

Review

A conceptual framework proposed to formalize the scientific investigation of automobile seat comfort

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Abstract

Consumer expectations for automobile seat comfort continue to rise. With this said, it is evident that the current automobile seat comfort development process, which is only sporadically successful, needs to change. In this context, there has been growing recognition of the need for automobile seat comfort researchers to establish a theoretical and methodological foundation. Only in this way can automobile seat comfort achieve recognition as a true scientific discipline and enable its further development. The present contribution hopes to stimulate and lead researchers to focus on a framework through which this recognition and development can take place. This paper describes the current automobile seat comfort development process and details the associated limitations. The limitations were the catalysts for the creation of a systematized framework intended to direct the investigative process associated with seat comfort research. The framework is expected to produce theories and methods that can explain, guide, and further legitimize the discipline of automobile seat comfort.

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1. Introduction

Automobile seat comfort, which is, oftentimes, practiced by individuals with a background in ergonomics, has developed as an applied science. Traditional research in

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this area has been motivated by: (1) a practical concern for the health and well-being of the consumer and (2) the view that comfort is a product differentiator in the eyes of the end consumer. However, the discipline has a tendency to be reactive to current needs, rather than proactive, and has often borrowed ideas and approaches from other fields (i.e. engineering and psychology). As a result, there has been little emphasis on nurturing theories and methods unique to automobile seat comfort.

There has been growing recognition of the need for automobile seat comfort research to establish a theoretical and methodological foundation, so as to achieve recognition as a more legitimate scientific discipline and to enable its further development. Unfortunately, seat comfort researchers are often uncomfortable theorizing (i.e. integrating groups of fundamental principles that underlie a science), yet theory is universally understood to be an essential underpinning for any discipline that aspires to be perceived as a true science. A lack of theory risks eroding the intellectual foundation of automobile seat comfort research.

The present contribution hopes to stimulate and lead the development of a theoretical basis for the science of automobile seat comfort and to formulate a methodology for this discipline.

2. The current state of automobile seat comfort development

Due to the perceived lack of proven analytical metrics, vehicle manufacturers [i.e. original equipment manufacturers (OEMs)] have opted to rely on subjective evaluations as the main indicator of seat comfort. In this context, the OEMs have developed elaborative subjective evaluation protocols (also known as clinics). The protocols usually involve highly structured questionnaires that direct occupants to assign feelings of discomfort to specific regions of the seat. The questionnaires, which typically contain numeric scales (e.g. 1 = very uncomfortable to 10 = very comfortable), produce subjective ratings that are translated into performance requirements/specifications. The nature of the relationship between the OEM and the seat supplier determines who is ultimately responsible for meeting the subjective comfort requirements. There are seat development programs in which the OEMs have completely rid themselves of the seat design responsibility (including comfort performance). This includes the sourcing of subassemblies (e.g. lumbar mechanisms, tracks, recliners, etc.). The seat supplier, in these situations, assumes a leading role. In other programs, the OEMs own the seat design and the seat supplier is simply the manufacturing source. These are obviously the extremes and the seat design responsibility is often divided (not always equally) between the OEM and seat supplier. The relationships are even more complicated as one considers the global perspective. The functional relationship between the same OEM and seat supplier can be different between hemispheres. Regardless of who is responsible, seats are

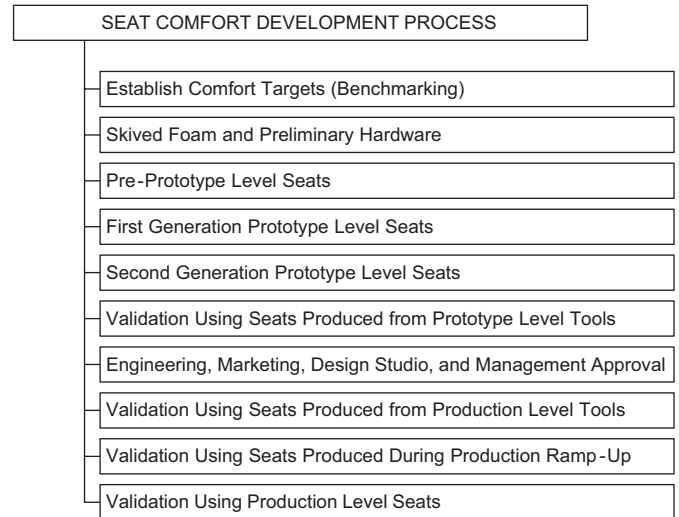


Fig. 1. Flow chart for typical seat comfort development process.

evaluated for comfort at certain points in the vehicle development process. Each point usually corresponds to a clinic and is typically considered a program milestone. An example of these milestones is provided in Fig. 1.

To assist the development team (including the supplier) in understanding the performance requirements, target seats are selected through the joint efforts of marketing, engineering, and program management. The decisions are, many times, based on consumer experiences with recently launched products. In this regard, *J.D. Power & Associates' (2006) Annual Seat Quality Report* is extremely popular. J.D. Power & Associates provide an analysis describing consumer experiences with the quality, design, comfort, and features of their automotive seats. Best-in-class seats are normally targeted.

The author, based on over 10 years of first-hand experience developing automobile seat comfort (at both the OEM and seat supplier level) is equipped to describe, through an example, what typically occurs once a target seat is identified. To begin, the target seat is benchmarked. As part of this exercise, a clinic is performed. The most effective/meaningful form of clinic involves a dynamic component (i.e. driving) and is referred to as a ride & drive. Although, in some instances (typically due to resource restrictions), a static clinic must suffice. The clinics can be internal (i.e. using employees affiliated with the OEM or seat supplier) or external (i.e. participants are drawn from either the general population or from vehicle owners in a particular market segment). Either way, the feedback, in terms of numeric ratings, is used to steer comfort development for the remainder of the program. That is, prototypes are built and evaluated using the same subjective evaluation approach. More specifically, the target seat is evaluated against the next generation seat until the new program seat meets or exceeds the comfort level offered by the target seat. The purported strength of this process lies in the A to B comparison of seats. A successful program (one that matches the performance of a

target seat), since it takes approximately three years to execute, will be just as comfortable as the best seat in the market three years ago. Clearly, this is a problem. It happens even though there is usually some aspect of “futuring” during the target setting process. Futuring is an especially difficult proposition when it comes to seat comfort. In the end, it must be said that excessively long development time impedes advances in comfort (i.e. advances associated with the science of comfort are slow to materialize).

