Field Study to Evaluate Driver Fatigue on Air-Inflated Truck Seat Cushions

by

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ABSTRACT

This study conducted a series of road tests in the regular fleet operations of a revenue service to better understand the relationship between vehicle seat design and driver fatigue, improve two newly proposed objective methods for evaluating driver fatigue, and provide design guidelines for evaluating and improving vehicle seat characteristics in terms of driver fatigue.

Each driver completed a test session on two seat cushions – one a polyurethane foam cushion and one an air-inflated cushion. Objective measurements of pressure distribution were taken throughout each test session, while subjective measurements were collected using surveys taken at one-hour intervals.

Based on these results, we find that the air-inflated seat cushion has advantages in terms of subjective measures of comfort, support, and fatigue. We show that the objective measure aPcrms highlights characteristic differences between seat cushions, as the air-inflated seat cushion provides less area in high pressure regions, thus occluding less blood flow to tissue in the seated area. While we were unable to effectively assess the validity of the proposed measures or improve them further, the characteristic difference between seat cushions is not highlighted by using previously existing objective measures. This implies that aPcrms is a more useful measure and should be considered when evaluating the subjective quality of seat cushion designs under dynamic conditions, such as those existing in commercial truck driving.

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Chapter 1
Introduction

This chapter provides an overview of this research. The first section describes the motivation for performing the experimental work. This is followed by the objectives for this study and the approach for achieving those objectives. The chapter concludes with a discussion of the potential contributions of this research and an outline of the remainder of this document.

1.1 Motivation

The need for the proposed research arises because driver fatigue is a major factor in commercial vehicle accidents, as shown by several investigators, including the U.S. Department of Transportation [1]. The need for this study is further heightened by a number of recent legislative initiatives set forward by various government agencies. For example, the Federal Motor Carrier Safety Administration (FMCSA) has released its Safety Action Plan, which calls for reducing fatalities in crashes involving large trucks by as much as 50% and decreasing injuries by at least 20% [2]. The DOT has submitted its commercial truck driver hours-of-service (HOS) reform plan to Congress to restrict the hours that truck drivers can work [3]. The Occupational Safety and Health Administration (OSHA) has proposed a set of ergonomic rules to reduce and prevent repetitive motion-related workplace injury [3]. Vehicle vibrations, which commercial vehicle drivers are subjected to, would be part of the OSHA ergonomic standard.

The above efforts require a better understanding of human fatigue in commercial vehicles, in particular as it relates to the vehicle design and operating environment, through efficient and scientifically based methods that can be used effectively in practice. Through the years, the transportation industry has attempted to address the issue of driver fatigue in vehicles. However, a large number of open issues regarding fatigue in general and the effect of the driver seat design in particular still remain. These must be addressed before we can create a less fatiguing and safer environment in commercial vehicles.

While the benefit of a reliable measure to evaluate driver fatigue caused by the dynamic environment is clear, there are many obstacles that have prevented researchers in establishing such measures. The fundamental difficulty is the effect of the dynamic human-vehicle interface on human fatigue is not well known. Studies have established several validated measures that can be used to evaluate driver comfort. These studies include objective and subjective measurements on a series of different seat cushions by a subset of drivers. Validation of these measures is performed by finding some deterministic relationship between physical data and driver comfort surveys. While these studies have had some successes identifying some measures of comfort on foam seat cushions, even this understanding is limited. Furthermore, it is unclear if these results directly apply to different seating technologies.

While there have been good results in the area of comfort, many studies have shown that there is little correlation between comfort (the short-term sensation) and fatigue (the long-term physical effect) of a seat. In other words, what may feel comfortable upon initial contact with the human body will not necessarily be less fatiguing in the long run. This means the studies performed for comfort cannot be directly applied to fatigue. Human fatigue is affected by many physical factors, including the pressure profile at the seat area, posture, body dynamics and vibrations, and a number of environmental factors in the vehicle cab.

Throughout this document, the term “comfort” is used to define the short-term effect of a seat on the human body, which is commonly the sensation that occurs from sitting on a seat for a short period of time. In contrast, the term “fatigue” is used to define the physical impairment that results from exposure to the seat dynamics for a long period of time. Fatigue may lead to decreased attention, perception, decision-making, vigilance, and reaction time.

Subjective testing is further complicated by subject variability, which includes physical, physiological, and psychological differences between drivers. Since this variability makes it harder to find significant trends, larger sample sizes are often used to reduce the effect of this variability. In the scope of a comfort study, a large sample size is feasible, as each subject's evaluation may take only a few minutes. In the case of a fatigue study, however, large sample size is not practical, as it can greatly increase both cost and time, since each subject's fatigue evaluation can take hours or even days.

Despite the difficulty in establishing these measures, a set of validated physical measurements to evaluate driver fatigue would have advantages in terms of increased understanding of the effect of a dynamic environment on driver fatigue and improved designs in terms of driver fatigue.

Therefore, the challenge facing the scientific community, original equipment manufacturers (OEM), and seat suppliers is how to evaluate fatigue based on a set of physical measurements that can be readily made in the vehicle and on the operator, and use that data to establish operator fatigue. Although a preliminary laboratory study has attempted to address this challenge [4,5], much work still remains in terms of further validating the proposed methodologies through more realistic field tests.

1.2 Objectives

This research seeks to develop an evaluation method to compare driver fatigue between a variety of different seat cushions. Specifically, we focus on evaluating fatigue between two distinct types of seat cushions, namely foam and air-inflated seat cushions. This work builds upon earlier studies on finding efficient and scientific methodologies that can be used by the commercial transportation community for relating seat dynamics to driver fatigue [4,5].

Whereas previous studies to evaluate these measures used a single axis test rig for understanding some of the fundamentals of the interaction between the dynamic human-vehicle interface and human fatigue, this study conducts a series of road tests with a group of Class 8 trucks for the purpose of

- Improving two newly proposed methods and increasing the transportation industry's confidence in their utility for objectively assessing the fatigue effects of vehicle seats,
- Better understanding the relationship between vehicle seat design and driver fatigue, and in particular how it can affect vehicle safety, in terms of driver alertness and attentiveness, reduced rates of accidents, frequency of near misses, and ability to perform the tasks that are commonly required while driving, and
- Providing design guidelines that can be used for evaluating and improving fatigue characteristics of vehicle seats, since most guidelines currently available are confined to comfort – an issue different from fatigue.

1.3 Approach

The following approach has been adopted to achieve the above objectives:

- Validate the use of two newly proposed measures to evaluate driver fatigue (aPcrms and SPD%) by conducting a field test in the daily operations of a revenue fleet service
- Highlight the advantages of using these measures to evaluate driver fatigue in seat cushions in a way that is relevant to the transportation community.

Road tests were performed using existing commercial trucks in the daily operations of Averitt Express to validate the proposed measures. A retrofit air-inflated seat cushion was installed in the fleet's trucks, and the drivers were allowed to adjust to the seats over approximately one week. After this adjustment period, twelve drivers rode on both the air-inflated seat cushion and their original foam seat cushion during their regularly scheduled routes, for a total of 120 hour and 4800 miles of field testing. Surveys were collected throughout the test sessions and the truck seats were fitted with instrumentation to capture physical measurements of seat pressure distribution.

The results of this investigation are expected to have significant impact. However, the significance of these results must be communicated to a large section of the transportation community to realize this impact. To this end, we have taken actions and are planning future action to make the results of this study relevant and available to the transportation community by several avenues.

We have conducted this study in close partnership with original equipment manufacturers such as Volvo Trucks North America, seat suppliers such as Sears Seating, and seat cushion manufacturers such as The ROHO Group. This has ensured that their input has been included throughout this study and, more importantly, the results of the study are relevant to the end users for improving their practices.

After ensuring that the results of this study are relevant to the end users, we must then actively make these results available and highlight their benefits for the transportation community. Through presentations of the results of this study at trade meetings and technical conferences, we intend to further communicate our findings to the transportation community and assist in transferring the results to the U.S. industries and trade organizations that can benefit from this work.

1.4 Contributions

The potential direct impact of the proposed research to the transportation industry would be quite significant, in terms of

- Promoting seat designs and driving practices that would reduce driver fatigue and increase vehicle safety,
- Establishing more effective methods for evaluating and estimating fatigue, and
- Understanding the relationship between driver fatigue and seat designs under different driving conditions.

It is worth noting that although we have used semi-trucks for conducting this research, the findings of the study are expected to be directly applicable to other areas of commercial transportation, including railway vehicles and inter-city busses. Many of the operator fatigue issues due to the vehicle seat, and the related safety issues, are common among different modes of commercial transportation.

In addition, based on research by the U.S. Department of Transportation (DOT) indicating that fatigue is a major factor in commercial vehicle accidents, the findings of this research will have the following potential payoffs in practice:

- Increased highway safety due to lower operator fatigue and increased task proficiency,
- Reduced incidents of health complaints due to prolonged exposure to seat dynamics,
- Increased productivity and reduced lost work time due to health issues, and
- Increased driver satisfaction and a higher rate of driver retention.

1.5 Outline

For convenience, this section outlines the content of the remainder of this document. This thesis is divided into seven chapters and four appendices. The appendices contain supplementary information referenced in the text. Chapter 2 contains a literature review, focusing on the concepts of comfort and fatigue and their application in the commercial truck environment. Chapter 3 outlines the experimental methods used in this study. Chapters 4 and 5 contains the results from the analysis of the subjective and objective data, where we highlight significant differences between the seat cushions and reduce the data into a condensed set of information. Chapter 6 relies on the results from the preceding two chapters and uses them to determine any possible relationships between subjective and objective data sets. Chapter 7 provides a conclusion and recommends future research in the field of evaluating human fatigue in commercial vehicles.

Chapter 2
Background

This section represents background information necessary to understand the issues of comfort and fatigue in relation to seat design. The accumulation of this background information was acquired through a literature review of both past and present research in the field of seat comfort. The section begins with a discussion of the truck seat and its development through recent years. Next, the ideas of comfort and fatigue are discussed along with their relationship to vibration and pressure. Evaluation methods are then examined followed by a summary that discusses how this study fits into the ongoing research into comfort and fatigue.

2.1 The Truck Driver's Environment

Commercial trucks are unique in the sense that they are specifically developed to transport heavy loads over long distances. Accordingly, high priority has been given to durability and functional efficiency [6]. In contrast, automobiles are made to comfortably accommodate passengers over relatively shorter distances. Factors including ride comfort, handling, and appearance are of high importance in selling personal automobiles. These requirements have driven the evolution of commercial truck design and personal automobile design in separate directions.

Of particular importance in the evolution of commercial trucks is the truck seat. Both the personal automobile and the commercial truck experience the same road excitations, but the vehicle response can be quite different. Accordingly, the truck seat has developed from the unique dynamic properties of the truck. Truck drivers spend long hours at the wheel compared to the average commuter. Long hours of seated activity in a dynamic environment can lead to discomfort and even fatigue, which can cause decreased attention, perception, decision-making, vigilance, and reaction time – all crucial to safe driving. It is this decreased driving proficiency that has prompted research scientists to identify the specific causes of discomfort and fatigue associated with truck seat design and furthermore to develop measures for evaluating them.

The Seat Suspension

Commercial trucks began with only a primary suspension at the wheels. For many of these years the truck seat was comprised of a metal base with a foam seat cushion. Later on metal springs were incorporated to provide additional vibration isolation. The advent of a secondary suspension, mounted to the truck cab, further isolated the driver from the rest of the truck. With the secondary suspension, the driver of a heavy truck typically experiences vibration in the range of 2 to 10 Hz. The truck seat, however, experienced very little change with regards to improved posture, vibration isolation, and seated interface pressure.

In recent years, the trucking industry has paid increased attention to the human factors of the seat because of its importance to the health and safety of truck drivers. Initially, researchers looked at road roughness as the primary source of vibration in vehicles and tried to measure and correlate the human response to these vibrations. For instance, vibration at 4 Hz was found to cause severe discomfort in humans due to the fact that the spine, shoulders, and the head resonate near this frequency [7]. Unfortunately, the vertical natural resonance frequency for a typical foam and metal spring seat is also near 4 Hz. In response, truck seat manufacturers began integrating a seat suspension consisting of a spring and damper. This became known as "air-ride". Addition of seat suspension in a truck seat has been shown to lower its vertical resonant frequency to approximately 2 Hz as well as lower the magnitude of transmission [8]. A sample seat frequency response is shown in Figure 2-1.

It was then realized that other important vibration sources existed from the tires, driveline, and engine [9]. Later studies evaluated human exposure to whole-body vibration from a vehicle and how it affected human discomfort. Afterward, researchers understood that vibration and acceleration were only part of the discomfort for the driver.

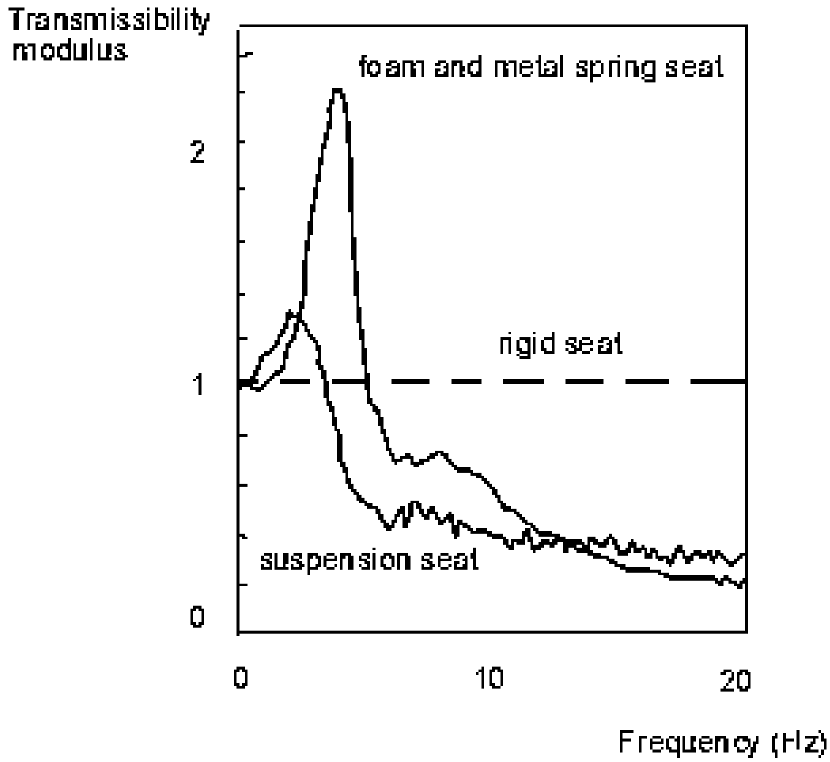

Figure 2-1. Effect of air-ride suspension, adapted from [3]

Additional Design Considerations

More recently, researchers have begun to consider other factors such as interface pressures and posture. Truck seat manufacturers have responded by adding foam or air bolsters, additional contouring, and ergonomic adjustments to provide some seating support for truck drivers. But the basic design is still a foam seat cushion, which leads to two major problems:

- Foam seat cushions cannot conform to all of the different sizes of individuals and shapes of buttocks [10]
- Foam degrades over time providing less cushioning [11]

Studies have shown that a single seat cushion design cannot ideally support a diverse group of drivers. For example, a survey of 124 CDL licensed truck drivers showed their preference for seat width was bimodal, with peaks at 20 in and 22 in, with lower preference between these peaks [10]. This suggests that at least two different seat cushion designs would be needed to satisfy this group of drivers.

To accommodate a larger group of drivers, manufacturers have increased focus on adjustability. Adjustable features such as seat width, side bolsters, lumbar support, and arm rests have been added to allow the drivers to adjust the seat to their preferences. Yet, few drivers have received proper instruction on using those features, so the utility of these adjustments may not be realized to its full potential [10].

The trucking industry has identified the following issues and needs of truck drivers to reduce driver fatigue, increase driver retention, and reduce workers compensation claims:

- Adjustable seats that fit and function properly to reduce tension, fatigue, and musculoskeletal diseases (MSD's) such as low-back pain,
- Seats that promote long-term comfort to help increase alertness and reduce strains on the body that cause fatigue,
- Reduction or elimination of vibration, poor posture, and insufficient support that puts stress on drivers' spinal discs,
- Better leg support to promote sufficient blood flow, which is key to alertness, and
- Ergonomically shaped seat with adjustable front and side support structures.

To eliminate the inherent problems of foam cushions, other support surfaces, specifically designed for long-term sitting, have been proposed. In order to evaluate the intrinsic worth of these new seat cushions, it is necessary to identify their comfort and fatigue properties.

2.2 Comfort and Fatigue

The term "seat comfort" is typically used to define the short-term effect of a seat on a human body; that is, the sensation that commonly occurs from sitting on a seat for a short period of time. Comfort, however, is a vague concept and subjective in nature. It is generally defined as lack of discomfort [12]. The short-term comfort offered by a seat is relatively easy to determine by many measures, 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 extremely 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 correlated with subjective data to determine the relative effects of each measure related to comfort.

In contrast, "driver fatigue" defines the physical impairment that results from exposure to the seat dynamics for a long period of time. These impairments are cognitive in nature and include deficiencies in attention, perception, decision-making, vigilance, and reaction time. While driving fatigue is often thought of as falling asleep while driving, a decline in driving performance often precedes sleep. Driver fatigue is a serious problem resulting in many thousands of road accidents each year. According to the National Transportation Safety Board (NTSB), fatigue may be a contributing factor in as many as 30 to 40% of all heavy truck accidents [13]. Some of the commonly recognized causes of fatigue are

- Driving with sleep debt
- Night-time driving
- Extended driving time
- Physical work, in addition to driving
- Monotonous driving conditions

A major study conducted by the U.S. Department of Transportation found that the most influential factor of driver fatigue was the time of day [14]. Specifically, peak drowsiness was observed during night driving. A 1998 study, however, reported that most fatal and non-fatal accidents involving large trucks occurred "in good weather, on dry road surfaces, during the day, and on weekdays" [15]. Quite possibly there are other factors involved in driver fatigue. Efforts to identify these factors require a better understanding of human fatigue and how it relates to the vehicle design and operating environment. The current problem in evaluating truck seats is that existing research focuses almost exclusively on comfort, while the relationship between comfort and fatigue remains unclear.

Many studies have shown that there is little correlation between comfort (the short-term sensation) and fatigue (the long-term physical effect) of a seat. In other words, what may feel comfortable on initial contact with the body will not necessarily be less fatiguing in the long run. This inverse relationship has also been supported regarding comfort where research has found that comfort evaluations for short-term and long-term driving do not agree [16]. A few studies have shown the possible association between fatigue and low frequency vibration typically experienced by truck drivers. Also, it has been found that vibration exposure causes changes in body chemistry that could lead to fatigue effects [17]. However, in most studies fatigue can only be logically deduced without supporting evidence.

The question that remains is, *when trying to quantify comfort and fatigue in a dynamic seating environment, what observable metrics should be considered?* Answering this question requires knowledge of what happens physiologically to a person when seated and furthermore what happens when exposed to a dynamic environment, such as driving.

Vibration Related to Comfort and Fatigue

Exposure to vibration can cause a broad spectrum of sensation to the human body depending on the type of vibration, the physical characteristics of the person, and the duration of exposure. Driving is a dynamic activity in which the seated person is exposed to various excitation sources. These sources include inputs from road roughness, the tire/wheel assembly, the driveline, and the engine [9]. The ability of the vehicle to minimize discomfort and fatigue due to these vibrations is of major concern of both suspension and seat design.

Vibration can lead to both discomfort and fatigue, but in different ways. Discomfort is usually associated with the dynamic properties of the human body and how it reacts to vibration. For example, it becomes quite uncomfortable when the neck and head are shaken at their resonant frequency. Fatigue due to vibration is thought to be caused by prolonged muscle activity, both voluntary and involuntary, resulting from the body's attempt to counteract the vibration. The muscle tissue and organs act both actively and passively act to control vibration and hence can become fatigued. Thus the goals of designing a driver environment to improve comfort and fatigue caused by vibration are:

- Reduce the magnitude of critical vibration components that reach the body
- Support the body in such a way to reduce the effect of the vibrations that reach the body.

This is especially important when the vibration is near resonant frequency levels. Research has also shown that humans reach a level of fatigue much quicker when subjected to 4-8 Hz vibration in the vertical direction and 1-2 Hz in the transverse (fore-aft and lateral) direction [6].

The human body's reaction to vertical vibration can be considered linear below the frequency range of 100 Hz. At around 5-10 Hz the abdomen goes into resonance. Other resonant frequencies are 20-30 Hz for the head, neck, and shoulders and approximately 60-90 Hz for the eyes [7]. Certain modes of vibration also have been shown to have an effect on consciousness. In particular, vibration in the range of 1-2 Hz has been shown to cause sleepiness [17].

Pressure and the Seated Person

Sitting is generally defined as the body position in which most of the weight is supported by the ischial tuberocities (bony prominences) of the pelvis and their surrounding soft tissues [7]. The pressure at the body-seat interface arises from the distribution of both static and dynamic loading. Figure 2-2 shows the breakdown of static load distribution for a typical seated person. As shown, the ischial tuberocities generally support around 45% of a person's weight.

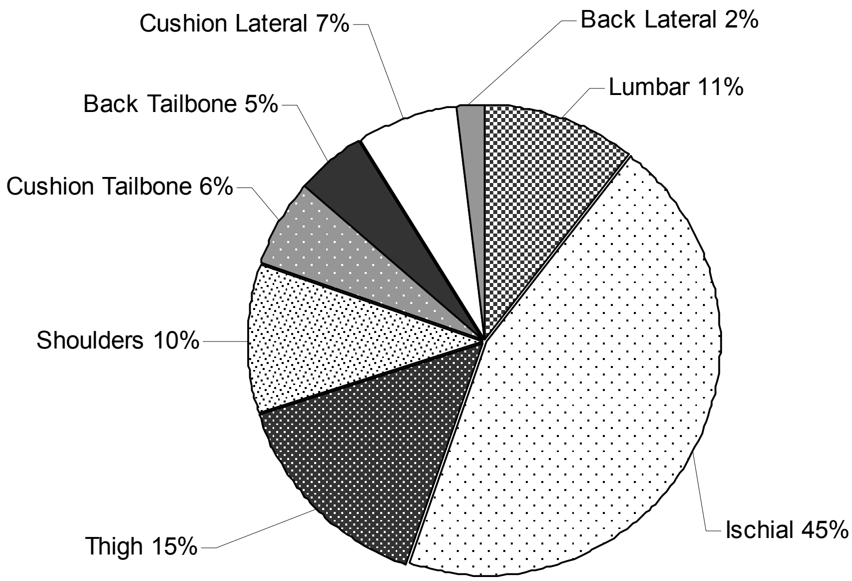

Figure 2-2. Typical weight distribution when seated, adapted from [18]

Weight bearing on soft tissues is unavoidable, and thus a person's posture is very important. Figure 2-3 shows the pelvis in different positions including sitting and standing. As a person sits the pelvis rotates backward and the lumbar spine tends to flatten. Normally a person would sit upright and the peak pressures on the soft tissue would be from the ischial tuberocities. When a person sits in a slumped position, the peak pressure is shifted away from the ischials onto the coccyx or the lower sacrum. When a person tilts the pelvis sideways, the trochanters will bear the greatest peak pressure. Results of pressure studies have shown that a good seat cushion should contain pressures between approximately 60 mmHg and 120 mmHg, or in other words, the average blood diastolic and systolic pressures. A person sitting on a hard surface, such as a wheelchair canvas, can have pressures in excess of 200 mmHg in the region of the ischial tuberocities [19].

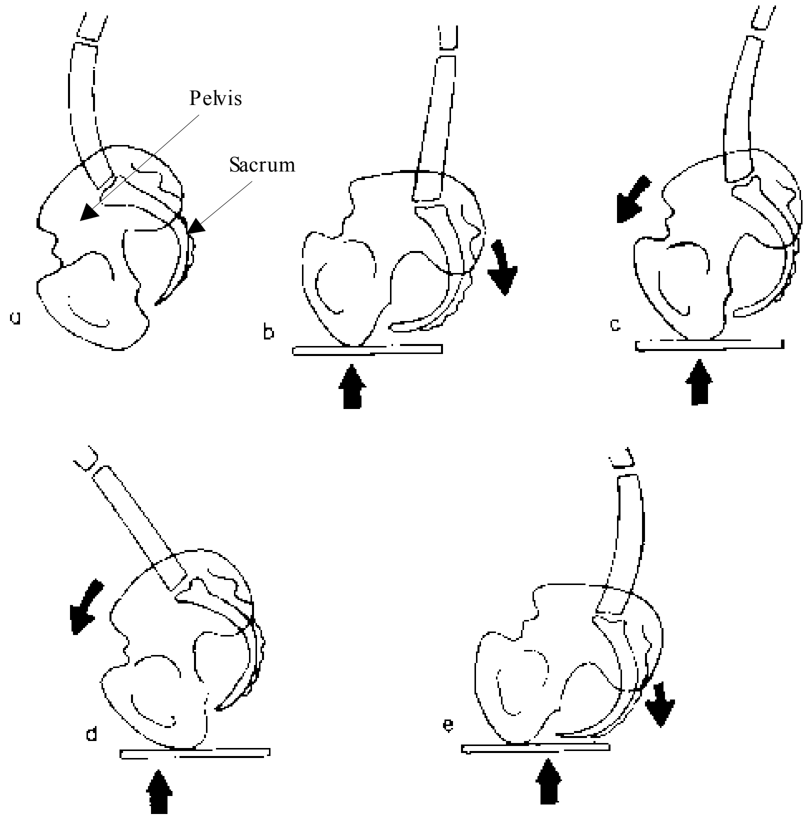

Figure 2-3. Pelvis alignment: (a) standing, (b) sitting relaxed, (c) sitting erect, (d) sitting forward; (e) sitting back [7]

The problem of excess pressure is apparent in the fact that all living cells require an adequate supply of nutrients, especially oxygen, to survive. Pulmonary blood flow carrying oxygen is transported to the cells by circulation. At the tissue capillaries, oxygen diffuses into the tissue due to the partial pressure differences that exist across the cell and capillary walls. The partial pressure of oxygen (PO_2) in the arterial blood is at about 95 mmHg, while the partial pressure in the interstitial fluid immediately outside the capillaries is about 40 mmHg. Therefore, a pressure difference of 55 mmHg exists that causes diffusion of oxygen into the surrounding tissue. If peak pressures in the tissue exceed 95 mmHg, then the cells are deprived of oxygen. When oxygen becomes unavailable or insufficient for the oxidation of glucose, cells can survive by releasing energy by glycolysis, which does not require oxygen [20]. There is, however, a limited amount of time for which the cells can survive under anaerobic conditions, and this is the limiting factor that determines the threshold of events that leads to a pressure sore. It has been known for many years that pressure alone cannot cause pressure sores; rather, it is the pressure-time factor that is of fundamental importance [21]. The general relationship between pressure magnitude and sitting duration is represented in Figure 2-4, suggesting lower pressures are needed to maintain tissue health during longer seating times. It is worth noting that the curve is only a helpful guideline and not an exact rule to be followed. For seat cushions, the peak pressures and duration of the peak pressures must be minimized to provide good sitting comfort and healthy tissue.

