In: AS. Mokhtar, EJ. Abdullah, NM Adam, AR. Abu Talib, NA. Abdul Jalil, R. Zahari, WMI. Hassan & ZA. Zulkefli (Eds.) Proceedings World Engineering Congress 2007 (pp. 51-61), Penang Malaysia.

[Mae] 008

VEHICLE SEAT DESIGN: STATE OF THE ART AND RECENT DEVELOPMENT

T.C Fai[1,2], F. Delbressine[1] and M. Rauterberg[1]
[1]Designed Intelligence Group Faculty of Industrial Design, Technical University Eindhoven, Den Dolech 2, Postbus 513, 5600 MB Eindhoven, The Netherlands.
[2]Universiti Teknikal Malaysia Melaka, P.O. Box 1200, Ayer Keroh, 75450 Melaka, Malaysia.
Email: c.f.tan@tue.nl

ABSTRACT

Seats are one of the most important components of vehicles and they are the place where professional driver spend most of their time. For example, according to Occupational Outlook Handbook by United State Department of Labor, the truck drivers frequently work 50 or more hours a week. The truck drivers sit while they are driving their 50 hours per week. Assuming four weeks vacation and one more for holidays, which is about 2350 hours driving time per year. Automotive seats, which are in contact with vehicle occupants, play an important role in improving the comfort and work environment of a driver and passengers. The improvement of automotive seating systems, particularly for the driver, has been the subject of intense interest for many years since a driver feels more fatigue than passengers. The paper describes a large variety of studies and up-to-date techniques developed for vehicle seats used by different type of transportation system such as cars, trucks, tractors, trains and aircrafts. The objective of this paper is to review the state of the art of vehicle seat design.

***Keywords**: vehicle seats, recent research and development.*

INTRODUCTION

Comfort is an attribute that today's consumers demand more and more. The seat has an important role to play in fulfilling these comfort expectations. Seating comfort is a major concern for drivers and other members of the work force who are exposed to extended periods of sitting and its associated side effects. More than four million truck drivers are engaged in interstate commerce as a result of the widespread dependence on surface transportation of shipping general freight and commodities in the United States [1]. Although there are several other categories of people such as patients who are concerned with seating comfort, drivers represent a large percentage. Research literature has shown that some of the main factors that affect seating comfort are seat-interface pressure distribution, whole-body vibration and pressure change rate.

Drivers of commercial vehicles, particularly heavy trucks, are required to drive long and sometimes irregular hours. In America, the driving limit for truck drivers, as defined by the Federal Highway Administration Hours-of Service (HOS) regulations, is 10 hours. Almost 20% of drivers, however, reported that they "always or often" exceed that limit [2]. Commercial trucks are unique in that they are specifically designed to transport heavy loads over long distances, where for trucks; high priority has been given to durability and functional efficiency. On the contrary, automobiles are made to comfortably accommodate passengers over relatively shorter distances [3]. The personal vehicles are emphasizing factors such as ride comfort; handling, technology and appearance are of high importance in vehicle market. The different requirements of commercial trucks and personal automobiles have led to separate directions in seat design.

Considering the long hours of hauling, it can be argued that one of the most important parts of the truck driver's working environment is the truck seat. Yet only recently has the design of the truck seat experienced major improvements. Improvements have emphasized bolster design to increase stability, and adjustments for backrest angle, contouring, and seat height to promote good posture. Also, the development of air suspension system has made the seat better capable of absorbing vibration transferred from the road surface to the driver [4].

This paper describes the research and development for vehicle seats based on literature review of journals, technical reports and thesis. Focus groups for vehicle seats are cars, buses, trucks, agriculture tractors, trains, air planes and others vehicle such as motorcycles. Current research and development efforts are described as well as areas for future development and the projected impact on better performance of these seats.

SEATING DISCOMFORT

The term "seat comfort" is typically used to define the short-term effect of a seat on a human body. Seating discomfort has been examined from a number of different perspectives. The problem with evaluating comfort in regards to pressure or any other factor is that, comfort is very subjective and not easily quantified. Seating discomfort varies from subject to subject and depends on the task at hand. Comfort, however, is a vague concept and subjective in nature. It is generally defined as lack of discomfort [5].