Having personally participated in this process on numerous occasions, the author has encountered several noteworthy limitations (in addition to the excessively long development time). For one, there is no research to suggest an appropriate ride & drive duration. At present, the length of the ride & drive is dependent on: (1) cost and (2) how many ratings per seat the development team feels are necessary to yield meaningful results. Assuming an 8-h day, four rotations at 2 h apiece are common. A 2-h rotation allows for ratings to be obtained at different points in the process. There are two underlying assumptions, both of which need to be substantiated: (1) comfort degrades over the course of 2 h rotation and the seat design can somehow combat this and (2) anything over 2 h makes for a long day of travel and can become uncomfortable for reasons other than the seat. With four rotations per day, it is only possible to get four people to evaluate one seat in a day. This is, obviously, too small a number to yield worthwhile results. For this reason, the ride & drive is typically conducted over the course of two days and, even then, at least two samples of each new seat are made available. While adding a significant amount of cost (additional prototype), this yields 16 ratings per seat. The sufficiency of this number, from the perspective of statistical power, is frequently debated.

An additional limitation stems from the fact that the ride & drive process requires a consistent sample of participants/respondents. Ideally, the participants, because they are representing the consumer, are slanted toward the demographics and anthropometric characteristics of the target buyers. Many times the sample is comprised of key stakeholders in the seat system (i.e. the seat development team). To minimize variations in subjective ratings, each respondent must be committed to the process for the duration of the program. Sample variation, particularly when coupled with questionable statistical power (as previously described), tends to produce a trial-and-error development process in which design modifications made to appease one sample of subjects receive poor ratings from another sample of subjects. Unfortunately, sample consistency is, very often, difficult if not impossible to achieve due to personnel changes (turnover, reassignment, etc.), which are commonplace in the automotive industry.

Program complexity is another factor that complicates the development process. From the seat design team’s perspective, the comfort development process requires the evaluation of all seat types (i.e. full bench, split bench, and

bucket), content (manual or power adjuster, manual or power recliner, adjustable or fixed head restraint, etc.), features (lumbar, front and/or rear cushion tilt, seat heaters, etc.), trim styles (i.e. base level, mid level, and up level), and fabrics (i.e. cloth, vinyl, leather) available for a particular platform that may include several marketing divisions. Manual transmissions are also a significant subset of certain vehicle lines. The operation of a manual transmission may create unique comfort requirements for the driver. Therefore, where appropriate, each major seat design configuration should be evaluated in a manual and automatic transmission environment. The number of vehicles required for a given ride & drive is based on all of these considerations.

For extremely large programs, it is not uncommon to have 100 different seat configurations. With this type of complexity, it is impossible to evaluate (through a single ride & drive) every possible combination. For this reason, initial comfort evaluations are very often performed on high vehicle volume seats (to the detriment of lower vehicle volume seats). While this appears to be a reasonable compromise it puts the development team at a huge disadvantage. Once an acceptable level of comfort is achieved for the high volume seats, other combinations are evaluated to ensure that comfort is not negatively affected. This usually involves an evaluation of different trim styles. Trim styles typically differ with respect to seam locations. If, for example, a seam in a particular trim style is located in a region that deteriorates seat comfort, efforts are taken to relocate the seam. Unfortunately, by the time the trim style in question is included in a ride & drive, it may be too late to change the design without incurring significant costs.

Another problem with this process is that design direction, early in the program, is based on subjective ratings obtained from seats comprised of skived foam and unrepresentative hardware. Skiving is the process of mechanically shaping a foam pad by cutting it out of block or sheet stock. Skived foam due to differences in material properties and therefore occupant penetration does not feel like molded foam. It should, therefore, not be used to direct decisions regarding cushion length, cushion width, lumbar location, etc. Consider, for example, a scenario in which the lumbar contour was perceived as being too low. With a skived sample, the effect may stem from an excessively firm cushion that did not allow for sufficient penetration. Hardware refers to the handles, switches, and controls used to operate the seat. Unless the production level hardware is used, it is unfair to evaluate functionality (locations, efforts, etc.) with respect to the seat system. Once again, design decisions, based on ride & drive feedback, should be withheld. Molded foam and representative hardware are, unfortunately, not available early in the process.

The process is also rendered ineffective by the fact that the seat interacts with the vehicle system, particularly the interior environment. Vehicles, just like seats, undergo

product development cycles. As a result, the power-train, vehicle suspension, and package characteristics (pedal locations, steering wheel position, etc.) are, very often, not finalized until production. This, obviously, affects the seat comfort ratings and associated design decisions.

In summary, the current process is an inefficient and outdated way to develop a comfortable automobile seat. The nature of the ride & drive makes it necessary to investigate the opinions of relatively large groups of occupants in order to determine the impact of various design attributes on impressions of seating comfort (Manenica and Corlett, 1973). This is extremely time consuming [if the key stakeholders in the seat system are spending all this time riding (or developing prototypes for the ride & drive), they are, obviously, not developing the product], expensive (excessive changes lead to tooling iterations), and prone to measurement error. It should also be noted that recent advances in seat comfort evaluation technologies are not reflected in this process. These limitations could, in some ways, be justified if the process could guarantee a comfortable seat. This is, unfortunately, not the case. Since good seats are an exception and not the rule, it must be concluded that the seat comfort development process is, at least, somewhat ubiquitous and in need of overhaul.

