental elements, which determine the tolerance band. The transition between different levels of design within a certain procedure of ergonomic modeling is shown in Fig. 1.

The selected areas of ergonomic modeling of a vehicle, their component elements, their characteristics and recommendations can vary in number, or in depth of treatment. They vary depending on the set priorities of ergonomic design, which are based on the choice of the commercial vehicle, the requested technical-technological and exploitation characteristics of the vehicle, the purpose of vehicle use, and the type of transport service the vehicle will be implementing.

Table 1

Design phases with attributed ergonomic procedures (adapted from [21])

Design phase	**Design (sub)task**	**Ergonomic procedure**
Definition	Definition of design objectives and identification of tasks	Preparation of general human-centered requirements
Concept	Designing the general structure Development of basic design alternatives	Allocation of tasks in the human – machine system Recommendation of ergonomic principles of design
Realization of model alternatives	General and detailed model / construction	Preparation and implementation of specific ergonomic requirements
Decision-making and final design	Evaluation of design/model alternatives Prototype development Identification of design weaknesses and re-design	Evaluation according to ergonomic criteria Laboratory studies Identification of ergonomic deficiencies and proposal for (design) changes of the model
Operation	Collecting technical documentation Evaluating the model during performance/operation (have the set objectives been reached?)	Identification and description of details connected to the operator Evaluation according to ergonomic criteria Field research

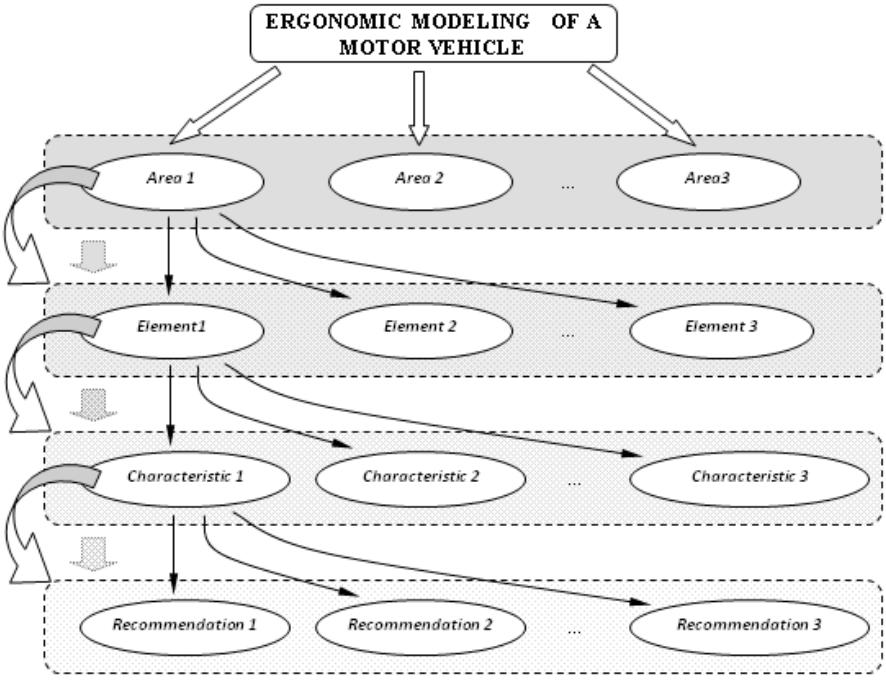

Fig. 1. The levels of design in the process of ergonomic modeling of motor vehicle elements
Rys. 1. Poziomy projektu w procesie ergonomicznego modelowania elementów pojazdów samochodowych

An example of element - areas structure of ergonomic modeling which are important in the design of goods vehicles that perform transport over long distances in international transport - is shown in Table 2. Drivers of this type of vehicle spend most of their time in the vehicle, whether driving, waiting or resting. The set priorities of vehicle design are related to the increased demands of the driver in view of comfort, ease of operation and daily maintenance, and reliability and safety of the

vehicle. The vehicle must ensure such working conditions in order for the drivers to work efficiently, with as little effort and risk to their health as possible.

