A Comparative Analysis of Air-inflated and Foam Seat Cushions for Truck Seats

by

Thomas Michael Seigler

Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

Approved:

Mehdi Ahmadian, Chairman

Donald Leo

Stefan Duma

May 2002
Blacksburg, Virginia
A Comparative Analysis of Air-inflated and Foam Seat Cushions for Truck Seats

by

Thomas Michael Seigler

Mehdi Ahmadian, Chairman

Mechanical Engineering

A comprehensive comparison between an air-inflated seat cushion designed for truck seats and a commonly used foam cushion is provided, using a single-axis test rig designed for dynamic seat testing. Different types of tests are conducted in order to evaluate various aspects of each type of cushion; in terms of their response to narrow-band (single frequency) dynamics, broadband input of the type that is commonly used in the trucking industry for testing seats (ISO2), and a step input for assessing the damping characteristics of each cushion. The tests were conducted over a twelve-hour period—in four-hour intervals—measuring the changes that occur at the seat cushion over time and assessing how these changes can affect the metrics that are used for evaluating the cushions. The tests indicated a greater stiffening of the foam cushion over time, as compared with the air-inflated cushion that showed almost no change in stiffness when exposed to a static weight for twelve hours. Furthermore, pressure measurements at the seat showed higher-pressure concentrations for the foam cushion at the bony prominence of the seat profile—namely, the ischial tuberosities—as compared to the air-inflated cushion. A series of tests aimed at evaluating the damping properties of each cushion showed both cushions to have nearly identical damping properties. Other methods used for evaluating the dynamic properties of the two seat cushions included those recommended by studies in the past, as well as new techniques that were developed specifically for this study. The new techniques, named Seat Pressure Distribution (SPD%) and Area Pcrms (aPcrms) for the purpose of this study, are formulated such that they can best highlight the dynamic differences between different types of seat cushions,
and their effect on driver comfort. The results show that the air-inflated seat cushion can provide significant improvements in pressure distribution between the seat cushion and the driver, therefore providing a more comfortable ride and causing less fatigue.
ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Mehdi Ahmadian for his guidance and encouragement throughout my graduate studies in the Mechanical Engineering Department. I would also like to thank Dr. Donald Leo and Dr. Stefan Duma for serving on my graduate committee. I would like to acknowledge the ROHO group for providing the funding for this project. I would especially like to thank Dennis Clapper and Tony Sprouse. Their cooperation and involvement have been critical to the completion of this work.

Finally, I would like to thank my mother and father, Thomas and Linda Seigler, my sister, Melinda, and especially my wife, Amy for their love and support during the time that I have spent at Virginia Tech.
# CONTENTS

Abstract ................................................................................................................................. ii  
ACKNOWLEDGEMENTS ...................................................................................................... iv  
LIST OF FIGURES ............................................................................................................... viii  
LIST OF TABLES ................................................................................................................ xiii  

1 INTRODUCTION ........................................................................................................... 1  

1.1 MOTIVATION ........................................................................................................ 1  
1.2 OBJECTIVES ......................................................................................................... 4  
1.3 APPROACH ........................................................................................................... 4  
1.4 OUTLINE .............................................................................................................. 6  
1.5 CONTRIBUTIONS .................................................................................................. 6  

2 BACKGROUND .......................................................................................................... 8  

2.1 THE TRUCK SEAT .................................................................................................. 8  
2.1.1 The Seat Suspension ....................................................................................... 9  
2.1.2 Additional Design Considerations ............................................................... 10  
2.2 COMFORT AND FATIGUE .................................................................................. 11  
2.2.1 Vibration Related to Comfort and Fatigue ................................................. 13  
2.2.2 Pressure and the Seated Person ................................................................. 14  
2.2.3 Theories of Pressure Distribution ............................................................ 17  
2.3 EVALUATING COMFORT .................................................................................. 18  
2.4 SUMMARY .......................................................................................................... 21  

3 EXPERIMENTAL SETUP .......................................................................................... 22  

3.1 AVDL SEAT-TESTING RIG .................................................................................. 22  
3.1.1 Hydraulic Actuation System ................................................................. 24  
3.1.2 Experimental Seat Cushions ...................................................................... 27  
3.2 DATA ACQUISITION ............................................................................................. 29  
3.2.1 Vibration Measurement ........................................................................... 29  
3.2.2 Pressure Measurement ............................................................................. 33
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>CUSHION LOADING INDENTOR (CLI)</td>
<td>37</td>
</tr>
<tr>
<td>3.4</td>
<td>TERMINOLOGY</td>
<td>39</td>
</tr>
<tr>
<td>3.5</td>
<td>INPUT TEST SIGNALS</td>
<td>40</td>
</tr>
<tr>
<td>3.5.1</td>
<td>Chirp Input</td>
<td>40</td>
</tr>
<tr>
<td>3.5.2</td>
<td>Step Input</td>
<td>41</td>
</tr>
<tr>
<td>3.5.3</td>
<td>ISO2 Input</td>
<td>42</td>
</tr>
<tr>
<td>4</td>
<td>TEST METHODS</td>
<td>44</td>
</tr>
<tr>
<td>4.1</td>
<td>VIBRATION METHODS</td>
<td>44</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Human Vibration Limits</td>
<td>46</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Step Response</td>
<td>48</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Transmissibility</td>
<td>48</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Seat Effective Amplitude Transmissibility</td>
<td>50</td>
</tr>
<tr>
<td>4.2</td>
<td>PRESSURE METHODS</td>
<td>51</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Pressure Mapping</td>
<td>51</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Pressure Change Rate (Pcrms)</td>
<td>54</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Area Pressure Change Rate (aPcrms)</td>
<td>54</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Seat Pressure Distribution (SPD%)</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>STANDARD FOAM CUSHION ANALYSIS</td>
<td>60</td>
</tr>
<tr>
<td>5.1</td>
<td>VIBRATION ANALYSIS</td>
<td>60</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Chirp Results</td>
<td>60</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Step Results</td>
<td>65</td>
</tr>
<tr>
<td>5.2</td>
<td>PRESSURE DISTRIBUTION ANALYSIS</td>
<td>66</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Chirp Results</td>
<td>67</td>
</tr>
<tr>
<td>5.2.2</td>
<td>ISO2 Results</td>
<td>72</td>
</tr>
<tr>
<td>5.3</td>
<td>SUMMARY</td>
<td>75</td>
</tr>
<tr>
<td>6</td>
<td>AIR-INFLATED CUSHION ANALYSIS</td>
<td>76</td>
</tr>
<tr>
<td>6.1</td>
<td>VIBRATION ANALYSIS</td>
<td>76</td>
</tr>
<tr>
<td>6.1.1</td>
<td>Chirp Results</td>
<td>76</td>
</tr>
<tr>
<td>6.1.2</td>
<td>Step Results</td>
<td>81</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 2-1. Affects of Air-Ride Suspension; Adapted from [4]................................. 10

Figure 2-2. Typical Weight Distribution When Seated [14].......................................... 14

Figure 2-3. Pelvis Alignment when (a) Standing; (b) Sitting relaxed; (c) Sitting erect; (d) Sitting forward; (e) Sitting back. Reprinted from [6]................................. 15

Figure 2-4. Relationship Between Pressure and Seated Duration; Adapted from [18] ... 16

Figure 3-1. AVDL Seat Tester.............................................................................. 22

Figure 3-2. Close-up of Rollers ........................................................................ 23

Figure 3-3. Experimental Truck Seat – Bostrom Talladega 915 ................................. 24

Figure 3-4. MTS 242 Series Hydraulic Actuator...................................................... 25

Figure 3-5. MTS 407 Controller ......................................................................... 25

Figure 3-6. MTS SilentFlo Hydraulic Power Unit.................................................... 26

Figure 3-7. MTS Hydraulic Service Manifold............................................................ 27

Figure 3-8. Standard Foam Truck Seat Cushion....................................................... 27

Figure 3-9. ROHO Air-Inflated Seat Cushion.............................................................. 28

Figure 3-10. dSPACE Data Acquisition Flowchart.................................................. 30

Figure 3-11. dSPACE AutoBox............................................................................. 31

Figure 3-12. Simulink Signal Processing Diagram .................................................. 32

Figure 3-13. Control Desk Software....................................................................... 33