3. Systematic approach to requisite research

Automobile seat comfort research appears to be fragmented. To counter this, the subject matter outlined in Fig. 2 must be systematically and sequentially addressed under the auspices of a unifying theoretical and methodological framework. While there exists a significant amount of published research associated with the defined subject matter, the applications are not immediately apparent to design teams. Instead, they view the published research as a series of independent investigations, unrelated to their existing seat comfort development process. For this reason, they have opted to rely on a process filled with limitations (refer to the preceding section). Automobile seat comfort research would be much more powerful (i.e. it would have a much larger impact) if it fit into a bigger picture. To be applied it must support/satisfy the needs of seat design teams. The remainder of this section describes some of the challenges associated with integrating the requisite research into the design process.

3.1. Define automobile seat comfort

Many within the automotive industry believe that the subjective nature of comfort makes theorizing impossible. This paper's premise is that, at the fundamental level, this difficulty has more to do with the lack of consensus concerning an operational definition of automobile seat comfort. The complications concerning the current development process can also, at least partly, be attributed to the lack of consensus.

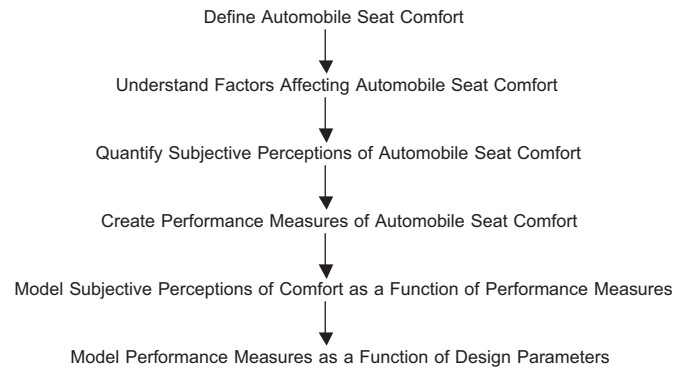


Fig. 2. Research required to establish a theoretical and methodological framework for the science of automobile seat comfort.

Although there exists substantial research in the field of automobile seat comfort, these investigations have generally occurred in a microcosm. Since published definitions reflect the disciplines of the researchers who formulated them, there is no universally accepted operational definition of comfort (Lueder, 1983). An operational definition would allow researchers to establish formal positions that could be advanced and subsequently defended through argumentation (i.e. to formulate testable hypotheses). The preceding sentence basically defines the term thesis. These are essential to theory because they integrate groups of fundamental principles underlying a science.

The task of creating a universally accepted operational definition is complex. Consider, for example, the fact that there is little agreement as to whether comfort and discomfort should be regarded as being a bipolar continuum or as composing two experiential dimensions. Branton (1969) assumed that an automobile seat is unlikely to impart a positive feeling to the sitter. That is, the best a seat can do is to cause no discomfort. From the same perspective, Hertzberg (1972) defined comfort as 'the absence of discomfort'. Many of today's researchers have adopted this definition because, in the current environment, it is more straightforward to quantify discomfort than to measure comfort.

Other researchers argue that seat comfort is a bipolar dimension that can be attributed to characteristics of design (Richards, 1980). Evidence to support this claim comes from the fact that occupants, when given the opportunity, rate their subjective responses across an entire continuum, ranging from positive comfort to discomfort. This is the school of thought subscribed to by researchers involved in designing comfort enhancing products (e.g. massaging seats).

There are other definitions. According to Lueder (1983), comfort relative to automobile seating might be viewed as a function of the patterns of physical supports and constraints on the occupant engaged in the task of driving. As such, comfort may be represented physiologically, psychologically, behaviorally, and in performance. Shen and Vertiz (1997) have proposed that comfort and discomfort coexist as separate dimensions, with the possibilities for

comfort increasing when discomfort decreases. They describe comfort as the result of a continuous behavioral process of decreasing discomfort. For example, a wider, more supportive seat may provide better comfort than a narrower seat, even though the narrower seat does not produce a different level of discomfort.

The debate and surrounding controversy concerning an operational definition must be resolved. Until researchers can agree, the discipline will remain splintered by competing schools of thought and several different frameworks. In the end, design teams will continue to produce automobile seats with sub-optimized levels of comfort. While the objective of this paper does not include a position concerning an operational definition of automobile seat comfort, it is, at the time, appropriate to submit a preliminary proposal. Specifically, automobile seat comfort can be defined as a consensually held construct (i.e. a large group of representative subjects perceive the seat in a similar manner) possessing a static and dynamic component that can be manifested objectively (i.e. is consistently quantifiable).

3.2. Understand factors affecting automobile seat comfort

There are many factors that affect automobile seat comfort. User subjectivity, occupant anthropometry, seat geometry, and amount of time spent sitting have previously been cited (Thakurta et al., 1995). The growth of the international automotive market, which has served to increase diversity in seat design, is another factor. In other words, unique, but functionally equivalent, seats are required to satisfy culture-based preferences and expectations of seat comfort. Western Europeans, for example, are, based on the author's experience, generally, thought to prefer firmer seats as compared to North Americans. Fig. 3 builds on the preceding factors to provide a more complete, although definitely not comprehensive, list. It demonstrates the multi-faceted nature of automobile seat comfort.

This paragraph, which is based on the author's experience, offers a little more insight into the rationale used for including the factors outlined in Fig. 3. Vehicle package, which may represent a segment-specific effect (i.e. seats in the same market segment probably have comparable packages), is thought to be a primary determinant of seat comfort. Vehicle package defines roominess (i.e. headroom, legroom, shoulder room, and hip room). It is

reasonable to contend that the same seat, when placed in two different packages, will receive different comfort ratings. Similarly, the same seat, when sold under a different nameplate, may receive different comfort ratings. Nameplate is related to purchase price of vehicle. For the purposes of this discussion, both nameplate and purchase price of vehicle are considered social factors. Individual factors, like age and body size, are thought to affect subjective perceptions of comfort. Posture may be the most important individual factor. While the effect of posture is assumed to be significant, it is difficult to address because occupants with similar anthropometric characteristics may sit in completely different body positions. The study of seated posture is an active and worthwhile area of future research. Stiffness, geometry, contour, breathability, and styling are considered seat factors. Stiffness refers to the resiliency of the seat system. Geometry defines seat shape in terms of width, length, and height, whereas contour deals with the profile of the seated surface (e.g. location and prominence of lumbar apex). The seat's geometry and contour must accommodate the anthropometric variability of the target population. Breathability, as it pertains to the soft trim (i.e. foam density and fabric construction), may affect automobile seat comfort in extreme environmental conditions. Styling must be included as a seat factor because aesthetic quality may affect perceptions of comfort, in the same way as nameplate or purchase price of vehicle.