Table 2

The structure of ergonomic modeling areas for heavy goods vehicles that perform transport over long distances

Area	***Element***		***Characteristic***
Entering/exiting the vehicle	Door		Opening angle
	Stairs		Number, width, height, depth, surface material, layout in front of or behind the first axis
	Holder	stair fence	Length, position
		handle	Form
Mobility in the vehicle cab	Flat cab floor		Presence of engine tunnel, height of engine tunnel, surface of the straight part of the floor
Seat	Seat comfort		Seat settings
Steering wheel	Settings		Angle settings, height settings
Elements of comfort	Trays and compartments		Number of compartments, easy accessibility
	Bed		Dimensions, hardness of mattress, putting the bed away

4. ERGONOMIC EVALUATION OF THE VEHICLE

The process of ergonomic modeling is extremely complex because of numerous, repeated and various links between the human technical element or the procedure, which interact in different ways. Its basic purpose is to create the best possible level of compatibility between the human and the machine or procedure, for all necessary tasks or activities, and at the same time protect human from unwanted effects.

The entire process of physical modeling of the vehicle is an iterative process. To determine whether the appropriate solution or model is satisfactory from the ergonomic point of view, and what the potential negative effects are, the model needs to be ergonomically evaluated, which means that it must be compared with a certain set of specifications. The specifications with the help of which the ergonomic evaluation is carried out are usually formed on the basis of:

- the presented specifications of users;
- relevant regulations, standards, and specific ergonomic guidelines, and
- trends of vehicle manufacturers in the development and introduction of technological innovations and market competition.

A special influence in vehicle design in road transport - apart from development and technological push, legal requirements and regulations - is also attributed to vehicle users' specifications defined as the needs and demands of customers. The characteristics of vehicles can be defined as characteristics which users (drivers, passengers) expect from the product, expressed in their own words (for example, opening doors must be simple); technical characteristics, on the other hand, can be described as necessary specifications of the product, in order to achieve the characteristics expressed by users (for example, after 20,000 door openings and the estimated impact of corrosion on the vehicle structure, the force required to open the door cannot exceed a certain value).

The users of motor vehicles often emphasize the usefulness. The ease of use of linking elements between the human and the machine - interfaces, inside the vehicle usually enables a safer use, considering that these elements substantially contribute to a decreased extent of interferences in the implementation of the driver's main task - driving. The likelihood of errors with their application and appropriate reactions is also considerably lower [17].

Different road vehicles may have identical or very similar technical characteristics, but the relative meanings of these characteristics and their requested values can be significantly different.

The approach that takes into consideration the users' suggestions ensures a constant encouragement of road transport vehicle manufacturers to improve their products, but the improvements are slow in coming. Systematic studies of links between the characteristics of products - for example, the force necessary for operation or the distance and tag sizes, and the work and preferences of users are usually not carried out and are therefore rarely found in the relevant literature. The relative importance of various product characteristics is also poorly studied and therefore relatively unknown - for example, is the distance of the driver from the controls of the same importance as the indicator light indicating the controls?

When addressing the negative effects of an ergonomically inadequate design of a product or system it is important that the ergonomic design can be assessed and evaluated. The ergonomic evaluation of the vehicle model - in the phase of its ergonomic design (modeling), which runs parallel to the phase of physical design (modeling) - appears twice:

- evaluation in the vehicle design phase: when it comes to deciding between individual alternatives of the physical vehicle model, and
- evaluation in the vehicle exploitation phase: when evaluation is performed in real operating and environmental conditions.

The inclusion of the evaluation process of each individual phase of ergonomic modeling and design is shown in Fig. 2.

The difference between the evaluation of physical vehicle models in the design phase and the testing of vehicles in real operating conditions, and ergonomic models created with the help of appropriate software are often such as to affect the acceptance of incorrect or inadequate decisions - the approval or rejection of a certain model. The form that is based on the instructions given for ergonomic design is considered to be an optimal ergonomic design of the model.

4.1. Ergonomic evaluation in the vehicle design phase

An ergonomic analysis of the user procedures of the designed product represents one of the most important approaches to the ergonomic evaluation in the product design phase. An analysis of elementary user procedures is used in the ergonomic modeling phase, primarily to study all interconnections between the elements of the system. The approach of ergonomic procedure analysis itself is not new; however, due to a relatively general addressing of the aspects of the designed system it is suitable primarily for the allocation of tasks between the human and the machine.