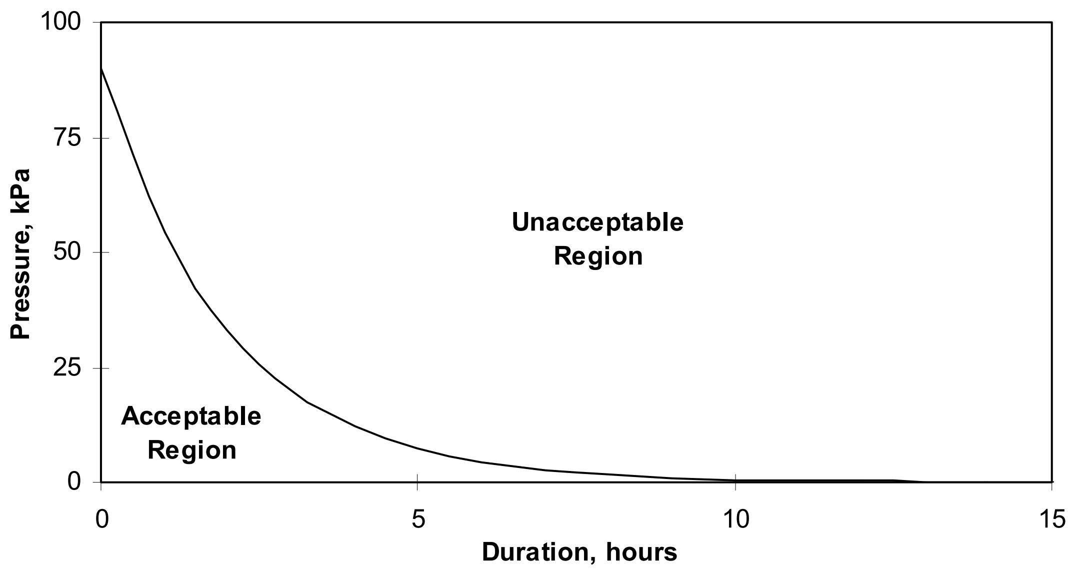

Figure 2-4. Relationship between pressure and seated duration, adapted from [22]

When a person feels uncomfortable due to high pressure areas, they will reposition themselves to achieve a more favorable pressure distribution. For a handicapped individual that either cannot feel their lower extremities or are physically unable to move, they will not be able to reposition themselves, which may lead to pressure sores [21].

Since foam cushions degrade over time, a seating position that was once comfortable may become uncomfortable over time. This requires the occupant to reposition themselves to find a new favorable position. In seats where movement is difficult, the effort required to move may cause fatigue. This leads to two important requirements in seat cushion design

- Provide mobility that reduces the effort required to be able to move to a favorable position, and

- Provide a contouring that reduces the occupant's desire to move once they do find a favorable position [23].

Measurement of the interface pressure between the human body and a seat cushion can be used to monitor the performance of support surfaces and to compare different products. The validity for the measurement of pressure is based on the relationship between the interstitial and capillary pressures within the tissues and the interface pressure between the body and a support surface.

2.3 Theories of Pressure Distribution

When designing for comfort, with regards to interface pressure distribution, there are two main theories:

1. Evenly distribute the applied pressure, and
2. Concentrate the pressure on more rigid parts of the body, such as the ischial tuberocities.

The theory of distributing pressure evenly is based on human experience. For instance, consider a force applied to the hand. First, let the object supplying the force have a very small surface area, such as the point of a knife. Assuming that the force is large enough, the knife can cause considerable pain due the large pressure created by the force and very small contact area. Next, consider an object having a much greater surface area, such as the tip of a finger. If the force remains constant, experience tells us that the finger would cause considerably less discomfort than the knife. Hence, the theory suggests that distributing a force over a greater area will result in less discomfort. Relating this theory to seat comfort, a cushion that more evenly distributes pressure and over a larger area will reduce pressure at the bony prominences, such as the ischial tuberocities, and hence be more comfortable.

Several studies support the theory of evenly distributed pressure. Research by Milivojevich et al., through correlation of objective and subjective data, found that decreasing pressure at the ischials resulted in a more comfortable seat [24]. A study examining the cause of pressure sores concluded that distributing pressure more evenly reduces the onset of ischemia [25].

Conversely, the concentrated load theory is based on an analogy of mechanical structures. That is, when loading a mechanical structure it is typically best to concentrate the forces on the strongest parts of the structure. By loading the structure in such a manner creep is minimized and the structure will be less likely to fail by fatigue. Comparing the human body to a mechanical structure, this theory suggests that loading stiffer parts of the body will result in less discomfort. Relating this theory to seat comfort, a cushion in which the majority of the person's weight is supported by the ischials will result in a more comfort.

Another way that the concentrated load theory is suggested is the spatial summation theory. This theory suggests that the body is comprised of many sensors, and a greater sensory response is experienced when the stimulated area is larger [26]. In terms of seat comfort, this implies that an uncomfortable force applied to the tissue activates more sensors when applied to a larger area when compared to a smaller area. Consequently, the more sensors that experience discomfort will create a cumulative effect resulting in an overall negative perception.

Research on maximum pressure tolerance (MPT) offers a compromise between uniform pressure and concentrated pressure theories. This theory suggests at low pressure, perceived comfort improves with increased contact area or more uniform pressure. However, at high pressure, perceived comfort improves with reduced contact area or concentrated pressure. This suggests that there is some critical pressure where the comfort-area relationship reverses [27]. That is, we want to minimize the area that is affected by the critical pressure. If the force is low, we want low discomfort or pressure for a large area, but if the force is high, we want high discomfort or pressure over a small area.

The best way to distribute pressure for maximum comfort continues to be debated. The topic becomes even more confusing when considering that there has also been research concluding that pressure distribution analysis is not sufficient for evaluating seat comfort [28].

2.4 Evaluating Comfort

There has been a trend in the transportation industry over the past 20 years for evaluating comfort. Researchers have always known that a driver experiences discomfort after sitting for extended periods of time in a vehicle, but they did not know the reason for the driver's discomfort. A wide variety of different measurements have been used in the field of comfort studies, which may be potentially confusing. These measurements, however, can be understood systematically by treating them as different types of measurements from the vehicle-human interaction, as shown in Figure 2-5, in a block diagram form.

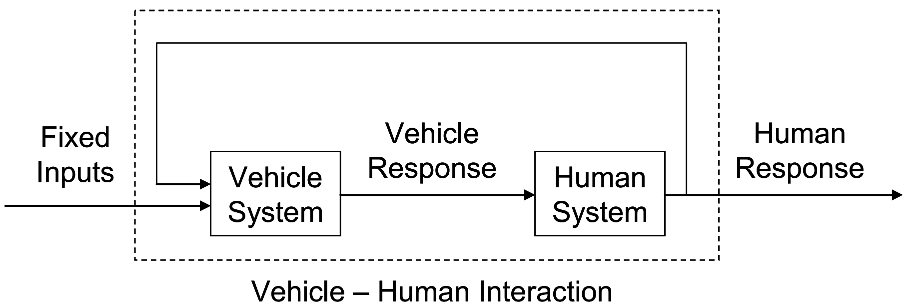

Figure 2-5. System representation of vehicle-human interaction

First, there are a series of fixed or uncontrolled inputs based on the driving environment, which all vehicles are subjected to, such as road excitations and other environmental factors. These factors would act as inputs to the vehicle system, which includes all designed vehicle components. Thus, the vehicle system consists of all elements within a control volume of the vehicle that excludes uncontrollable external inputs and the human body. The vehicle system creates a physical response, which drives the human system. The human system then has both a subjective and a physical response, which also acts to drive the vehicle system. Measurements can then be classified by their location on the system representation, as shown in Table 2-1.

Table 2-1. Classification of measurements for comfort studies

Human Response		Vehicle Response	Vehicle System
Subjective	*Objective*		
Surveys CMM	Eye Motion Head Motion Body Motion EMG Lane Tracking Driver Error Task-Related Tests Cognitive Tests	Vibration Pressure Noise Temperature Humidity	Geometry Inertia Stiffness Damping Hysterysis Creep

Of prime importance is the human response. Measurements of subjective human response include surveys and cross-modality measurements (CMM). These measures provide direct insight on the driver's state of mind, which is essential in any comfort study. Objective measures of human response are numerous: eye motion, head motion, body motion, electromyography (EMG), lane tracking, driver errors, and secondary tests to evaluate task-related and cognitive performance. While these measures are objective, they observe the effect of driver fatigue, and not the cause. As such, the objective human response provides useful details of the driver's condition as fatigue increases, but it cannot replace the subjective measurement, as no well-validated human response measurement currently exists. A well-validated objective human response measurement would have the added application as a fatigue monitoring system.

To develop an understanding of comfort, it is necessary to understand the physical causes of comfort. This study considers the input/output relationships for the human system, between the vehicle response inputs and the human response outputs. This makes the vehicle response measurements essential in this field of study. The importance of vehicle response is further heightened when we consider that the dynamics of the vehicle system are well understood compared to the human system. Thus, if we knew what vehicle response caused an ideal subjective response, we could design the vehicle system based on this knowledge. Measures of vehicle response include: vibration, pressure, noise, temperature, humidity, and various other environmental effects within the cabin.

Since the controllable elements within the system are in the vehicle system, the design engineer often tries to directly relate properties of the vehicle system to human response.

These include the geometry and dynamic characteristics of the seat cushion, suspensions, and other related vehicle components. While these elements act to provide a favorable vehicle response, the driving factor that causes the human response is the vehicle response, not a list of properties for a specific seat cushion. Thus, the applications of such studies are limited, as they apply to parameters of a single seat cushion design, and not a more general vehicle response. This implies that the results from comparing the vehicle system measures to human responses are limited, as each seat cushion would have a different relationship to subjective performance. The design of improved seats is more favorably approached by answering the following two fundamental questions:

- How does one characterize a favorable vehicle response?
- What vehicle design will best provide the desired response?

Accordingly, the fundamental measurements to consider for comfort studies are measures that characterize the vehicle response and the human response.

During all of the 1980's and early 1990's, researchers concentrated on vibration as the sole source of discomfort for drivers. Initially, researchers looked at road roughness as the sole source of vibration in vehicles and tried to measure and correlate the human response to these vibrations. Studies were later performed that evaluated human exposure to whole-body vibration from a vehicle and how it affected human discomfort. Afterward, researchers understood that vibration and acceleration were only part of the discomfort for the driver.

In 1990, researchers shifted their focus away from analytical methods of measuring vibration and the human response, and they shifted to using subjective questionnaires to evaluate comfort. During the early 1990's, researchers discovered that a driver's posture and the seat suspension were important in comfort. Then in the mid-1990's, studies were performed on driver fatigue and low-back disorders showing that the vehicle seat and environment were detrimental to the driver's health and safety.

More recently, researchers have begun to use interface pressures between the driver's body and the seat to evaluate comfort. New scientific developments have allowed easy and accurate measurement of interface pressure. The body pressure measurement system (BPMS) by Tekscan, for instance, provides a thin resistive-based pad that allows unobtrusive measurement of interface pressure between the driver and the seat cushion. Several recent papers have shown a good correlation between distribution of interface pressures, pressure change rate, and comfort. The interface pressures take into account many factors in evaluating comfort, such as road and vehicle vibrations, seat design (including the suspension and driver posture), and physiological condition.

The development of objective methods for evaluating comfort is important when considering the fact that subjective evaluation is both time consuming and expensive. The process of performing a subjective evaluation includes gathering test subjects of different height, weight, age, gender, and race. These subjects must then be used to evaluate a particular seat and/or seat cushion in varying environments. Furthermore, these same experiments must be conducted for many different seats in order to provide a source of comparison, due to the fact that comfort is a relative measure.

In order to obtain an objective method of comfort, the experiments must include multiple objective measurements such as vibration, pressure, and posture. These objective measures must then be correlated with subjective evaluation to determine their relationship, if any. Once an objective measure is found to be highly correlated with the subjective analysis it can be considered an effective comfort metric. The benefit of the objective measure is that now simple experiments can be performed with the seat in question and a reasonable judgment can be made as to how much comfort it will provide.

Current research in the field of seat comfort has successfully identified comfort metrics for establishing the comparative comfort characteristics of different seat cushions. Some of the more recent include:

- 1998: Researchers at the Korea Research Institute, Chung-Nam University and Joen-Ju University have developed a test protocol using measured body pressure distribution and a questionnaire of seat characteristics for objective seating comfort [29].

- 2000: Researchers at the University of Tokyo and Toyota Central R&D LABS, Inc. developed a new seat evaluation method for riding comfort. Static seating comfort was evaluated using body pressure distribution. The speed of human body pressure distribution and acceleration of body parts was used to evaluate dynamic riding comfort. Using the physical, physiological, and conventional sensory data, researchers were able to produce a new seat evaluation index [30].
- 2000: Researchers at the Daihatsu Motor Co. developed a new human engineering index for riding comfort, which used body pressure change rate over time. The smaller the change in the body pressures over time, the better the riding comfort [31].
- 2000: Researchers at the Woodbridge Group determined that there is a relationship between subjective comfort response and the measured objective body pressure distribution. A uniform body pressure distribution (contact area) generated a higher comfort score. By quantifying psychometric responses to body pressure distribution, researchers were able to develop a comfort score [24].
- 2001: Engineers at ROHO used the dynamic pressure data to develop, in conjunction with the Advanced Vehicle Dynamics Lab at Virginia Tech, a new seat evaluation index: area pressure change rate. The advantage of using the aPcrms is that it evaluates the effect of the body pressure change rate for the contact area in the equivalent pressure range. The aPcrms is integrated over the entire body pressure distribution to develop the new seat evaluation index [4,5].

The metrics used in this study are discussed in detail in Chapter 3. The chapter provides a complete discussion of the theory and application of the metrics. Also discussed are two new metrics created specifically for comparing dissimilar types of seat cushions.

2.5 Summary

The research presented in this study is based on the background information given in this section and relies on both subjective and objective measures for evaluating and comparing a standard truck foam seat cushion and an air-inflated replacement seat cushion. Current research has provided objective measures pertaining to seat comfort. However, many of these measures have resulted from testing and comparing similar types of foam cushions. It is unclear whether these methods are appropriate for evaluating dissimilar seat cushions. Therefore, the goal of the current study is to validate the objective measures to determine if they can be used to evaluate dissimilar seat cushions.

The one major problem that remains is that there are currently no validated measures for evaluating the fatigue properties of seat cushions. The ultimate goal of this work is to provide seat manufactures with objective measures for assessing both the comfort and fatigue properties of seats and seat cushion. We deal with this problem by comparing our objective and subjective measures, and determining what relationship, if any, exist between the two.

Chapter 3
Experimental Methods

This section highlights the methods used for this study. First, we consider the experimental design, and then we consider the subjective and objective methods used in this study.

3.1 Experimental Design

This section highlights the development of the test plan. We discuss the selection of several elements of the experiment. First, we consider general experimental design considerations. We then describe the seat cushions used in our study, summarize test routes and driver information, and conclude by summarizing the test plan.

Design Considerations

There are two fundamentally different types of field tests that could be performed to establish the relationship between subjective and objective measures:

- Recruit drivers from local trucking services and have them come to our laboratory and drive our Volvo VN 300 commercial truck on designed routes that last over four hours, or
- Use the planned routes of a revenue trucking service with routes that last over four hours.

This choice is fundamental to the experimental design. The first option is more of a controlled experiment, where we specify an artificial test route outside a normal fleet operation. The second option is more of an observational study, where we place a seat cushion in their truck and observe their response during their natural activities. While the first option offers a more controlled field test which would provide more repeatable objective data, we also need reliable subjective data. We believe that the first plan may not motivate the drivers to provide accurate responses, as they would be driving a simulated route, with no real connection to their daily jobs. In addition, since the driver would need to adjust to an unfamiliar cab environment and test route, they may have less ability to evaluate the differences between the foam and air-inflated cushions.

The second design considers any uncontrolled variables as random variables that would normally be experienced in real commercial trucking operations. Since we are not directly controlling the routes, this design is like a random sampling of the conditions that actually exist in the field. We feel that the physical differences between the two seat cushion will be large enough that they will overshadow much of the noise created by our random sampling. If we are able to make these conclusions based on naturally-occurring routes, the results will have more validity than similar results for a controlled experiment.

Based on these factors, we realized that the better alternative would be to complete our road testing using the planned routes of a revenue trucking service with routes that last over four hours. We decided incorporating our study into existing revenue service fleet over a period of several weeks had benefits over an independent experiment in terms of driver motivation, realism, familiarity, judging long-term effects, and cost. While this option provides the least amount of control and repeatability for the tests, it offers the greatest amount of realism and validity.

Our test plan is to install the retrofit air-inflated seat cushions into selected trucks, and allow the drivers to adjust to the new seats by riding on them for approximately two weeks. At the end of the two weeks, we instrument their trucks, ride along, and collect objective and subjective data on regularly scheduled routes. During each of these test sessions, the drivers ride on both seat cushions – their normal foam seat cushion and the air-inflated seat cushion. The order of testing seat cushions was randomized to reduce any order effects.

This cooperation gives the driver motivation for driving normally, as the driver would be driving as part of their job, instead of as part of a study in which they have no direct responsibility. Also, since the driver is participating in a study that may directly improve their working environment, they will have more motivation to provide clear and honest feedback than if they had no personal investment in the project.

Since the driver will be doing their job as we observe them, this will increase the realism of our study. With more realistic test conditions, we will be able to make more valid conclusions that apply to real truck fleet operations, not just a specific controlled experiment.

We feel that placing a driver in a new truck that they are unfamiliar with will also lead to noisy subjective results, as the driver will not be as familiar with the environment and may judge subjectively based on the new truck environment. This is undesirable, as we want to only reflect the changes in the truck seat. Allowing the drivers to adjust to the seat cushions over a period of two weeks will provide a better subjective baseline for the drivers, because they are more familiar with the test truck environment. When we collect data after two weeks, we are observing them for a short period after they have already adjusted to the test seat. With a stronger baseline, the driver should be able to focus on giving feedback on the new seat cushion.

Another important advantage with allowing the drivers to use the seats over a period of several weeks is that they may experience comfort and health advantages that they would not see in one session. It is possible that the driver would not realize advantages of a particular cushion until hours or days after first using the seat cushion. Also, chronic pain will not likely disappear during a few hours, but it may improve over a few weeks. This allows us to avoid initial driver perceptions and focus on long-term perceptions, which are more relevant when considering how this seat cushion would perform in real fleet operations.

It should be noted that this study may contain Hawthorn Effect bias, which means that subject responses may be biased or altered as an effect of knowing they are being observed. While implicit bias has been removed explicitly from the survey questions, since we are asking for subjective responses, it is not possible to remove the effect of knowing they are being observed. Moreover, it should be apparent to the drivers that the air-inflated seat is the experimental group and the standard foam cushion is the control, so they may infer that we hope to find the air inflated cushion superior.

Seat Cushion Designs

Road tests were performed using two different seat cushions, specifically a ROHO air-inflated seat cushion and National Seating foam seat cushion. Since these two seat cushions are quite different in nature, we expect that the results will be significantly different between these two cushions so that it will overcome the variability naturally associated with a field test.

Originally, the investigators considered testing on three or more different seat cushions. While we realize that additional testing on different air-inflated or foam seat cushions with different designs would improve our assessment of the proposed physical measures to evaluate fatigue in a variety of seat cushions, adding seat cushions would greatly increase the effort required for this study. Instead, we will focus on highlighting the differences between two distinct seat cushions, one a standard in the trucking industry and one an emerging technology.

Furthermore, our experimental design makes it impractical to test more than two seat cushions. Our plan is to test on each seat cushion for about one half of the driver's shift, so the drivers would get about five hours of seat time on each seat cushion. By driving on both seat cushions during the same shift, drivers can make a back-to-back comparison of the performance between the two seat cushions, which should provide more valid subjective responses. If we wanted to run more than two seat cushions in a ten hour shift, we would have to reduce the seat time on each cushion under four hours, which may not be acceptable for a fatigue study.

Each truck has a National Seating truck seat with air-ride installed, which will be used for all road testing. The foam seat cushion used in this study is the cushion that comes with the truck seat, and it is the seat cushion that the truck drivers normally use on their routes. This is a high profile, standard width, foam seat cushion with cloth cover. All the truck seats and foam cushions were in good or excellent condition.

The retrofit air-inflated seat cushion that was selected for this study is shown in Figure 3-1. This cushion is a prototype developed by The ROHO Group that replaces the original foam cushion and mounts to the underlying truck seat frame. Its construction has several layers:

- A cloth seat cover that wraps around the entire seat assembly,
- A thin foam layer over the air cells that provides a more "natural" feel to the seat cushion and better heat transfer to reduce the sweaty feeling one may have by sitting directly on the rubber air cells,
- A series of air cells that provide air-inflated support, which can be adjusted by the driver, and
- A foam and plexiglass base that bolts to the truck seat frame, replacing the original seat cushion, and provides a stiff platform for the rest of the seat cushion, while allowing for some compliance under the air cells, adds some contouring, and allows for compliance.

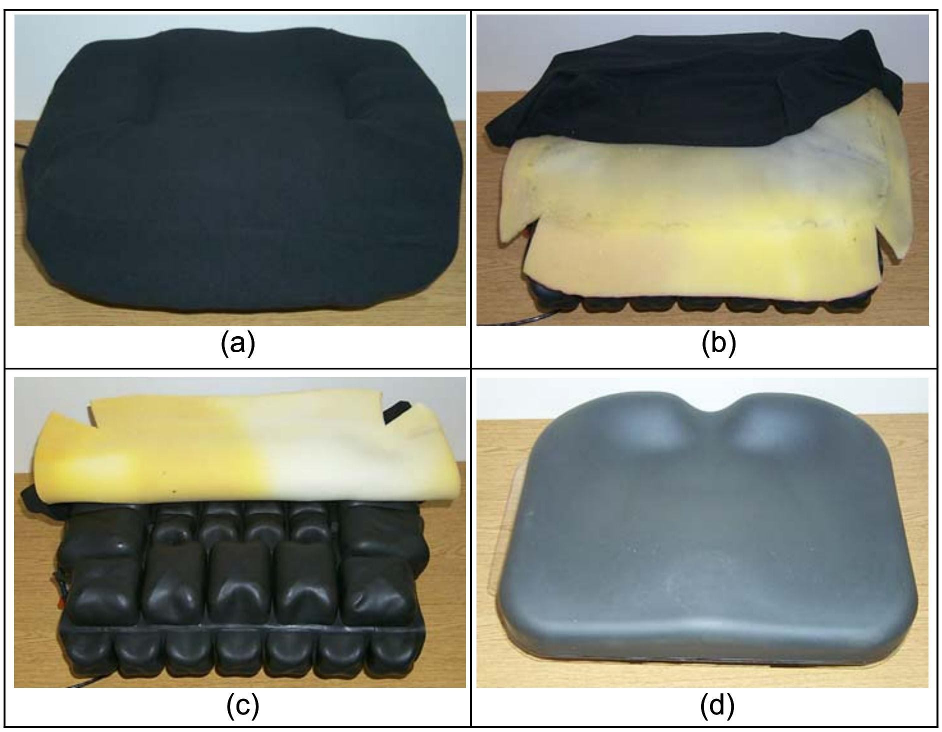

Figure 3-1. Construction of the retrofit air-inflated seat cushion used in this study: (a) cloth seat cover, (b) thin foam layer, (c) air cells, (d) foam and plexiglass base

Both the original foam cushion and the retrofit air-inflated seat cushion were mounted to the original truck seat for road testing. Figure 3-2 shows the retrofit air-inflated seat cushion mounted on the original truck seat. Also shown is the pressure pad that is used for pressure measurement during each test session.

The air-inflated cushion provides the advantage of increased adjustability compared to standard foam seat cushions. The prototype we used in this test has five independent sections of air cells that can be adjusted by the driver, as shown in Figure 3-3. This allows the seat cushion to adjust to a more diverse group of drivers.

Figure 3-2. Air-inflated seat cushion mounted on original truck seat

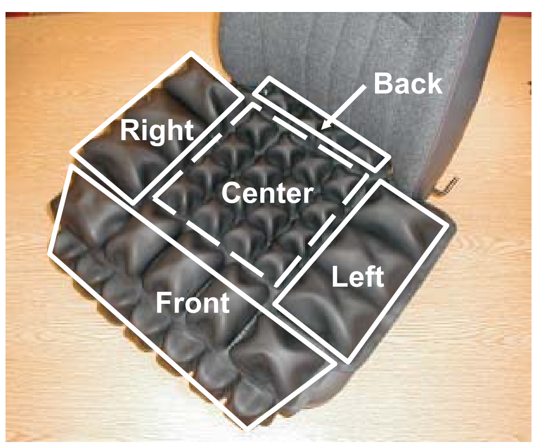

Figure 3-3. Sections of air cells in air-inflated seat cushion

Test Route and Driver Information

The tests were conducted using existing trucks in the dual-service fleet of the Greensboro, NC terminal of Averitt Express. This fleet consists of the Volvo VN 300, such as that shown in Figure 3-4. Each of these vehicles has an air-ride seat with foam seat cushion in good or excellent condition from National Seating. This study used most of the dual-service vehicles available at the Averitt Express facility. These dual-service vehicles perform local delivery service during the day and shuttle service between terminals at night.