There are other factors, not shown in Fig. 3, which may indirectly affect subjective perceptions of seat comfort. It is conceivable that a problem with quality, as indicated by durability or noise [i.e. (1) buzz, squeak, and rattle, (2) road, wind, engine, and tire noise, and/or (3) radio and music system acoustics], may negatively affect the consumer's opinion of the entire vehicle, including seat comfort. The same can be said for problems with the HVAC system [temperature, humidity, and air quality (cabin climate)], the instrument panel controls [in terms of reach and touch (i.e. location of features, ease of operation, and visibility and lighting)], and storage.

There are also important interactions between the factors listed in Fig. 3. These interactions can and should be studied. While this is more difficult than it appears, factor analysis may help to reduce the problem to more manageable proportions. Once identified, the critical interactions can be formulated into hypotheses that lend

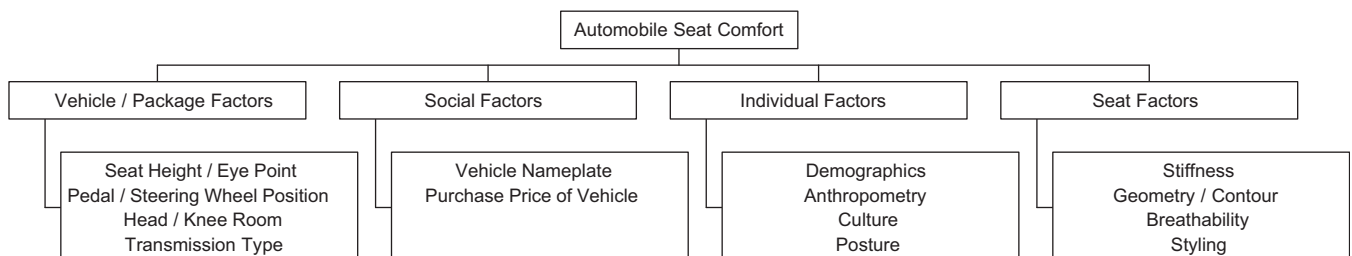


Fig. 3. Factors affecting subjective perceptions of automobile seat comfort.

themselves well to the investigative process familiar to most researchers. Consider, for example, the relationship between seat height (listed as a vehicle/package factor) and posture (listed as an individual factor), as manifested through occupant selected seat position. It is known that humans search instinctively for the body posture allowing the lowest expenditure of energy within the limits of that which is physiologically and biomechanically possible, as well as that which allows an ease and efficiency in task execution (Judic et al., 1993). It is impossible to quantify automobile seat comfort without first defining a space in which a postural compromise is possible. The seat adjusters, in combination with the anthropometric characteristics of the occupant, help to define this space.

An understanding of the contributing factors (and interactions), as they relate to a universally accepted operational definition of automobile seat comfort is essential to the development of a theoretical and methodological research basis.

3.3. *Quantify subjective perceptions of automobile seat comfort*

After operationally defining comfort and understanding the contributing factors, the task becomes one of quantification. This includes the subjective data, which, as previously described, are typically obtained through structured questionnaires included as an integral part of the ride & drive process. In this context, a properly designed questionnaire (i.e. one that is crafted from the perspective of a universally accepted operational definition of automobile seat comfort and one that addresses the critical factors affecting automobile seat comfort) is paramount because it affords researchers an instrument from which to establish theories. The lack of emphasis on seat comfort questionnaire design (exceptions include Reed et al., 1991; Shen and Parsons, 1997; Kolich, 1999; Kolich and White, 2004) is surprising given: (1) the extent to which seat comfort development relies on questionnaire data and (2) the fact that many of the problems related to the collection of subjective data have been well known for some time (particularly in domains like psychology).

A good questionnaire is reliable and valid. This involves reducing the questionnaire measures into two components: a true score component and a measurement error component. A reliable questionnaire item contains little measurement error. It is, however, impossible to directly observe the true score and error components of an actual score on a questionnaire item. Instead, correlation techniques are used to give an estimate of the extent to which the questionnaire item reflects true score rather than measurement error. Important indicators are test–retest reliability, internal consistency, criterion-related validity, construct-related validity, and face validity (Kolich, 1999; Kolich and White, 2004).

Reliability and validity can be assured by considering the following principles: (a) the wording of questionnaire items

(Oppenheim, 1966), (b) the number of rating scale categories (Guilford, 1954; Grigg, 1978), (c) the verbal tags associated with the categories (Osgood et al., 1957), and (d) the interest and motivation of the respondent, as a function of questionnaire length. The type of rating scale (i.e. nominal, ordinal, interval, or ratio) must also be considered, since seat comfort questionnaires are, typically, subjected to some form of quantitative analysis, whether it is a simple frequency count or a more complex statistical treatment (Stevens, 1946; Cozby, 1989). Only when the method of quantification is well thought-out, can the questionnaire results be used as the basis for design decisions. Failure to attend to the quantitative aspects of questionnaire design will produce results that are, at best, biased and, at worst, totally invalid. This obviously has a detrimental effect on the advancement of theory and it forces comfort development to take on a trial-and-error approach. As previously indicated, this is an expensive and inefficient way to impact design.

At a minimum level, if researchers were to apply a questionnaire developed with this type of rigor, along with a structured data analysis approach, the current process would improve. This paper aims higher. Specifically, a good questionnaire could be used to define meaningful dependent variables for the purposes of prediction. This notion, in terms of its impact on the creation of a theoretical and methodological basis for the science of automobile seat comfort, is described later in this section.