An ergonomic analysis of elementary procedures means that the tasks or the human procedures in the human-machine system are accurately reflected and addressed. In the process of ergonomic design, this allows for the design of variables that will enable the fulfilment of the established requirements in the designed element. In fact, ergonomic design and modeling can also be defined as a process of determining the values of the variables designed, so that they meet the established requirements in the form of desired or avoidable effects of the conditions created in this manner. The person responsible for modeling and designing follows the feedback process between synthesis and analysis. This iterative nature is reflected in the following: the designers implement a certain design proposal and test it, as a result of which they can approve it, or, on the basis of a new synthesis, look for a completely new or modified version of the previous solution. During this evaluation, different ergonomic aspects are analyzed.

The analysis of elementary procedures is used in the modeling and design process of different vehicle elements, such as the operating elements (steering wheel, handles, switches, buttons), meters and displays, and other elements, such as seats, working surfaces, and holders. The analysis offers support to the designer in determining specific requirements, where individual designed variables must be allocated with adequate values to enable the fulfilment of a certain task or procedure.

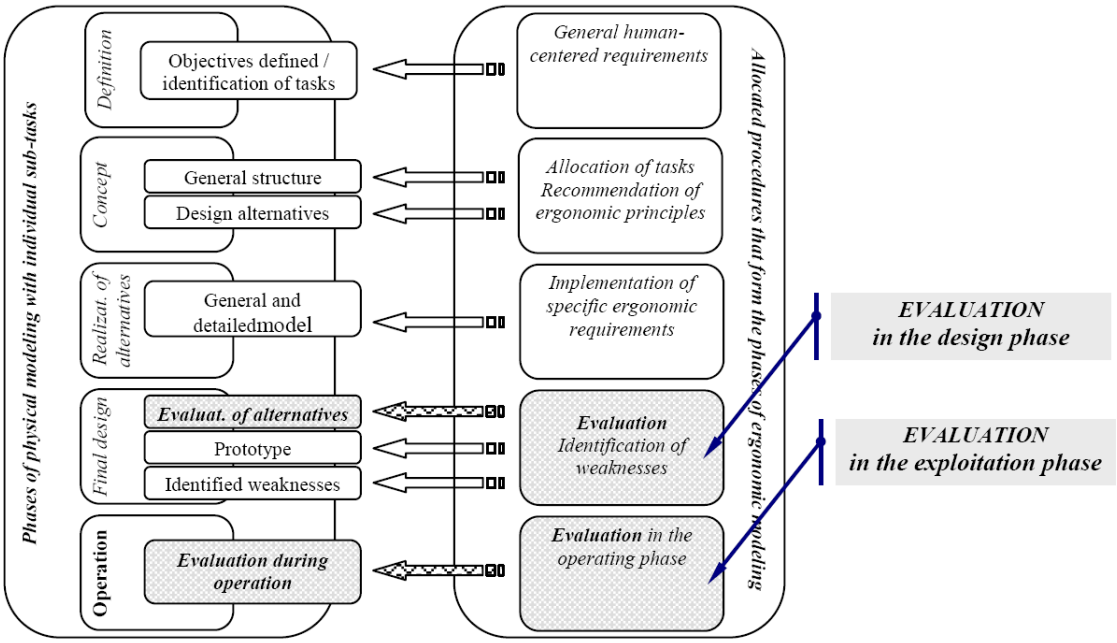

Fig. 2. The evaluation in the process of ergonomic modeling of commercial vehicles
Rys. 2. Ewolucja w procesie ergonomicznego modelowania pojazdów komercyjnych

4.2. Ergonomic evaluation of the vehicle in the exploitation phase

The ergonomic evaluation in the vehicle exploitation phase also represents one of the options for an early focus on the user because it enables, besides the evaluation of the existing model, the acquisition of information that is later used when designing a similar vehicle or re-designing an existing vehicle. An example of this is the introduction of designing changes in certain areas, in certain generations or models of the same commercial vehicle - this is when we talk about renewing or refreshing the vehicle.