Figure 3-4. Volvo VN 300 in Averitt Express dual-service fleet

To provide information from a variety of truck drivers, we chose four local drivers and eight shuttle drivers. The routes included in this project are summarized in Table 3-1. Each route begins and ends at the Greensboro, NC terminal. Overall, our field test data includes more than 4700 miles and 116 hours of driving.

Drivers were selected because they were assigned to these trucks during our field testing. Demographic information was not used to select drivers for this study; rather it was collected so that we may assess the validity of our test population to represent a range of characteristics present in the general truck driver population. Prior to each test session, each driver was asked a series of questions to establish demographic information, summarized in Table 3-2. All twelve drivers were male, ages ranged from 32 to 49, weight ranged from 165 to 310 pounds, height ranged form 66 to 74 inches, and years of truck driving experienced ranged from 7 years to 32 years. This variety in different characteristics shows that our test population is reasonably diverse, and is a suitable representation of the general truck driver population.

Table 3-1. Summary of test routes

Session	Date	Truck	Route	Est Mileage	Est Time
S01b	3/8/2004	T8794	City: Greensboro, Ashboro	75	9:00
S02b	3/10/2004	T8795	City: Greensboro	93	9:20
S03b	3/11/2004	T8840	City: Danville, VA; S Boston, VA	200	9:10
S04b	3/12/2004	T8920	City: Burlington, VA	105	7:30
S05a	3/16/2004	T8795	Shuttle: Norfolk, VA	430	9:00
S06a	3/17/2004	T8840	Shuttle: Greenville, NC; Greensboro, NC; Raleigh, NC	463	9:30
S07a	3/18/2004	T8920	Shuttle: Winchester, VA	520	9:45
S08a	3/19/2004	T8336	Shuttle: Knoxville, TN	545	9:45
S09b	3/29/2004	T8764	Shuttle: Greenville, SC; Norcross, GA	603	11:15
S10b	3/30/2004	T7957	Shuttle: Knoxville, TN	550	10:30
S11b	3/31/2004	T8434	Shuttle: Norcross, GA	560	10:00
S12b	4/1/2004	T8734	Shuttle: Norcross, GA; Charlotte, NC	630	12:00
			Totals	**4774 miles**	**116:45 hours**

Table 3-2. Summary of demographic information

ID	Gender	Age	Weight	Height	Years Truck Driver
S01b	M	38	220	6' 2	18
S02b	M	32	181	5' 8	7
S03b	M	39	190	6' 0	18
S04b	M	47	225	5' 11	30
S05a	M	46	175	5' 7	28
S06a	M	43	205	5' 8	15
S07a	M	35	185	5' 6	15
S08a	M	49	245	6' 0	31
S09b	M	49	195	5' 11	32
S10b	M	42	310	6' 1	15
S11b	M	47	200	5' 9	25
S12b	M	38	165	5' 9	10

Test Plan

We present an overview of our final test plan, as it was implemented in our field testing. The test plan also serves as a summary of the preceding sections in this chapter, where we develop the elements of the test plan.

Road tests were performed using existing commercial trucks during the daily operations of Averitt Express, whose fleet consists of the Volvo VN 300. Each of these vehicles has an air ride seat with a foam seat cushion in good or excellent condition from National Seating. This study used most of the dual-service vehicles available at the Greensboro, NC terminal of Averitt Express. These dual-service vehicles perform local delivery service during the day and shuttle service between terminals at night.

Six retrofit air-inflated seat cushions were installed in the fleet trucks, and the drivers were allowed to become familiar with the seats during approximately two weeks. This settling time was designed to give the drivers sufficient time to find a comfortable seat adjustment and develop some long-term impressions on the seat cushion. Each driver was personally instructed on how to adjust the air-inflated seat cushion to better accommodate their preferences, and they were also given a copy of a procedure for installing and adjusting the cushion, which is shown in Appendix A.

After the adjustment period, twelve drivers rode on both the air-inflated seat cushion and their original foam seat cushion during their regularly scheduled routes. Drivers were selected because they were assigned to these trucks during our field testing. Each driver rode on the first seat cushion for the first half of their shift, the seat cushions were swapped as close to the middle of their shift as practical, and the drivers rode on the second seat cushion for the second half of their shift. The testing order was varied to reduce order effects. As each driver's shift was approximately 10 hours, each driver rode on each seat cushion for slightly under 5 hours.

Prior to each test session, drivers filled out an Informed Consent to verify that they understand the scope of the study and are willing participants. The Informed Consent is provided in Appendix B. The drivers were then asked a series of questions to establish demographic information that may influence driver responses. This includes information such as physical characteristics, driving history, and health information. These questions are captured in the entrance interview section of the study packet, provided in Appendix C. While this information was not used to select participants, it is useful for establishing the relevance of the selected sample to the truck driver population as a whole.

Surveys were collected throughout the test sessions, and the truck seats were fitted with instrumentation to capture physical measurements of seat pressure distribution, as documented in the next sections on subjective and objective measures.

At the conclusion of each testing session, drivers were asked a series of questions to rate their overall opinions of the two seat cushions. This information includes which cushion they would prefer to ride on, their likes and dislikes of the seat cushions, and detailed questions rating their opinions. This information is used to assess the driver's overall preference, whereas the surveys that are collected throughout the test session provide a finer measure of subjective impressions over time.

After the field testing is completed, data is stored on a personal computer. Subjective data is tabulated and objective data is transferred to ASCII format and processed to find the objective measures using the Matlab code in Appendix D. This data was then used to complete the analysis presented in this document.

3.2 Subjective Data

Various surveys are collected during each test section, and statistical methods are used to draw conclusions on this data. This section outlines the collection and analysis methods for the subjective data for this study.

Subjective Measures

Surveys were administered throughout each test session. Prior to each test session, a survey was administered to collect personal information from each subject, including the demographic information summarized above in Table 3-1. These were based on an internal survey from The ROHO Group [32]. During each driving session, a "test drive" survey was taken at the 10 minute mark to record initial perceptions of seat comfort and support. This was adapted from Kolich [33], as shown in Table 3-3. This survey includes 9 comfort questions rating comfort level on a scale of 1 to 7, 1 being "Very Uncomfortable", 4 being "Neutral", and 7 being "Very Comfortable". This means that the most favorable comfort response is 7. It also has 5 support questions rating support level on a scale of 1 to 7, 1 being “Too Little”, 4 being “Just Right”, 7 being “Too Much”. This means that the most favorable support response is a 4. This scale was thoroughly explained to the drivers prior to completing each questionnaire.

An extended version of this survey, which includes fatigue questions, was taken at the end of each hour of driving. This includes one additional support question and 12 fatigue questions rating fatigue level on a scale of 1 to 7, 1 being “Low”, 4 being “Moderate”, 7 being “High”. This means the most favorable fatigue response is 1. The additional information for the fatigue questions was based on Sheridan [23], as shown in Table 3-4.

At the end of each test session, an exit interview was collected, where the driver was asked a series of questions to rate the air-inflated seat cushion compared to their regular truck seat. This provides a measure of the drivers overall preferences when comparing the two seat cushions.

These surveys were compiled into a study packet, provided in Appendix C. This packet also provides instructions for the test administrator to perform throughout the course of the test session and provides areas to record responses and take notes during the test session. At the completion of field testing, data from these surveys were tabulated for further analysis.

Table 3-3. "Test drive" survey for initial driver perceptions

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
2	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
3	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
4	Overall Back	☐	☐	☐	☐	☐	☐	☐	☐
5	Ischial/Buttocks	☐	☐	☐	☐	☐	☐	☐	☐
6	Thigh	☐	☐	☐	☐	☐	☐	☐	☐
7	Cushion Lateral	☐	☐	☐	☐	☐	☐	☐	☐
8	Overall Cushion	☐	☐	☐	☐	☐	☐	☐	☐
9	Overall Seat	☐	☐	☐	☐	☐	☐	☐	☐

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
11	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
12	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
13	Seat Back Firmness	☐	☐	☐	☐	☐	☐	☐	☐
14	Cushion Firmness	☐	☐	☐	☐	☐	☐	☐	☐

Table 3-4. Driving survey for each hour

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
2	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
3	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
4	Overall Back	☐	☐	☐	☐	☐	☐	☐	☐
5	Ischial/Buttocks	☐	☐	☐	☐	☐	☐	☐	☐
6	Thigh	☐	☐	☐	☐	☐	☐	☐	☐
7	Cushion Lateral	☐	☐	☐	☐	☐	☐	☐	☐
8	Overall Cushion	☐	☐	☐	☐	☐	☐	☐	☐
9	Overall Seat	☐	☐	☐	☐	☐	☐	☐	☐

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
11	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
12	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
13	Seat Back Firmness	☐	☐	☐	☐	☐	☐	☐	☐
14	Cushion Firmness	☐	☐	☐	☐	☐	☐	☐	☐
15	Cushion Hold	☐	☐	☐	☐	☐	☐	☐	☐

	Fatigue Level	1 Low	2	3	4 Moderate	5	6	7 High	Abstain
16	Drowsy	☐	☐	☐	☐	☐	☐	☐	☐
17	Eyes Tired	☐	☐	☐	☐	☐	☐	☐	☐
18	Dull or Listless	☐	☐	☐	☐	☐	☐	☐	☐
19	Stiff Neck	☐	☐	☐	☐	☐	☐	☐	☐
20	Shoulders Stiff	☐	☐	☐	☐	☐	☐	☐	☐
21	Arms Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
22	Aching Back	☐	☐	☐	☐	☐	☐	☐	☐
23	Buttocks Sore	☐	☐	☐	☐	☐	☐	☐	☐
24	Thighs Sore	☐	☐	☐	☐	☐	☐	☐	☐
25	Legs/Knees Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
26	Feet/Ankles Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
27	Whole Body Fatigue	☐	☐	☐	☐	☐	☐	☐	☐

Analysis Methods

This section highlights the rationale for the statistical analysis performed in this project. Readers familiar with hypothesis testing rationale in general and hypothesis tests for paired data and correlation can skip this section without loss of continuity. Hypothesis tests are used to generalize the results from an experiment of a relatively small sample size to a larger population by using some assumptions about the population in general. Several hypothesis tests are used throughout the analysis, but they all have the same rationale.

To illustrate the hypothesis testing rationale, we will describe a *paired t-test*. This is a practical method that is used throughout this study to find differences between two samples.

More specifically, suppose we ask subject i a question about Seat A. Denote this response as X_{Ai}. Similarly, we ask them the same question about Seat B. Denote this as X_{Bi}. We also ask these questions for all of our n subjects. This means that we have $2n$ samples; however, these are not $2n$ independent samples. It is expected that the subject's second response depends on his first response. This means that we only have n independent samples, which can be represented by the difference

$$D_i = X_{Bi} - X_{Ai} \quad \text{for } i = 1, 2, \ldots, n \tag{3-1}$$

We calculate all these differences, and then we find the average difference. Say the difference is positive, so the response for Seat B is greater than for Seat A. Now we ask, even though we observed a difference in our test, is the response for Seat B really greater than Seat A? We could have just observed a difference because we only looked at a few samples, not the *entire* population. For the entire population, the average difference may be different – it may be zero or even negative – due to much larger numbers of test subjects and randomness in the data. That is, *if we took samples from everyone in the population instead of just n samples, and we averaged all the D_i values, would there still be a difference?*

In order to test this, we have to make some assumptions about the larger population. First, we assume that the D_i *values* are independent and identically distributed as Gaussian with unknown mean μ_d and unknown variance σ_d^2. We then pose a hypothesis test as

$$H_o: \mu_d = 0 \quad \text{(Null Hypothesis)} \qquad \text{(3-2)}$$
$$H_a: \mu_d > 0 \quad \text{(Alternative Hypothesis)}$$

That is, we are trying to prove the alternative hypothesis, that the difference is positive. If we have strong enough evidence to accept the alternative hypothesis, we accept that there is a significant difference. If we do not have strong enough evidence to accept the alternative hypothesis, we cannot prove there is a difference. Note that we can only prove the alternative or not prove the alternative – we cannot prove the null or disprove the alternative. This subtlety is critical to the structure of the hypothesis test, and must be considered when evaluating the results from any hypothesis test.

We can calculate a *test statistic* as

$$T_{obs} = \frac{\bar{d}}{s_d / \sqrt{n}} \qquad \text{(3-3)}$$

where $\bar{d}$ is the sample average, s_d is the sample standard deviation, and n is the number of subjects. If the null hypothesis is true and the distribution assumptions above hold true, the test statistic is distributed as a t-distribution with $(n-1)$ degrees of freedom [34]. That is, we know the probability of observing different test statistics if there was no difference, so we can find the probability that we would observe a test statistic that would give us the same (or more) evidence of the alternative hypothesis, given the null hypothesis is true. This is called the *p-value* of the hypothesis test. Since we try to avoid making conclusions that are wrong, we like the p-value to be small before we make a conclusion. As the p-value goes down, the null hypothesis becomes less likely, and at some point we reject the null and say there is a significant difference. The cutoff p-value where we reject the null hypothesis is called the *significance level* of the hypothesis test, and this is the probability that we would observe a test statistic where we would incorrectly conclude the alternative is true.

There are several things that can go wrong with hypothesis tests. First, we need our distribution assumptions to hold. If the data points are not both independent and identically distributed, the hypothesis test is not accurate. Given that the distribution assumptions hold true, there are also Type I and Type II errors. Type I error occurs when we accept the alternative and the null is true, or a false positive. The probability of Type I error is our significance level. Type II error occurs when we fail to accept the null and the alternative is true, therefore it is often referred to as a false negative. The complement to the probability of Type II error is called the power of the hypothesis test, and it depends on both the true distribution of the test statistic and the significance level.

Another common hypothesis test that we use in this analysis is a test for correlation. *Correlation* is a measure of the linear dependence between two random variables. The sign of correlation determines the direction of the trend. *Positive correlation* means both variables tend to increase at the same time. *Negative correlation* means as one variable increases, the other tends to decrease. A common misconception about correlation is that it indicates the slope of the best fit line. While it is true that the sign of the correlation is the same as the slope of the best fit line, the magnitude determines how much of the data lies on the best fit line, not the slope. The magnitude of the correlation shows the strength of the relationship. If all the points lie on a straight line, the magnitude of the correlation is one. As the points move farther away form the best-fit line, the correlation approaches zero.

Sample correlation is calculated by

$$r_{XY} = \frac{S_{XY}}{\sqrt{S_{XX} S_{XY}}} \tag{3-4}$$

where S_{AB} is the sum over all samples of the products (A_i – mean A)(B_i – mean B). As in the paired t-test, we want to make an inference on the entire population based on our small test, so we use another hypothesis test.

Specifically we ask, are measures 1 and 2 really correlated, or are they linearly dependent? Say that we observe each measure n times. We find the sample correlation to be positive, and we want to test that the true correlation ρ is positive. We then pose the hypothesis test as

$$H_o: \rho = 0 \quad \text{(Null Hypothesis)} \qquad (3\text{-}5)$$
$$H_a: \rho > 0 \quad \text{(Alternative Hypothesis)}$$

Denote the i^{th} observation of measure 1 as X_i and the i^{th} observation of measure 2 as Y_i. Let the X values be independent and identically distributed and the Y values be independent and identically distributed, and let (X_i, Y_i) be sampled from the bivariate Gaussian distribution with a correlation ρ. We then find the test statistic

$$T_{obs} = r_{xy}\sqrt{\frac{n-2}{1-r_{xy}^2}} \qquad (3\text{-}6)$$

This test statistic is distributed as a t-distribution with *(n - 2)* degrees of freedom under the null hypothesis [34]. We use this information to calculate the p-value for the hypothesis test. If the p-value is less than our significance level, then we reject the null hypothesis and conclude there is a positive correlation.

3.3 Objective Data

This section highlights the objective data, first describing the pressure measurement system, then outlining the measures that are used to summarize the pressure data.

Pressure Measurement

Pressure distributions at the body's interface with the seat cushion are captured using the Tekscan Body Pressure Measurement System (BPMS), shown in Figure 3-5. This system has 4 main components:

- Pressure Sensing Pad

- Sensor Handle
- PC Interface Board and BPMS 5.01 Software
- Equilibration Unit

Figure 3-5. Tekscan BPMS system

Pressure distribution mapping is performed using a thin flexible resistive-based sensor pad featuring a 42 by 48 array of individual 0.16 in^2 pressure-sensing elements. The pressure-sensing pad is resistive-based. The application of pressure to an active sensor results in a change in the resistance of the sensing element in inverse proportion to the pressure applied [35].

Pressure is recorded either for a single static frame or for a series of dynamic frames on each cell into a movie file in the BPMS Software, seen in Figure 3-6. Static maps will be taken before and after each test session. Dynamic maps are recorded while driving once every 10 minutes for 10 seconds at 30 frames per second. The movie files are exported into ASCII format for post-processing in MATLAB. The processing code used to reduce the pressure data is shown in Appendix D.

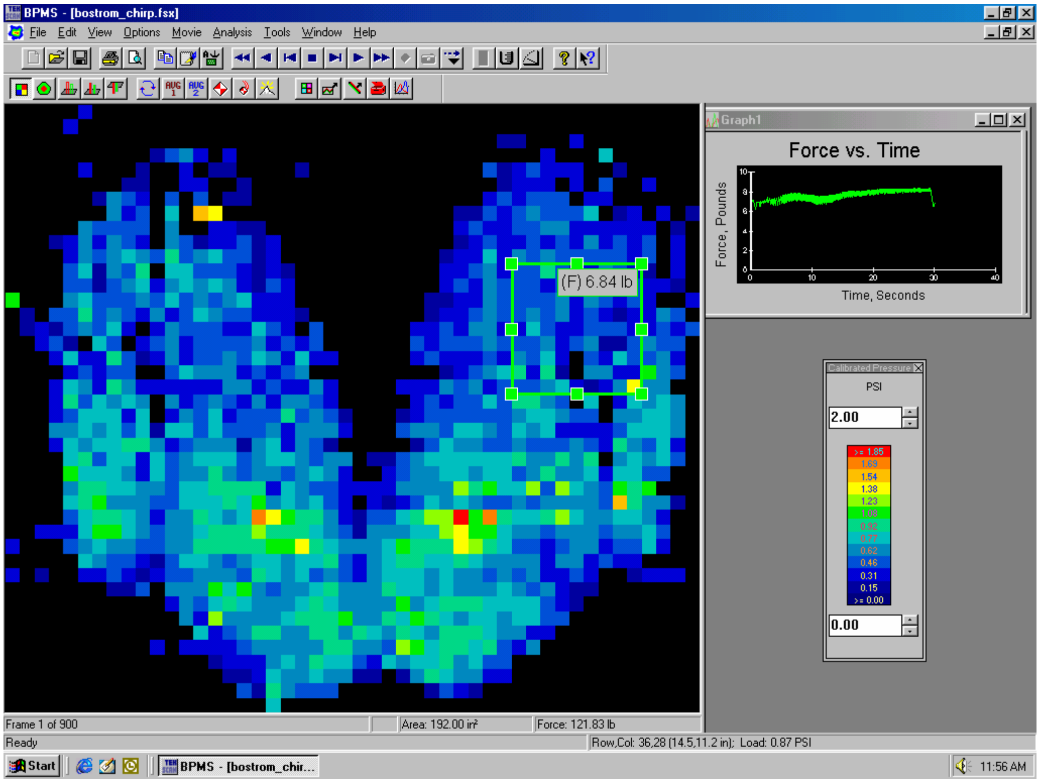

Figure 3-6. Tekscan BPMS software

The raw data from the sensor pad is converted to engineering units, such as psi or mmHg, through Calibration. Static loads are applied to the sensor pad, and the software measures the raw data from the pressure pad and calibrates the system to produce the known load. As many as two different loads can be applied, and the software determines the calibration curve between the measured force in raw units and the applied force in engineering units by either a straight line or power law fit through the two data points. For this study, straight line calibration was performed at 100 lbs and 150 lbs. The calibration is more accurate as the pressure distribution is more uniform and the number of loaded cells increase, as this accounts for the characteristics of more cells and also reduces highly concentrated pressures that may saturate individual cells or fall between cells. To improve the pressure distribution, weights were placed on top of a beanbag that covered the surface of the pressure pad, which alleviated highly concentrated pressure and distributed the load to a larger sensor area.

Equilibration is the method by which the software determines a unique scaling factor for each sensing element. This is done to allow for minor variations in sensitivity for each pressure cell. To perform equilibration, a uniform pressure is applied to all the cells, and the software adds a scaling factor to provide constant output. This is done using the uniform pressure from the air bladder in conjunction with BPMS software. For this study, equilibration was performed at 2 psi.

In this study, we use a pressure pad over the seat cushion to capture seat cushion pressure interfaces, as shown in Figure 3-7, allowing us to focus on the interface between the seat cushion and the driver. This helps us interpret our subjective results, and improve our understanding of how pressure distribution on the seat cushion is related to driver comfort and fatigue.

Figure 3-7. Air-inflated seat cushion mounted on original truck seat

To keep the pressure pad from sliding during each driving session, Velcro® was sewn along the edges of the green pressure pad sleeve. Special care must be taken to position the pressure pad sleeves without loading the pressure pad before the driver is seated.

Analysis Methods

When sitting on a surface, the soft tissues can be compressed and deformed by the underlying skeletal structure, particularly at the bony prominences (ischial tuberocities). At extreme pressures, this creates an obstruction of the blood supply, resulting in a deficiency of oxygen to tissue, causing discomfort and possibly fatigue. For this reason, it is believed that the pressure distribution at the human-seat interface must be incorporated into any objective measurement of comfort and/or fatigue.

Studies have shown relationship between comfort and the RMS value of the pressure change rate (Pcrms) [31]

$$Pcrms = \left\{ \frac{1}{T} \int_0^T \left[\left(\frac{dP}{dt} \right)^2 dt \right] \right\}^{1/2} \tag{3-6}$$

While Pcrms has been used to rate comfort on foam seat cushions, previous work has shown a relationship between fatigue and a weighted form of the Pcrms, known as the aPcrms [4]. This measure is found by partitioning the pressure map into n pressure ranges, where the i^{th} range has area A_i. Then Pressure Change Rate for each range ($Pcrms_i$) is weighted by the area (A_i) and some weighting factor (W_i), as shown in Equation (3-7).

$$aPcrms = \sum_{i=1}^{n} Pcrms_i \; A_i \; W_i \tag{3-7}$$

This method allows for fine-tuning of Pcrms using a discrete weighting function that can be adjusted to better predict human response. The selections of the weighting factors in Table 3-5 are based on the physiological effect of pressure on human cells in different pressure ranges. Past studies have established that the partial pressure of oxygen (PO_2) in the arterial blood is about 95 mmHg, and the partial pressure in the interstitial fluid immediately outside the capillary is approximately 40 mmHg. Therefore, a pressure difference of 55 mmHg exists and causes diffusion of oxygen into the surrounding tissue. If peak pressures in the tissue exceed 95 mmHg, then the cells are deprived of oxygen. Therefore, we select a higher weighting factor for pressures exceeding 60 mmHg, and increase it every 20 mmHg to more accurately reflect the effect of higher pressures on the human tissue.

Based on this idea, the following procedure has been suggested to calculate aPcrms in this study [4]:

1. Determine the contact area (A_i) from the pressure map data for each of the pressure ranges r_i in Table 3-5.

2. Determine cells with average pressure greater than 40 mmHg.

3. Eliminate bad pressure data by computing the average pressure reading and standard deviation for each cell over an entire data block. Eliminate any pressure reading that is greater than +3 standard deviations from the average. Recalculate average pressure reading for each cell.

4. Calculate Pcrms for each cell using Equation 3-6.

5. Calculate an Average Pcrms (*Pcrms*$_i$) for each of the pressure ranges r_i in Table 3-5.

6. Calculate aPcrms using Equation 3-7 and the weighting factors in Table 3-5.

Table 3-5. Weighting factors for aPcrms

i	**Pressure Range, r_i**	**Weighting Factor, W_i**
1	40 to 60 mmHg	1
2	60 to 80 mmHg	2
3	80 to 100 mmHg	3
4	Over 100 mmHg	4

Research in seat comfort has established a positive relationship between uniform pressure distribution and perceived comfort [24]. Furthermore, lower pressures are always more desirable in terms of long-term tissue integrity. Since a uniform pressure alleviates high concentrated pressure, it follows that a more uniform distribution may be preferable in terms of comfort and fatigue. Seat Pressure Distribution (SPD%) is a measure that is used to evaluate the ability of a seat cushion to uniformly distribute pressure. This is found by

$$SPD\% = \frac{\sum_{i=1}^{n}(p_i - p_m)^2}{4np_m^{\;2}} \text{ x } 100\% \approx \left(\frac{v}{2}\right)^2 \text{ x } 100\% \qquad (3\text{-}8)$$

where *pi* is the pressure of the i^{th} cell, p_m is the mean pressure of the active cells, and n is the number of active cells. One may note that SPD% is proportional to the squared coefficient of variation (v) for the pressure distribution, so SPD% is a scaled measure of the pressure variance from the mean pressure within the contact area.

A lower percentage value describes a more uniform pressure distribution at the seat cushion. For a uniform seat pressure distribution, each pressure (p_i) would be equal to the mean pressure (p_m) resulting in a value of zero. Note that SPD% can be used for both static and dynamic environments. A dynamic SPD% calculation uses the SPD% for each frame of pressure data within a data block. A time trace of dynamic SPD% can be examined to determine the ability of the seat cushion to maintain uniform pressure.

Several other common pressure measurements are used in this study. This section highlights these measures for clarity. One measure that is used for summarizing pressure data is the center of pressure on the seat cushion. Center of pressure can be found for a single static pressure map or for each frame within a dynamic pressure map. The center of pressure measurement is calculated using the static pressure map in the pressure pad's local coordinate system defined by the rows and columns of the pressure pad, which follows the seat contour. This is then transferred to the SAE vehicle coordinate system. We also set the origin at the center of the pressure cell in the corner closest to the pressure handle, which is located at the front-right corner of the seat cushion, as shown in Figure 3-8.