As an interesting alternative to questionnaires, Desmet et al. (2000) has developed a method using emo-cards. This system uses 16 cards that show faces with varying emotions. A test subject is asked to choose the card that best fits with their emotion on seeing the product or a precursor of the product in drawing form. Firstly, they use the cards to define the ideal emotion related to the product (in this case, the automobile seat). Then several seats are rated and the best can be chosen. Novel approaches to quantifying subjective perceptions of automobile seat comfort have a definite place in the proposed framework.

3.4. *Create performance measures for automobile seat comfort related to physiology and biomechanics*

Many within the automotive seating industry (OEMs together with seat suppliers), because they understand that consumers will continue to evaluate comfort in very subjective ways and because they have themselves struggled with the current development process, consider the subjective nature of seat comfort as an impediment to design. The common belief is that seat system design teams desperately need objective, measurable laboratory standards that can be linked to subjective perceptions of comfort (i.e. performance measures). Evaluation methods that provide insight into human physiology and biomechanics are, therefore, currently being examined. Recent advances in sensing technologies have allowed for new and improved characterization of the occupant–seat interface

(Park and Kim, 1997; Sheridan et al., 1991). The application of these technologies permits a wide variety of experiments to be conducted, in real-time, without requiring modification to the seats under investigation. These technologies will be instrumental in understanding the underlying mechanism of automobile seat comfort, particularly as it relates to physiology and biomechanics.

There is technology, for example, that can be used to assess the pressure distribution at the occupant–seat interface. Some researchers have suggested that pressure distribution affects perceptions of seat comfort (Diebschlag et al., 1988; Hertzberg, 1972; Kamiyo et al., 1982; Kohara and Sugi, 1972). This is controversial. What can be said, given the current state of knowledge, is that a good pressure distribution indicates sufficient and balanced support to body areas in contact with the automobile seat. How to achieve balanced support and what constitutes balanced support is debatable. This topic requires more research.

Thermal comfort, in terms of both temperature and humidity, can be monitored using different types of sensors. A buildup of temperature and humidity at the skin surface can lead to discomfort, partly because of an increase in the coefficient of friction when the skin is moist. Perspiration that is trapped against the skin by the soft trim (foam and fabric) can produce a sticky feeling if the skin is warm, or a clammy feeling if it is cold. The soft trim is thought to be an important determinant of the microclimate.

There is little published literature that can be used to design a comfortable microclimate. Nevertheless it is possible to derive generalities (Diebschlag et al., 1988). For example, (1) body heat and water vapor must be allowed to pass through the seat (i.e. soft trim that substantially impedes heat or water vapor transfer is to be avoided), (2) perforated cover materials are desirable because of reduced resistance to water vapor diffusion, and (3) soft foam should be avoided because it increases the resistance to water vapor diffusion. Even without clear design direction, efforts are now being made to actively control thermal comfort (e.g. seat heaters and ventilation devices). These innovations cannot be optimized without a clear understanding of what constitutes thermal comfort and what factors affect thermal comfort (i.e. performance metrics are required to assess the viability of the product designs).

Fatigue, as indicated by the electrical activity in contracting muscle (i.e. EMG signals), can also be detected using today's technology. There are advantages and disadvantages to this method. According to Giroux and Lamontagne (1990), surface electrodes (which are the type of electrodes most commonly used for automotive seating studies) are reliable on a day-to-day basis, quick and easy to attach, do not cause discomfort or pain, and have good reproducibility. In terms of disadvantages, the EMG signals are influenced by a specific subject's muscle

geometry, diet (glucose levels), variation in sleep patterns, and activity levels preceding the test (Lee et al., 1995). To counter these concerns, the electrodes must be attached to the individual in a way that achieves low electrical impedance. Often this requires clinical-type experimental controls (e.g. shaving hair, removing dry skin cells, and using a biocompatible electrode paste), which may be overly invasive for laboratories commonly found in the automotive seating industry. Other disadvantages include the cumbersome test equipment and data acquisition systems (i.e. electrodes, amplifier, personal computer), the fact that the electrodes may be perceived as annoying and may, therefore, negatively affect perceptions of comfort, and the considerable amount of time it takes to obtain a measurable effect. While some automobile seat comfort researchers are turned off by these limitations, others have continued to use EMG as an objective indicator of fatigue (Kolich et al., 2000, 2001; Bush et al., 1995; Greiff and Guth, 1994; Lee and Ferraiuolo, 1993; Sheridan et al., 1991). Unfortunately, the research has failed to produce standards for acceptable EMG levels.

Accelerometers allow researchers to quantify the vibration transmitted through the seat to the occupant. Vibration transmissibility, particularly in the vertical direction, is one of the most studied objective measures of automobile seat comfort, yet the topic is clearly not well understood, as demonstrated by the automotive seating industry's difficulty with vibration control (Kolich et al., 2004). Just as with the other methods, generalities, as opposed to design criteria, can be gleaned from the published literature. Griffin (1994) suggests that occupants, due to the primary flexion mode of the trunk, show a resonance in vertical vibration between 4 and 8 Hz. Vibration transmissibility should, therefore, be minimized in the 4–8 Hz range. This is complicated because occupied vehicle seats tend to produce a resonance in the same range.

The physiology and biomechanics associated with back pain, which Coventry (1968) referred to as a disease of the automotive age, represents another topic that begs to be understood from the perspective of performance metrics. One of the predominant factors associated with back pain is the time spent driving (Kelsey and Hardy, 1975). The risk factor stems from what Grieco (1986) calls postural fixity. This phenomenon occurs when an individual sits in one position, without significant postural movement, for an extended period of time. In the driving environment, where postures are determined and therefore fixed by the pedals, the steering wheel, the seat belt, the visual demands of the task, and the seat itself, the resulting static loading of the body's musculature has many detrimental effects including the flow of blood (which transports metabolic products) to and from localized areas. More recent literature is mixed. Burton et al. (1996) showed that vehicle exposure had a small effect on low back pain while Battie et al. (2002) found that low back pain did not differ between occupational drivers and a control group.