Figure 3-14. Tekscan Body Pressure Measurement System.................................... 34
Figure 3-15. Tekscan BPMS Software ................................................................. 35

Figure 3-16. Simplified Electronics Schematic of Tekscan BPMS Data Acquisition;
Reprinted from [28] .................................................................................................. 36

Figure 3-17. Components of Cushion Loading Indentor ........................................ 37

Figure 3-18. Cushion Loading Indentor Positioned on Truck Seat ....................... 38

Figure 3-19. Seat Tester With Position of Dynamic Measurements .................... 39

Figure 3-20. Input Chirp Signal; (a) Time Trace (b) Power Spectrum ................. 41

Figure 3-21. Step Input with 1 inch Amplitude .................................................. 42

Figure 3-22. Power Spectrum of ISO2 Excitation ............................................. 43

Figure 3-23. Sample Time History of ISO2 Displacement ................................. 43

Figure 4-1. Vertical Vibration Exposure Criteria Curves Defining Equal Fatigue-
Decreased Proficiency Boundaries; Reprinted from [31] ................................ 47

Figure 4-2. Lateral Vibration Exposure Criteria Curves Defining Equal Fatigue-
Decreased Proficiency Boundaries; Reprinted from [31] ................................. 47

Figure 4-3. Typical Acceleration Response Showing Peak Response and Settling Time

Figure 4-4. Dynamic Model of Seat Tester .......................................................... 49

Figure 4-5. 3-Dimensional Pressure Map of a Seated Person ............................ 52

Figure 4-6. 2-Dimensional Pressure Map of a Seated Person ............................ 53

Figure 4-7. Pressure Maps of Three Seating Surfaces Using Human Subject ....... 58

Figure 4-8. Static SPD% for Three Seat Surfaces (Air-Inflated Cushion, Standard Foam
Cushion, Hard Board) ............................................................................................ 59
Figure 5-1. Power Spectral Density of Base Acceleration for Chirp Input (Foam Cushion) ............................................................. 61

Figure 5-2. Power Spectral Density of Seat Acceleration for Chirp Input (Foam Cushion) .................................................................................................................... 61

Figure 5-3. Transmissibility From Floor to Seat Base (Foam Cushion) ........................................ 62

Figure 5-4. Transmissibility from Base to Seat (Foam Cushion) ............................................... 63

Figure 5-5. Transmissibility from Floor to Seat (Foam Cushion) ............................................. 64

Figure 5-6. Base Acceleration Time Response to a 1-inch Step Input (Foam Cushion) .......... 65

Figure 5-7. Base Acceleration Response to a 1-inch Step Input (Foam Cushion) ................. 66

Figure 5-8. Foam Cushion Pressure Distribution Summary for Chirp Input ......................... 67

Figure 5-9. Movie-Averaged Pressure Occurrences from Hour 0 Through Hour 12 (Foam Cushion) .................................................................................................................... 69

Figure 5-10. Average Contact Pressure Over Time (Foam Cushion) ................................... 70

Figure 5-11. Dynamic Pressure Change Rate Over Time (Foam Cushion) ......................... 70

Figure 5-12. Seat Pressure Distribution Percent Over Time (Foam Cushion) .................... 71

Figure 5-13. Pressure Distribution Summary Chart for ISO2 Input (Foam Cushion) ......... 72

Figure 5-14. Movie-Averaged Pressure Occurrences from Hour 0 through 12 (Foam Cushion) .................................................................................................................... 73

Figure 5-15. Dynamic Pressure Change Over Time (Foam Cushion) ................................. 74

Figure 5-16. Seat Pressure Distribution Over Time (Foam Cushion) ................................. 74

Figure 6-1. Power Spectral Density of Base Acceleration for Chirp Input (Air-Inflated Cushion) .................................................................................................................... 77
Figure 6-2.  Power Spectral Density of Seat Acceleration for Chirp Input (Air-Inflated Cushion)................................. 78
Figure 6-3.  Transmissibility from Floor to Seat Base (Air-Inflated Cushion) ............ 79
Figure 6-4.  Transmissibility from Floor to Seat Cushion (Air-Inflated Cushion) .... 79
Figure 6-5.  Transmissibility from Seat Base to Seat Cushion (Air-Inflated Cushion) ... 80
Figure 6-6.  Base Acceleration Time Response to a 1-inch Step Input (Air-Inflated Cushion) ........................................................................................................... 81
Figure 6-7.  Seat Acceleration Time Response to a 1-inch Step Input (Air-Inflated Cushion) ........................................................................................................... 82
Figure 6-8.  Air-Inflated Cushion Pressure Summary Chart for Chirp Input ............. 83
Figure 6-9.  Movie-Averaged Pressure Occurrences from Hour 0 Through 12 ............. 84
Figure 6-10.  Average Contact Pressure Over Time (Air-Inflated Cushion) ............... 85
Figure 6-11.  Dynamic Pressure Change Rate Over Time (Air-Inflated Cushion) ....... 86
Figure 6-12.  Seat Percent Distribution Over Time (Air-Inflated Cushion) ............... 86
Figure 6-13.  Air-Inflated Cushion Pressure Summary Chart for ISO2 Input .......... 87
Figure 6-14.  Movie Averaged Pressure Occurrences from Hour 0 through 12 (Air-Inflated Cushion) .............................................................. 88
Figure 6-15.  Dynamic Pressure Change Over Time (Air-Inflated Cushion) .......... 89
Figure 6-16.  Seat Pressure Distribution Over Time (Air-Inflated Cushion) .......... 90
Figure 7-1.  Vertical Cushion Transmissibility (Seat Acceleration Divided By Base Acceleration) for the Standard Foam Cushion; ............................................................. 93
Figure 7-2. Vertical Cushion Transmissibility (Seat Acceleration Divided By Base Acceleration) for the Air-Inflated Seat Cushion ................................................................. 93

Figure 7-3. Change in Resonant Frequency Over Time .................................................. 94

Figure 7-4. Vertical Seat Acceleration Response to a 1-inch Step Input ................................. 95

Figure 7-5. SEAT% for Air-Inflated and Foam Seat Cushions ............................................. 95

Figure 7-6. Vertical Transmissibility (Base Acceleration Divided By Floor Acceleration and Seat Acceleration Divided By Floor Acceleration); (a) Standard Foam Cushion (b) Air-Inflated Cushion .................................................................................................................. 96

Figure 7-7. Static Interface Pressure Distribution; (a) Standard Foam Cushion (b) Air-Inflated Cushion ........................................................................................................ 98

Figure 7-8. Pressure Occurrences From Hour 0 Through Hour 12 (Foam Cushion) ...... 99

Figure 7-9. Pressure Occurrences From Hour 0 Through Hour 12 (Air-Inflated Cushion ................................................................................................................................. 99

Figure 7-10. Comparison of Dynamic Seat Percent Pressure Distribution (SEAT%) .. 100

Figure 7-11. Comparison of Averaged Dynamic SPD% ..................................................... 101

Figure 7-12. Comparison of Pressure Change Rate ............................................................ 101

Figure 7-13. Comparison of Pcrms for Foam and Air-Inflated Cushion ......................... 102

Figure 7-14. Comparison of aPcrms between Foam and Air-Inflated Cushion .......... 102

Figure 8-1. Percent Improvement Offered by an Air-inflated Seat Cushion in Comparison with a Foam Cushion, using Different Metrics ................................. 104
LIST OF TABLES

Table 4-1. Vibration and Pressure Analysis Methods for Evaluating Comfort.............. 45

Table 4-2. Frequency Dependent Weighting Factors for Calculating SEAT% [5]......... 50

Table 4-3. Pressure Ranges and Weighting Factors Used in Calculating apcrms.......... 55

Table 5-1. SEAT% Values For Standard Foam Seat Cushion..................................... 64

Table 6-1. SEAT% Values for Chirp Input (Air-Inflated Cushion).............................. 80
1 Introduction

This chapter presents introductory material compulsory in understanding the work described in this thesis. The first section describes the motivation for performing the analytical and experimental work included, followed by the objectives and approach of the study. Finally, an overall outline is given that summarizes the contents of the thesis followed by a section that discusses the potential contribution of this work to the field of seat comfort.