For example, truck drivers require sitting for long periods of time approximately eight hours. The extended period of sitting includes higher risk of back problems, numbness and discomfort in the buttocks due to surface pressure under the thighs [6]. The sources of such discomfort are listed in Table 1.

Table 1: Causes of seating discomfort [7]

Human experience mode	Biomechanical		Seat/environment
	Physiology causes	Engineering causes	source
Pain	Circulation occlusion	Pressure	Cushion stiffness
Pain	Ischemia	Pressure	Cushion stiffness
Pain	Nerve occlusion	Pressure	Seat contour
Discomfort	-	Vibration	Vehicle ride
Perspiration	Heat	Material Breathability	Vinyl upholstery
Perception	Visual/auditory/tactile	Design/vibration	Vehicle cost

The short-term comfort offered by a seat is relatively easy to determine by many measures [1, 4, 7, 15], the most effective of which is to survey potential users of the seat as they compare the "feel" of a seat for a short period of time against other seats in the same class. This practice is often adopted for different vehicles, ranging from passenger vehicles to commercial vehicles such as trucks, busses, and off road vehicles. The problem, however, with subjective evaluations is that they are costly and time-consuming. In response, a great deal of research has been performed in recent years to find objective measures for predicting seat comfort perception. Some of the proposed objective measures include vibration, interface pressure, and muscle activity. These objective measures are then correlated with subjective data to determine the relative effects of each measure related to comfort [8]. Research has shown that some of the main factors that affect seating comfort are seat-interface pressure distribution, whole-body vibration and pressure change rate [9].

VIBRATION APPROACH

A major portion of the vibrations experienced by the occupants of an automobile enters the body through the seat [10]. Whole-body vibrations, which are mainly vertical vibrations, tend to affect the human body the most. These vibrations are transmitted to the buttocks and back of the occupant along the vertebral axis via the base and back of the seat [11]. Since the natural frequency for the human trunk falls in the range of 4-8 Hz, it is expected that the whole-body vibrations that will most largely affect passengers will occur in this frequency range [9].

Many researchers have performed vibration studies of seats. Van Niekerk et al. [12] conducted research to compare experimental data to the Seat Effective Amplitude Transmissibility (SEAT) values. The experiment used 16 different automobile seats ranging from sedans to SUVs and pickups. The SEAT value is the ratio of the vibration experienced on top of the seat and the vibration that one would be exposed to when sitting directly on the vibrating floor. SEAT values have been widely used to determine the vibration isolation efficiency of a seat. Frechin et al. [13] studied on an active seat to isolate the equipment and passengers in the vehicle from vibration and to compensate, to certain extent, for acceleration in all directions. The main objective is to reduce the negative effects of vibration and acceleration on embarked equipment and passengers. Also, vibration to the whole body was investigated under different driving conditions [14-20].

Whole-body vibration of forest equipment operators often exceeds recommended limits due to the rough terrain and heavy-duty vehicles. Suspension seats can isolate the operator from shock and vibration, improving overall occupational health in forest equipment operation. There are also several types of seat suspensions such as magneto-rheological (MR) seat suspension and semi-active electro-rheological (ER) seat suspension were proposed and their vibration isolation and damping force controllability were investigated [21-30].

ISBN 978-983-43571-1-5

There are some unsolved problems related to vibration on vehicle seats. The nonlinearities of the apparent mass functions which were not quantified by the measuring technique available. Such factors could include the tissue dynamics at the interface between subject and seat, the relative motions within the body and the active response of muscles. Further studies should be performed with further combinations of different axes and tested on the road. Besides, the experimental testing should be conducted on different types of vehicles and road conditions.

PRESSURE APPROACH

Drivers' comfort is as important as the functional and aesthetic design of automobiles since consumers are more and more concerned about safety and comfortable driving. Enhancement of comfort performance of automotive seats necessitates considerations of the human-seat interface pressure distribution under dynamic vibration environment. The characteristics of pressure distribution on a rigid seat under whole-body vehicular vibrations have recently been reported [31].