The overwhelming lack of consensus regarding the findings derived from the available performance measures is immediately apparent. This may be due, at least partly, to differences in protocol. Methodological standards are required. This is critical to any scientific discipline; automobile seat comfort is no exception. The lack of standardization has impeded the advancement of a theoretical and methodological basis for automobile seat comfort research. As part of establishing standards, the performance measures must be shown to be reliable and valid, in much the same way as reliability and validity needs to be established for subjective data. Only in this way, will the automotive seating industry be able to quantify comfort in a manner that will allow for different seats to be distinguished.

The lack of methodological standardization is most apparent in terms of subject selection/sampling. A common, although not uniformly applied, practice is to use a subject group that has an equal distribution of small females, medium males, and large males. The rationale is that seats are designed to accommodate the population from small (5th percentile female) to large (95th percentile male). The selection criteria are usually stature and mass. This is limited in that someone who is 50th percentile in height is not necessarily 50th percentile in hip breadth, seating height, body mass, popliteal length, etc. Another widespread approach is to select subjects that match the anthropometric and demographic characteristics of the target buyers.

Both of the preceding selection strategies may, however, be flawed given selected performance measures. Consider, for example, the fact that some occupants will produce relatively even pressure distributions, even on hard seats, because of ample adipose tissue, while other more lean subjects will produce high-pressure peaks even on a well-padded seat. Since the former are not likely to experience discomfort because of excessive local pressure, it is reasonable to restrict many pressure distribution investigations to specific subpopulations who are particularly sensitive to changes in stiffness, geometry, and contour; namely, heavy, lean subjects, and small subjects for whom cushion-leg interference is more likely. It is not difficult to envision how the same types of concerns may affect the microclimate at the occupant–seat interface. Different amounts of subcutaneous fat may also affect the EMG signal, particularly when the electrodes are configured to target the lower back musculature. In terms of vibration transmissibility, the structures of the human body are known to vary widely in terms of compliance and damping characteristics (e.g. bones vs. soft tissues). This variance may affect the results. Given these concerns, it may be more valuable for sampling procedures to target worst-case anthropometric characteristics under the assumption that the resulting seat designs are likely to be acceptable to a larger percentage of the population.

Another methodological problem stems from the fact that subjects participating in experimental investigations

into pressure distribution, microclimate, EMG, and vibration transmissibility are usually asked to sit in prescribed postures. There is a difference between preferred and prescribed postures (Reed et al., 1995). Therefore, the performance measures obtained from an experiment may not extend to actual driving conditions.

In the end, the methodological standards would, ideally, include instructions on how to reduce the data into meaningful characteristics. It may be useful, for example, to consider pressure (perhaps peak pressure) in specific body regions, along with contact area. Thermal comfort could be assessed using total heat and water vapor transfer at the occupant–seat interface. EMG signals can be analyzed for both amplitude and frequency. This can be done for specific muscle groups. Resonant frequency, resonant amplitude, and isolation frequency can be derived from vibration transmissibility studies. Sensitivity analyses could be conducted with a standard set of performance measures to determine the difference required to affect subjective perceptions of comfort (this is another area in which reliable and valid questionnaires will be required).

With standard method for pressure distribution, thermal comfort, muscle fatigue, and vibration transmissibility it would be possible for any researcher, scientist, or engineer anywhere in the world to compare seat designs and determine if they are significantly different. Coupled with the recommended sensitivity analyses, it should be possible to determine whether the difference is expected to affect subjective perceptions of comfort. Not only would this contribute to advancing the theoretical and methodological basis for automobile seat comfort development, it would prevent unnecessary design changes (i.e. those based on effects that do not, in reality, exist).

This discussion should not discourage researchers from creating new methods. Researchers should, however, realize that their findings are more likely to be accepted and incorporated by the automotive seating industry if standard methods are employed. New methods should be developed from the perspective of a universally accepted definition of comfort and with an eye on future standardization.

3.5. Model subjective perceptions of comfort as a function of performance measures

The occupant–seat interface is characterized using physiological and biomechanical indicators (e.g. pressure distribution, temperature and humidity, EMG, and vibration transmissibility) in order to explain comfort. It is essential that researchers formalize the implied relationship by developing predictive instruments linking performance measures (obtained through scientifically sound and standardized methodologies) to subjective perceptions of comfort (derived from a questionnaire with proven levels of reliability and validity). Modeling alternatives include statistical techniques (Kolich and Taboun, 2004) and artificial neural networks (Kolich, 2004). The models may

also be improved by considering the previously described social factors.

Model development of this type would require a substantial database of performance measures and corresponding subjective measures for a broad range of automobile seats. In addition to forecasting automobile seat comfort for a new sample of performance measures, the prediction models would provide insight into: (1) how well subjective perceptions of comfort can be explained by knowing the value of a set of predictor variables and (2) which subset from many measures is most effective for estimating subjective perceptions of comfort (i.e. weighting the performance measures). Validated models would help seat system design teams focus on the most important performance measures.

Using the prediction models, human criteria for the performance measures can be deduced. That is, researchers can determine what input values result in the target output. This is basically an optimization exercise. Established human criteria would represent a valuable contribution, especially in the context of seat comfort assessment.

3.6. *Model performance measures as a function of design parameters*

The types of models described in the preceding section are a critical component of the conceptual framework for automobile seat comfort. They do not, however, provide design teams with recommendations for how to impact the performance measures. If lumbar pressure, for example, is proven to affect perceptions of comfort, then the question is how can a seat be designed to produce an optimal amount of lumbar pressure? Design teams deal with vehicle/package factors and seat factors—refer to Fig. 3 for more detail. They do not deal with human criteria related to pressure distribution, microclimate, EMG, and vibration transmissibility. For this reason, the remainder of this section details two separate modeling approaches to design guidelines generation, both of which are a form of virtual engineering.