1.1 Motivation

Drivers of commercial vehicles, particularly heavy trucks, are required to drive long and sometimes irregular hours. In America, the driving limit for truck drivers, as defined by the Federal Highway Administration Hours-of-Service (HOS) regulations, is 10 hours. However, almost 20% of drivers reported that they “always or often” exceed that limit [1]. With such long hours of seated activity it can be argued that the most important part of the truck driver’s working environment is the truck seat. Yet only recently has the design of the truck seat experienced major improvements. Improvements have emphasized bolster design to increase stability, and adjustments for backrest angle, contouring, and seat height to promote good posture. Also, the development of the air ride system has made the seat capable of absorbing vibration transferred from the road surface to the driver. Outside of posture improvements, however, no significant advancements have been made to the seat cushion. Almost always, truck seat cushions have been constructed of urethane foam with a polyester top coated cloth. Foam cushions are the most widely prescribed seat cushions because they offer the advantages of being low cost and lightweight. However, a common problem with foam seat cushions is that they degrade over time and the foam becomes denser, providing less cushioning. Alternative technologies, such as air-inflated seat cushions, have been proposed as replacements for foam cushions in order to eliminate their shortcomings. Evaluating these new technologies, however, requires methods for comparing the comfort and fatigue characteristics of different types of seat cushions. Furthermore, the ideas of
comfort and fatigue and their relation must be understood more thoroughly in order to determine if and why one seat cushion is “better” than another.

Comfort and fatigue are important for different reasons. Comfort is important to a truck driver in terms of job satisfaction. Hence, it is also important to his employer. Fatigue is more critical in that it can lead to driver impairment that can cause serious accidents. Driver fatigue is a serious problem resulting in many thousands of road accidents each year. According to the National Transportation Safety Board, fatigue may be a contributing factor in as many as 30 to 40% of all heavy truck accidents [2].

The importance of comfort and fatigue has resulted in a number of legislative initiatives set forward by various government agencies. To name a few, 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% [3]. 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 [4]. The Occupational Safety and Health Administration (OSHA) have proposed a set of ergonomics rules to reduce and prevent repetitive motion-related workplace injury [4]. Vehicle vibrations, which commercial vehicle drivers are subjected to, would be part of the OSHA ergonomic standard.

The potential direct impact of comfort and fatigue research to the transportation industry would be quite significant, in terms of:

- Establishing more effective methods for evaluating and estimating comfort and fatigue,
- Using the proposed methods to better understand the relationship between driver comfort/fatigue and seat designs under different driving conditions, and
- Promoting seat designs and driving practices that cause less driver discomfort and fatigue.

Based on the research by the U.S. Department of Transportation (DOT), which indicates that fatigue is a major factor in commercial vehicle accidents, resultant research would have the following payoffs:
• Increased highway safety (i.e., smaller number of accidents, near misses, etc.) due to lower fatigue and increased driver task efficiency,

• Reduced incidents of health complaints, such as backaches, internal organ disorders, and hemorrhoids, 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 due to a less physically demanding work environment.

The current study relies entirely on objective measures for evaluating and comparing a standard truck foam seat cushion and an air-inflated replacement seat cushion. However, many of these objective measures have resulted from testing and comparing foam cushions. It is unclear whether these methods are appropriate for evaluating dissimilar seat cushions. Therefore, the goal of the current study is to evaluate the objective measures to determine if there are substantial disparities between seat cushion performances. Furthermore, new objective measures are offered to specifically identify inherent attributes of each cushion type.

Throughout this document, the term “comfort” is 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. In contrast, the term “fatigue” defines the physical effect that results from exposure to the seat dynamics for a long period of time. 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. Herein lies the challenge: How can one possibly take a set of physical and dynamic measurements (some of which may be used for assessing comfort) and analyze them in a manner that enables the estimation of fatigue? Presently, there are no effective and accepted methods for measuring driver fatigue; therefore, due to the complexities associated with it, only inferences will be made to fatigue. Subsequent research including subjective evaluation is necessary to confirm or deny these assumptions.
1.2 Objectives

The primary objectives of this research are to:

1. identify existing objective comfort and fatigue measures for evaluating and comparing seat cushions,
2. evaluate the existing objective measures to determine their ability to highlight the inherent differences of foam and air-inflated seat cushions,
3. establish new objective test measures that can be used to evaluate different types of seat cushions—particularly foam and air-inflated seat cushions—in a dynamic environment, and
4. compare the dynamic performance—in terms of comfort and fatigue—of the two seat cushion types.

The overall objective of this research was to compare the comfort and fatigue characteristics of two entirely different types of seat cushion designs for truck seats—namely a standard foam seat cushion and an air-inflated seat cushion. Current research in the field of dynamic seat comfort has identified several objective measures for comparing seat cushions. These objective measures are implemented to highlight the differences between cushion types. Furthermore, two objective measures are introduced and implemented as new methods for comparing different classes of seat cushions for truck seats, particularly air-inflated seat cushions and foam seat cushions.

1.3 Approach

The approach that was adopted for the work presented in this study included:

- Performing a comprehensive survey of past studies in the area of human fatigue and the physiology of a seated person, and
- Using a single-axis seat rig to conduct a series of fundamental laboratory tests aimed at better understanding the existing methods and establishing their—as well as new proposed methods—application for evaluating the effect of seat designs on human comfort and fatigue.

Our preliminary literature survey showed that a number of studies exist on physiology of the human body in the seated position and the factors that affect human comfort and fatigue. We have used these studies along with our experience with vehicle seating
systems to determine the approaches that can be adopted for evaluating the effect of seat design on human comfort and fatigue. This resulted in current objective methods and provided sufficient information to establish new objective methods for evaluating seat cushions. The investigation of these objective methods was performed using a single-axis test rig.

A single-axis seat rig was used to conduct a series of fundamental laboratory tests for better understanding and evaluating the application of the methods resulting from our literature survey. As the purpose of these tests was to establish the scientific merits of the methods that are selected from past studies, as well as those suggested by this investigation, we used a number of sensors to collect dynamic data in a repeatable manner, such that the validity of the theories and hypothesis that are tested can be effectively determined. The tests were performed with an indenter designed and built specifically for the purpose of this study. This further increased the repeatability of the tests and allowed us to concentrate on the scientific merits of the methods that are evaluated. The proposed indenter was designed to emulate, as closely as possible, the interface between a seat and a seated human body. The use of the indenter, as opposed to a human test subject, allowed us to better control the test conditions and increased the test repeatability, such that the only variables in our tests were the evaluation methods that were considered and the seat designs that were studied.

The laboratory tests included vibration and pressure analysis using experimental inputs such as a chirp, step, and ISO2 test signals. Furthermore, in order to assess the effect of the set that occurs at the seat cushion interface due to the static weight applied to it, each test was performed overt a 12-hour period, repeated every 4 hours. This is analogous to a condition that can readily occur in the field during extended hours of driving. In other words, repeating the tests over a 12-hour period was intended to measure how much change would occur at the seat cushion over time and how these changes can affect the metrics that are used here to assess comfort and fatigue.
1.4 Outline

The contents of this thesis are organized into eight chapters and two appendixes. The appendices include supplementary information not discussed in the text as well as source code used in data reduction. Chapter 2 begins by providing a detailed discussion of the ideas of comfort and fatigue. This chapter is based on a literature review and presents the history of comfort and fatigue research leading all the way up to current ideas in the field. Chapter 3 describes the test setup, which includes test equipment and data acquisition used for all experiments performed in this study. The chapter also provides a description of the input signals used for testing along with the reasons for using them. Test methods are presented in Chapter 4. This includes all of the objective test measures—taken from the literature review of Chapter 2—with discussion of their relevance in this study. Two new objective measures are also presented to highlight attributes of seat cushion performance not revealed with former methods. Chapters 5 and 6 present the experimental results for the standard foam seat cushion and the air-inflated seat cushion, respectively. In these chapters the two seat cushion types are analyzed independently of one another. A comparative analysis is then presented in Chapter 7, which highlights the major differences between seat cushion performances in terms of comfort metrics. Chapter 8 provides concluding remarks and a summary of the significant results of the work. A section discussing future research is also included.

1.5 Contributions

The contributions of this research to the field of ride comfort is that it provides:

- Experimental evaluation of an air-inflated seat cushion, and
- New objective measures for evaluating seat cushions.