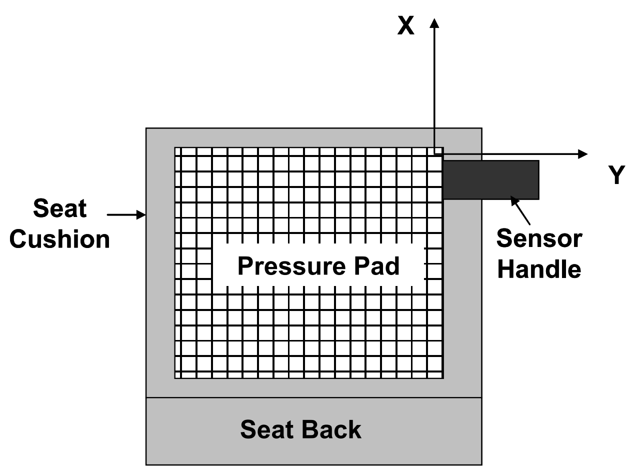

Figure 3-8. Top view of pressure pad in vehicle coordinate system

For reporting center of pressure, we assume the pressure pad's coordinate system aligns with the vehicle coordinate system. This is an approximation since the pressure pad may be slightly misaligned with the vehicle coordinate system and the pressure pad's coordinate system follows the seat contour, so it does not lie in any single plane. It should be noted, however, that the center of pressure measurement is in the pressure pad's coordinate system, which follows a surface in space, so it is only approximate in the vehicle coordinate system.

In addition to the above measures, Average Contact Pressure and Contact Area can be calculated for one static frame or for each frame in a dynamic data block. Several of these measures that result in a time trace for each data block are summarized by taking means and standard deviations over time.

We calculate 16 measures for each block of dynamic pressure data, as shown in Table 3-6. In addition to aPcrms measure in Item 1, we also analyze the areas and Pcrms values used in the aPcrms calculation in Items 2 through 9. We also consider means and standard deviations over time of measures that are found for individual frames in Items 10 through 16.

Table 3-6. Summary of dynamic pressure measures

		measure	units
aPcrms-Related	1	aPcrms	lbf/s
	2	Area 1	in^2
	3	Area 2	in^2
	4	Area 3	in^2
	5	Area 4	in^2
	6	Pcrms 1	lbf/s
	7	Pcrms 2	lbf/s
	8	Pcrms 3	lbf/s
	9	Pcrms 4	lbf/s
Means	10	Mean SPD%	-
	11	Mean Pressure	psi
	12	Mean Area	in^2
	13	Mean COPx	in
	14	Mean COPy	in
Standard Deviations	15	St Dev COPx	in
	16	St Dev COPy	in

3.4 Summary of Experimental Methods

This section has described the experimental methods used in this study. The field testing is conducted in the daily operations of a commercial trucking service to evaluate the effect of air-inflated seat cushions on driver fatigue. Subjective measures are taken using surveys and objective measures are taken using pressure distribution across the seat cushion. The subjective and objective results from the field testing are presented in the following two chapters.

Chapter 4
Field Test Results: Subjective Analysis

This section details some of the key subjective results from this study. First, we consider the overall driver preference, as collected in the exit interviews. Then, we compare the results from the "test drive" survey. Finally, we reduce road data from all the test sessions into a minimal data set for further comparison with the objective data.

4.1 Overall Driver Preference

First we consider the overall driver preference, as collected in the exit interviews. This is useful to provide an overview of the drivers' preferences, which is important to keep in mind when considering more detailed analysis. When asked how the air-inflated seat cushion compared to their regular seat cushion, 10 out of 12 drivers said the air-inflated cushion performed much better and they would prefer to drive on it during their daily route. The other two subjects said the air-inflated cushion performed about the same for them, and they were neutral as to which one they preferred. This is a key result from a standpoint of satisfying fleet customers, because it indicates that the air-inflated cushion would be preferred by a large percentage of drivers, while the smaller percentage that does not favor the air-inflated seat cushion would not be unhappy. In terms of the distribution of overall driver preference, this suggests a distribution where the mean favors the air-inflated seat cushion, while a small tail of the distribution is opinion-neutral or negative. This is preferable to a bimodal distribution, where a certain population of drivers loves the seat, while another population hates the seat.

Drivers were also asked to list their likes and dislikes of the air-inflated seat cushion. These responses are summarized in Table 4-1. For clarity in displaying these results, responses were grouped by comfort, support, adjustability, and general feedback. We see that overall, drivers like the comfort of the air-inflated seat cushion. Additionally, they like the support in the seat cushion, while some drivers found that the seat cushion made their back support better, and some found it made back support worse. Drivers also liked the ability to make adjustments to the seat cushion; however, they didn't like the difficulty in making the adjustments. Also, drivers noted that the seat cushion was too thick, it was harder to get in and out, and it didn't support their legs on the sides as well.

Table 4-1. Driver likes and dislikes for air-inflated seat cushion

	Likes	Dislikes
Comfort	better ride very comfortable doesn't hurt as much	
Support	better back support raises me up onto back support better buttocks and thigh support better hold good firmness cushy	tilts me off back support height throws off back support needs matching back doesn't hug legs well on sides
Adjustability	able to adjust feels good when adjusted	needs more controls hard to adjust needs buttons like on seat ride height need to adjust sections individually
General	not as hot	hard to get in too thick sits high overall

We now consider more detailed questions in the exit interview. First, we asked each driver a series of "yes" or "no" questions to rate the air-inflated seat cushion. From these results, summarized in Table 4-2, we see that the main problems from this list were adjusting the cushion pressure, using the valve, and getting in and out of the seat. None of the drivers found the air-inflated cushion uncomfortable, while only 1 in 12 drivers said the cushion made them sweat or it constricted their legs. This suggests that overall the air-inflated cushion performed well; however, adjustments could be made to make the seat cushion adjustments more user-friendly.

Table 4-2. Exit interview question 1

Answer the following "yes" or "no" questions about the air cushion	# Yes	% Yes
Was the cushion uncomfortable?	0	0%
Was it too hot or make you sweat?	1	8%
Did it pinch or constrict your legs?	1	8%
Did you have difficulty getting in and out of your seat?	2	17%
Did you have problems adjusting the cushion pressure?	5	42%
Did you have problems adjusting the valve for the cushion?	3	25%

Since an air-inflated seat cushion has more adjustment than a foam cushion, it requires more driver adjustments to get it to a comfortable position, and this increased complexity requires a learning curve for using air-inflated seat cushions, as compared to foam cushions. This shows that it is important to have proper driver instruction and a more intuitive driver interface for the air-inflated seat cushion.

Additionally, since an air-inflated seat cushion naturally has lower lateral shear stiffness, it becomes harder to get in and out from the seat, as the seat tries to follow the driver as they get in and out. Perhaps some additional elements to improve lateral shear stiffness of the overall cushion coupled with reduced friction across the seated area could improve this component of seat performance.

Next, we asked the drivers to rate the air-inflated cushion in comparison to their regular seat cushion on a scale of 1 to 7, where 1 is “Much Worse”, 4 is “Same”, and 7 is “Much Better”. These results are summarized in Table 4-3. In all cases, the average response was between 5 and 6, which says the air-inflated cushion performed better than the foam cushion in the areas questioned. Aside from one driver that rated comfort at 1, and one driver that rated lower back pain at 1, all other ratings were neutral or favorable for the air-inflated seat cushion. It should be noted that the two ratings of 1 came from the two drivers that were opinion-neutral on the seat cushion overall.

Table 4-3. Exit interview question 2

Rate the air-inflated cushion in comparison to your regular truck seat on a scale of 1 to 7, where 1 is "Much Worse", 4 is "Same" and 7 is "Much Better".	counts 1	2	3	4	5	6	7	x	Average Response
Comfort	1	0	0	1	1	4	5	0	5.75
Tired feeling after driving	0	0	0	3	2	3	4	0	5.67
Numbness in legs	0	0	0	6	1	1	3	1	5.09
Reduced vibration and shock	0	0	0	5	2	1	4	0	5.33
Lower back pain	1	0	0	3	0	2	5	1	5.45
Hemmorrhoid pain	0	0	0	4	0	0	4	4	5.50
Sitting pain or discomfort	0	0	0	5	1	0	5	1	5.45
Alertness after driving	0	0	0	4	2	2	4	0	5.50

Finally, we asked the drivers to rate the air-inflated cushion on several different areas, as shown in Table 4-4. Four items had individual responses below 4 or "Average": styling, using seat controls, adjusting seat, and getting in and out. Again, this suggests that a seat that is more user-friendly and has increased lateral shear stiffness would see marked improvements. Additionally, some attention should go into improving the cosmetic appearance.

Table 4-4. Exit interview question 3

Rate the air-inflated seat cushion on the following areas. Use a scale of 1 to 7, where 1 is "Unacceptable", 4 is "Average", and 7 is "Outstanding".	counts 1	2	3	4	5	6	7	x	Average Response
Styling of the seating unit	0	1	1	5	4	1	0	0	4.25
The look/feel of the seat material	0	0	0	5	2	3	2	0	5.17
How easy it is to reach/operate seat controls	0	3	1	3	2	2	1	0	4.17
Ability to adjust driver's seat to comfortable position	1	2	1	3	2	1	2	0	4.17
How easy it to put on seat belt	0	0	0	6	2	1	3	0	5.08
How seat holds you in place during cornering	0	0	0	2	3	2	5	0	5.83
Ability to get in and out of the driver's seat easily	0	1	1	2	2	3	3	0	5.17

Overall, the exit interviews indicate that the air-inflated seat cushion was preferred by most drivers, while no drivers preferred the foam seat cushion. However, several improvements should be considered to improve future results for air-inflated seat cushions based on the results of the exit interviews:

- A seat cushion that is specifically designed for the seat, not a retrofit: In this study, several drivers complained that the seat cushion pushed them into their back support.
- Thinner, less bulky design: Drivers complained that since the air-inflated seat cushion was thicker than their original seat cushion, they felt they were sitting too high, and this either made it harder for them to reach the vehicle controls and had their line of sight higher than they liked, or they had to drop the suspension near bottoming. Since most of the drivers rode with their seat close to bottoming, the second was not an option for many drivers.
- User-friendly controls: Drivers had a hard time learning how to adjust the seat cushion, which frustrated drivers. A seat cushion that could be adjusted easily while driving may see marked improvements with the same seat cushion design in both subjective and objective data, simply because the driver will be able to play with the seat controls until they find an ideal setting. This ease of use allows the user to realize a major advantage of the air-inflated seat cushion: adjustability.
- Easier to slide over seat surface: Drivers did not like the difficulty to get in and out of the seat. Improving the shear stiffness, particularly in side bolsters, coupled with a better sliding surface may remedy this issue.
- Stiffer side bolsters: Drivers noted that they preferred the more rigid contoured side bolsters on the foam seat cushion. Increasing the stiffness in the side bolsters would also reduce the effort required to get in and out of the seat.
- Better aesthetic design: While this seat cushion was a prototype, a more aesthetically pleasing seat cushion may give a more positive perception of the seat cushion.

4.2 Test Drive Survey

Next, we consider the results of the "test drive" surveys that were administered at the 10-minute mark. This was done so that we could capture the driver's initial perceptions of the seat before long-term effects, such as fatigue, began to set in.

To reduce the test drive survey information into a more compact data set, the responses for each of the 14 test drive questions were correlated against the responses for the other 13 questions. On both cushions, we found strong positive correlations within groups of comfort and support questions, such as between a comfort question and a different comfort question. We also found low correlations across groups, such as correlation between a comfort question and a support question. This indicates that the drivers either were unable to differentiate within these two areas of comfort or support questions, or their responses were dominated by one factor within each group of questions. In any case, the responses within groupings of comfort and support are linearly dependent, and can be averaged into one average comfort rating and one average support rating for each subject.

Figure 4-1 shows the average comfort response for each subject on both seat cushions. In all cases except subject 9, the comfort response favors the air-inflated seat cushion. Using a one-tailed paired t-test for average comfort ratings finds a significant improvement in average comfort rating for the air-inflated seat cushion (p-val = 2%).

Figure 4-2 shows the average support rating for each subject on both seat cushions. For support, the ideal rating is 4 or "Just Right". For our test, the air-inflated cushion is closer to 4 in almost all cases, and only marginally further away from 4 in the other cases. One observation that can be made is that different subjects found the foam cushion either supports too much or too little. This reflects one of the shortcomings in a seat cushion design that does not allow user adjustment, as it cannot be made to accommodate a diverse group of users.

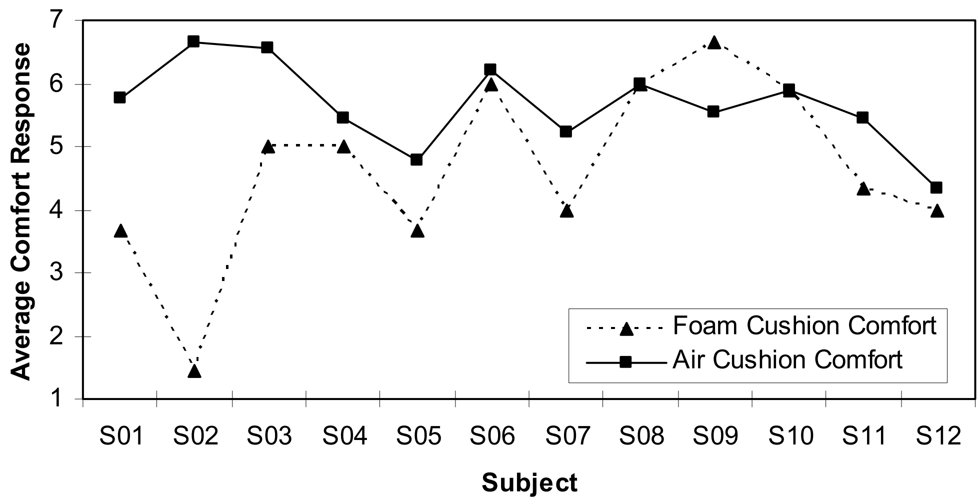

Figure 4-1. Average comfort response for "test drive" surveys

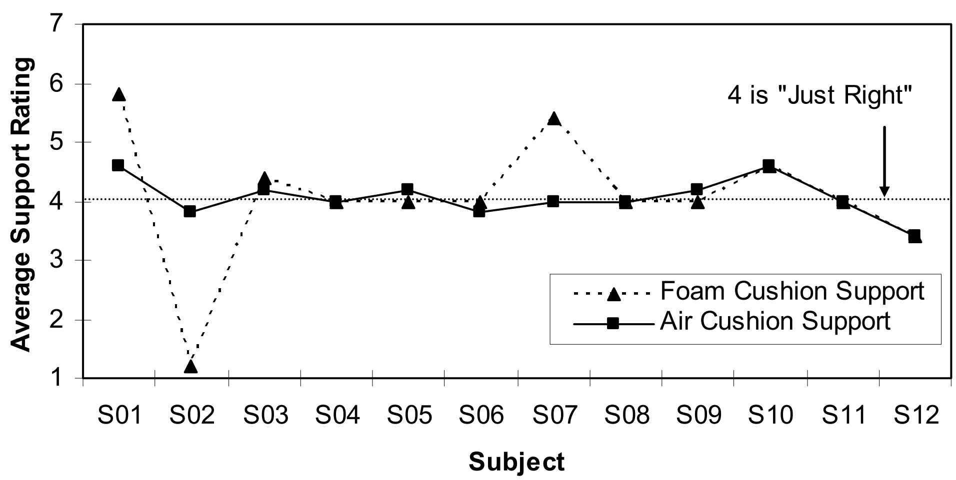

Figure 4-2. Average support response for "test drive" surveys

When the seat designer specifies a given contour, it is set – some drivers will find it supports too much and some will find it supports too little, and there is not much the drivers can do about it. If the distribution of driver preference to physical seat characteristics is multi-modal, there is no single ideal seat design, so the seat designer will have to either choose a design that is optimal for a single group of drivers, or settle for a seat design that is not optimal to any set of drivers, but offers some desirable compromise between all sets of drivers. In an air-inflated cushion, there is naturally a large amount of adjustability that can be used to reduce these tradeoffs and better accommodate a diverse group of drivers.

These “test drive” survey results were then further reduced into a comfort score and a support score for each seat cushion, which will be used with the road data. The comfort score was calculated by averaging the comfort responses over all subjects for a given seat cushion, as defined in Equation (4-1). A higher comfort score corresponds to more comfort. An ideal comfort score is 7.

$$\begin{matrix}\text{comfort}\\ \text{score}\end{matrix} = \frac{1}{12}\sum_{12\ \text{subjects}}\begin{pmatrix}\text{average}\\ \text{comfort}\\ \text{response}\end{pmatrix} \tag{4-1}$$

For support, the subjective performance worsens as it moves up or down from the ideal value of 4. The support score is calculated by the average over all subjects of the absolute difference between the support response and the ideal response of 4, as defined by Equation 4-2. Support score can be considered the average absolute support error. A lower support score corresponds to better support. For ideal support, support score is zero.

$$\begin{matrix}\text{support}\\ \text{score}\end{matrix} = \frac{1}{12}\sum_{12\ \text{subjects}}\left|\begin{pmatrix}\text{average}\\ \text{support}\\ \text{response}\end{pmatrix} - 4\right| \tag{4-2}$$

Scores for the “test drive” survey are shown in Table 4-5. After 10 minutes, the air inflated cushion has a score about one better than the foam cushion, while the support score is better than the foam cushion. These scores will be also used as an initial data point when comparing road data.

Table 4-5. Scores for “test drive” survey

	Comfort Score	Support Score
Foam Cushion	4.64	0.63
Air-Inflated Cushion	5.66	0.23

4.3 Road Survey

We now consider data from the road surveys that were taken at the end of each hour of driving. The road survey was used to capture the driver's perception of comfort, support, and fatigue throughout a day of driving on both the foam and the air-inflated seat cushion.

First, to reduce the data set to a more minimal set of useful information, we found the correlation matrix for the 9 comfort questions, 6 support questions and 12 fatigue questions for each hour and seat cushion. In each case, we found high correlations within groups of comfort, support, and fatigue questions, such as between a comfort question and a different comfort question. We also found low correlations across groups, such as correlation between a comfort question and a fatigue question. As in the "test drive" survey case, this suggests that the drivers either weren't able to differentiate between these different areas of comfort, support, or fatigue questions, or their responses were dominated by one factor within each group of questions. In any case, the questions within the groupings of comfort, support, and fatigue are linearly dependent, and can be averaged into one average comfort, support, and fatigue rating for each subject at each time.

To see which differences were statistically significant, we performed paired t-tests on an hourly basis between foam and air-inflated cushions for comfort and fatigue. The results of the t-tests are summarized in Table 4-6. In each test, we took the paired difference as air-inflated cushion minus the foam cushion, so a positive difference corresponds to a higher air-inflated seat cushion response.

For comfort, we found that the air-inflated cushion has a better (higher) average comfort rating during each time period, and all the differences, except the difference at Hour 3, are significant at 10% significance. For fatigue, we observed that the air-inflated seat cushion has a lower (better) average fatigue rating during 3 out of 4 time periods. The favorable differences during Hour 1 and Hour 2 are significant at 10%. During Hour 3, the air-inflated cushion had a slightly higher (worse) average fatigue rating than the foam cushion, but this difference was highly insignificant with a p-value of 40%.

Table 4-6. Summary of significant differences on hourly basis, air-inflated cushion - foam seat cushion

		average air-foam	*p-val*
Comfort	**H0**	1.02	2.3%
	H1	1.17	1.8%
	H2	1.08	3.8%
	H3	0.22	23.1%
	H4	0.44	9.7%
Fatigue	**H1**	-0.38	10.0%
	H2	-0.38	8.2%
	H3	0.07	39.8%
	H4	-0.33	21.3%

For an overall summary of the road data, we created a fatigue score, by averaging over all subjects their fatigue response during each hour, as defined in Equation 4-3. A lower fatigue score corresponds to better fatigue performance. Ideal fatigue score is 1. Combining the fatigue score with the comfort score and support score defined in Equations (4-1) and (4-2), we can summarize our subjective data by plotting these three scores over time, as shown in Table 4-7 and Figures 4-3 to 4-5.

$$\begin{matrix}\text{fatigue}\\\text{score}\end{matrix} = \frac{1}{12}\sum_{12\ \text{subjects}}\begin{pmatrix}\text{average}\\\text{fatigue}\\\text{response}\end{pmatrix} \qquad (4\text{-}3)$$

Table 4-7. Hourly scores for road test

	H0	H1	H2	H3	H4
Foam Comfort	4.6	4.4	4.3	4.5	3.9
Air Comfort	5.7	5.5	5.4	4.7	4.3
Foam Support	0.63	0.51	0.92	1.44	2.50
Air Support	0.23	0.38	0.23	0.28	1.54
Foam Fatigue		1.7	1.8	1.9	1.7
Air Fatigue		1.3	1.5	1.9	1.4

First, we show the support scores in Figure 4-3. Recall that the support score is the average of the support error, for all subjects, therefore the lower the support score is, the better the support would be. At all times, the support is better for the air-inflated seat cushion than the foam seat cushion. This is expected, as the air-inflated cushion can be adjusted by the driver to accommodate their individual support needs, where a foam cushion is fixed and cannot be individually adjusted. Additionally, the support steadily worsens for the foam cushion, while the air cushion stays relatively constant until the last hour. This indicates that the foam's support performance drops off more quickly than an air-inflated seat cushion.

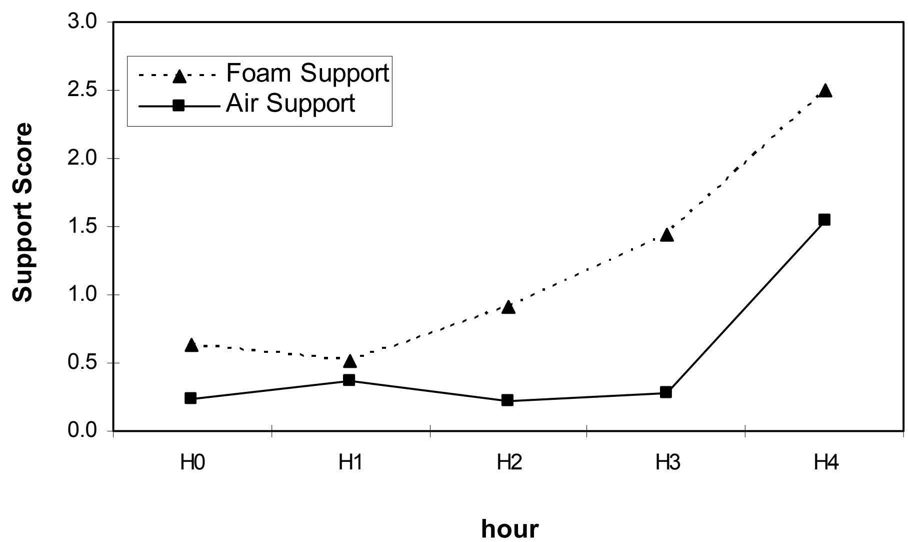

Figure 4-3. Support score over time

In the case of comfort and fatigue scores, the score is calculated by a direct average, so a significant difference in comfort or fatigue scores corresponds to a significant paired t-test, as summarized in Table 4-6. This gives us a measure of significance when looking at each point on the comfort and fatigue plots.

Next, consider comfort score, shown in Figure 4-4. As we have shown before, the comfort score is higher for the air-inflated seat cushion at all times. Additionally, the improvement is significant at 10% significance level for all times, except Hour 3. During Hour 3, the significance is reduced to close nearly 25%. Also note that during Hour 4, the difference is significant at only 9%, so the last two differences are less significant than the first three. It seems that the difference in comfort scores seems to be relatively constant over earlier times, then difference become less significant at later times.

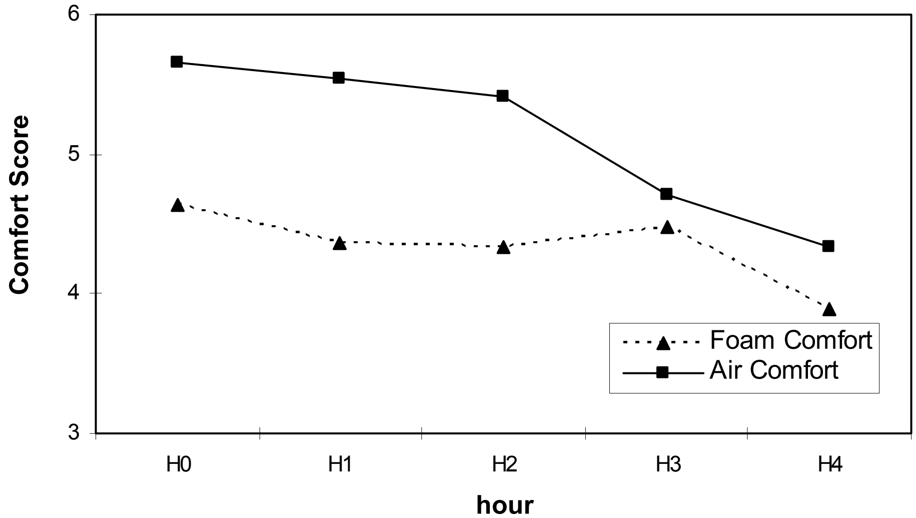

Figure 4-4. Comfort score over time

Finally, consider fatigue score, shown in Figure 4-5. The air-inflated cushion's fatigue score is better at most times, except during the third hour. The difference is significant for the first two hours (10% and 8% p-values), while the difference is not significant for the last two hours (40% and 20% p-values). Like the comfort scores, this suggests a significant difference in fatigue scores during earlier times, and a less significant difference at later times.

To summarize comfort, support, and fatigue over the entire test session, we then averaged the comfort, support, and fatigue scores and found the percent improvement for the air inflated seat cushion, as shown in Figure 4-6. We see that the air-inflated cushion offers improvements in all three areas: 18% in comfort, 56% in support, and 14% in fatigue.