The first takes advantage of human-based dynamic models that account for internal and external forces. To date, these models have been used mainly for impact situations but could, through additional research, be extended to apply to seat comfort assessments. These finite element human models are comprised of volumes, surfaces, lines, etc. (collectively known as elements), which are interconnected at discrete points, referred to as nodes. The stresses are derived from the deformations and the constitutive properties of the bones, soft tissue (e.g. muscles), and skin. Several finite element models have been published focusing on specific body parts—so-called segment models (Brosh and Arcan, 2000; Chow and Odell, 1978; Todd and Thacker, 1994). Examples of complete finite element human models include those developed by Hubbard et al. (1993), the CASIMIR model in ABAQUS, the ROBBY model in PAM-CRASH, and MADYMO.

Researchers are actively working on ways to couple human finite element models with seat finite element models with the objective of simulating pressure distribution and vibration transmissibility. In this way, the stiffness, geometry, and contour characteristics that produce the desired human criteria/performance measures can be identified. It can be surmised that this approach will, eventually, pervade the entire industry; it will become the manner in which seats are designed for comfort.

There are other types of dynamic models: namely lumped mass and multi-body models. Lumped mass models can be used for vertical vibration transmissibility studies (Cho et al., 2000; Wu et al., 1999; Amirouche et al., 1997; Gurram and Vertiz, 1997; Zhao et al., 1994). In this type of model, the human system is represented by one or more rigid elements often connected by massless elements, like springs and dampers. In multi-body models, various joint types that constrain the number of degrees of freedom connect elements in a chain. External forces stemming from accelerations, spring-damper elements, restraint models, and contact models cause the motion of the joint-connected elements. Multi-body techniques also allow for the definition of flexible bodies instead of rigid bodies. Examples of multi-body packages with human models include DYNAMICUS in ALASKA (Jodicke, 2001), FIGURE in ADAMS (McGuan, 2001), and MADYMO (Verver and van Hoof, 2004).

Until the human-based dynamic models are perfected, prediction models developed using statistical techniques and/or artificial neural networks may represent a viable alternative (akin to the models described in the preceding section). A model relating design parameters to performance measures cannot be created without data. The first step is to create a database of design parameters and corresponding performance measures for a broad range of automobile seats. The design parameters, particularly geometry and contour, should be compared in manufacturer specified design position. In the automotive seating industry, the H-Point (i.e. hip point) is the principle reference point. The H-Point is based on a manikin that represents how medium-sized men sit in, and interact with, different vehicle seats and vehicle environments (Society of Automotive Engineers, 1995). The CAD data from competitive seats or competing seat designs should then be overlaid over H-Point [with special emphasis on standard sections (centerline and cross car) related to specific anthropometric criteria] and dimensioned in terms of pre-established traits like cushion/seatback width, cushion length, bolster/wing height, seatback height, location of apex of lumbar contour, etc. Through this process the differences between seats would become apparent. A reasonable starting point for the determination of these standard sections is the latest revision to SAE J1100 (Society of Automotive Engineers, 2002).

In both approaches, model development, validation, and optimization can occur just as before. Optimization would be geared toward targeted human criteria that were

derived from subjective perceptions of comfort. The optimization exercise would result in more in-depth understanding of the seat factors affecting the human criteria. This understanding could be parlayed into design guidelines, thereby drastically improving the seat comfort development process.

4. Discussion

Many major automobile manufacturers fail to consider the people who purchase their products (Porter, 1994). In the early 1980s, the familiar slogan ‘safety does not sell cars’ was believed to be true by many manufacturers, and maybe it was. The last two decades have seen a large increase in public awareness concerning developments in primary and secondary safety and a quick browse through any car magazine shows that safety features take pride of place. Similarly, society’s attitudes toward comfort are beginning to change—not only in the home and office, but in the automobile as well. Comfortable seating is no longer considered a luxury; it is a requirement.

Seat comfort is distinct and inherently valuable to the automotive industry. Convention, among those in the automotive seating industry, is to design seats using empiricism and intuition. Without a methodological and theoretical basis, automobile seat comfort, as a scientific discipline, will never be systematized, and thus will remain a subject that is difficult to practice. The author, together with the many design teams he has been affiliated with, has had limited success quantifying comfort even with numerous technologies available. This manuscript does not intend to advance any one aspect of the subject matter pertaining to the science of automobile seat comfort. Instead, it aims to present a viable framework for the integration of said subject matter into a form that will produce a closely reasoned set of propositions (i.e. theories) that can be used to explain, guide, and further legitimize the science of automobile seat comfort. The unifying framework, which should advance the discipline by providing focus, represents the essence of this contribution.

The first consideration in the unifying framework is to operationally define automobile seat comfort. This is arguably the most important and most controversial element. The goal of this type of definition is to become universally accepted. This paper’s contention is that the lack of consensus has hindered advances in automobile seat comfort research.

Seat comfort cannot be quantified without an understanding of the consumers’ likes and dislikes. That is, factors affecting automobile seat comfort must be specified. The most common way to obtain this information is to gauge perceptions of comfort through a questionnaire. While the questionnaires used and the studies performed by seat system design teams offer credible evaluations in terms of face validity, the comparisons are poor in terms of experimental rigor. Consequently, the results are questionable on the grounds of methodological weaknesses. The

development of a conceptual seat comfort framework must, therefore, consider the quantification of subjective perceptions of comfort. The protocol should strive to put forward a standard benchmark against which all present and future automobile seat comfort questionnaires may be evaluated. This implies that the questionnaire, as well as the corresponding approach to data analysis, is reliable and valid. There exists a vast array of information pertaining to survey construction that automobile seat comfort researchers have not yet tapped. This is surprising given the extent to which the current automobile seat comfort development process relies on questionnaire data. In the end, automobile seat comfort development, not to mention prediction capability, should no longer be compromised by the lack of an acceptable subjective instrument. This would represent a significant improvement to the current process.