The research that is included in this thesis is the foundation for a larger investigation into the underlying cause and prevention of discomfort and fatigue. The concept of this future research involves establishing effective methodologies for assessing the impact of vehicle seats on driver fatigue and, ultimately, driving safety due to long-term exposure to the dynamics of the seat. The innovation of this research is in introducing an efficient and
scientific method that can be used by the transportation industry for relating seat
dynamics with driver comfort and fatigue.
2 Background

This section represents background information necessary in understanding the issues of comfort and fatigue in relation to seat comfort. 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 Seat

The commercial truck is unique in that it was specifically developed to transport heavy loads over long distances. Accordingly, high priority has been given to durability and functional efficiency [5]. On the contrary, 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. The requirements driving the evolution of commercial trucks and personal automobiles have led their designs 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 vehicles’ response can be quite different. Accordingly, the truck seat has developed from the unique dynamic properties of the truck. Truck drivers spend extremely long hours at the wheel, relative 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.
2.1.1 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 has the trucking industry has paid increasing 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 [6]. The vertical natural resonance frequency for a typical foam and metal spring seat is around 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 [7].

It was then realized that other important vibration sources existed from the tires, driveline, and engine [8]. Subsequent studies were 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.
2.1.2 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:

1. Foam seat cushion cannot conform to all of the different sizes of individuals and shapes of buttocks
2. Foam degrades over time providing less cushioning

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 functions 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 the 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 [9]. 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, much 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
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 [2]. 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 [10]. Specifically, peak drowsiness was observed during night driving. However, a 1998 study 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” [11]. Quite possibly there are other factors involved in driver fatigue. Efforts to identify these factors require a better understanding of human fatigue, in particular as 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 and 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 [12]. 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.
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, to what observable metrics should be considered? To answer 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.

2.2.1 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 in fact 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 [8]. 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 as absorbers that dampen vibration and hence can become fatigued. This is especially apparent 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 [5].

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 [6]. Certain modes of vibration also have been shown to have an
affect on consciousness. In particular, vibration in the range of 1-2 Hz has been shown to cause sleepiness [13].

2.2.2 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 of the pelvis and their surrounding soft tissues [6]. Figure 2-2 shows the breakdown of 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 [14]](image)

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 tuberosities (bony prominence). 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 to 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 tuberosities [15].

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 tissues by a process of partial pressure differences that exist across the cell and capillary walls. The partial pressure of oxygen \( (PO_2) \) in the arterial

**Figure 2-3. Pelvis Alignment when (a) Standing; (b) Sitting relaxed; (c) Sitting erect; (d) Sitting forward; (e) Sitting back. Reprinted from [6]**
blood is at about 95 mmHg, and the PO₂ 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 cells. 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 [16]. 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 [17]. The general relationship between pressure magnitude and sitting duration is represented in Figure 2-4. 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 [18]](image)

The 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.

2.2.3 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 tuberosities.

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 to the large pressure created by the force and very small contact area. Next, consider that the object has 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 will reduce pressure at the bony prominences, such as the ischial tuberosities, 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 [19]. A study examining the cause of pressure sores concluded that distributing pressure more evenly reduces the onset of ischemia [20].

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. Assuming that human
body reacts in the same way as a mechanical structure, the theory suggests that, in sitting, loading stronger 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. Presented in 1937, this theory suggests that the body is comprised of many sensors and that a greater sensory response is experienced when the area stimulated is larger [21]. In terms of seat comfort this implies that an uncomfortable force applied to the tissue activates more sensors when applied to a larger area as supposed 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) supports the spatial summation theory and suggests that, above a critical pressure, a force distributed over a larger area is less discomforting than the same force concentrated in a small area [22].

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 [23].

2.3 Evaluating Comfort

There has been a trend in the transportation industry over the past 20 years for evaluating ride 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. During all of the 1980’s and early 1990’s, researchers were concentrating 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 shifted to using subjective questionnaires to evaluate riding comfort. During the early 1990’s, researchers discovered that a driver’s posture and the seat suspension were important in riding 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 driving the vehicle.

More recently, researchers have begun to use interface pressures between the driver’s body and the seat to evaluate riding 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 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 riding comfort. The interface pressures take into account many factors in evaluating riding comfort, such as road and vehicle vibrations, seat design (including the suspension and a driver’s 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 be 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 relative.

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 is considered a 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 [24].

- **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 [25].

- **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 [26].

- **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 [27].

- **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 aPerms is that it evaluates the effect of the body pressure change rate for the
contact area in the equivalent pressure range. The aPerms is integrated over the entire body pressure distribution to develop the new seat evaluation index.

The comfort metrics—including vibration and pressure metrics—used in this study are discussed in detail in Chapter 4. The chapter provides a complete discussion of the theory and application of the metrics. Also discussed are two new comfort metrics created specifically for comparing dissimilar types of seat cushions.

### 2.4 Summary

The research presented in this study is based on the background information given in this section and relies entirely on the 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. Many of these measures, however, 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 evaluate the objective measures to determine if there are substantial disparities between seat cushion performances. Furthermore, new objective measures are offered to specifically identify inherent attributes of each cushion type.

The one major problem that remains is that there are currently no available measures for evaluating the fatigue properties of seat cushions. We deal with this problem by making the assumption that what has been proven to be unhealthy will eventually lead to fatigue. Future research will confirm or deny this assumption. 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.
3 Experimental Setup

The following chapter includes a detailed description of the experimental setup for all experiments conducted for the current study. The experimental setup description includes testing equipment, data acquisition hardware and software, and testing procedures.

3.1 AVDL Seat-Testing Rig

The seat-testing rig was designed to provide a controlled environment for evaluating properties of seats and seat cushions. The single axis test rig is shown in Figure 3-1.

![AVDL Seat Tester](image)

Figure 3-1. AVDL Seat Tester

The rig consists of a primary supporting structure and a mobile frame connected by 80/20 Rolling Wheels, as shown in Figure 3-2, to allow for low friction movement in the
vertical direction. A flat plate, called the floor, is mounted onto the mobile frame to support the truck seat. A MTS hydraulic actuator is mounted to the floor to excite the truck seat in the vertical direction. The actuator provides varying road input excitation to the truck seat.

![Figure 3-2. Close-up of Rollers](image)

The truck seat, mounted directly on the floor of the rig, was a Talladega Series 915 by Bostrom Seating. The seat, shown in Figure 1-3, conforms to Federal Motor Vehicle Safety Standards 207 and 302 for heavy truck seats and is typical of most truck seats found in heavy commercial vehicles in the United States. The truck seat came equipped with a suspension consisting of an air spring and a damper, commonly referred to as “air-ride”. Adding to or removing air from the air spring controls the stiffness of the seat suspension. The vertical natural resonance frequency for a typical foam and metal spring seat is around 4 Hz. 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 [4]. In addition to air-ride, other attributes included a 6-inch ride zone, 7-inch fore and aft adjustment, and a fixed lumbar support.
3.1.1 Hydraulic Actuation System

Input disturbances were modeled with a hydraulic actuator manufactured by Material Testing Systems (MTS). The actuator is capable of inputs ranging from single frequency waveforms to multi-frequency signals as well as step and ramp inputs. The hydraulic actuator, shown in Figure 3-4, was one of four components included in the actuation system. This particular model, MTS model 242.09, has a dynamic stroke of ±2 inches (±5 cm) and a force capacity of ±2200 lb (±10 kN). An internal load cell and position sensor allow for force and position measurements. To avoid any lateral loading on the actuator, MTS swivel ends were incorporated into installation on both ends of the actuator.
The actuator is controlled by the MTS 407 Controller shown in Figure 3-5. Offering two modes of control, displacement or force, the 407 Controller is a single-channel, digitally supervised, servo controller. All input signals to the actuator, whether external or internal, must go through or be generated by the 407 Controller.

A SilentFlo Hydraulic Power Unit, MTS Model 505.20, is used to provide fluid to the actuation system. The hydraulic pump, shown in Figure 3-6, has a flow rate of 20 gal/min (75 L/min) and an operating pressure of 3000 psi (210 bar).
Linking the hydraulic pump and the actuator, a MTS Model 263 Hydraulic Service Manifold is used to regulate the hydraulic pressure and flow to the actuator. The manifold is shown in Figure 3-7. The regulated flow is necessary to ensure proper dynamic response of the actuator.
3.1.2 Experimental Seat Cushions

Two types of truck seat cushions were used in the study. The first seat cushion, meant to characterize seat cushions most commonly used in the trucking industry, was a urethane foam cushion that comes standard with the Bostrom Talladega 915 truck seat. This seat cushion, shown in Figure 3-8, consists of a molded polyurethane foam base with a polyester cloth cover.