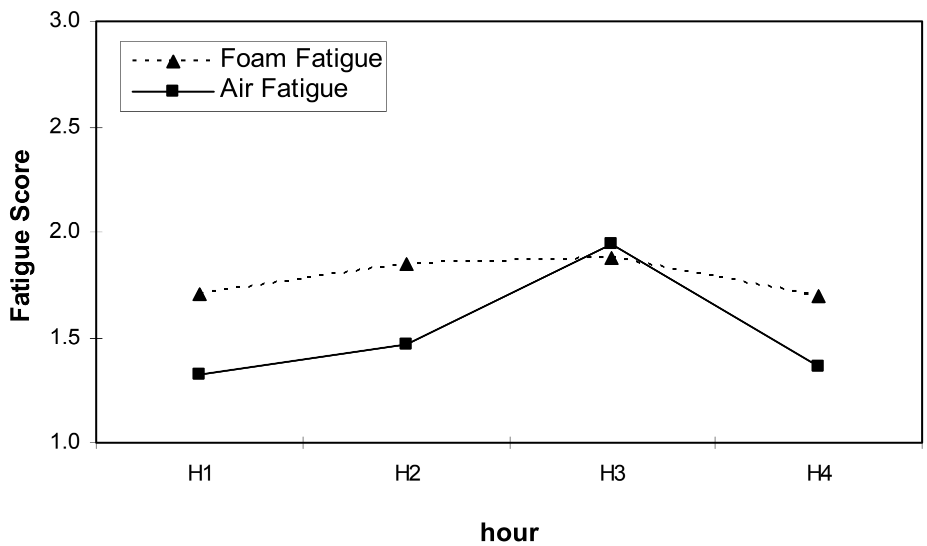

Figure 4-5. Fatigue score over time

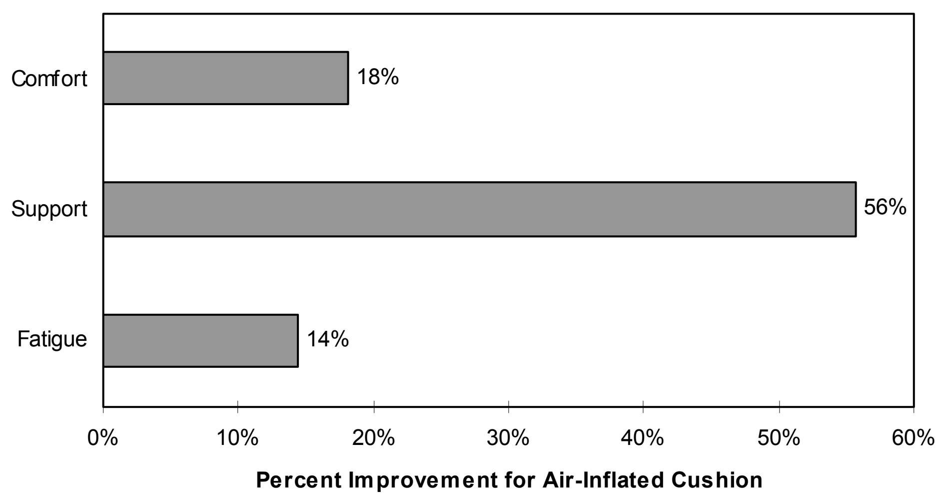

Figure 4-6. Percent improvement for air-inflated seat cushion

4.4 Summary of Subjective Analysis

This section has summarized several key subjective results from this project. Based on these results, we find that air-inflated cushions offer advantages in terms of comfort, support, and fatigue. The increased adjustability in an air-inflated cushion leads to an improved ability to accommodate diverse populations of drivers. This increased adjustability also carries with it some difficulty, such as increased complexity and making it harder for drivers to get in and out of the seat. Even with these weaknesses, air-inflated cushions were preferred over foam cushions by most of the drivers that we tested, while none of the drivers favored the foam cushion.

Air-inflated seat cushions naturally offer advantages over foam cushions, and with an improved detail design and increased industry awareness of the benefits of air-inflated seat cushions, they should become a popular alternative to standard foam seats in the near future.

Chapter 5

Field Test Results: Objective Analysis

This section details some of the key objective results in this study. First, we consider static pressure distributions, collected before and after the drivers rode on each seat cushion. Next, we consider dynamic pressure distributions, collected throughout the test sessions.

5.1 Static Pressure Maps

Static pressure maps were taken before and after drivers rode on each seat cushion. This was done to consider the seat pressure distribution in absence of road excitations. A sample of the static pressure distributions is shown in Figure 5-1. By simply comparing the static pressure distributions, we see little difference between seat cushions. Comparing both cushions before driving, we see that the pressure distributions look similar. Comparing both cushions after driving, we see the foam cushion shows a small amount of higher pressure, while the air-inflated cushion is nearly unchanged. Aside from this minor difference, the static pressure maps look very similar.

Some of the differences are reflected by the averaged histogram of the pressure distribution, as shown in Figure 5-2. Since we are mainly concerned with high pressures, pressures below 40 mmHg were omitted from this plot. The most significant trend we see is that the percent area after each test session is higher for the foam cushion than for the air cushion for all four pressure ranges. Second, the percent area increases for the foam cushion over the test session in all four pressure ranges, while it only increases slightly for the air-inflated seat cushion in the 80-100 mmHg and the greater than 100 mmHg range.

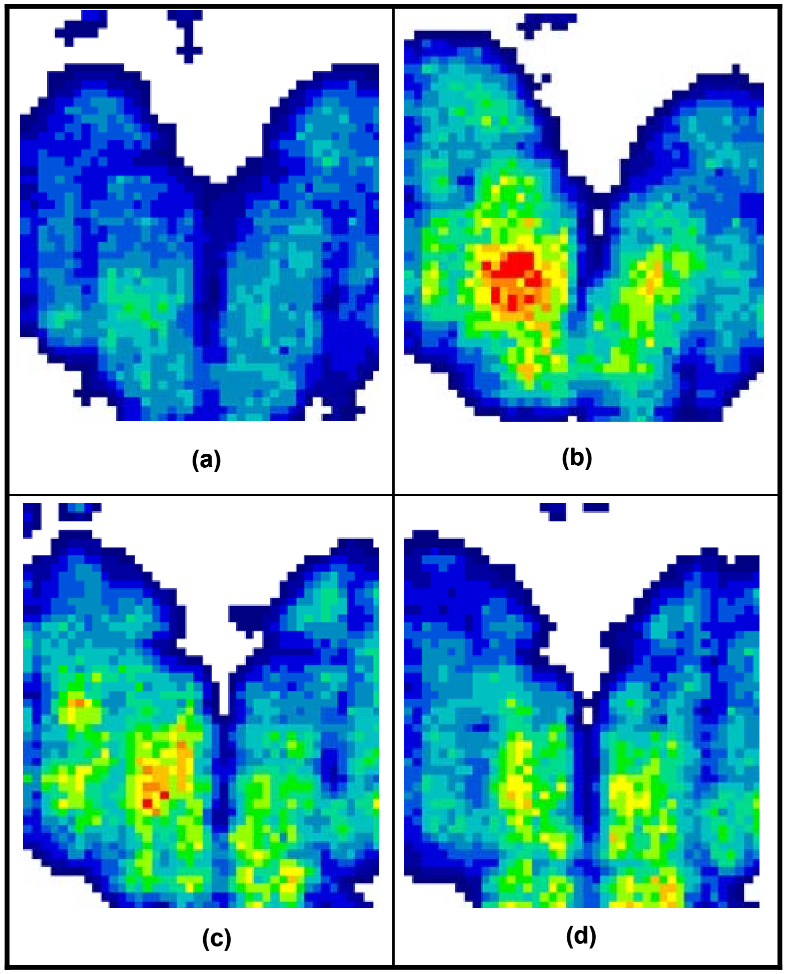

Figure 5-1. Sample static pressure distributions:
(a) foam before, (b) foam after, (c) air-inflated before, (d) air-inflated after

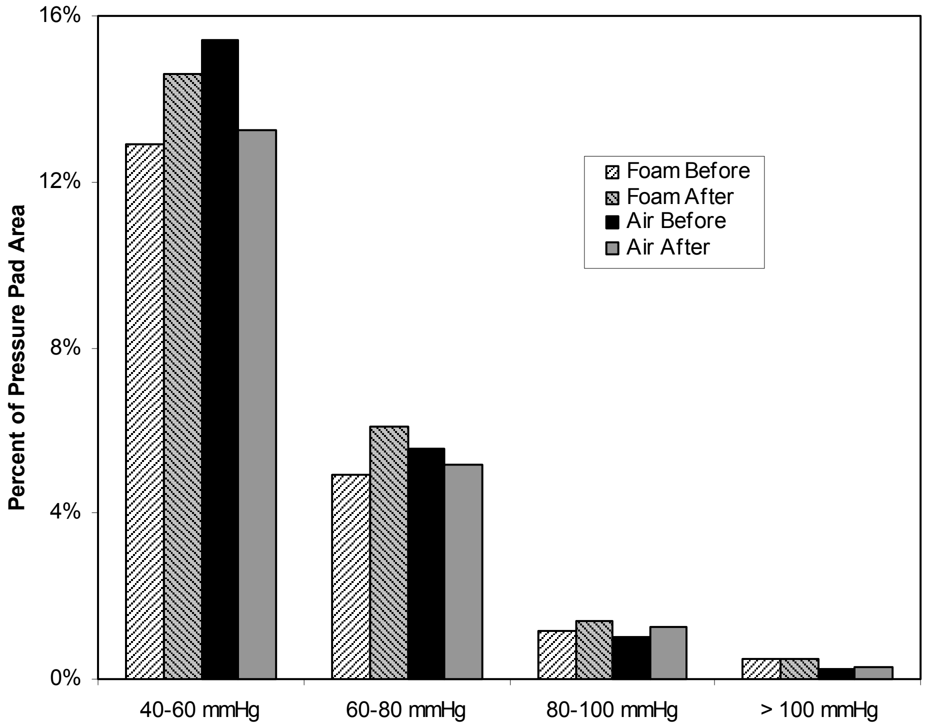

Figure 5-2. Averaged histogram of static pressure distributions

Next, we consider static pressure, area, Seat Pressure Distribution Percent (SPD%), longitudinal center of pressure (COPx), and lateral center of pressure (COPy). The average of these measures for the twelve test subjects were found for each seat cushion, both before and after driving. To highlight significant differences between before and after driving on one cushion, and between cushions before or after driving, we performed four paired t-tests, as summarized in Table 5-1. Signs in parenthesis indicate the observed sign for the difference defined in the first column, where a "+" sign indicates a positive difference, and a "-" sign indicates a negative difference.

Table 5-1. P-Values for difference tests on static pressure data, sign indicates sign of difference

Test	*Pmean*	*Area*	*SPD%*	*COP X*	*COP Y*
Before Driving: Air-Foam	**(+)** 49.2%	**(+)** **2.0%**	**(+)** 46.1%	**(-)** **12.5%**	**(+)** 38.7%
After Driving: Air-Foam	**(-)** **12.1%**	**(+)** **18.3%**	**(+)** **1.4%**	**(-)** **0.0%**	**(+)** 26.3%
On Foam: After-Before	**(+)** **17.8%**	**(-)** 33.6%	**(-)** **17.6%**	**(+)** **0.4%**	**(-)** 29.5%
On Air: After-Before	**(-)** 42.3%	**(-)** **5.4%**	**(+)** **18.0%**	**(-)** **0.6%**	**(-)** 44.4%

This analysis highlights several significant differences, which indicate characteristic trends within the data. First, consider mean pressure. After driving, mean air pressure for the air-inflated seat cushion is less than the foam. For the foam cushion, the mean pressure increases while driving. Next, we consider the contact area. Both before and after driving, the contact area on the air cushion is greater than for the foam cushion. On the air-inflated seat cushion, the contact area decreases while driving. Next, consider SPD%. After driving, SPD% on the air inflated seat cushion is greater than SPD% on the foam cushion. On the foam cushion, SPD% decreases, while on the air-inflated seat cushion it increases while driving. Next, consider COPx. The center of pressure is further back on the air cushion for both times. Additionally, the center of pressure on the foam cushion moved forward while the center of pressure on the air-inflated seat cushion moved backwards. After driving, the center of pressure is about 2 inches further back in the seat cushion than the foam cushion. Finally, we consider COPy. There are no significant differences in COPy between the foam and air-inflated seat cushions. The center of pressure is near the line of symmetry on the seat cushion.

In summary, mean pressure starts about the same for both seat cushions, but mean pressure increases on the foam cushion. The air-inflated seat cushion has a higher area than the foam cushion, but the air-inflated seat cushion's area decreases while driving. COPx is further back in the air-inflated seat cushion than the foam cushion, and this difference grows while driving from 0.3 inches to 2.3 inches. COPx is similar in all four cases, and it falls near the line of symmetry of the seat cushion.

SPD% is similar before driving, but it decreases on the foam cushion and increases on the air-inflated seat cushion, ending with a higher SPD% on the air-inflated seat cushion after testing. While SPD% was higher on the air-inflated seat cushion after driving, the mean pressure was lower, contact area was higher, and the air inflated seat cushion exhibited less pressures in the critical pressure regions after driving. This suggests a case where SPD% is insufficient to evaluate subjective performance, since we know that subjective performance was superior on the air-inflated seat cushion. This is highlighted by rearranging SPD% as

$$SPD\% = \frac{1}{4}\left[\frac{1}{p_m}\left(\frac{1}{n}\sum_{i=1}^{n} p_i^{\,2}\right) - 1\right] \qquad \text{5-1}$$

As shown by this representation, SPD% is directly related to the average over the contact area of the squared pressure divided by the squared mean pressure. If all pressures are equal, SPD% will indeed be zero. However, in our case, the air-inflated seat cushion has a lower mean pressure, but similar pressures in the high pressure regions. Since SPD% considers the average squared pressure, it will heavily weight the larger pressures. For two seat cushions that have nearly identical area in the higher pressure regions, the SPD% will be similar if the mean pressures are the same. If the mean pressures are different, the SPD% will always be higher for the seat cushion with the lower pressure. This is certainly counter to our intuition – if SPD% can be used to predict subjective ratings, it should be lower for the cushion with lower pressure, all other things being equal. In the next section, we show that the SPD% does not show a significant difference in the road data overall, and it seems that the problem discussed above with SPD% is accounted for by aPcrms.

5.2 Dynamic Pressure Maps

Dynamic pressure maps were sampled in 10-second blocks at 30 frames per second after every 10 minutes of driving. Sixteen measures were calculated for each data block, as summarized in Table 5-2. These measures were then used to evaluate seat performance during each driving session.

First, the dynamic measures were averaged over all subjects. This gives us one time series for each of the 16 measures on each cushion. We now want to find measures that show a significant difference that outweighs the random variations in the data. The importance of these significant differences is they indicate a shift in physical characteristics between seat cushions, not random variations. Since we are looking for measures that highlight the characteristic differences between foam and air-inflated seat cushions, we can eliminate measures that do not show significant differences between the two seat cushions. To check for significant differences, we run a one-sided paired t-test on the difference between the air-inflated and foam cushions for each measure. The results for the t-tests are shown in Table 5-2. Based on this analysis, we reduced the number of measures we consider from 16 measures to 6 measures that show significant differences. This leaves us with 6 measures that show characteristic physical differences between seat cushions.

Table 5-2. Significant objective differences between seat cushions during road test

		measure	units	difference (air - foam)	p-val
Time-Related	1	**aPcrms**	*lbf/s*	-7.17	0%
	2	**Area 1**	*in* ^{2}	-2.53	1%
	3	**Area 2**	*in* ^{2}	-2.89	0%
	4	**Area 3**	*in* ^{2}	-1.45	8%
	5	**Area 4**	*in* ^{2}	-0.29	39%
	6	**Pcrms 1**	*lbf/s*	0.02	49%
	7	**Pcrms 2**	*lbf/s*	-0.01	50%
	8	**Pcrms 3**	*lbf/s*	-0.16	44%
	9	**Pcrms 4**	*lbf/s*	-0.09	47%
Means	10	**Mean SPD%**	-	-0.03	49%
	11	**Mean Pressure**	*psi*	-0.05	48%
	12	**Mean Area**	*in* ^{2}	6.36	0%
	13	**Mean COPx**	*in*	1.45	0%
	14	**Mean COPy**	*in*	0.16	35%
Standard Deviations	15	**St Dev COPx**	*in*	-0.01	49%
	16	**St Dev COPy**	*in*	0.00	50%

This analysis highlights several significant differences. First notice that aPcrms is significantly higher for the foam cushion. The increase is about 8%. Considering the components that go into the aPcrms calculation (items 2 to 9 in Table 5-2), we see that all four areas and all four averaged Pcrms values for aPcrms calculations are lower for the air-inflated seat cushion. Individually, the differences for Area 1 to Area 3 are also significant. This tells us that the areas within the 40-60, 60-80, and 80 to 100 mmHg ranges are less for the air-inflated seat cushion. The remaining components that go into the aPcrms calculation are highly insignificant, with p-values above 39%. This highlights the fact that the Pcrms in the different regions is similar between seat cushions, yet the difference in aPcrms is different because of the weighting function being applied.

Other significant differences are found in the means: contact area is 3% higher and center of pressure is about 1.5 inches further back on the air-inflated seat cushion on average.

It may also be instructive to note some of the insignificant differences. First, note that mean SPD% and mean pressure differences are highly insignificant, with p-values near 50%. This is also consistent with our static pressure maps, which said that the pressure distributions between seats are fairly consistent. Also, the lateral center of pressure difference is insignificant, and it tends to fall on the line of symmetry of the seat cushion. We also find that the standard deviations of the center of pressure differences are insignificant, which suggests that both seats hold the center of pressure similarly and provide similar pelvis stability.

Now that we have found that these 6 measures show a characteristic difference between seat cushions, data can then be further reduced by removing measures that do not carry new information. This is done by calculating the correlation on the difference between air and foam, and running a t-test on the correlation. Since we are interested in evaluating aPcrms, we found the correlation of the remaining 6 measures with aPcrms. The results of this analysis are shown in Table 5-3.

Table 5-3. Correlation of difference with aPcrms to find independent pressure measures

	Correlation	p-val
Area 1	0.60	0.0%
Area 2	0.69	0.0%
Area 3	0.70	0.0%
Mean Area	0.14	23.0%
Mean COPx	-0.25	9.7%

Based on these results, we see that aPcrms has positive correlation to 3 of the measures at 5% significance level, meaning these measures are redundant. We also found that the remaining measures that were not dependent on aPcrms, specifically Mean Area and Mean COPx, were not correlated at 5% significance (p-val = 11%). This leaves aPcrms, Mean Area, and Mean COPx as three unique measures with a significant difference between cushions. While deciding to correlate the remaining measures against aPcrms automatically makes aPcrms part of our reduced data set, since at least one measure will be independent, this decision can be made arbitrarily amongst the 6 measures. Note that the measures that were removed based on the correlation analysis were the three area components that are used inn the aPcrms calculation.

From our original set of 16 measures, this leaves us with only 3 measures that are useful to describe the characteristic physical differences between seat cushions. These three measures are plotted over time in Figures 5-3 to 5-5. First, we see that aPcrms starts out similarly in both cushions, but over time aPcrms on the air-inflated seat cushion drops below the foam cushion after Hour 2. As shown earlier in the static histogram, there is less exposure to high pressure at later times on the air-inflated seat cushion compared to the foam cushion. As there is little difference in Pcrms values over time, the reduction in aPcrms at later times is consistent with the drop in exposure to high pressure areas at later times.

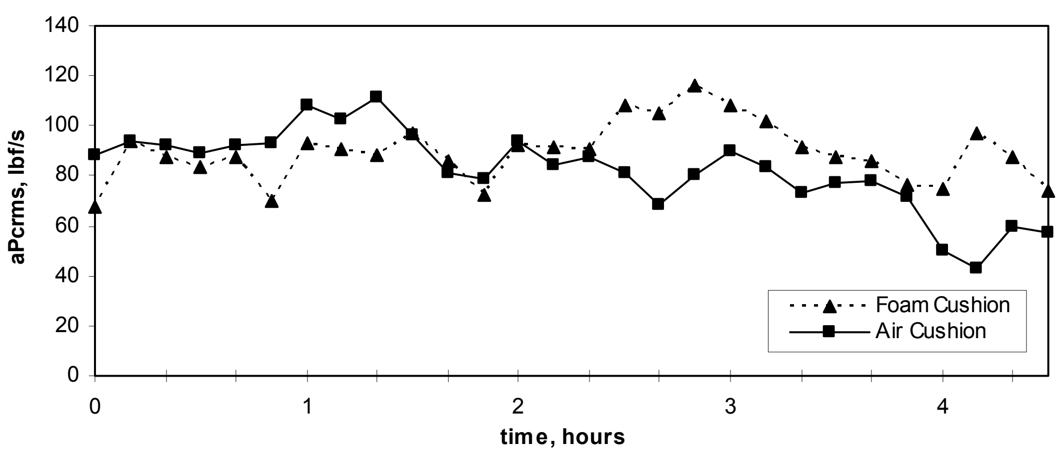

Figure 5-3. aPcrms over time

Next, we see that mean area for the air cushion starts out higher than the foam cushion, drops to about a similar level between Hours 1.5 and 2.5, and becomes higher again after Hour 2.5. This is significant because an increase in contact area causes a decrease in mean pressure for a constant applied force. This reduction in mean pressure will also reduce the exposure to higher pressure regions across the seated area, which also reduces aPcrms.

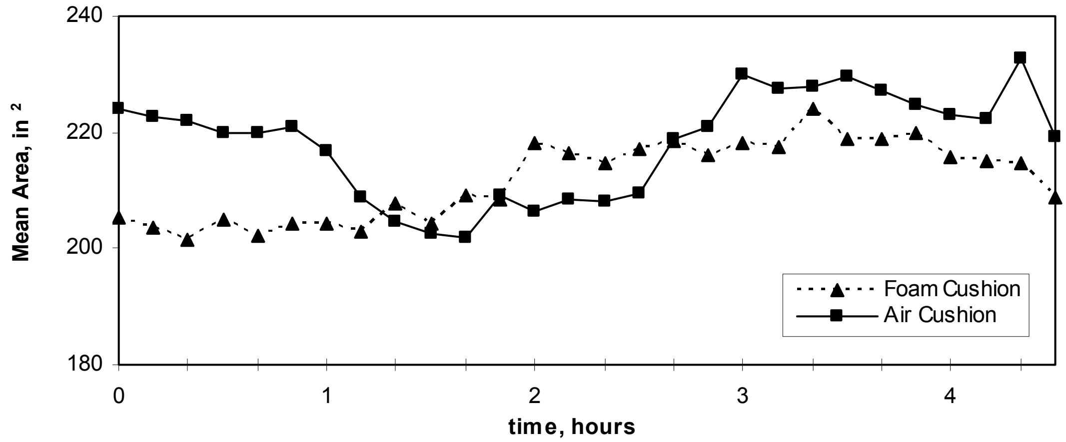

Figure 5-4. Mean Area over time

Finally, we see that the center of pressure on the air-inflated seat cushion starts further back than the foam cushion, and continues to fall further back while the foam seat cushion falls forwards while driving. This shift backwards in the longitudinal center of pressure also reflects a decreased force on the seat cushion and an increased force on the seat back. The increased force on the seat back can have good effects or bad effects, depending on the driver's physical composition and preferences. This mixed result was also reflected in the subjective data when some drivers indicated the seat back was better, and some indicated it was worse. The decrease in force on the seat cushion will also reduce mean pressure, which will act to reduce aPcrms.

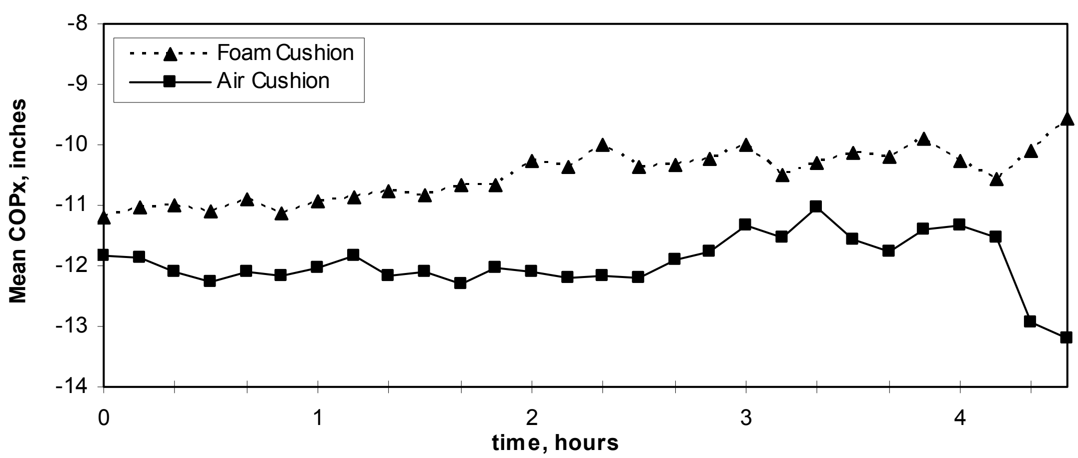

Figure 5-5. Mean COPx over time

Considering all three measures at once, we see that both mean area and center of pressure act to reduce aPcrms on the air-inflated seat cushion. This may lead one to conclude that these three measures are also redundant. However, each measure characterizes a unique aspect of the differences between the two seat cushions. Mean area considers the area that the weight is distributed over and also mean pressure, and it indicates the effect of pressure distribution on the driver. Center of pressure considers the seated position, and it indicates a change in weight distribution and posture. aPcrms considers both the differences in dynamic response and the averaged pressure distribution, and it indicates the effect of dynamics on the driver. In the case of this study, the difference in dynamic response, as described by Pcrms, between seat cushions was not significant. This makes the reduction of high pressure regions the dominant effect between seat cushions. In a study that shows significant differences in Pcrms, however, aPcrms may be a compromise between both pressure distribution and dynamic response. Thus, aPcrms is a required measure to characterize this significant difference when it is present.

The subjective data that was collected in this study was collected on an hourly basis. For future comparisons of these objective measures to the subjective data, the measures were averaged by hour. These results are shown in Table 5-4.

Table 5-4. Summary of hourly measures

	Foam Cushion			Air-Inflated Cushion		
Hour	aPcrms lbf/s	Mean Area in^2	Mean COPx in	aPcrms lbf/s	Mean Area in^2	Mean COPx in
1	81.8	204	-11.1	91.5	222	-12.1
2	88.0	206	-10.8	96.5	207	-12.1
3	100.5	217	-10.3	82.5	212	-12.0
4	91.9	219	-10.2	78.8	228	-11.4
5	83.4	214	-10.1	52.5	224	-12.2

To provide an overall summary of the road data, we found the average over all time for each measure on each cushion. We then calculated percent change for the air-inflated seat cushion, as shown in Figure 5-6. We see that overall aPcrms is 8% lower, mean area is 3% higher, and COPx is 14% or 1.5 inches further back in the air-inflated seat cushion compared to the foam seat cushion.