The quantification and subsequent design of automotive seating for improved occupant comfort is, presently, one of the primary goals for seat system design teams. This is due to the fact that comfort, as it is currently understood, is recognized as a subjective concept that is difficult to measure. Part of the proposed framework includes the development of performance measures for pressure distribution, microclimate, EMG, and vibration transmissibility (to name a few). These measures should be held to the same reliability and validity standards as the subjective measures. These measures and corresponding methods should be able to distinguish between competing seat designs. This would come with methodological standardization.

Many of these technologies have been available to the automotive seating industry for some time. The technology is, unfortunately, useless without an understanding of how the output relates to subjective perceptions of comfort. One of the problems with past seat comfort quantification efforts is that there was no good way to translate perceptions of comfort into something tangible. The next part of the framework is geared toward proving that automobile seat comfort, which is a subjective construct, can be predicted from performance measures, along with certain social factors. This type of forecasting ability would effectively improve the efficiency with which seats are designed. Presently, seats are developed in an iterative manner because subjective feedback drives the design. Iteration requires time and costly prototypes. This could be justified if the process guaranteed a comfortable seat. Unfortunately, this is not the case. From the validated models, human criteria for the performance measures should be established.

If this research is to affect design practices, direction on how to impact the performance measures is required. To this end, guidelines for seat height, eye point, pedal position, steering wheel location, headroom, legroom, and transmission type (i.e. vehicle/package factors) and stiffness, geometry, contour, breathability, and styling (i.e. seat factors) should be derived. The guidelines must consider demographics, anthropometry, culture, and

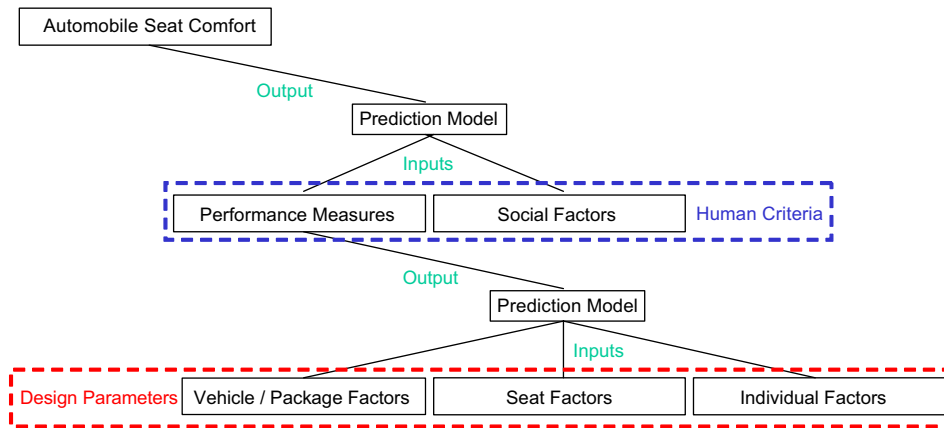


Fig. 4. Qualitative framework for the development of a theoretical and methodological basis for the science of automobile seat comfort.

posture (i.e. individual factors). These guidelines represent an important advancement in the body of knowledge dealing with automobile seat comfort and are best formalized through virtual engineering capabilities that relate performance measures to design parameters. Statistical models, neural networks, and human based dynamic models (finite element, lumped mass, and multi-body) are critical parts of the framework, especially since OEMs are focusing on getting products to market quicker while maintaining (or exceeding) their quality objectives. Three to five year vehicle development cycles were, once upon a time, commonplace. Today, 15 months is state-of-the-art. OEMs will, in all likelihood, continue to push for further decreases in development time.

Based on the information presented in this manuscript, it is possible to outline a qualitative framework for the development of a theoretical and methodological basis for automobile seat comfort research. This was done in Fig. 4. The framework should direct the investigative process associated with seat comfort research and establish a scientific foundation for the design of comfortable automobile seats. Note, however, that good research answers questions and, at the same time, generates new questions (i.e. reveals future research opportunities). The recommended framework is flexible enough to allow for this type of exploration, provided that it is related to the advancement of the automobile seat comfort discipline.

Even with all this research done, there will always be residual or unexplained elements to automobile seat comfort. This is due to consumer subjectivity. Through the methodological and theoretical framework established as part of this manuscript, it should be possible to determine what percentage of the variance in subjective perceptions of seat comfort is due to consumer subjectivity. Depending on the percentage, seat design teams can decide how to assign resources between research and application. If the percentage is high, more research needs to be done, perhaps comfort needs to be redefined, or a greater understanding needs to be forged, or the quantification

methods need to be revisited—all of this will affect the subsequent models, human criteria, and design guidelines. If, on the other hand, the percentage is sufficiently low, the theories can be used for the purposes of product development (shift from research to application).

5. Conclusion

One of the problems with automobile seat comfort development today is that it is, in the majority of cases, based on opinion. The available research, which is plentiful, is difficult for design teams to apply. They fail to see how each independent piece of research can help them produce a comfortable automobile seat. With no other recourse, they allow opinion to drive the design. Almost anyone who has worked seat comfort development for any period of time can recount an instance in which a high-ranking manager's opinion led to a design change. Often these changes occur late in the development process. This is an expensive and inefficient way to design a comfortable seat. This manuscript was written, in part, to underscore the fact that it is time to base automobile seat comfort design on data from proven theories. The proposed conceptual framework, which was derived from the drawbacks associated with currently employed automobile seat comfort development processes, is offered as an enabling mechanism.

This manuscript's contribution is, in and of itself, the framework. It would be overly ambitious to expect a single manuscript to quantitatively support all the assumptions related to the proposed framework. In fact, one of the arguments of this manuscript is that the perception surrounding automobile seat comfort development is that it lacks legitimacy because the requisite quantitative support does not exist. The hope is that this manuscript will spur automotive researchers around the world to populate the framework (i.e. to justify the contribution of each group of factors and the interactions among groups); thereby establishing/gaining recognition for the discipline

of automotive seat comfort. The detail, which will be left to upcoming contributions by this author, as well as others, will come from future research.

“Disclaimer. The opinions expressed in this paper are those of the author and do not necessarily represent the views of Ford Motor Company.”

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