Figure 3-8. Standard Foam Truck Seat Cushion
The cushion is specifically contoured to provide support, stability, and to reduce contact pressure at the seated interface by increasing the corresponding contact area. This foam seat cushion is representative of the standard in the commercial trucking industry. Designs typically differ with respect to foam type, cover cloth material, contouring, and posture adjustments.

The second experimental cushion used was an air-inflated seat cushion made by The ROHO Group. The air-inflated seat cushion is based on the application of Pascal’s law, which states that the pressure exerted at any point upon a confined liquid is transmitted undiminished in all directions. This implies that uniform seated pressure is the result of sitting on an air-inflated seat cushion. The seat cushion consists of interconnected air cells that allow for airflow between adjacent cells. Interconnection allows each cell to act as a shock absorber with damping characteristics dependent on the pressure, cell size, and air transfer rate between cells. The cushion is constructed of neoprene rubber and there is a contoured orthotic urethane foam base placed below the air-inflated seat cushion. As shown in Figure 3-9, the entire seat cushion assembly is enclosed in a cloth cover. The seated air pressure is determined by the weight of the driver. Tests have indicated that a pressure between 35 and 40 mmHg is optimal for seated comfort.

![Figure 3-9. ROHO Air-Inflated Seat Cushion](image)

28
3.2 Data Acquisition

Data acquisition hardware and software components are separated into two measurement categories—vibration and pressure. Vibration measurement hardware consisted of four accelerometers, an LVDT, a signal conditioner, a dSPACE digital signal processor, the MTS 407 hydraulic controller, and a PC. Matlab/Simulink and dSPACE Control Desk were used as the vibration measurement software. Interface pressure measurements were performed using a Tekscan Body Pressure Measurement System (BPMS) in conjunction with the corresponding BPMS software. The following sections, divided into vibration and pressure measurement, describe the data acquisition setup along with comprehensive descriptions of the hardware and software components.

3.2.1 Vibration Measurement

The 407 controller is used to control the actuator that excites the seat-testing rig as well as monitor the actuator displacement and force. The 407 was used to select both frequency and amplitude of the input signal based on force limitations of the actuator along with physical limitations of the test rig. Transducers consist of four PCB model U352L65 accelerometers and one UniMeasure VP510-10 Velocity-Position transducer for measuring:

- Floor Acceleration
- Base Acceleration
- Seat Acceleration
- Transverse Acceleration
- Relative Displacement
- Relative Velocity

As shown in Figure 3-10, the acceleration signals are passed through a Frequency Devices model 9002 LP01 8-pole, 6-zero elliptic low pass filter. For current experiments, the cutoff frequency was set at 10.5 Hz. The dSPACE Autobox provides
digital signal processing of the transducer and actuator signals. These signals are then digitally converted and stored in a personal computer.

Figure 3-10. dSPACE Data Acquisition Flowchart

Three components made up the data acquisition system for vibration measurement: dSPACE, MATLAB, and Simulink. MATLAB was the foundation for Simulink, which, through the Real Time Workshop toolbox, the three components were linked. All models for data acquisition and controller implementation were built within Simulink, complete with inputs and outputs. dSPACE was used to compile these models and load them to the dSPACE DSP chip. The dSPACE system consists of two components, Control Desk and the AutoBox.

The hardware component of dSPACE is the dSPACE AutoBox, which contains the DS 1003 processor board. The AutoBox also contains an I/O card with 20 inputs and 8 outputs that were used to collect data and output control signals. Information flows to
and from the AutoBox via a dedicated Ethernet connection. The AutoBox is shown in Figure 3-11.

![AutoBox](image)

**Figure 3-11. dSPACE AutoBox**

The signals we are measuring on the seat testing rig are coming into the AutoBox through the DS2201ADC (analog to digital converter). Within Simulink, the 20 input channels of the AutoBox are multiplexed into 5 ports with 4 input channels per port. For this reason, the signals must pass through a demultiplexer that separates the incoming signals. Real-time control occurs through the use of the DS2201DAC (digital to analog converter). In this case, the 8 ports correspond directly to the 8 output channels on the AutoBox.

Testing software includes MATLAB and Simulink 5.3, dSPACE Control Desk 3.0, and Tekscan BPMS 5.01. Control Desk is the user interface software. Within Control Desk data can be viewed and model parameters can be tuned in real-time. The ability to adjust controller parameters real-time simplifies controller development and makes dSPACE a powerful tool for rapid prototyping. Signal processing systems are built in Simulink via block diagrams as shown in Figure 1-9. These block diagrams are used to specify and manipulate output controller signals and input transducer signals. These block diagrams are then downloaded into the Control Desk software, which communicates with the Autobox. MATLAB is the communicating language between Simulink and dSPACE. Subsequently, all data analysis occurs within MATLAB. Control desk provides real-time analysis of input signals as shown in Figure 3-13.
Figure 3-12. Simulink Signal Processing Diagram
3.2.2 Pressure Measurement

Dynamic interface pressure was measured using the Tekscan Body Pressure Measurement System (BPMS). Shown in Figure 3-14, the system is comprised of 4 components.

1. Pressure Sensing Pad
2. Sensor Handle
3. PC Interface Board and BPMS 5.01 Software
4. Calibration Unit

Pressure distribution mapping of the CLI was 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 [28].

![Figure 3-14. Tekscan Body Pressure Measurement System](Image)

The pressure pad is connected to the PC interface board via a sensor handle. Tekscan BPMS software, shown in Figure 3-15, is used to process pressure information from the interface board, present the information as a color-coded real-time display, and record the information (as a ‘movie’) for later review and data analysis. The BPMS software allows multiple views of the pressure maps such as the standard 2D view, 2D contoured view, 3D wireframe view, and 3D solid view. Another important feature of the software is that it can create a “movie-averaged” view in which each cell is averaged over the entire test run to form a composite pressure map.
Figure 3-16 presents a diagram illustrating the sensing system and a simplified electrical schematic of the 8-bit electronics, which scans the intersecting points of the sensor's rows and columns and measures the resistance at each contact point. These points are read in the presence of multiple contacts, while simultaneously limiting the possible current flow through the device. Each contact location is represented by a variable resistor whose value is high when no force is applied to it.

The Tekscan sensing system is controlled using a personal computer and software. The sensor is read sequentially by driving one of the rows and sensing one of the columns. The microprocessor selects the row and column to be read by identifying the proper address for each intersecting row and column.
Post processing of pressure data was performed in Matlab. Pressure data was saved in ASCII format using the Tekscan BPMS software and then, through Microsoft Excel, converted to a format readable by Matlab. The Microsoft Excel VBA conversion code along with all Matlab data reduction code can be found in Appendix B.

The digital output from the sensor pad is converted to engineering units, such as psi or mmHg, through Calibration. The calibration unit allows for uniform pressure application using a bladder tester, which inflates a rubber diaphragm against the sensor surface. The sensor pad is placed inside the uniform pressure applicator and the bladder is inflated to a known pressure. The pressure along with the digital output from the pressure pad is used by the BPMS software to individually calibrate each pressure-sensing element. This method is termed Calibration.

Equilibration is the method by which the software determines a unique scaling factor for each sensing element to ensure that each sensor outputs equivalent readings when a
uniform pressure is applied. To perform equilibration, the uniform pressure applicator is used in conjunction with BPMS software.

3.3 Cushion Loading Indentor (CLI)

For the purpose of researching comfort and long-term fatigue of a seated driver, an indenter system was designed and built by the Advanced Vehicle Dynamics Laboratory at Virginia Tech. The purpose of the indenter system was to adequately simulate variable pressure distribution, similar to what would be attained by a seated person, in a repeatable manner. As highlighted on Figure 3-17, the indenter system consists of the following 5 components:

1. a 0.5mm thin layer of neoprene,
2. a human buttocks shaped polyurethane plastic mold,
3. a soft weighting system,
4. a base plate with loading rings, and
5. 3.5 x 5 inch weights for variable loading capability.