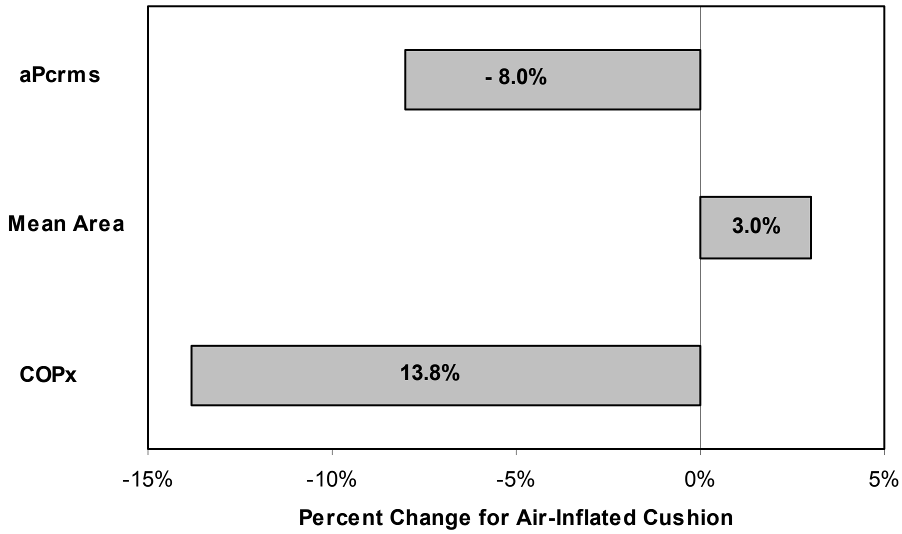

Figure 5-6. Percent change for air-inflated seat cushion

5.3 Summary of Objective Analysis

This section has summarized key objective results from our field study. From our original set of 16 dynamic measures, we eliminated measures that either did not show a significant difference or were dependent on other measures. This led us to a reduced set of measures to consider: aPcrms, mean area, and longitudinal center of pressure. For the air-inflated cushion, on the average, we found aPcrms to be 8% lower, mean area to be 3% higher, and the center of pressure to be 13.8% further back, as compared to the foam cushion.

The next step will be to compare these objective results against the subjective results reported previously and use this comparison to assess the capacity of the proposed measures to evaluate subjective performance.

Chapter 6
Field Test Results: Combined Analysis

This section highlights the relationships between subjective and objective data. The comparison proceeds by answering the following questions:

1. Subjective Response: Was the response to one seat cushion more favorable than the other? If so, do we have subjective data to support it?
2. Objective Measures to Support Subjective Response: Are there physical measures that agree with the subjective test data? If so, what data supports it?
3. Relationship between Subjective Response and Objective Measures: Using the metrics that best agree with the subjective data, can one claim that there exists a statistical correlation between the subjective and objective data? Why?
4. Improved Experimental Design: What approach is needed to enable one to establish this statistical correlation between subjective and objective data? How should future tests be conducted? What are the challenges?

This analysis summarizes much of the analysis performed in the two previous sections on subjective and objective data analysis, where needed to answer the above questions. The analysis also uses correlation analysis between subjective ratings and relevant objective measures to establish some dependence between the objective and subjective measures and considers how one may improve experimental designs in future tests to further improve results.

6.1 Subjective Response

The overall subjective response was more favorable toward the air-inflated seat cushion. When asked “which seat would you prefer to drive on?”, 10 out of 12 drivers said they preferred the air-inflated seat cushion, while the remaining two were opinion-neutral.

When asked to list their specific likes and dislikes of the air-inflated seat cushion, drivers said they preferred the comfort of the air-inflated seat cushion and the ability to adjust; they disliked the difficulty of making adjustments, seat height, and difficulty of getting in and out; and they were split on their opinion of back support.

When asked to compare the air-inflated seat cushion with their regular truck seat in a series of questions, all individual ratings were neutral or favorable, except for two. In addition, all the average ratings were between 5 and 6, which favors the air-inflated seat cushion.

In the test drive surveys that were taken within 10 minutes of driving on each seat cushion, 11 of 12 drivers rated air-inflated seat cushion comfort favorably, and 9 of 12 drivers rated air-inflated seat cushion support favorably, while 3 drivers rated support only slightly worse. Also, the comfort and support scores for the air-inflated cushion were better than for the foam seat cushion.

In the road surveys that were taken after each hour of driving, the air-inflated seat cushion offers significant improvements in comfort for all times and in fatigue for all but Hour 3. In addition, the support score on the air-inflated seat cushion is also better for all time. In addition, the average comfort, support, and fatigue scores are better for the air inflated seat cushion. Overall, we observed:

- 18% improvement in Comfort Score
- 56% improvement in Support Score
- 14% improvement in Fatigue Score

6.2 Objective Measures to Support Subjective Response

In the previous section, we have shown that the air-inflated seat cushion shows significant improvements in terms of subjective ratings of comfort, support, and fatigue. This section highlights the objective differences between the foam seat cushion and the air-inflated seat cushion. Since the major physical difference between these two types of seat cushions is the pressure distribution at the body-seat cushion interface, it follows that any significant change in subjective rating would be related to a significant change in the measures used to summarize the pressure distribution. Therefore, we should see differences in pressure measures that highlight the characteristic differences between the two seat cushions, which cause the difference in subjective rating.

In the static data, we see that the contact area is larger in the air-inflated seat cushion, and the center of pressure is further back. We also see that after driving, the mean pressure is lower in the air-inflated seat cushion, and the SPD% is higher.

In examining the road data, we observe 6 significant differences for the air-inflated seat cushion compared to the foam seat cushion:

- aPcrms is lower
- Area 1 is lower
- Area 2 is lower
- Area 3 is lower
- Mean Area is higher
- Mean COPx is further back

This shows that aPcrms is more favorable for the air-inflated seat cushion, and this difference is caused by a reduction in the areas with 40-60 mmHg, 60-80 mmHg, and 80-100 mmHg pressures. This indicates that the air-inflated seat cushion would promote better blood flow to the tissue in the seated area. The reduction of area in these higher pressure regions is caused by a larger contact area, which allows for lower pressures over the seated area. There is also a significant difference for the longitudinal center of pressure, where it is further back for the air-inflated seat cushion. This is perhaps due to a difference in contouring, where the body's weight is shifted further back on the seat cushion. It is also useful to note that the force on the seat cushion is reduced for the air-inflated seat cushion by 6 pounds on average, indicating that the weight is being shifted more into the backrest. As weight is being shifted onto the backrest, the contouring of the backrest becomes a more important factor, and this may have some effect on subjective performance. Since this particular backrest was not considered as part of the seat cushion design, the increased weight on the backrest may have positive or negative effects, which was also reflected in our mixed subjective opinions for the back support.

On further consideration of the road data, we see that only 3 out of 6 of these measures are linearly independent, meaning that 3 measures carry redundant information. Since we are interested in considering aPcrms, we also consider the two measures that are independent to aPcrms, specifically Mean Area and Mean COPx. This correlation eliminates the three areas used in aPcrms calculation. For the air-inflated seat cushion, we find that aPcrms is 8% lower, Mean Area is 3% higher, and COPx is 14% further back on the seat cushion.

6.3 Relationship between Subjective and Objective Measures

This section considers the relationships between subjective ratings and relevant objective measures to establish some dependence between the objective and subjective measures. First, we tabulate the reduced hourly subjective scores and objective measures, as shown in Table 6-1. The subjective and objective measures are then plotted against each other, as shown in Figure 6-1.

Table 6-1. Subjective and objective scores

Subjective Data, Foam Cushion

	H0	H1	H2	H3	H4
Comfort	4.6	4.4	4.3	4.5	3.9
Support	0.63	0.51	0.92	1.44	2.50
Fatigue		1.7	1.8	1.9	1.7

Objective Data, Foam Cushion

	1	2	3	4	5
aPcrms, lbf/s	81.8	88.0	100.5	91.9	83.4
Mean Area, in^2	204	206	217	219	214
Mean COPx, in	-10.7	-10.4	-9.9	-9.8	-9.7

Subjective Data, Air Cushion

	H0	H1	H2	H3	H4
Comfort	5.7	5.5	5.4	4.7	4.3
Support	0.23	0.38	0.23	0.28	1.54
Fatigue		1.3	1.5	1.9	1.4

Objective Data, Air Cushion

	1	2	3	4	5
aPcrms, lbf/s	91.5	96.5	82.5	78.8	52.5
Mean Area, in^2	222	207	212	228	224
Mean COPx, in	-11.7	-11.7	-11.6	-11.0	-11.8

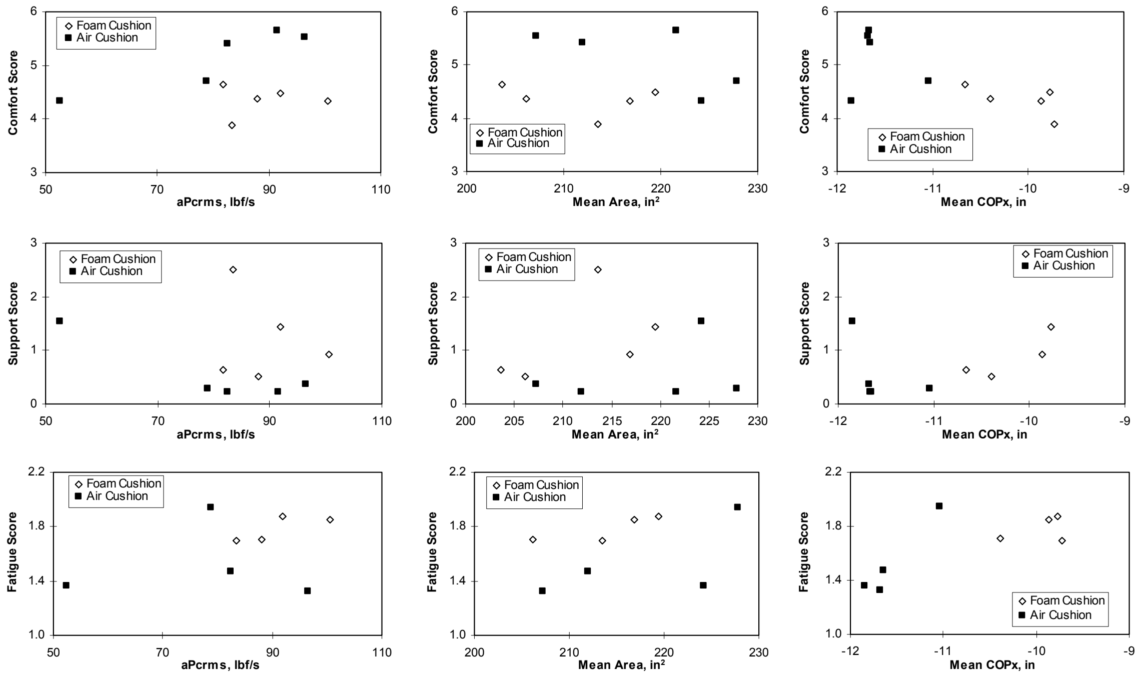

Figure 6-1. Plots of objective and subjective scores

Before performing the correlation analysis, it is important to note that the correlation analysis needs to be carried out on the relative response between the two seat cushions, and not on the absolute response. These two different types of correlations are shown in Figure 6-2. From a standpoint of the hypothesis test that is performed, it requires tall the X values and Y values to be independent and identically distributed. First, notice that two samples taken from the same subject will not be independent. Second, we have already shown that the means for the two seat cushions are not the same, so they are not identically distributed.

From a practical standpoint, since we have already shown that there are significant differences between seat cushions in all three objective and subjective measures that we are using, we know that there is a significant difference in the means of the data between seat cushions. Since there is a significant shift on both axes, the data will be distributed about two distinct points – one around the mean of the foam cushion and one around the mean of the air-inflated cushion, as shown in Figure 6-2a. Since the magnitude of the correlation between two distinct points is always one, any absolute correlation of this data will be artificially high. For example, consider the Fatigue-Mean COPx plot in the lower right corner of Figure 6-1. As we have shown previously, Fatigue is higher and Mean COPx is further back in the air-inflated seat cushion. Since there are significant differences along both axes, the absolute correlation calculation will tend to treat the data as being centered at the mean values, which have been shown to be distinct points. This will provide artificially high correlations.

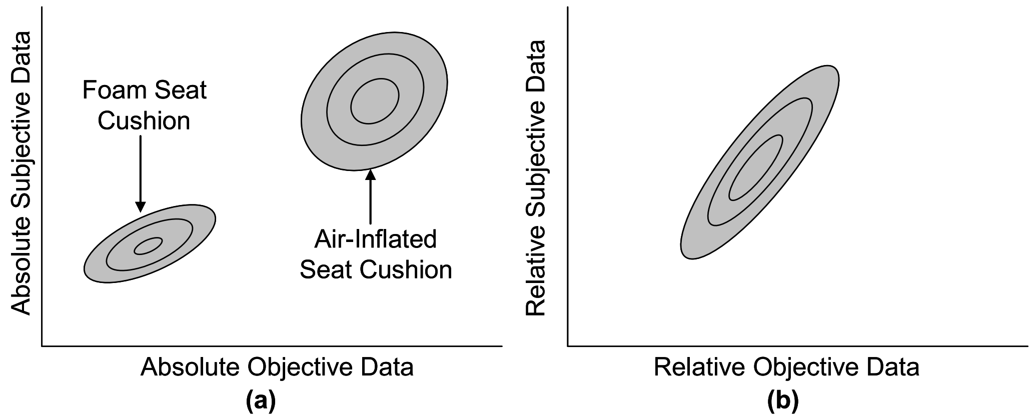

Figure 6-2. Correlations of objective and subjective data: (a) absolute data correlation, (b) relative data correlation

This means that we cannot perform correlation to see if, on average, a change in subjective rating will correspond to a change in objective measure. The weakness in performing the correlation using the relative data is that any mean effect between seat cushion is treated as a constant and is lost. If the mean effect dominates and the remaining effect of changes in relative data is small, the subjective response may not be able to follow the small changes in objective data within cushions. This will cause correlations within the relative data to be weak, despite a significant difference in the means. Based on this argument and the significant effect of the seat cushion, some of the correlations that we find for the relative data should be expected to be low.

This weakness also prevents analysis that could be used to find more suitable weighting factors for aPcrms. If we assert that the mean effect is valid and the relative effect is less valid, we do not have enough means to perform a regression analysis between the components used to find aPcrms and subjective performance. This analysis would include a mean and at least four coefficients, requiring more than 5 data points to draw any conclusions on the validity of the adjusted coefficients.

This problem with correlation and with fitting weighting factors can be circumvented by a different experimental design, where there are more than two seat cushions tested. This alternative and its difficulties will be discussed as part of Question 4.

In our case, we will first report the mean effects to show the direction of the trend of objective vs. subjective data between seat cushions. This will show the trend between the means of the data, before the means are removed in the relative data. Notice that this cannot be considered a statistical correlation, because the mean effects were all found to be significant, and the data will appear like two distinct points. Next, we will perform a correlation of the difference between the air-inflated data and the foam data, which effectively takes out the mean effect of the change in seat cushion. This can be viewed as the rating of the air-inflated seat cushion relative to the foam seat cushion. This will tell us if a relative (but not absolute) increase in the subjective data is related to a relative change in the objective data.

We summarize the average reduced objective and subjective data for both seat cushions in Table 6-2. This allows us to observe the relationships between the means of this data. First note that comfort score increases, while support score and fatigue score decrease on the air-inflated seat cushion. This implies that the air-inflated seat cushion would provide improvement in subjective ratings for all three categories. While subjective ratings improved on the air-inflated seat cushion, aPcrms decreased, Mean Area increased, and Longitudinal Center of Pressure fell further back on the air-inflated seat cushion.

Table 6-2. Comparison of means for objective and subjective data

		units	Foam Cushion	Air Cushion	Increase for Air Cushion	% Increase for Air Cushion
Objective Measures	aPcrms	*lbf/s*	89.5	82.4	-7.1	-8%
	Mean Area	*in*^{2}	211.8	218.2	6.4	3%
	COPx	*in*	-10.1	-11.6	-1.4	-14%
Subjective Ratings	Comfort	-	4.3	5.1	0.8	19%
	Support	-	1.2	0.5	-0.7	-58%
	Fatigue	-	1.8	1.5	-0.3	-17%

Since the major physical difference between these two seat cushions is the pressure distribution at the body-seat cushion interface, it follows that any significant change in subjective rating would correspond to a significant change in the measures used to summarize the pressure distribution. This indicates that some of these objective measures may have a significant effect on the subjective ratings. As shown previously, the decrease in aPcrms is due to a reduction of areas in the 40-100 mmHg range. Since these pressures are critical to blood flow to the surrounding tissue, a lower area exposed to these pressure ranges indicates better blood flow. Notice that these mean effects agree with our concept that an increase in aPcrms will improve subjective performance.

Similar to aPcrms, an increase in contact area would correspond to lower pressures and improved blood flow. Finally, a shift backward in the longitudinal center of pressure indicates that the seat cushion either allowed or encouraged a posture that placed more weight on the back support, which may be beneficial for this particular seat design.

Next, we take the correlation over time of the difference in objective and subjective measures. At 5% significance level, we find a Support-aPcrms correlation. At 25% significance (note this is not a strong conclusion), we also find a Support-aPcrms, Fatigue-Mean Area, Support-Mean COPx, and Fatigue-Mean COPx correlation.

To consider these relationships in finer detail, correlations were performed for each hour over each subject's responses. This analysis may reveal time trends not seen in earlier analysis of the overall time correlation. The findings of this analysis has been summarized by tabulating all correlations found significant at 15%, as shown in Table 6-3. For both hours 1 and 2, we observe that Fatigue-Area is correlated at 10% significance level. For Hour 3, we observe that Comfort-COPx at 10%; and Comfort-aPcrms and Fatigue-aPcrms at 15%.

Table 6-3. Summary of relative correlation results

Correlation	Overall	Hour 1	Hour 2	Hour 3
Comfort – aPcrms	x	x	x	r_{xy} = - 0.56 p-val = 12 %
Comfort – Area	x	x	x	x
Comfort – COPx	x	x	x	r_{xy} = - 0.75 p-val = 4 %
Support – aPcrms	r_{xy} = 0.79 p-val = 6%	x	x	x
Support – Area	x	x	x	x
Support – COPx	x	x	x	x
Fatigue – aPcrms	x	x	x	r_{xy} = - 0.55 p-val = 13 %
Fatigue – Area	x	r_{xy} = - 0.48 p-val = 6 %	r_{xy} = - 0.43 p-val = 9 %	x
Fatigue – COPx	x	x	x	x

This summary suggests several relationships between these relative objective and subjective measures. First, consider Mean Area. Fatigue shows some relationship to Mean Area during hours 1 and 2. In both cases, the correlation were negative, indicating an increase in Relative Mean Area corresponds to improved (decreased) Relative Fatigue Score. These results follow our concept that an increase in aPcrms will improve subjective performance and are consistent with the trend in the mean effects.

Next, consider longitudinal center of pressure (COPx). We see a negative correlation with comfort, indicating that as Relative COPx moves further back (decreases), Relative Comfort improves (increases). Finally, consider aPcrms. Comfort, Support, and Fatigue show some relation to aPcrms. During Hour 3, Comfort and aPcrms show a negative correlation; indicating that a decrease in Relative aPcrms improves Relative Comfort Score improves (increases). On the overall correlation, Support and aPcrms are positively correlated; indicating a decrease in Relative aPcrms improves (decreases) Relative Support Score. These results are consistent with the trend for the mean effects.

A potentially confusing and unexpected result occurs between Fatigue and aPcrms during Hour 3 – as Relative aPcrms increases, Relative Fatigue improves. While this is counter to our concept that decreased aPcrms improves subjective feedback, this result points out the characteristic weakness of the relative correlation mentioned earlier – it neglects the mean effects. Earlier, we had noted that the subjective fatigue rating improved (decreased) on the air-inflated seat cushion, and aPcrms also decreased. Based on this mean information alone, we would think there exists a positive correlation, which supports our motivation for using aPcrms. The relative correlation, however, is negative. This either represents a complex interaction in the relationship between human fatigue and aPcrms or it indicates that the drivers were unable to differentiate anything but the mean effect. Based on our sample size and the expected ability of the drivers to assess a fatigue rating, we would have to conclude the latter – drivers were often unable to assign a relative change in aPcrms to a relative change in Fatigue.

6.4 Improved Experimental Design

While performing correlation analysis on the relative objective and subjective data is necessary to prevent overestimated correlations, it effectively neglects the mean effect of the seat cushion. If the mean effect dominates, and the remaining effect of changes in relative data is small, the correlations within the relative data may be weak, despite a significant difference in the means. Based on this argument and the significant effect of the seat cushion, some of the correlations that we found for the relative data should be expected to be low.

One then may ask, "Is there a better experimental design, allowing us to find relationships between mean effects?" This would allow us to see if a change in seat cushion characteristics directly correlates to a change in subjective performance on an absolute basis, and avoid the weaker relationships formed by considering relative data.

The answer is that there is an experimental design that accounts for this – testing on three or more seat cushions, as shown in Figure 6-3. In fact, for the purpose of drawing conclusions on the effect of objective measures on subjective performance, this is the ideal design. This avoids the problem of doing an absolute correlation with only having two seat cushions, so we avoid the strength of relationship that can be lost using a relative correlation. By considering the mean effect of the seat cushion as part of the correlation, we strengthen the relationship and observe the trend we wish to find.

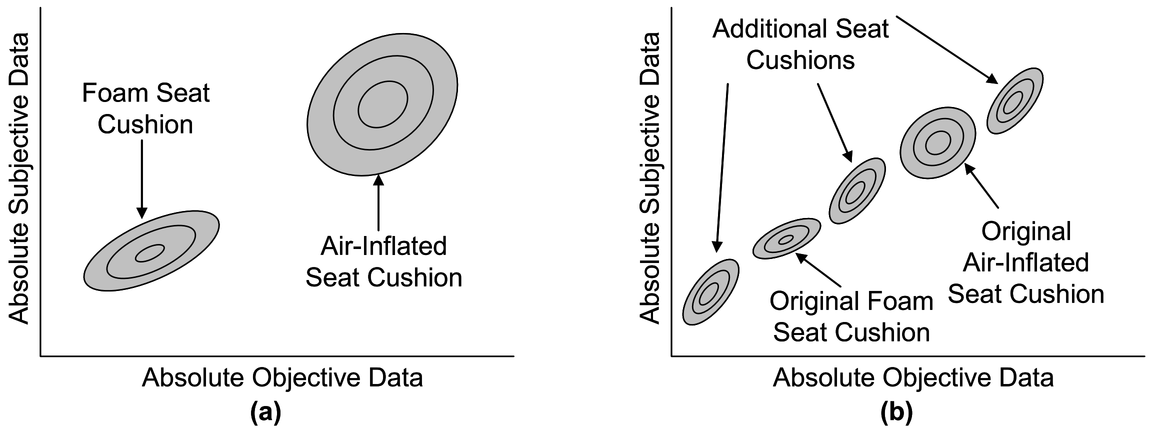

Figure 6-3. Effect of experimental design on absolute correlation: (a) this study, (b) ideal design

As mentioned earlier, an absolute correlation with our present experimental design is not possible, because the mean seat cushion effects are significant. This causes the data to look like two points, as shown in Figure 6-3a, which causes an artificially high correlation. This forces us to consider a relative correlation which neglects these strong mean effects. To avoid this problem, we must alter our experimental design. For example, say we modified this experimental design to include three additional seat cushions, and we found the data to be distributed like 6-3b. Now, the data will center around five different means, so the data will no longer automatically look like a straight line. If we performed an absolute correlation with data that was distributed like this, we would find a strong positive correlation due to the means, and it would be more valid than in our original experimental design.

The previous argument clearly highlights the benefit of using three or more seat cushions. The natural question then becomes, "why isn't this design used?" The reason is a practical one – it greatly increases the effort to conduct a study of the same scale. When increasing complexity of the experimental design, it is important to maintain a sufficient sample size.

For example, consider our experiment, where drivers ride on one seat cushion for half of their shift, then ride on the other seat cushion for the other half of their shift. Since the drivers' shifts are about 10 hours, this allows for about 10 hours of road testing on each seat cushion, which is reasonable for a fatigue study. This gives the drivers a back-to-back comparison of the two seat cushions, allowing for good relative comparisons. If we chose to move to three or more seat cushions, we would have to do one of the following:

1. Test three cushions in one shift and reduce the time on each seat cushion to about 3 hours,
2. Test three cushions in one shift and increase the daily drive time to about 12-15 hours, or
3. Test three seat cushions on different shifts.

None of these three options seems preferable. The first option would give too short of a length for a fatigue study. The second option requires an uncommon, unsafe, and illegal number of commercial driving hours. In addition, the first two options require the driver to compare three different seat cushions during the course of the day instead of only two. The third option allows for a suitable test length, but it requires the driver to compare seat cushions a day or more after riding on previous seat cushions. This can cause loss of information and a poor relative comparison. In addition, the second and third option increase the time required to collect the same amount of data. The complexity of this alternative design is further complicated when more than three seat cushions are used.

The fundamental problem of collecting data in a fatigue study at a level necessary for rigorous statistical analysis is a matter of effort required and validity of subjective comparisons. Testing on each seat cushion requires at least four hours of testing, which makes it difficult to collect data on three or more seat cushions during one day. This leads to testing on separate days, but since the test sessions will be separated by a day or more, the drivers will not have a direct reference to the previous seat cushions, which may cause invalid relative subjective performance.

After considering the advantages of each design, we recommend either the design we used in our study or using three or more seat cushions on different (ideally sequential) days. We say this with the reservation that if the experimenter feels that the error introduced by not having a back-to-back comparison is significant, then they should pursue our experimental design. If the experimenter feels this effect is less important, several seat cushions should be added to see if there exists a correlation when including mean effects. Since we have already observed a significant difference in aPcrms between the two seat cushions used in our study, the additional seat cushions should be added such that the aPcrms values for the test seat cushions show about equal spacing to provide stronger conclusions.

Chapter 7
Conclusions and Future Research

This section presents conclusions based on the preceding analysis and recommendations for future research in the field of evaluating subjective performance in commercial vehicles.