Gyi et al. [32] evaluated the seat pressure measurement technologies that used in the prediction of driver discomfort for various car seat designs, and provide designers and manufacturers with rapid information early in the design process. Wilker et al. [33] demonstrated a database of intradiscal pressure measurements together with anthropometric data as basis for the validation of models that predict spinal loads. Seigler and Ahmadian [34] formulated two techniques, namely, Seat Pressure Distribution (SPD%) and Area Pressure Change (aPcrms) for the purpose to highlight the relative dynamics between different types of seat cushion, and their effect on driver comfort. The results show that the air-inflated seat cushion can provide significant improvements in pressure distribution between the seat cushion and the driver, therefore providing a more comfortable ride [35-38].

There is a major set of objective measures used for evaluating comfort. They were created based on the comparison of different seat designs with similar types of seat cushions that are widely used in the automotive industry, i.e. urethane foam cushions. The dynamics of air-inflated seat cushions is very different from that of foam cushions in terms of their interface with the human body. Further studies should be performed to use alternative methods of evaluation that can effectively assess the dynamics at the interface between the cushion and the human body. In addition, the design of the vehicle seat should consider the soft body tissue in contact with a soft seat surface.

ERGONOMIC APPROACH

The automotive industry strongly encourages research in the field of objective comfort assessment, especially dedicated to the seat and the related postures [39, 40]. Driver posture is one of the most important issues to be considered in the vehicle design process [41] regarding not only the car and the user [42, 43] but also the experimental conditions.

Alem and Strawn [44] designed and evaluated an energy absorbing truck seat for a 5 ton military truck for increased protection from landmine blasts. Chang et al. [45] developed a practical method for measuring seat-pan and seatback contours and a graphical presentation for visual evaluation. Seat designers can use this method for evaluating seat comfort such as support, fitness and accommodation. Cho and Yoon [46] developed a biomechanical model of humans on a seat with a backrest for evaluating the vehicular ride quality. Rakheja et al. [47] developed a model to study the seated occupant interactions with seat backrest and pan, and biodynamic response under vertical vibration. Wang et al. [48] studied the role of seat geometry and posture on the mechanical energy absorption characteristics of seated occupants under vertical vibration. The results show that the absorbed power quantity increases approximately quadratically with the exposure level by the person. The results also reveal that the absorbed power is strongly dependent upon the individual anthropometry variables such as body mass, fat and mass index. But there is no real proof of the variables given.

Coelho and Dahlman [49] conducted a pilot evaluation and experimental study on car seat side support. The introduction of side supports is aggravating the problem of designing a seat to fit every human being in the range of accommodation targeted in the seat's design. The side support is built-in in both sides of the seat and people with varying body widths must be accommodated for. Three seat design factors were manipulated: the cover's friction properties, the distance between the opposing side supports and the side support's size at the hip-lower torso level. The hypothesis used to study the seat side support is insufficient, factors of importance have

ISBN 978-983-43571-1-5

not been investigated. Some research used the seated man model [50-52] and anthropometrics [53-56] to study the driver's ergonomics. Besides ergonomics, low back pain research is reported in [57-58]. Much research has been performed on building up specific biodynamic models based on certain experimental data under prescribed testing conditions; a thorough investigation of mathematical human models in seated posture has not yet received the same level of attention.

In future studies, research should be concentrated on knowledge improvement of the exposure–response relationship between whole-body vibration and the occurrence of low back disorders, and to advance understanding of the other physical and psychosocial factors that combine to result in the progression of low back symptoms. In addition, an optimization procedure should be used to establish the lumped parameter models with required complexity according to the analysis requirement. The objective functions are the above three biodynamic functions with human body anthropometric data as constraints. With the incorporation of a vehicle model, the vehicle–occupant system can be evaluated to obtain vertical vibration responses or ride quality in driving situations. Also, the seat design should be further researched in order to reduce human vibration originating from the interaction between road profile and vehicle.

SIMULATION AND MODELING

A simulation is the execution of a model, represented by a computer program that gives information about the system being investigated. The simulation approach of analyzing a model is opposed to the analytical approach, where the method of analyzing the system is purely theoretical. A simulation approach may be more reliable, depending on the quality of the model.