Figure 3-17. Components of Cushion Loading Indentor
The indenter system is prepared, as shown in Figure 3-18, by placing the 0.5mm sheet of neoprene directly onto the surface of the seat cushion. The neoprene is used specifically to simulate the resiliency of human tissue. Placed on top of the neoprene is the human shaped polyurethane mold, made based on an average 200 lb seated person. Two golf balls are placed inside the mold to simulate high-pressure areas analogous to the high-pressure areas created by the ischial tuberosities. On top of the mold is placed a soft weighting system used to fill voids between the mold and base plate created by the inherent contouring of the cushion. The base plate, which is instrumented with six weight loading rings for repeatable loading, is then placed on top of the soft weight. The 3.5 x 5 inch weights are then placed on the loading rings of the base plate and secured to the base plate by a washer and nut. The user has the option of loading the base plate in any configuration necessary.
3.4 Terminology

Vibration measurements are made at the floor, base, and seat of the test rig. Transverse acceleration of the cushion loading indentor and relative measurements were also measured.

![Figure 3-19. Seat Tester With Position of Dynamic Measurements](image)

Referring to Figure 3-19, the terminology is as follows:

1. **Seat**: vertical measurements made on top of the seat cushion at the interface between the indentor and the seat cushion.
2. **Base**: vertical measurements made at the base of the seat on the frame that is directly below the seat cushion.
3. **Floor**: vertical measurements made at the interface of the seat attachment to the vehicle structure; commonly, the truck floor.
Based on these definitions, the following are defined:

- **Transverse**: horizontal measurements made at the seat.
- **Relative displacement**: displacement of the base relative to the floor.
- **Relative velocity**: velocity of the base relative to the floor.

### 3.5 Input Test Signals

Truck cabs vibrate at a frequency of 2-10 Hz. Accordingly, input signals were chosen to accurately simulate real driving conditions for truck drivers. Three distinct input signals were used for testing. To evaluate the vibration characteristics of the seat and seat cushion, chirp and step signals were implemented; the chirp to determine the natural frequency and transmissibility and the step to evaluate damping characteristics for each cushion type. For pressure measurements, the third input used was a broadband random excitation ISO2 signal. The ISO2 signal was developed by the International Standard Organization to simulate the low frequency content typically experienced by heavy trucks. The following sections describe the input signals used for testing.

#### 3.5.1 Chirp Input

The chirp input signal in MATLAB generates samples of a linear swept-frequency signal from 0.5 to 10.5 Hz with starting amplitude of 0.75 inches and duration of 30 seconds as shown in Figure 3-20. This signal is then fed through a 1.5 Hz highpass filter to produce a decaying chirp signal. The application of a filter was necessary due to the physical limitations of the hydraulic actuation system.
3.5.2 Step Input

Simulation of impact excitation was accomplished with a step input. The step input was used for the express purpose of observing the damping properties of each seat cushion type. The step input used was 1 inch amplitude, as shown in Figure 3-21.
3.5.3 ISO2 Input

ISO2 input is specified by International Standard Organizations, and it is usually used as test input for products that relate to human comfort, such as seat suspensions. As shown in Figure 3-22, with frequency content shown in Figure 3-23, ISO2 is a broadband random excitation signal with an acceleration power spectrum that spreads from approximately 1 to 5 Hz. The low frequency signal is typical of road excitation experienced by heavy trucks. For this reason, pressure measurements are of significant importance when experimenting with the ISO2 signal. The excitation signal was created in Matlab, and the data file was downloaded to the dSPACE AutoBox for input to the hydraulic actuator.
Figure 3-22. Power Spectrum of ISO2 Excitation

Figure 3-23. Sample Time History of ISO2 Displacement
4 Test Methods

Objective measures for predicting the relative comfort of one seat compared to another can be divided into the two categories of vibration analysis methods and interface pressure analysis methods due to the known consequences that vibration and pressure have on the human body. Vibration affects the human body by causing the person to contract muscles in an attempt to dampen vibration [6]. This ultimately results in discomfort and muscle fatigue. High pressure at bony prominences, such as the ischial tuberocities, can cause loss of blood and nutrient flow resulting in discomfort and possibly fatigue [29]. Others measures, including physiological and anthropomorphic measurements, have also proved influential, but are beyond the scope of the current study. Table 1 provides a summary of current objective analysis methods, broken up into categories of vibration and pressure. It includes specific measurements used and the information that results. These objective measures represent the latest methods in ride comfort research.

This section presents the some of the objective measures used for quantitatively describing the differences between foam and air-inflated seat cushions. Also provided, is a detailed description of the effects that pressure and vibration have on the comfort perception of the seated driver.

4.1 Vibration Methods

Practical limitations of road construction and maintenance result in structural damage that causes road roughness experienced by the driver. Road roughness encompasses a wide variety of excitation sources including random deviations and potholes defined by uneven road surfaces. Different work vehicles expose the driver to different types and different levels of vibration. The terrain over which it passes affects a vehicle’s vibration pattern. The tendency of each of the many spring/mass systems within the vehicle is to vibrate at, or near to, their particular resonant frequency. The level of this vibration is dependent upon the input to the vehicle at the frequency in question.
### Table 4-1. Vibration and Pressure Analysis Methods for Evaluating Comfort

<table>
<thead>
<tr>
<th>Category</th>
<th>Analysis Method</th>
<th>Measurement</th>
<th>Information</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration</td>
<td>Time Domain</td>
<td>• Single Frequency Response</td>
<td>Measures response of seat at important frequencies; can be related to human tolerance / comfort curves such as Figure 1</td>
<td>[6]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Step Response</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Magnitude (r.m.s, avg, peak)</td>
<td>Ability of seat to dissipate energy from sudden impact excitations, i.e. damping</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vibration Dose Value (VDV)</td>
<td>Statistical comparison values; can be related to human tolerance/comfort curves.</td>
<td>[7]</td>
</tr>
<tr>
<td></td>
<td>Frequency Domain</td>
<td>• Transmissibility</td>
<td>Measures how much vibration is transmitted from the road to the driver</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Power Spectral Density (PSD)</td>
<td>Measures how vibration magnitude varies with frequency</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• SEAT%</td>
<td>Measures transmissibility, frequency-weighted by subjective comfort scales</td>
<td>[7]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Component Ride Value</td>
<td>Measures SEAT% taking into account all axes of vibration</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>Static Evaluation</td>
<td>• Peak/Average Pressure</td>
<td>Statistical comparison values; can be used to predict ischemia</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Contact Area</td>
<td>Ability of seat cushion to comfort to seated person</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Static SPD%</td>
<td>Ability of seat cushion to uniformly distribute pressure</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Seat Compliance (Cp)</td>
<td>Measures pressure distribution taking into account seat deflection</td>
<td>[30]</td>
</tr>
<tr>
<td>Pressure</td>
<td>Dynamic Evaluation</td>
<td>• Pcrms</td>
<td>Ability of seat cushion to limit pressure changes of the seated person due to transient inputs</td>
<td>[26]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• aPcrms</td>
<td>Measure of Pcrms taking into account pressure distribution</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Dynamic SPD%</td>
<td>Ability of seat cushion to maintain uniform pressure distribution under dynamic conditions</td>
<td></td>
</tr>
</tbody>
</table>
Vibration levels for a heavy transport truck typically range from 0.42 to 2.0 m/s² in the vertical direction with a mean value of 0.72 m/s² [31]. According to the International Standard for whole-body vibration most vehicle rides will exceed the comfort level of 0.315 m/s² after only a few hours. Some of the rougher truck rides will be in some likely health risk zone in less than 8 hours [31]. According to Randall, truck drivers suffer severe discomfort within minutes on very rough roads, within an hour or two on poor roads, and within a few hours on good roads [32]. Furthermore, spinal injuries have also been associated with prolonged vibration exposure. For instance, research has found that truck drivers are four times more susceptible to disc herniation [33].