7.1 Conclusions

This report summarized the work to validate two newly proposed measures in the context of a realistic field study. A series of road tests were performed using commercial truck drivers in the daily operations of a revenue service fleet. Drivers were asked a series of questions to assess subjective performance of the vehicle environment, and pressure distribution measurements were collected throughout each test session. This data was then analyzed to assess the validity of two newly proposed measures to evaluate subjective ratings of driver fatigue. The results highlight the advantages of using these measures to evaluate the fatigue performance of distinct types of seat cushions – namely foam and air-inflated seat cushions.

The overall subjective response was favorable to the air-inflated seat cushion. When asked which seat they would prefer to drive on, 10 out of 12 drivers said they preferred the air-inflated seat cushion, while the remaining two were opinion-neutral. Overall, we observed 18% improvement in Comfort Score, 56% improvement in Support Score, and 14% improvement in Fatigue Score.

Based on our results, we found air-inflated cushions to offer advantages in comfort, support, and fatigue. The increased adjustability in an air-inflated cushion leads to an improved ability to accommodate diverse populations of drivers. In spite of some complaints by drivers about more difficulty in getting in and out and adjusting the Even air-inflated cushions, they were preferred over foam cushions. Air-inflated seat cushions naturally offer advantages over foam cushions, which with an improved design for getting in and out and adjusting the seat cushion, along with increased industry awareness to the benefits of air-inflated seat cushions, they should become a popular alternative to standard foam seats in the future.

Since the major physical difference between these two seat cushions is the pressure distribution at the body-seat cushion interface, it follows that any significant change in subjective rating would correspond to a significant change in the measures used to summarize the pressure distribution. From our original set of 16 dynamic measures, we eliminated measures that either did not show a significant difference or were dependent on other measures. Six significant differences were found in the road data for the air-inflated seat cushion compared to the foam seat cushion:

- aPcrms is lower (better)
- Area 1 is lower (better)
- Area 2 is lower (better)
- Area 3 is lower (better)
- Mean Area is higher (possibly better)
- Mean COPx is further back (mixed effect)

We also found only 3 out of 6 of the above measures were independent. This led us to a reduced set of measures to consider: aPcrms, Mean Area, and longitudinal center of pressure. On the air-inflated cushion, we found aPcrms to be 8% lower, Mean Area to be 3% higher, and the center of pressure to be 1.5 inches further back compared to the foam cushion on average. Also note that there is no significant difference in SPD%, reflecting this measure is not a significant contributing factor in the subjective ratings between these seat cushions, although it may be important in other cases.

This shows that aPcrms is more favorable for the air-inflated seat cushion, and this difference is caused by a reduction in 40-60 mmHg, 60-80 mmHg, and 80-100 mmHg pressure ranges. Because lower pressures created by the air-inflated cushion, it promotes better blood flow to tissue in the seated area. The reduction of area in higher pressure regions is caused by a larger contact area, which allows for lower pressures over the seated area. There is also a significant difference in the longitudinal center of pressure, where it is further back in the air-inflated seat cushion. This is perhaps due to a difference in contouring, where the body's weight is shifted further back on the seat cushion.

We then compared the mean effect of objective and subjective data for both seat cushions in Table 7-1. This allows us to observe the relationships between the means of the data. As noted earlier, the air-inflated seat cushion caused an improvement in subjective rating for comfort, support, and fatigue. While subjective ratings improved on the air-inflated seat cushion, aPcrms decreased, Mean Area increased, and Longitudinal Center of Pressure fell further back on the air-inflated seat cushion. We also considered the correlation of the relative objective, and subjective data, but since the data was dominated by the mean effect of the seat cushion, the small changes of subjective and objective data on an individual seat cushion showed weaker results that were less conclusive.

Table 7-1. Summary of means for objective and subjective data

		units	Foam Cushion	Air Cushion	Increase for Air Cushion	% Increase for Air Cushion
Objective Measures	aPcrms	*lbf/s*	89.5	82.4	-7.1	-8%
	Mean Area	*in^2*	211.8	218.2	6.4	3%
	COPx	*in*	-10.1	-11.6	-1.4	-14%
Subjective Ratings	Comfort	-	4.3	5.1	0.8	19%
	Support	-	1.2	0.5	-0.7	-58%
	Fatigue	-	1.8	1.5	-0.3	-17%

We then considered alternative experimental designs, where three or more seat cushions must be tested. This design is needed to establish a correlation with data dominated by the mean effect. The challenges involved in implementing these designs are then discussed. Despite these alternatives, we feel that our original experimental design is favorable to maintain valid relative subjective responses between seat cushions.

Based on these results, we find that aPcrms and Mean Area best highlight the advantages of the air-inflated seat cushion. The lower aPcrms for the air-inflated seat cushion causes better blood flow to tissue in the seated area. The reduction of pressure in higher pressure regions is due to an increased contact area on the air-inflated seat cushion. This result is consistent with uniform pressure distribution theory, as evident by the agreement between increased contact area and improved subjective ratings. From a standpoint of mean pressure tolerance theory, this suggests the pressures experienced in this study are largely below the critical pressures.

Lateral center of pressure on the seat cushion was significantly farther back on the air-inflated seat cushion, which corresponded to more weight placed on the backrest. Since the seat cushion was not specifically designed for this particular backrest, the added weight on the backrest may cause mixed results. This was reflected in our subjective results that show back support was better for some subjects and worse for some others. Since the seat cushion was the only varied element in the experimental design, the seat cushion contours must place different loading on the back support, perhaps due to pelvis alignment. This loading is favorable for some subjects and unfavorable for other subjects based on their physical characteristics and preferences.

We also found the difference in SPD% to be insignificant in our road tests. This suggests that SPD% is either not a significant predictor of subjective response or was not as critical of a measure as aPcrms and Mean Area for this study.

7.2 Recommendation for Future Research

While this study has been a significant effort towards validating two objective measures for evaluating fatigue, it still leaves many questions unanswered. One area of future research has been proposed as a future phase to this project. This would include a longer-term field study, where various seat cushions are used in long-haul trucking. Drivers would drive on various seat cushions over a period of several weeks, and after this period, surveys and objective measures would be collected over a longer time period than used in this study.

In order to develop more reliable methods of evaluating driver fatigue in commercial vehicles, a larger-scale study would be needed, similar to the alternative experimental design discussed in Chapter 6. This would require about 5 different seat cushions with various compositions, to give a wide range of objective measures. This database could then be used to perform regression analysis to improve existing measures and create new measures based on the vehicle response.

Studies should also consider measures of the human response. These measures both serve to better understand how fatigue manifests itself in human response in terms of measurable quantities, and also provide a basis for designing fatigue monitoring devices which can be used to warn drivers when they are fatigued.

One important result that should be considered in future studies is the fact that the mean objective value on the seat cushion was the most significant effect, not the individual differences. This suggests that the individual subject objective measurements are less significant, and a good estimate of the subjective performance could be found by the average objective ratings for the test population. If we neglect the individual variances between subjects, and only consider the mean on each seat cushion, this tells us that a subjective rating could be predicted with a very small number of objective data. Moreover, if one could develop a dummy that would be consistent with the average objective response, the subjective performance could be predicted with a series of simple laboratory tests.

Another important result is differences between seat cushions that may not be present at earlier times may dominate response at later times. In our objective data, we showed that the pressure distributions before driving were similar for both seat cushions. While the air-inflated cushion maintained a similar pressure distribution throughout driving, the pressure distribution for the foam seat cushion degraded while driving, with greater occurances of high pressure ranges. Other measures, such as aPcrms, mean area, and lateral center of pressure also showed greater differences over time. This suggests a very important issue on how seat cushions are tested in a laboratory or modeling environment. While earlier pressure data would suggest comparable performance between seat cushions, later data clearly indicates the advantages for the air-inflated seat cushion. To capture this information, tests must consider the pressure distribution and how it changes in a dynamic environment over time.

Studies have been conducted to develop indenters that are consistent with human subjects in terms of different physical measures [36]. To develop an indenter that can be used to evaluate fatigue characteristics of seat cushion, the indenter would need to reliably predict the validated measures developed from field studies.

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Appendix A: Seat Cushion User Instructions

Fleet Maintenance of ROHO Air-Inflated Seat Cushions

Provided for Drivers and Maintenance at Averitt Express Greensboro
Revised 2/26/04

Scope

This document provides instructions for fleet maintenance of a retrofit ROHO Air-Inflated seat cushion to replace an existing foam cushion on a National truck seat. The procedure describes installation and driver adjustments of the ROHO cushion.

Installation

This section describes the procedure for installing the ROHO cushion

Recommended Tools and Hardware

Remove Foam Seat:

- 3/8" Socket, Drive, and Extension Bar

Install ROHO Seat:

- 7/16" Socket, Drive, and Extension Bar
- 5/32" Allen Key
- 9/16" Open End Wrench
- 7/32" Allen Key
- Needle-Nose Pliers

Directions

- Rotate up foam seat
- Remove 4 screws in seat front mounting bracket and remove seat from truck (3/8" Socket, Drive, and Extension Bar)
- Keep mounting brackets for use on ROHO seat
- Screw screws into foam seat cushion for storage
- Untie seat cover on ROHO seat cushion and disconnect the Velcro holding the Plexi-glass base to the seat cushion

- Use the provided bolts and nuts to attach the first two sets of holes in the Plexi-glass seat base to the seat using the mounting bracket from the foam seat cushion (7/16” Socket, Drive, and Extension Bar; 5/32” Allen Key)
- If the air regulator interferes with the truck seat when the Plexiglass base is turned down onto the truck seat, use the slot in the air regulator mount to adjust it (9/16” Open End Wrench; 7/32” Allen Key)
- Disconnect the splice to the truck seat air supply behind the truck seat (Needle-Nose Pliers)
- Connect the T-connection that is attached to the seat’s air supply line in place of the splice you just removed
- Line up the seat cushion to the seat base and Re-Velcro them together
- Make sure that the air cells are not folded over and all the parts of the seat are sitting naturally on the foam base
- Re-cover the seat and tie the seat cover under the seat
- Make sure that the seat cover isn’t bunched up or have any folds in it
- Rotate down the ROHO seat cushion

Driver Adjustments

The ROHO Retrofit Air-Inflated Seat Cushion uses pockets of air to better contour to the drivers seated area reduce high pressure areas more than a standard foam seat. However, in order to see the advantages of these seats, they must be properly adjusted for each driver.

Many drivers will initially complain that it doesn’t fit them right, or that the pressure in certain sections is too high, such as the front or sides of the thighs. Several driver adjustments can be made to alleviate some of these complaints. The next sections explain how the seat can be adjusted so that it fits the driver’s preferences, details of the seat anatomy, and how to troubleshoot several common driver complaints.

Directions

- Make sure seat is installed properly and the seat cover isn’t bunched up
- Push red knob forward on right side of seat to let out some air in the front and sides
- When you are comfortable with the air level, push the red knob backward about ¼” to close the valve
- Adjust seat suspension height, front/back adjustment, seat back tilt, and experiment with different air settings to find the best settings for you

Seat Anatomy

This section describes the construction of the ROHO seat cushion. The ROHO Seat Cushion has 5 separate sections of air cells: front, back, left, right, and center, as shown in Figure A-1.

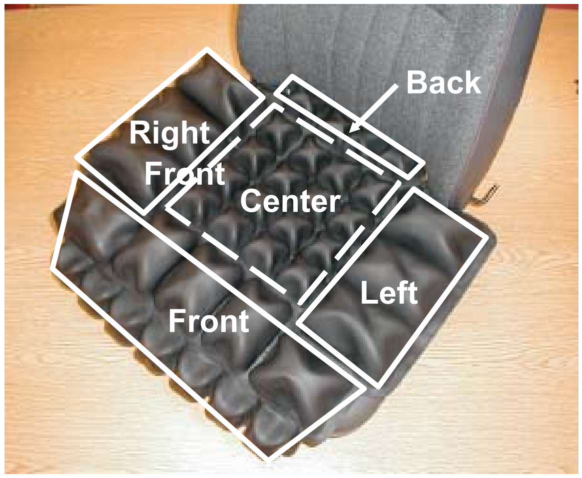

Figure A-1. Sections of Air Cells in ROHO Seat Cushion.

All 5 sections are filled with air from the seat's main air supply; however, the 4 sections on the outside of the seat cushion (front, back, left, and right) can be closed off by shutting the valve (push backward) on the right of the seat. The center section is not affected by the valve, and is always connected to the pressure regulator to maintain a constant pressure in those cells.

The air pressure in the seat's air cells can be adjusted through the valve located on the right side of the seat cushion. To release air from the outside 4 sections and deflate the air cells, the valve must be opened. When the preferred air pressure is reached, the valve needs to be closed, which locks off those air cells.

To close the valve, push the red stem all the way back, as shown in Figure A-2. To open the valve, simply pull the red stem forward about half an inch.

Figure A-2. ROHO Cushion Air Valve.

With the seat empty and the valve open (pushed forward), the air cells will fully inflate. When the driver sits on the seat, some of the air to will be released from the cells. The center section will maintain a constant pressure, and the outer sections will release air as pressure is applied. Once the driver gets the right amount of air out of the seat, they should close the valve (push backward), and that will lock the pressure in the sides and front.

Troubleshooting

Some people have had complaints with the ROHO seat cushions. Most of these complaints can be taken care of with a few simple adjustments:

1. Too much pressure at the front of the seat on lower thighs

Open the valve and lean forward on the front of the seat to release some air from those cells. Close the valve and lean back. This will lock the front section of air cells with less air, and lower pressure on your thighs.

2. Seat doesn't contour well to my butt

Before sitting, open the valve and let the cells fill up. Sit down to remove air from all the cells. Leave the valve open for a while to let air out. If any of the cells in the outer sections are a problem, lean on them to remove more air. Then close the valve to lock in those cells.

Appendix B: Informed Consent

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants in Research Projects Involving Human Subjects

Title of Project: Safety Effects of Operator Seat Design in Large Commercial Vehicles

Investigator(s): Dr. Mehdi Ahmadian

I. Purpose of this Research

This study is being performed by the Advanced Vehicle Dynamics Lab (AVDL), which is part of the Department of Mechanical Engineering at Virginia Tech. We are sponsored by partners in both industry and government, who are aimed at improving truck seat design for reducing driver fatigue.

This study will be led by Dr. Mehdi Ahmadian who has extensive experience with dynamic testing and vibration testing, for a variety of applications including truck seats. Specifically, this work will include using trucks in your company's fleet in a series of road tests to measure dynamic body pressure distributions and establishing effective methods for analyzing such data and correlating it to human comfort and driver perception of ride quality. The study will take advantage of using human subjects to collect the data that will assist in establishing the correlation between the subjective and objective measures on the seat.

II. Procedures

This study will be specifically directed toward the influence of seat cushions on human comfort and fatigue. In particular, we will attempt to establish a correlation between objective data that is commonly collected on a vehicle seat by accelerometers and the human perception of the seat comfort and fatigue.

To this end, we intend to conduct a series of tests as part of your commercial fleet's daily operations that will allow us to simultaneously collect acceleration data on the seat and also get feedback from you, while you are riding on the seat, in regard to your perception of the seat comfort and fatigue induced due to riding in the seat for a prolonged period of time of up to four hours.

Each participant is asked to complete one testing session. Each session will last approximately 8-10 hours, depending on the length of your assigned route. During the testing session, you will drive on two different seat cushions, and you will also be asked to answer some simple questions rating your opinion of how the seat cushion is performing throughout the day.

About one week prior to the test session, we will install a test seat in your truck. After you have a chance to use the test seat, we will conduct the test session.

In the test session, which is expected to last 8-10 hours, we will

1. conduct an informal interview with you to answer any questions that you may have and also brief you on the upcoming session's activities,
2. ensure that you are willing to participate in the study,
3. conduct a road test where you will be driving while using the first test seat. These tests will be intended to get a feedback from you on your perception of the seat comfort, immediately after you sit on the seat and throughout the test session,
4. install a second test seat 4-5 hours into the test session and repeat step 4, and
5. wrap up the session by answering any questions you may have.

III. Risks

The risks to you as a result in participating in this study will be minimal, in the sense that the risks of harm anticipated in the proposed research are not greater, considering the probability and magnitude, than those encountered in daily life while operating a heavy truck. While this is a driver fatigue study, the 8-10 hour sessions that we will focus on will be during your regularly assigned route. Even though you are accustomed to these type of driving sessions, we realize there is a possibility that you may become too tired to continue driving, in which case we will immediately stop the test and provide you the option of excusing yourself from continuing with the study. If needed, we will assist you to recover by allowing you to rest for a while.

IV. Benefits

Although there are no direct benefits to you as a result of this study, we expect that you would benefit indirectly from this study by the improvements to truck seats that you use in your trade. Additionally, we welcome hearing from you in the future, and if you are interested to receive a copy of the final report of the study or hear more on the future direction of our research, please let us know.

V. Extent of Anonymity and Confidentiality

Your name will not be used in any reports that will be generated as a result of this study. In all such reports you will be identified only by a number. Further, you will remain anonymous to other test subjects that will participate in this study. Your identity and information will only be known to those who are directly involved in conducting this study, such as Dr. Ahmadian, the Principal Investigator of this study, and his graduate research assistants. All your information will be kept in a locked cabinet at the Advanced Vehicle Dynamics Laboratory of Virginia Tech.

VI. Compensation

We appreciate your participation in our study; however, we will be providing no monetary compensation for your time. Since your will be participating in the study as part of your regularly scheduled routes, your employer will be compensating you for your time as normal.

VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty. Furthermore, you are free not to answer any questions or respond to experimental situations that you choose without penalty.

There may also exist circumstances under which we may determine that you should not continue in this study. If such circumstances arise, you will be promptly informed and released from the study without penalty.

VIII. Approval of Research

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and the Department of Mechanical Engineering.

_______________________________ _______________________________
IRB Approval Date Approval Expiration Date

IX. Subject's Responsibilities

I voluntarily agree to participate in this study. I understand that I am responsible for following the safety procedures that are established at the Advanced Vehicle Dynamics Laboratory of Virginia Tech while I am participating in this study.

X. Subject's Permission

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

____ __________
Subject signature Date

Should I have any questions about this research or its conduct, I may contact:

Dr. Mehdi Ahmadian (540) 231-4920 / ahmadian@vt.edu
Investigator Telephone/e-mail

Dr. Walter F. O'Brien (540) 231-7183 / walto@vt.edu
Department Head Telephone/e-mail
Mechanical Engineering

Dr. David M. Moore (540) 231-4991 / moored@vt.edu
Chair, IRB Telephone/e-mail
Office of Research Compliance
Research & Graduate Studies

Subjects must be given a complete copy (or duplicate original) of the signed Informed Consent.

Appendix C: Test Session Packet

Session Code: ________________

Date: ________________________

Driver name: __________________

Start Time: ____________________

Start Mileage: __________________

The session code describes the subject and the first seat cushion tested.
The complementary session code describes the second seat cushion tested.

IDEA Program Test Session Packet

This document is intended to provide the test administrator a step-by-step procedure, including verbal instructions at certain key points in the procedure, giving each participant the same information to complete the tasks they are required to perform. It is hoped that this level of procedural detail will reduce bias or ambiguity during test sessions, which should yield results that are both more consistent and easier to interpret.

For convenience, surveys and hand-collected data may be recorded in this packet.

Contents

Installation Checklist

- Apply calibration and equilibration data to pressure pad
- Mount pressure pad to cover seat with no preloaded cells
- When driver sits on seat, make sure pad doesn't fold or bunch
- Look at pressure map for excessive number of dead or saturated cells
- Make sure the driver doesn't have bulky items in their back pockets
- Verify acquisition parameters set to 300 frames at 30 fps

Introduction and Sign Informed Consent

Hello, my name is Chris Boggs from the Advanced Vehicle Dynamics Lab (AVDL) at Virginia Tech. Thank you for agreeing to participate in our study!

The purpose of this study is to gather information from commercial truck drivers on their opinions of different seat cushions. I will be riding along with you today to take some pressure measurements as you are driving. I will also be asking you questions throughout the day so you can rate various aspects of the seat cushion. At some point during the day, we will change seat cushions and repeat the process on the other seat cushion.

Before we continue with our testing, first make sure you have reviewed and signed the attached Informed Consent document. This document explains your responsibilities and confidentiality in our study, and we are required to have you review this document and sign it before we collect any other information from you.

Ask driver to sign Informed Consent and give him/her a copy.

Driving on First Seat Cushion

Static Pressure Map (Initial)

Before you get into the cab, please remove your wallet or anything bulky from your back pockets. Please get into the cab and adjust the seat to a comfortable driving position. (*assist subject*)

Notes:

Record Seat Adjustment

Ride Height: ________

Fore/Aft: ________

Please sit stationary in a comfortable driving position with both hands on the steering wheel and your foot on the accelerator.

Collect two static pressure maps:
H0a.fsx H0b.fsx

Pre-Testing Survey

Allow driver to begin driving

Gender: ________________ Age: ________________

Weight: ________________ Height: ________________

1. Please rate the frequency you experience different levels of pain or discomfort during driving. Use a scale of 1 to 7, where 1 means “Rarely”, 4 means “About Half the Time”, and 7 means “Constantly”, or you may choose “None”.

Mild Pain/Discomfort	None 1 2 3 4 5 6 7
Moderate Pain/Discomfort	None 1 2 3 4 5 6 7
Severe Pain Discomfort	None 1 2 3 4 5 6 7

2. Rate the locations where you have pain or discomfort while driving. Use a scale of 1 to 7, where 1 means “Very Little”, 4 means “Moderate”, and 7 means “Severe”, or you may choose “None”.

Lower Back	None 1 2 3 4 5 6 7
Thighs or Legs	None 1 2 3 4 5 6 7
Buttocks	None 1 2 3 4 5 6 7

3. After how many hours of driving do you typically experience pain or discomfort?

1 2 3 4 5 6 7 8 It varies Never

4. Do you suffer from any of the following specific problems?

Numbness in thighs or legs?	Yes	No
Stiffness in your back?	Yes	No
Lower back pain?	Yes	No
Hemorrhoids?	Yes	No
Sciatic nerve pain?	Yes	No

5. Do you have any constant pain or discomfort?

___ Yes (If yes, answer follow up questions below)

Where? _______________________________________

What do you think is the source of this constant pain or discomfort?

____ Driver position or motion
____ Transportation accident
____ Overexertion in lifting
____ Road vibration
____ Trip or loss of balance without a fall
____ Fall
____ Something else, What? __________________________

___ No

6. How many hours do you spend driving in a typical day?
_______ Hours

7. How many hours do you typically drive before you get out of the truck?
______ Hours

8. How many times per day do you typically get in and out of your truck?
______ Times

9. How many years have you been a professional truck driver?
______ Years

10. What impact does back pain or discomfort have on you personally, such as missed days of work, more frequent breaks, less alert or tired, etc.

____

____

11. Did you do any heavy lifting or strenuous work within the last 3 days? _____
Explain____

12. How many hours have you worked so far
Today? _____ Yesterday? ____ The Day Before? _____

13. Are you experiencing any pains in the neck, back or legs? _____
How Long? ____
Explain____

14. Are you experiencing any muscle stiffness or soreness? _____
How Long? ____
Explain____

15. Are you taking any medications for pain? _____
How Long? ____
Explain____

16. Are you experiencing any other aches or pains? _____
How Long? ____
Explain____

“Test Drive” Survey (take at 10 minute mark)

As you continue driving, I will ask you some questions rating your opinion of how the seat is performing right now.

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
2	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
3	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
4	Overall Back	☐	☐	☐	☐	☐	☐	☐	☐
5	Ischial/Buttocks	☐	☐	☐	☐	☐	☐	☐	☐
6	Thigh	☐	☐	☐	☐	☐	☐	☐	☐
7	Cushion Lateral	☐	☐	☐	☐	☐	☐	☐	☐
8	Overall Cushion	☐	☐	☐	☐	☐	☐	☐	☐
9	Overall Seat	☐	☐	☐	☐	☐	☐	☐	☐

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
11	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
12	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
13	Seat Back Firmness	☐	☐	☐	☐	☐	☐	☐	☐
14	Cushion Firmness	☐	☐	☐	☐	☐	☐	☐	☐

Additional Comments:

Road Test: Cushion 1, Hour 1

End Time: _______________ **End Mileage:** ___________________

Take measurements 6 times per hour on 10 minute intervals.
Record seat pressure for 10 seconds at 30 fps.
Resample for any "bad" data blocks.

Pressure	*Time*	*Sample Notes*
H1a.fsx	*0-10*	
H1b.fsx	*10-20*	
H1c.fsx	*20-30*	
H1d.fsx	*30-40*	
H1e.fsx	*40-50*	
H1f.fsx	*50-60*	

Notes:

Number of Driver Weight Shifts/Squirms:

As you continue driving, I will ask you some questions rating your opinion of how the seat is performing right now.

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
2	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
3	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
4	Overall Back	☐	☐	☐	☐	☐	☐	☐	☐
5	Ischial/Buttocks	☐	☐	☐	☐	☐	☐	☐	☐
6	Thigh	☐	☐	☐	☐	☐	☐	☐	☐
7	Cushion Lateral	☐	☐	☐	☐	☐	☐	☐	☐
8	Overall Cushion	☐	☐	☐	☐	☐	☐	☐	☐
9	Overall Seat	☐	☐	☐	☐	☐	☐	☐	☐

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
11	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
12	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
13	Seat Back Firmness	☐	☐	☐	☐	☐	☐	☐	☐
14	Cushion Firmness	☐	☐	☐	☐	☐	☐	☐	☐
15	Cushion Hold	☐	☐	☐	☐	☐	☐	☐	☐

	Fatigue Level	1 Low	2	3	4 Moderate	5	6	7 High	Abstain
16	Drowsy	☐	☐	☐	☐	☐	☐	☐	☐
17	Eyes Tired	☐	☐	☐	☐	☐	☐	☐	☐
18	Dull or Listless	☐	☐	☐	☐	☐	☐	☐	☐
19	Stiff Neck	☐	☐	☐	☐	☐	☐	☐	☐
20	Shoulders Stiff	☐	☐	☐	☐	☐	☐	☐	☐
21	Arms Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
22	Aching Back	☐	☐	☐	☐	☐	☐	☐	☐
23	Buttocks Sore	☐	☐	☐	☐	☐	☐	☐	☐
24	Thighs Sore	☐	☐	☐	☐	☐	☐	☐	☐
25	Legs/Knees Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
26	Feet/Ankles Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
27	Whole Body Fatigue	☐	☐	☐	☐	☐	☐	☐	☐

Additional Comments:

Road Test: Cushion 1, Hour 2

End Time: ______________ **End Mileage: ______________**

Take measurements 6 times per hour on 10 minute intervals.
Record seat pressure for 10 seconds at 30 fps.
Resample for any "bad" data blocks.