Mathematical models are used to simulate and study the seat comfort virtually [59-60]. Bouzara and Richard [59] developed a mathematical model to simulate the dynamic behavior of a 3-D vehicle. With this model, various types of non-linear suspensions, such as active and semi-active suspensions, can be investigated. The results obtained from the simulation of the 3-D vehicle demonstrate that the use of active and semi-active suspension models on road vehicles prove to be beneficial for comfort without unduly compromising road holding capability. Fatollahzadeh [60] constructed a mathematical model which clarifies and predicts the drivers' comfortable sitting posture and position. It was hypothesized that the length and height characteristics of some body segments as well as the body weight and waist circumference of the driver have a great impact on the selection of a specific sitting posture.

De Cuyper and Verhaegen [61] introduced a novel approach for trajectory tracking on seat test rigs. Classically, a digital Fourier transform (DFT) approach, based on a Frequency Response Function (FRF) model, is used in this domain. The novel approach proposes state space models to identify the test rig and uses the recently developed Stable Dynamic Inversion (SDI) to invert the obtained state space models. Gillberg et al. [62] studied and compared the sleepiness and performance of professional drivers in a truck simulator, it compared differences between day and night driving. Mavrikios et al. [63] performed human motion modeling using experimental motion data analyzed by a statistical design of experiments (SDoE) approach. The goal of this work is the development of semi-empirical models that could be used for predicting a realistic accessibility motion, having as input human anthropometrics. Song and Ahmadian [64] studied two semiactive adaptive control algorithms through simulation: the non-model based skyhook control, and the newly developed model-based nonlinear adaptive vibration control. This study includes a discussion of suspension model setup, dynamic analysis approach, and controller tuning. The simulation setup is from a heavy-duty truck seat suspension with a magneto-rheological (MR) damper.

Computer-aided engineering (CAE) methods such as finite element analysis and simulation techniques have also been used to study and to develop vehicle seats [65-73]. Verver et al. [65] used a finite element (FE) model of the human buttocks to predict the static pressure distribution between human and seating surface by its detailed and realistic geometric description. A validation study based on volunteer experiments shows reasonable correlation in pressure distributions between the buttocks model and the volunteers. Both for simulations on a rigid and a soft cushion, the model predict realistic seat pressure distributions. Hix et al. [66] developed engineering methods and expertise in the area of truck seat modeling to capture the effects of seat dynamics on ride quality.

For modeling purposes and for evaluation of driver's seat performance in the vertical direction various computer-aided design models of the seated human body have been developed and standardized by the ISO such as ISO 2631. No such models exist hitherto for human body sitting in an upright position in a cushioned seat upper part, used in industrial environment, where the fore-and-aft vibrations play an important role. Besides, some models that presented can be applied only to a specific vehicle model. Future research should develop the computer models that can be used in different type of vehicles. Environmental parameters also need to be considered for the modeling analysis.

ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) is a term that in its broadest sense would indicate the ability of a machine or artifact to perform the same kinds of functions that characterize human thought. The term AI has also been applied to computer systems and programs capable of performing tasks more complex than straightforward programming, although still far from the realm of actual thought [74].

Kolich [75] demonstrated the used of a neural network(s) to predict subjective perceptions of automobile seat comfort. The inputs included eight seat interface pressure sensors, three anthropometric (gender (SEX), standing height (SH), and body mass (BM)), some demographic variables such as cushion contact area (CCA) (cm^2), cushion total force (CTF) (N) and seatback total force (BTF) (N), and a subjective rating of the seat's aesthetic quality. The output was an overall comfort index derived from occupant responses to a survey with proven levels of reliability and validity. The neural network was developed and validated using data collected from 12 subjects, representing a broad range of anthropometry. Kolich et al. [76] studied the prediction of automobile seat comfort by using a statistical model and a neural network model. From the study to predict subjective perceptions of comfort, the neural network was deemed superior to the statistical model. Yildirim [77] presented a neural scheme for controlling a bus suspension system. The suspension system, designed as quarter bus model, is used to simplify the problem to a one-dimensional mass-spring–damper system.

Gundogdu [78] used genetic algorithms to optimize a four-degrees-of-freedom quarter car seat and suspension system in order to determine a set of parameters to achieve the best performance of the driver. The optimization results are compared through step-response and frequency responses of the seat and suspension system for the optimum and currently used suspension systems.