4.1.1 Human Vibration Limits

Objective measures for evaluating comfort in the presence of vertical vibrations are generally in the form of human tolerance limits. That is, for a given frequency range there is a threshold of vibration magnitude that should not be exceeded. Although some controversy exists, these standards are generally agreed upon. Particular standards were created, beginning in 1974, by the International Organization for Standardization (ISO) in an attempt to “give numerical values for limits of exposure for vibrations transmitted from solid surfaces to the human body in the frequency range 1 to 80 Hz”. These standards were published in the form of ISO Standard 2631, which define human fatigue limits to varying modes of vibration. ISO 2631 has been modified several times from its initial form to eliminate any ambiguity. Figure 1-1 displays the results of the 1985 standard in the form of a plot displaying human tolerance to vertical vibrations as a function of both time and frequency. It can be seen that the human body is most sensitive to the frequency range between 4 and 8 Hz. This frequency range is extremely important when designing for human comfort. That is, input vibration between 4 and 8 Hz should be attenuated as much as possible to prevent fatigue. However, according to the plots, prolonged vibration at lower and higher frequencies can also become intolerable. Another form of ISO 2631 is given by Figure 4-2, which focuses on a smaller excitation frequency bands.
Figure 4-1. Vertical Vibration Exposure Criteria Curves Defining Equal Fatigue-Decreased Proficiency Boundaries; Reprinted from [31]

Figure 4-2. Lateral Vibration Exposure Criteria Curves Defining Equal Fatigue-Decreased Proficiency Boundaries; Reprinted from [31]
4.1.2 Step Response

The step response is an effective method for evaluating the comparative damping characteristics of automobile seats. Characteristics such as peak response and settling time, shown in Figure 4-3, were used to compare seat cushions as well as to observe the effects of cushion degradation over time. Cushion degradation was determined by testing the seat cushion over a 12-hour period at 4-hour intervals. The step response is a valid measure of seat performance when subjected to impact excitation such as a pothole.

![Figure 4-3. Typical Acceleration Response Showing Peak Response and Settling Time](image)

4.1.3 Transmissibility

The most effective method of determining the vibration characteristics of a seat is by measuring the transmissibility. That is, to compare the acceleration on the seat with that at the base or floor of the seat in the frequency range of interest. From Figure 4-4, the transmissibility between the seat and floor is defined as TR1 and the transmissibility between the seat and base is defined as TR2. TR1 is referred to as base transmissibility and TR2 as seat cushion transmissibility.
Mathematically, the equations for base and cushion transmissibility are calculated as

\[ TR1(f) = \frac{G_{ss}(f)}{G_{ff}(f)} \]  

(1)

and

\[ TR2(f) = \frac{G_{ss}(f)}{G_{bb}(f)} \]  

(2)

where \( G(f) \) is the power spectrum (or auto spectrum) of the frequency signal. The power spectrum can be expressed as

\[ G_{yy}(f) = Y(f) \cdot Y^*(f) \]  

(3)

where \( Y^*(f) \) indicates the complex conjugate of the collection of frequency spectrum \( Y(f) \). The frequency spectrum was obtained by using an “nfft” point Fast Fourier Transform algorithm, where nfft is the length of the conditioned acceleration time signal.
4.1.4 Seat Effective Amplitude Transmissibility

A valuable method for comparing one seat to another is the objective measure of Seat Effective Amplitude Transmissibility (SEAT%), which is defined as

\[
SEAT\% = \left[ \frac{\int G_{ss}(f)W^2(f)df}{\int G_{ff}(f)W^2(f)df} \right]^{1/2} \times 100
\]  

(4)

This method is a measure of the transmission of acceleration from the floor to the seat cushion where \(G_{ss}(f)\) and \(G_{ff}(f)\) are the seat and floor power spectra, respectively. The frequency dependent weighting factor \(W(f)\), as defined in Table 2, is based on research of human discomfort [7]. The SEAT% value may be considered to be the ratio of the frequency weighted ride experienced on the seat to the frequency weighted ride, which would be experienced if the seat were rigid, expressed as a percentage. That is, for a seat with no vibration suppression, the output seat acceleration would be the same as the input floor excitation resulting in a SEAT% value of 100%.

Table 4-2. Frequency Dependent Weighting Factors for Calculating SEAT% [5]

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Weighting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 &lt; f &lt; 2.0</td>
<td>(W(f) = 0.4)</td>
</tr>
<tr>
<td>2.0 &lt; f &lt; 5.0</td>
<td>(W(f) = f/5.00)</td>
</tr>
<tr>
<td>5.0 &lt; f &lt; 16.0</td>
<td>(W(f) = 1.00)</td>
</tr>
<tr>
<td>16.0 &lt; f &lt; 80.0</td>
<td>(W(f) = 16/f)</td>
</tr>
</tbody>
</table>

The method is especially valuable in evaluating automotive seats because it incorporates human discomfort levels to vibration in all three axes. For the current evaluation, however, only vertical vibration is considered. A value of 100% would indicate that the seat is providing no isolation and is no more comfortable than sitting on the floor of the vehicle.
vehicle. Decreasing values indicate a more comfortable seat. There is no accepted method of relating a value of SEAT% to the level of comfort or discomfort incurred. It is more useful as a quantitative tool for comparing different seats.

4.2 Pressure Methods

It is widely known that high concentrated pressures applied to human tissue, particularly over bony prominences, can cause loss of blood and nutrient flow and over time lead to ischemia. It has been shown that there is an inverse relationship between pressure magnitude and time to develop pressure sores. Capillary arterial pressure is 30 mmHg. Several studies have suggested that a pressure of 60 mmHg applied for 1 hour would result in tissue ischemia [34].

When designing for seat comfort, there are two main theories regarding pressure distribution. The first is to distribute pressure uniformly across the seated area and the second is to concentrate forces on stronger parts of the body [18]. Both theories have supporting evidence. Research on the cause and prevention of pressure sores, however, has always suggests that lower pressures are desirable for long-term sitting. This seems to indicate that what is comfortable might not always be healthy.

In recent years there has been a great deal of new research in the field of ride comfort that focuses on pressure measurement. This research has prompted new methods for measuring pressure such as Tekscan’s resistive based pressure pad. The ability to measure pressure easily and effectively has led to different methods for quantifying subjective comfort. This following section discusses some of these methods and their merits.

4.2.1 Pressure Mapping

The pressure map is a qualitatively effective way of getting an overall picture of pressure distribution. The Tekscan BPMS software allows several modes of viewing the pressure map of a seated individual. The 3-dimensional view, shown in Figure 4-5, gives an overall picture of pressure distribution and immediately reveals high and low pressure areas. The 3-dimensional view was generally used for Equilibration process of making
sure that each sensing cell output equal pressure in the presence of an equally distributed load. The 2-dimensional view, shown in Figure 4-6, gives a more precise picture of pressure distribution. High-pressure areas and their exact locations can be pinpointed immediately using the color-coded legend as an indicator of pressure level. The Tekscan software also offers a variety of display options including averaging.

Averaging is the process by which each cell’s pressure value is modified to reflect the value of its neighbor. This results in a smoother image. For example, for a group of nine cells shown below, the averaged pressure value of the middle cell $X$ is given by Equation 5.

![Figure 4-5. 3-Dimensional Pressure Map of a Seated Person](image)
where the load recorded in each cell (A-G) is used to calculate the averaged pressure in cell X [28]. If cell X is on or near the edge of the sensor, the values of the neighboring cells that are not loaded are not used in the calculation.

Figure 4-6. 2-Dimensional Pressure Map of a Seated Person
4.2.2 Pressure Change Rate (Pcrms)

Researchers at Daihatsu Motor Co, Ltd, when comparing three different types of foam seats, found that pressure change rate root-mean-square (Pcrms) was the most accurate measure for “unpleasant sensations” due to transient vibrations [26]. Pcrms is calculated as follows:

\[
P_{crms} = \left\{ \frac{1}{T} \int_{0}^{T} \left( \frac{dP(t)}{dt} \right)^2 \, dt \right\}^{1/2}
\]  

where \( T \) is the total time period and \( P(t) \) is the dynamic pressure. The research suggests that a lower pressure change rate will result in a more comfortable seat cushion. Similar to SEAT\%, there is no threshold value that separates a comfortable seat from an uncomfortable one. There is also no difference in Pcrms values that indicates a discrepancy in perceived comfort. Pcrms, however, can be used as an objective comparison for evaluating different seat cushions made of similar materials.