Pressure	*Time*	*Sample Notes*
H2a.fsx	*0-10*	
H2b.fsx	*10-20*	
H2c.fsx	*20-30*	
H2d.fsx	*30-40*	
H2e.fsx	*40-50*	
H2f.fsx	*50-60*	

Notes:

Number of Driver Weight Shifts/Squirms:

As you continue driving, I will ask you some questions rating your opinion of how the seat is performing right now.

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
2	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
3	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
4	Overall Back	☐	☐	☐	☐	☐	☐	☐	☐
5	Ischial/Buttocks	☐	☐	☐	☐	☐	☐	☐	☐
6	Thigh	☐	☐	☐	☐	☐	☐	☐	☐
7	Cushion Lateral	☐	☐	☐	☐	☐	☐	☐	☐
8	Overall Cushion	☐	☐	☐	☐	☐	☐	☐	☐
9	Overall Seat	☐	☐	☐	☐	☐	☐	☐	☐

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
11	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
12	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
13	Seat Back Firmness	☐	☐	☐	☐	☐	☐	☐	☐
14	Cushion Firmness	☐	☐	☐	☐	☐	☐	☐	☐
15	Cushion Hold	☐	☐	☐	☐	☐	☐	☐	☐

	Fatigue Level	1 Low	2	3	4 Moderate	5	6	7 High	Abstain
16	Drowsy	☐	☐	☐	☐	☐	☐	☐	☐
17	Eyes Tired	☐	☐	☐	☐	☐	☐	☐	☐
18	Dull or Listless	☐	☐	☐	☐	☐	☐	☐	☐
19	Stiff Neck	☐	☐	☐	☐	☐	☐	☐	☐
20	Shoulders Stiff	☐	☐	☐	☐	☐	☐	☐	☐
21	Arms Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
22	Aching Back	☐	☐	☐	☐	☐	☐	☐	☐
23	Buttocks Sore	☐	☐	☐	☐	☐	☐	☐	☐
24	Thighs Sore	☐	☐	☐	☐	☐	☐	☐	☐
25	Legs/Knees Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
26	Feet/Ankles Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
27	Whole Body Fatigue	☐	☐	☐	☐	☐	☐	☐	☐

Additional Comments:

Road Test: Cushion 1, Hour 3

End Time: ______________ **End Mileage: ______________**

Take measurements 6 times per hour on 10 minute intervals.
Record seat pressure for 10 seconds at 30 fps.
Resample for any "bad" data blocks.

Pressure	*Time*	*Sample Notes*
H3a.fsx	*0-10*	
H3b.fsx	*10-20*	
H3c.fsx	*20-30*	
H3d.fsx	*30-40*	
H3e.fsx	*40-50*	
H3f.fsx	*50-60*	

Notes:

Number of Driver Weight Shifts/Squirms:

As you continue driving, I will ask you some questions rating your opinion of how the seat is performing right now.

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar								
2	Mid-Back								
3	Back Lateral								
4	Overall Back								
5	Ischial/Buttocks								
6	Thigh								
7	Cushion Lateral								
8	Overall Cushion								
9	Overall Seat								

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar								
11	Mid-Back								
12	Back Lateral								
13	Seat Back Firmness								
14	Cushion Firmness								
15	Cushion Hold								

	Fatigue Level	1 Low	2	3	4 Moderate	5	6	7 High	Abstain
16	Drowsy								
17	Eyes Tired								
18	Dull or Listless								
19	Stiff Neck								
20	Shoulders Stiff								
21	Arms Sore or Stiff								
22	Aching Back								
23	Buttocks Sore								
24	Thighs Sore								
25	Legs/Knees Sore or Stiff								
26	Feet/Ankles Sore or Stiff								
27	Whole Body Fatigue								

Additional Comments:

Road Test: Cushion 1, Hour 4

End Time: ______________ **End Mileage: ______________**

Take measurements 6 times on 10 minute intervals.
Record seat pressure for 10 seconds at 30 fps, vibration 30 seconds at 100 Hz.
Resample for any "bad" data blocks.

Pressure	*Time*	*Sample Notes*
H4a.fsx	*0-10*	
H4b.fsx	*10-20*	
H4c.fsx	*20-30*	
H4d.fsx	*30-40*	
H4e.fsx	*40-50*	
H4f.fsx	*50-60*	

Notes:

Number of Driver Weight Shifts/Squirms:

As you continue driving, I will ask you some questions rating your opinion of how the seat is performing right now.

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
2	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
3	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
4	Overall Back	☐	☐	☐	☐	☐	☐	☐	☐
5	Ischial/Buttocks	☐	☐	☐	☐	☐	☐	☐	☐
6	Thigh	☐	☐	☐	☐	☐	☐	☐	☐
7	Cushion Lateral	☐	☐	☐	☐	☐	☐	☐	☐
8	Overall Cushion	☐	☐	☐	☐	☐	☐	☐	☐
9	Overall Seat	☐	☐	☐	☐	☐	☐	☐	☐

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
11	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
12	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
13	Seat Back Firmness	☐	☐	☐	☐	☐	☐	☐	☐
14	Cushion Firmness	☐	☐	☐	☐	☐	☐	☐	☐
15	Cushion Hold	☐	☐	☐	☐	☐	☐	☐	☐

	Fatigue Level	1 Low	2	3	4 Moderate	5	6	7 High	Abstain
16	Drowsy	☐	☐	☐	☐	☐	☐	☐	☐
17	Eyes Tired	☐	☐	☐	☐	☐	☐	☐	☐
18	Dull or Listless	☐	☐	☐	☐	☐	☐	☐	☐
19	Stiff Neck	☐	☐	☐	☐	☐	☐	☐	☐
20	Shoulders Stiff	☐	☐	☐	☐	☐	☐	☐	☐
21	Arms Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
22	Aching Back	☐	☐	☐	☐	☐	☐	☐	☐
23	Buttocks Sore	☐	☐	☐	☐	☐	☐	☐	☐
24	Thighs Sore	☐	☐	☐	☐	☐	☐	☐	☐
25	Legs/Knees Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
26	Feet/Ankles Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
27	Whole Body Fatigue	☐	☐	☐	☐	☐	☐	☐	☐

Additional Comments:

Static Pressure Map (Final)

Please sit stationary in a comfortable driving position with both hands on the steering wheel and your foot on the accelerator.

Collect two static pressure maps:
Hfa.fsx   Hfb.fsx

Change seat cushion

Driving on Second Seat Cushion

Static Pressure Map (Initial)

Before you get into the cab, please remove your wallet or anything bulky from your back pockets. Please get into the cab and adjust the seat to a comfortable driving position. (*assist subject*)

Notes:

Record Seat Adjustment

Ride Height: ________

Fore/Aft: ________

Please sit stationary in a comfortable driving position with both hands on the steering wheel and your foot on the accelerator.

Collect two static pressure maps:
*p_**S01b**H0a.fsx   p_**S01b**H0b.fsx*

Allow driver to begin driving

“Test Drive” Survey

I will ask you some questions rating your opinion of how the seat is performing right now.

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
2	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
3	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
4	Overall Back	☐	☐	☐	☐	☐	☐	☐	☐
5	Ischial/Buttocks	☐	☐	☐	☐	☐	☐	☐	☐
6	Thigh	☐	☐	☐	☐	☐	☐	☐	☐
7	Cushion Lateral	☐	☐	☐	☐	☐	☐	☐	☐
8	Overall Cushion	☐	☐	☐	☐	☐	☐	☐	☐
9	Overall Seat	☐	☐	☐	☐	☐	☐	☐	☐

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
11	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
12	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
13	Seat Back Firmness	☐	☐	☐	☐	☐	☐	☐	☐
14	Cushion Firmness	☐	☐	☐	☐	☐	☐	☐	☐

Additional Comments:

Road Test: Cushion 2, Hour 1

Start Mileage: ______________ End Mileage: __________________

Take measurements 6 times per hour on 10 minute intervals.
Record seat pressure for 10 seconds at 30 fps.
Resample for any "bad" data blocks.

Pressure	*Time*	*Sample Notes*
H1a.fsx	*0-10*	
H1b.fsx	*10-20*	
H1c.fsx	*20-30*	
H1d.fsx	*30-40*	
H1e.fsx	*40-50*	
H1f.fsx	*50-60*	

Notes:

Number of Driver Weight Shifts/Squirms:

As you continue driving, I will ask you some questions rating your opinion of how the seat is performing right now.

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
2	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
3	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
4	Overall Back	☐	☐	☐	☐	☐	☐	☐	☐
5	Ischial/Buttocks	☐	☐	☐	☐	☐	☐	☐	☐
6	Thigh	☐	☐	☐	☐	☐	☐	☐	☐
7	Cushion Lateral	☐	☐	☐	☐	☐	☐	☐	☐
8	Overall Cushion	☐	☐	☐	☐	☐	☐	☐	☐
9	Overall Seat	☐	☐	☐	☐	☐	☐	☐	☐

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
11	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
12	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
13	Seat Back Firmness	☐	☐	☐	☐	☐	☐	☐	☐
14	Cushion Firmness	☐	☐	☐	☐	☐	☐	☐	☐
15	Cushion Hold	☐	☐	☐	☐	☐	☐	☐	☐

	Fatigue Level	1 Low	2	3	4 Moderate	5	6	7 High	Abstain
16	Drowsy	☐	☐	☐	☐	☐	☐	☐	☐
17	Eyes Tired	☐	☐	☐	☐	☐	☐	☐	☐
18	Dull or Listless	☐	☐	☐	☐	☐	☐	☐	☐
19	Stiff Neck	☐	☐	☐	☐	☐	☐	☐	☐
20	Shoulders Stiff	☐	☐	☐	☐	☐	☐	☐	☐
21	Arms Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
22	Aching Back	☐	☐	☐	☐	☐	☐	☐	☐
23	Buttocks Sore	☐	☐	☐	☐	☐	☐	☐	☐
24	Thighs Sore	☐	☐	☐	☐	☐	☐	☐	☐
25	Legs/Knees Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
26	Feet/Ankles Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
27	Whole Body Fatigue	☐	☐	☐	☐	☐	☐	☐	☐

Additional Comments:

Road Test: Cushion 2, Hour 2

End Time: ______________ **End Mileage: ______________**

Take measurements 6 times per hour on 10 minute intervals.
Record seat pressure for 10 seconds at 30 fps.
Resample for any "bad" data blocks.

Pressure	*Time*	*Sample Notes*
H2a.fsx	*0-10*	
H2b.fsx	*10-20*	
H2c.fsx	*20-30*	
H2d.fsx	*30-40*	
H2e.fsx	*40-50*	
H2f.fsx	*50-60*	

Notes:

Number of Driver Weight Shifts/Squirms:

As you continue driving, I will ask you some questions rating your opinion of how the seat is performing right now.

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable		Abstain
1	Lumbar	☐	☐	☐	☐	☐	☐	☐		☐
2	Mid-Back	☐	☐	☐	☐	☐	☐	☐		☐
3	Back Lateral	☐	☐	☐	☐	☐	☐	☐		☐
4	Overall Back	☐	☐	☐	☐	☐	☐	☐		☐
5	Ischial/Buttocks	☐	☐	☐	☐	☐	☐	☐		☐
6	Thigh	☐	☐	☐	☐	☐	☐	☐		☐
7	Cushion Lateral	☐	☐	☐	☐	☐	☐	☐		☐
8	Overall Cushion	☐	☐	☐	☐	☐	☐	☐		☐
9	Overall Seat	☐	☐	☐	☐	☐	☐	☐		☐

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much		Abstain
10	Lumbar	☐	☐	☐	☐	☐	☐	☐		☐
11	Mid-Back	☐	☐	☐	☐	☐	☐	☐		☐
12	Back Lateral	☐	☐	☐	☐	☐	☐	☐		☐
13	Seat Back Firmness	☐	☐	☐	☐	☐	☐	☐		☐
14	Cushion Firmness	☐	☐	☐	☐	☐	☐	☐		☐
15	Cushion Hold	☐	☐	☐	☐	☐	☐	☐		☐

	Fatigue Level	1 Low	2	3	4 Moderate	5	6	7 High		Abstain
16	Drowsy	☐	☐	☐	☐	☐	☐	☐		☐
17	Eyes Tired	☐	☐	☐	☐	☐	☐	☐		☐
18	Dull or Listless	☐	☐	☐	☐	☐	☐	☐		☐
19	Stiff Neck	☐	☐	☐	☐	☐	☐	☐		☐
20	Shoulders Stiff	☐	☐	☐	☐	☐	☐	☐		☐
21	Arms Sore or Stiff	☐	☐	☐	☐	☐	☐	☐		☐
22	Aching Back	☐	☐	☐	☐	☐	☐	☐		☐
23	Buttocks Sore	☐	☐	☐	☐	☐	☐	☐		☐
24	Thighs Sore	☐	☐	☐	☐	☐	☐	☐		☐
25	Legs/Knees Sore or Stiff	☐	☐	☐	☐	☐	☐	☐		☐
26	Feet/Ankles Sore or Stiff	☐	☐	☐	☐	☐	☐	☐		☐
27	Whole Body Fatigue	☐	☐	☐	☐	☐	☐	☐		☐

Additional Comments:

Road Test: Cushion 2, Hour 3

End Time: _______________ **End Mileage:** _______________

Take measurements 6 times per minute on 10 minute intervals.
Record seat pressure for 10 seconds at 30 fps.
Resample for any "bad" data blocks.

Pressure	*Time*	*Sample Notes*
H3a.fsx	*0-10*	
H3b.fsx	*10-20*	
H3c.fsx	*20-30*	
H3d.fsx	*30-40*	
H3e.fsx	*40-50*	
H3f.fsx	*50-60*	

Notes:

Number of Driver Weight Shifts/Squirms:

As you continue driving, I will ask you some questions rating your opinion of how the seat is performing right now.

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
2	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
3	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
4	Overall Back	☐	☐	☐	☐	☐	☐	☐	☐
5	Ischial/Buttocks	☐	☐	☐	☐	☐	☐	☐	☐
6	Thigh	☐	☐	☐	☐	☐	☐	☐	☐
7	Cushion Lateral	☐	☐	☐	☐	☐	☐	☐	☐
8	Overall Cushion	☐	☐	☐	☐	☐	☐	☐	☐
9	Overall Seat	☐	☐	☐	☐	☐	☐	☐	☐

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar	☐	☐	☐	☐	☐	☐	☐	☐
11	Mid-Back	☐	☐	☐	☐	☐	☐	☐	☐
12	Back Lateral	☐	☐	☐	☐	☐	☐	☐	☐
13	Seat Back Firmness	☐	☐	☐	☐	☐	☐	☐	☐
14	Cushion Firmness	☐	☐	☐	☐	☐	☐	☐	☐
15	Cushion Hold	☐	☐	☐	☐	☐	☐	☐	☐

	Fatigue Level	1 Low	2	3	4 Moderate	5	6	7 High	Abstain
16	Drowsy	☐	☐	☐	☐	☐	☐	☐	☐
17	Eyes Tired	☐	☐	☐	☐	☐	☐	☐	☐
18	Dull or Listless	☐	☐	☐	☐	☐	☐	☐	☐
19	Stiff Neck	☐	☐	☐	☐	☐	☐	☐	☐
20	Shoulders Stiff	☐	☐	☐	☐	☐	☐	☐	☐
21	Arms Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
22	Aching Back	☐	☐	☐	☐	☐	☐	☐	☐
23	Buttocks Sore	☐	☐	☐	☐	☐	☐	☐	☐
24	Thighs Sore	☐	☐	☐	☐	☐	☐	☐	☐
25	Legs/Knees Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
26	Feet/Ankles Sore or Stiff	☐	☐	☐	☐	☐	☐	☐	☐
27	Whole Body Fatigue	☐	☐	☐	☐	☐	☐	☐	☐

Additional Comments:

Road Test: Cushion 2, Hour 4

End Time: _______________ **End Mileage:** _______________

Take measurements 6 times per minute on 10 minute intervals.
Record seat pressure for 10 seconds at 30 fps.
Resample for any "bad" data blocks.

Pressure	*Time*	*Sample Notes*
H4a.fsx	*0-10*	
H4b.fsx	*10-20*	
H4c.fsx	*20-30*	
H4d.fsx	*30-40*	
H4e.fsx	*40-50*	
H4f.fsx	*50-60*	

Notes:

Number of Driver Weight Shifts/Squirms:

As you continue driving, I will ask you some questions rating your opinion of how the seat is performing right now.

	Comfort	1 Very Uncomfortable	2	3	4 Neutral	5	6	7 Very Comfortable	Abstain
1	Lumbar								
2	Mid-Back								
3	Back Lateral								
4	Overall Back								
5	Ischial/Buttocks								
6	Thigh								
7	Cushion Lateral								
8	Overall Cushion								
9	Overall Seat								

	Amount of Support	1 Too Little	2	3	4 Just Right	5	6	7 Too Much	Abstain
10	Lumbar								
11	Mid-Back								
12	Back Lateral								
13	Seat Back Firmness								
14	Cushion Firmness								
15	Cushion Hold								

	Fatigue Level	1 Low	2	3	4 Moderate	5	6	7 High	Abstain
16	Drowsy								
17	Eyes Tired								
18	Dull or Listless								
19	Stiff Neck								
20	Shoulders Stiff								
21	Arms Sore or Stiff								
22	Aching Back								
23	Buttocks Sore								
24	Thighs Sore								
25	Legs/Knees Sore or Stiff								
26	Feet/Ankles Sore or Stiff								
27	Whole Body Fatigue								

Additional Comments:

Static Pressure Map (Final)

Please sit stationary in a comfortable driving position with both hands on the steering wheel and your foot on the accelerator.

Collect two static pressure maps:
Hfa.fsx   Hfb.fsx

Exit Interview

End Time: ______________   End Mileage: ______________

You have completed your road testing. I have some questions regarding your overall test session experience before you leave.

Questions after Road Test

1. Please answer the following "yes" or "no" questions.

Was the cushion uncomfortable?	Yes No
Was it too hot or make you sweat?	Yes No
Did it pinch or constrict your legs?	Yes No
Did you have any difficulty getting in & out of your seat?	Yes No
Did you have problems adjusting the cushion pressure? (air only)	Yes No
Did you have problems using the valve for the cushion? (air only)	Yes No

2. Now I'd like you to rate the cushion we tested today in comparison to your regular truck seat. Use a scale of 1 to 7, where 1 is "Much Worse", 4 is "Same" and 7 is "Much Better", or you may choose "Does Not Apply".

Comfort	1 2 3 4 5 6 7 N/A
Tired Feeling after Driving	1 2 3 4 5 6 7 N/A
Numbness in Legs	1 2 3 4 5 6 7 N/A
Reduced Vibration & Shock	1 2 3 4 5 6 7 N/A
Lower Back Pain	1 2 3 4 5 6 7 N/A
Hemorrhoid Pain	1 2 3 4 5 6 7 N/A
Sitting Pain or Discomfort	1 2 3 4 5 6 7 N/A
Alertness after Driving	1 2 3 4 5 6 7 N/A

3. Rate the locations where you have pain or discomfort while driving on the cushion we tested today. Use a scale of 1 to 7, where 1 is "Very Little", 4 is "Moderate", and 7 is "Severe", or you may choose "None".

Lower Back	None 1 2 3 4 5 6 7
Thighs or Legs	None 1 2 3 4 5 6 7
Buttocks	None 1 2 3 4 5 6 7

4. Please rate the seat on the following areas. Use a scale of 1 to 7, where 1 is “Unacceptable”, 4 is “Average”, and 7 is “Outstanding”.

Styling of the seating unit	1 2 3 4 5 6 7
The look/feel of the seat material	1 2 3 4 5 6 7
How easy it is to reach/operate seat controls	1 2 3 4 5 6 7
Ability to adjust driver’s seat to comfortable position	1 2 3 4 5 6 7
How easy it is to put on the seat belt	1 2 3 4 5 6 7
How seat holds you in place during cornering	1 2 3 4 5 6 7
Ability to get in and out of the driver’s seat easily	1 2 3 4 5 6 7

5. What do you **like** about the cushion we tested today?

6. What do you **dislike** about the cushion we tested today?

7. How does this seat compare with **your regular seat**?

8. If you had a choice, which cushion would you drive on?

9. Are you having any problems or do you have any questions about the seat that you’d like to discuss?

That’s all the questions I have for today. Thank you for participating!

Do you have any questions?

Appendix D: Matlab Processing Code

```
function []=pfunc(MAfile,Mfile,N,fs,pathloc,subj,firstline)

%This is the processor for pressure data. It reads and
processes the raw data, then
%records the processed data, along with other information,
including pressure metrics.

MAdata=textread(MAfile,'%q');  %average 1 movie-averaged
file
Mdata=textread(Mfile,'%q');  %whole movie file
whos Mdata
convert = 51.715; %1 psi = 51.715 mmHg
T = N/fs; dt = 1/fs; t = 0:dt:(N-1)*dt;
num_rows = 42; num_cols = 48; n = num_cols*num_rows;

for ii = 1:N
    st=firstline+(ii-1)*(num_rows-1+3);
    fin=st+(num_rows-1);
    pp=char(Mdata(st:fin));
    qq=str2num(pp);
    %whos pp qq
    Z(:,:,ii) = qq;
    whos Z
end

for i=1:42
    Zma(i,:)=str2num(char(MAdata(i+firstline-1)));
end

%----START aPcrms CALCULATIONS----------------------
Xma=reshape(Zma,1,n)*convert; %convert to units of mmHg
X=reshape(Z,n,N)*convert;

Xmin=mean(X,2)-3*std(X,0,2); Xmax=mean(X,2)+3*std(X,0,2); %
limit data to within 3 std of mean

%Finds areas for aPcrms
I1 = find(Xma>=40&Xma<60); I2 = find(Xma>=60&Xma<80);
I3 = find(Xma>=80&Xma<100); I4 = find(Xma>=100);

area1 = length(I1)*0.16; area2 = length(I2)*0.16;
```

```
area3 = length(I3)*0.16; area4 = length(I4)*0.16;

if length(I1)==0
    Pcrms1 = 0;
else
    for i = 1:length(I1)
        I11 = find( (X(I1(i),:)>Xmin(I1(i))) &
(X(I1(i),:)<Xmax(I1(i))) );
        t1 = 0:dt:(length(I11)-1)*dt;
        Pcrms1(i) =
sqrt(1/N*sum((diff(X(I1(i),I11))./diff(t1)).^2));%Pcrms1
for each cell
    end
end

if length(I2)==0
    Pcrms2 = 0;
else
    for i = 1:length(I2)
        I22 = find( (X(I2(i),:)>Xmin(I2(i))) &
(X(I2(i),:)<Xmax(I2(i))) );
        t2 = 0:dt:(length(I22)-1)*dt;
        Pcrms2(i) =
sqrt(1/N*sum((diff(X(I2(i),I22))./diff(t2)).^2));
    end
end

if length(I3)==0
    Pcrms3 = 0;
else
    for i = 1:length(I3)
        I33 = find( (X(I3(i),:)>Xmin(I3(i))) &
(X(I3(i),:)<Xmax(I3(i))) );
        t3 = 0:dt:(length(I33)-1)*dt;
        Pcrms3(i) =
sqrt(1/N*sum((diff(X(I3(i),I33))./diff(t3)).^2));
    end
end

if length(I4)==0
    Pcrms4 = 0;
else
    for i = 1:length(I4)
        I44 = find( (X(I4(i),:)>Xmin(I4(i))) &
(X(I4(i),:)<Xmax(I4(i))) );
        t4 = 0:dt:(length(I44)-1)*dt;
```

```
        Pcrms4(i) =
sqrt(1/N*sum((diff(X(I4(i),I44))./diff(t4)).^2));
    end
end

avgPcrms1 = mean(Pcrms1)/convert;%average Pcrms for
pressure range across cells in psi
avgPcrms2 = mean(Pcrms2)/convert;
avgPcrms3 = mean(Pcrms3)/convert;
avgPcrms4 = mean(Pcrms4)/convert;

areaPcrms1 = 1*(avgPcrms1)*area1;
areaPcrms2 = 2*(avgPcrms1)*area2;
areaPcrms3 = 3*(avgPcrms1)*area3;
areaPcrms4 = 4*(avgPcrms1)*area4;

aPcrms = (areaPcrms1+areaPcrms2+areaPcrms3+areaPcrms4);

%SPD Calculation
for j=1:N
    nz=find(X(:,j)>0);
    pm(j)=mean(X(nz,j));
    SPD(j)=sum((X(nz,j)-
pm(j)).^2)/(4*length(nz)*(pm(j))^2)*100;
    Area(j)=length(nz)*0.16;
end

% COP Calculation
px=0; py=0;  p=0;
for i=1:42
    for j=1:48
        px=px+j*reshape(Z(i,j,:),length(t),1);
        py=py+i*reshape(Z(i,j,:),length(t),1);
        p=p+reshape(Z(i,j,:),length(t),1);
    end
end
COPx=px./p; COPy=py./p;

%-----SAVE POSTPROCESSED DATA-----
Z=Z; %movie data (psi)
tp=t; %time vector (seconds)
Zma=Zma; %movie averaged data (psi)
aPcrms=aPcrms; %aPcrms metric (lbs/s)
avgPcrms14=[avgPcrms1; avgPcrms2; avgPcrms3; avgPcrms4];
%Pcrms for each region (psi)
area14=[area1;area2;area3;area4]; % area of each pressure
region (in^2)
```

```
SPD=SPD; % Dynamic SPD timetrace (fraction)
Area=Area; %dynamic area timetrace (in^2)
pm=pm/51.715; %real time mean pressure (psi)
F=pm.*Area; % contact force (lbs)
COP=[COPx COPy]; % COP data (cells)


outname=[subj,'_',Mfile(1:(length(Mfile)-4)),'.mat'];
eval(['save ',outname, ' Z tp Zma aPcrms avgPcrms14 area14
SPD Area pm F COP']);

fprintf('Raw Data File: %20s Completed... \n',MAfile)
fprintf('      Output to File: %20s \n',outname)
fprintf('      File Path: %80s \n',pathloc)

%-----END SAVE POSTPROCESSED DATA-----
```