The AI can be used to predict automobile seats comfort; future research should focus on the derivation of an optimized set of inputs. There should be more input to the neural network in order to get maximum vehicle seats comfort. There are many optimization algorithms available for this purpose. Also, future investigations should broaden the scope of the models to include seats from other market segments and other seating positions. The assumption is that expectations of automobile seat comfort vary by market segment and seating position. Besides, AI can be used to provide thermal and humidity comfort for the drivers.

MEDICAL APPROACH

Johnson and Neve [79] examined structural properties of automobile seats that might be a source of lower lumbar pain (LBP) for the passenger, modified the seat design accordingly, and had it tested by drivers who have LBP.

With a projected rise in the number of elderly, most of whom have also relied primarily on the private automobile for their mobility; it is likely that future adaptations in vehicle design will be linked in some part to the physical infirmities often faced by the elderly. Shaheen and Niemeier [80] proposed two methods that bridge between medical research on the physical impairments of the elderly and automobile design and driving safety. Soloman et al. [81] designed a cross-sectional study to assess healthcare among long distance truck drivers.

The published studies have been focusing on health risks among long-haul truckers in the United States, including retrospective data that grouped long-haul drivers among several types of professional drivers. More study should be concentrated on different types of vehicle drivers such as agriculture trucks.

MECHANICAL RESEARCH

Mechanical research on vehicle seats concentrated on the actuators, the suspensions and dampers. Liu and Wagner [82] designed the controllers and evaluated semi-active hydraulic and active electromechanical hydraulic actuators. A series of four model-free and model based control strategies are presented for each actuator to attenuate road vibrations transmitted to the occupant's lower and upper torso. The controller designs

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include relative, proportional-integral, variable structure system, and optimal control. Perisse and Jezequel [83] published a paper overviewing a theoretical study on active seat suspension. The principal objective of this study is to improve ride passenger comfort by reducing transmitted seat forces.

In addition, Perisse and Jezequel [84] also investigate the experimental feasibility of active seat suspension to improve ride comfort. The prototype of a reversible electromechanical actuator used in an active seat suspension is presented. A reversible electromechanical actuator was used to provide a continuous variable damper/an active force generator to realize a control policy. Choi et al. [85] developed a cylindrical ER (electro-rheological) seat damper and studied the control performances of a semi-active suspension using ER fluids for a commercial vehicle seat.

So far, most of researches for ER seat damper have been focused on the dynamic modeling and field-dependent performance analysis. Research on the vibration isolation of the seat suspension system installed with ER dampers is very rare. Experimental studies should be conducted with different type of vehicle as well as different road condition. AI techniques can be embedded into the controller of the mechanical damper to improve the driver seats comfort.

CRASH AND SAFETY

Motor vehicle crashes have the potential to produce serious thoracic and abdominal injury. In particular, lateral crashes (i.e., side impacts) have been implicated as a causal factor in thoracoabdominal injury. Newgard et al. [86] studied the relationship between seat position (i.e., near-side, middle-seat, and far-side, regardless of row), side of lateral motor vehicle crash (MVC), and serious thoracoabdominal injury after adjusting for important crash factors. Lower extremity injuries are common in front seated occupants of motor vehicles involved in collisions. Atkinson and Atkinson [87] examined lower extremity injury trends from injuries recorded in the National Automotive Sampling System (NASS) database from 1995 to 1999. These data were compared to previous data to determine whether the introduction of air bags in recent years has resulted in a change in the nature or frequency of lower extremity injury. The research showed that air bag deployment does not appear to alter the risk of lower extremity injury, while seat belt use tends to slightly decrease the risk.

Hill and Boyle [88] gathered information on the preferred front seat position of vehicle occupants and to determine the effect of variation in seat position on safety during crashes. The study evaluated the relationship between seat position and occupant size using the chi-square test and compared the risk of severe injury for small females and large males with regard to forward and rearward seat position using logistic regression. Charbotel and Gadegbeku [89] studied the severity factors for truck drivers' crashes from 1995-1999 in France. Park and Park [90] analyzed the crash behavior and designed a belt integrated seat for occupant safety.

Lin and Cohen [91] describe the scope and magnitude of common injuries and illness experienced by workers in the trucking industry such as due to the driver seat. The study served as a guideline for the reduction of injuries and improvement of the work environment. Zacharia et al. [92] describe the summary of the topics and discussions related to bus and truck safety.