In practice it often turns out that despite careful preliminary planning and a detailed consideration of specifications and ergonomic principles for design, the vehicle does not meet certain expectations or even the established requirements. This is only determined when the driver tests the vehicle on the road in the manner the vehicle has been designed for. This is the subjective ergonomic evaluation of the vehicle by the actual user of the vehicle – the driver.

One of the reasons for the expectations and/or requirements of the vehicle not being met can be attributed to problems with the anthropometric design of the vehicle, which is based on the use of anthropometric data. The data is only slightly different in the case of the general population and the population of personal vehicle drivers. However, there are discrepancies between the ISO standards (ISO 3411) that present information about vehicle operators worldwide, according to which vehicles and anthropometric parameters of goods vehicles are designed [18], and the information for a regular population and the population of goods vehicle drivers in certain countries [19].

Therefore, in the vehicle exploitation phase, the driver is the one who evaluates the vehicle from an ergonomic point of view. In cases of certain types of commercial vehicles, the drivers place emphasis on specific elements or characteristics of the vehicle, the ranking of which is attributed to them by the drivers themselves when operating a vehicle. The most important elements and characteristics are those that have a positive influence on feelings of comfort, functionality and safety during the daily operation of the vehicle.

A very illustrative example of ergonomic evaluation of individual models of commercial vehicles before deciding to make a purchase is the case of a bus company where drivers faced a relatively large number of work-related health problems. Before purchasing the vehicles, the company decided to have

a trial period to test the different models of buses, which were then evaluated by the drivers. This approach has proved to be extremely positive for two reasons - new vehicles ensured better physical working conditions for the drivers, as well as better mental and social working conditions; the drivers felt that the company had taken their opinions into consideration, improving the relationship between the management and the employees [20].

These cases of active involvement of a company's employees in the process of ergonomic evaluation can be classified as participatory ergonomics. In order to make this ergonomic evaluation of vehicles even more successful it is recommended that the persons carrying out the evaluation also have adequate knowledge of ergonomics, among which includes knowledge of the human body, energy consumption in body movement, working posture, fatigue and prevention of fatigue, ergonomic relations between humans, equipment, and processes of work and the psychological implication of job satisfaction as well as ergonomics of sex-difference and ageing [21].

5. CONCLUSION

In literature pertaining to the field of ergonomics it is difficult to identify examples of ergonomic evaluations of commercial motor vehicles that would be based on quantitative measurements and subjective evaluations of vehicle users. Ergonomic evaluation is usually based only on the performed quantitative measurements and their comparison with specific reference values, or only on a subjective evaluation of a (usually only one) person who evaluates this vehicle.

The areas or factors that require special attention when ergonomically designing a commercial vehicle and its parts or systems, and at the same time dictate the need for an adequate ergonomic evaluation of the vehicle during its design in the exploitation phase, are especially the changing anthropometric characteristics and the ageing of the population of commercial vehicle drivers as well as the introduction of information technology applications and intelligent transport systems in the transport industry and in commercial vehicles.

The process of globalization, which increases the extent of competitiveness, and rapid technological changes, create demands for increased productivity on the part of both companies and individuals [13]. Rationalizing working processes represents an important factor of increasing productivity and adapting to rapidly changing conditions. However, rationalization can have an influence on the decrease of the importance and the impact of the traditional ergonomic design of workplaces and the working environment, and contribute to an increased incidence of problems associated with employees' welfare and health [13] as well as work safety and efficiency.

The growing demands for increased efficiency of motor vehicles and a decrease of environmental effects of their use can have, seen from the ergonomic point of view, a negative influence on the efficiency and safety of vehicle operation, considering that they dictate the use of systems and devices that provide the drivers with additional information, which occupy their limited capacities of perception and distract attention from their primary task – driving [1, 3].

Knowing, understanding and taking into consideration the effects of an appropriate, ergonomically designed manner and content of work and the working environment can contribute to the establishment of sustainable production systems [13]. Systems created in this manner will have a sustainable nature both from the viewpoint of competitiveness and working conditions, as well as from the point of view of safety and reliability of the work performed.

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