Despite the volume of literature on these associations, definitive conclusions and generalizability is tempered by methodological limitations in the majority of studies, including restriction to severely injured patients or occupants in certain seat positions of drivers, limited comparison groups, too small sample sizes, difficulty controlling for crash severity, missing variables, and non-uniform criteria for assessing severity of injury.

THERMAL COMFORT

Thermal comfort is an important aspect to be considered in the ergonomics evaluation of the driver seats, which are significant interfaces between man and machine in autos. Determining thermal comfort in autos is a complex task, because thermal comfort involves the interaction of many variables and automobiles are susceptible to temporal fluctuations in their thermal environments [93]. The temperature inside is dynamic and non-uniform and drivers can experience discomfort from more than one thermal heat or cold source simultaneously. However, poor climatic conditions may affect the driver performance, as described by Norin and Wyon [94].

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Fung [95] studied the properties of the car seat laminate that influences seat thermal comfort. Twenty three trial laminates were evaluated by human subjects. Cengiz and Barbalik [96] performed an evaluation of thermal comfort in an extended road trial study. In the experiments used, the 100% polyester seat cover had three different cover materials, which were velvet, jacquard and a micro fiber. Ratts et al. [97] describe an experimental method to quantify the capability of an automotive seat to move heat and moisture away from the heat and water sources.

In airplane seats, Bartels [98] determined the influence of different cover and cushion materials on the thermal comfort. Different materials, as well as readymade seats, were investigated by the physiological laboratory test methods, namely skin model and seat comfort tester. Additionally, seat trials with human test subjects were performed in a climatic chamber. Results show that a fabric cover allows for a considerably higher sweat transport than leather.

There is a lack of research on thermal and humidity comfort on driver seats. Most of the studies described in papers [95-98] were conducted in climate chamber. Future research on thermal and humidity should be performed on different kind of weather condition as well as different type of vehicles.

OTHER RESEARCH TOPICS

Petit et al. [99] performed an experimental programme to understand the fire behavior of aeronautical seat cushion materials and kerosene burner standard tests. Extended analysis of the experiment results has enabled the identification parameters strongly influencing standard test results (mainly geometry and positioning of the test seat), and also, for the particular case of fire resistant foams, to derive rules of classification with respect to fire response.

Nishimatsu et al. [100] used factor analysis to investigate the hand feeling on automotive seats fabrics. The correlations between the hand feel and the physical properties of seat fabrics were examined by the correlation analysis. How the covering fabric influences feeling of automotive seats was also investigated.

Shin et al. [101] developed a new design methodology for effective automobile seat design. The axiomatic approach is employed to consider multiple safety regulations such as Federal Motor Vehicle Safety Standard (FMVSS) 202, 207, and 210, and the seat manufacturer standard is the “Hige Test”. Axiomatic design is utilized in order to establish a seat design process satisfying various regulation codes.

SUMMARY

The paper surveys a large number of studies and up-to-date techniques developed for vehicle seats used by different types of transportation systems. The objective of this paper is to describe the state of the art and recent development of vehicle seat design which are available in current literature and to give a general idea about unsolved problems that arise in practice. From this literature review, it can be seen that the majority of vehicle seats studies are concentrating on vibration, pressure and ergonomics. Besides, these topics, driver “fatigue” also needs to be considered in vehicle seat design. The term “fatigue” is used to define the physical impairment that results from exposure to the seat vibrations for a long period of time. Fatigue may lead to decreased attention, perception, decision-making, vigilance, and reaction time.

Thermal and humidity comfort also is one of the areas of interest to be considered in future seat research. The Majority of the early studies on thermal comfort have been performed in a climatic chamber. The drivers in a laboratory cannot give a realistic reaction, because they drive using a simulating program. But on the road, they experience real traffic conditions. They must pay attention to traffic lights, speed limits, other traffic, etc. during the experiment. All these conditions affect the body thermal comfort. Future research on seat thermal and humidity comfort can be concentrated on intelligent thermal and humidity control system and evaluate the physiological seat comfort for drivers by using on-the-road experiment testing.

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