4.2.3 Area Pressure Change Rate (aPcrms)

There are inherent health issues with sitting for long periods of time. When sitting on a surface, the soft tissues can be compressed and deformed by the underlying skeletal structure (bony prominence), particularly at the ischial tuberocities [34]. At extreme pressures this creates an obstruction of the blood supply resulting in a deficiency of oxygen to tissue cells resulting in 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. A new method suggested for comparing seat cushions from interface pressure measurements is Area Pressure Change Rate (aPcrms). The method is an adaptation of Pcrms to include the pressure distribution of the seated person.

\[
aPcrms = \sum_{i=1}^{4} A(r_i)Pcrms(r_i)W(r_i)
\]
For each of the n individual pressure cells an average pressure, \( p_m(n) \), is calculated over the test run. Each area \( A(r_i) \) is determined by calculating the total area of cells with average pressure within the specified pressure ranges, \( r_i \). There are \( N=4 \) pressure ranges where \( r_i \) defines the \( i^{th} \) pressure range. The weighted pressure change rate, \( P_{crms}(r_i) \), is the average \( P_{crms} \) of cells within each pressure range. A weighting factor, \( W(r_i) \), is incorporated for each pressure range. The pressure ranges and weighting factors are defined in Table 2.

**Table 4-3. Pressure Ranges and Weighting Factors Used in Calculating aPcrms**

<table>
<thead>
<tr>
<th>Pressure Range, ( r_i )</th>
<th>Weighting Factor, ( W(r_i) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_1 : 40 \leq p_m(n) &lt; 60\text{mmHg} )</td>
<td>( W(r_1) = 1 )</td>
</tr>
<tr>
<td>( r_2 : 60 \leq p_m(n) &lt; 80\text{mmHg} )</td>
<td>( W(r_2) = 2 )</td>
</tr>
<tr>
<td>( r_3 : 80 \leq p_m(n) &lt; 100\text{mmHg} )</td>
<td>( W(r_3) = 3 )</td>
</tr>
<tr>
<td>( r_4 : p_m(n) &gt; 100\text{mmHg} )</td>
<td>( W(r_4) = 4 )</td>
</tr>
</tbody>
</table>

The choosing of these pressure ranges and the corresponding weighting factors requires some justification. From Chapter 2, all living cells require adequate oxygen to survive. Loss of oxygen, due to applied pressure, over extended durations leads to tissue necrosis. The external pressure required to close blood capillaries at normal human arterial pressures and flows is generally accepted as approximately 32 mmHg [16]. If capillary flow is obstructed by such external pressures, it is presumed that the resulting ischemia leads to the critical tissue damage that initiates a decubitus ulcer. For this reason, we approximate a lower threshold of pressure as 40 mmHg and assign the lowest weighting factor of \( W(r_1) = 1 \). Interface pressures below this threshold value is of little concern due to the fact that blood flow is not restricted. Similarly, the partial pressure of oxygen in the arterial blood is at approximately 95 mmHg [16]. Hence, pressure above 95-mmHg will cause oxygen flow to be restricted. For this reason, we approximate an upper limit of desired pressure to be 100 mmHg. Any pressure above this threshold is considered extremely undesirable and is given the largest weighting factor of \( W(r_4) = 4 \). Pressures
between these two extremes of 40 mmHg and 100 mmHg are divided into 4 pressure ranges incremented by 20 mmHg.

The weighting factors for the aPcrms calculation were chosen for need of a starting point. The affects of varying applied pressure levels on human tissue is not well known, at least not to the level of knowledge that we have for how vibration affects the human body. For instance, research on human vibration has shown that vertical vibration at 4 Hz carries a weighting factor 2 times greater than vertical vibration at 2 Hz. That is, it is twice as discomforting to experience vertical vibration at 4 Hz as opposed to 2 Hz. On the contrary, for instance, it is not known whether pressures of 100 mmHg is 2 or possibly even 10 times more discomforting than pressures of 60 mmHg. Knowledge of such weighting factors requires subjective research to determine the level of discomfort associated with each pressure range. For this reason, we have chosen a simple approach by dividing the ranges into relatively small increments of 20 mmHg and separating them by a linearly increasing weighting scale. It is apparent that the calculation of aPcrms favors a seat cushion that distributes pressure more evenly, hence lowering high-pressure regions. Justification for such preferential treatment comes from discussion in Section 2.2.3, which references research showing that higher levels of comfort have been associated with more evenly distributed pressure.

For the purposes of this study the following procedure was used to calculated aPcrms:

1. Determine the contact area, A(r<sub>i</sub>) from the pressure map data for each of the following pressure ranges – 40 to 60mmHg, 60 to 80mmHg, 80 to 100mmHg, and greater than 100mmHg.

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

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

4. Calculate Perms for each cell.
5. Calculate an average Pcrms, defined as $P_{crms(r_i)}$, within each of the following pressure ranges – 40 to 60mmHg, 60 to 80mmHg, 80 to 100mmHg, and greater than 100mmHg.

6. Calculated a “Weighted Pcrms” for each of the pressure ranges – 1 times the average Pcrms for 40 to 60mmHg, 2 times the average Pcrms for 60-80mmHg, 3 times the average Pcrms for 80 to 100mmHg, and 4 times the average Pcrms for greater than 100mmHg.

7. Calculate the $aP_{crms(r_i)}$ by multiplying each weighted Pcrms value by the corresponding contact area $A(r_i)$.

8. Calculate $aP_{crms}$ by summing each value of $aP_{crms(r_i)}$.

The $aP_{crms}$ accounts for the pressure distribution, contact area, and the rate of change of pressure across the seated area. A larger contact area along with a smaller pressure distribution and lower rate of change results in a smaller $aP_{crms}$ value. The subjective field-testing that has been conducted in an un-published study shows a direct correlation between the $aP_{crms}$ numbers and ride comfort. The results of that study show that the lower the $aP_{crms}$ is, the higher the seat cushion is rated in subjective evaluations for both comfort (short time exposure) and fatigue (long-time exposure).

### 4.2.4 Seat Pressure Distribution (SPD%)

Research in seat comfort has established a positive relationship between uniform pressure distribution and perceived comfort [27]. Furthermore, lower pressures are always more desirable in terms of long-term tissue integrity. Since a uniform pressure alleviates high concentrated pressure, we assume that a more uniform distribution is better in terms of comfort and fatigue. One way of quantitatively measuring the ability of a seat cushion to uniformly distribute pressure is with Seat Pressure Distribution (SPD%), defined as:

$$SPD\% = \frac{\sum_{j=1}^{n}(p_i - p_m)^2}{4np_m^2} \times 100$$

(8)
This method is used in conjunction with a body pressure mapping system where \( n \) is the total number of nonzero cell elements, \( p_i \) is the pressure at the \( i^{\text{th}} \) cell, and \( p_m \) is the mean pressure of the \( n \) elements. A lower percentage value is descriptive of a more uniformly distributed seat cushion. For a perfectly uniformly distributed seat cushion 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 average pressure from each individual pressure-sensing element over a test run. Furthermore, a time trace of SPD\% can be examined to determine the ability of the seat cushion to maintain uniform pressure.

As an example, Figure 4-7 shows the static pressure distribution maps for a human test subject when seated on three different support surfaces; a hard board, a standard foam seat cushion, and an air-inflated seat cushion. These support surfaces offer varying levels of support and pressure distribution; the hard board being the most extreme case. The objective metric SPD\% offers a method for quantifying these differences.

![Pressure Maps of Three Seating Surfaces Using Human Subject](image)

**Figure 4-7. Pressure Maps of Three Seating Surfaces Using Human Subject**

Figure 4-8 presents the static SPD\% value applied to the three support surfaces. There is a 58% increase in uniform distribution from the board to the foam cushion and a further 48% increase in from the foam cushion to the air-inflated seat cushion. It is worth noting that a lower value indicates a more evenly distributed support surface.
Figure 4-8. Static SPD% for Three Seat Surfaces (Air-Inflated Cushion, Standard Foam Cushion, Hard Board)
5 Standard Foam Cushion Analysis

This section presents the experimental results for the standard foam seat cushion. Analysis of the standard foam seat cushion is divided into two parts—vibration analysis and pressure distribution analysis. Within each of these categories specific input test signals were used to determine specific properties of the seat cushion. Input signals used for vibration analysis included a chirp input and a step input. Input signals used for the pressure distribution analysis were the chirp input and the ISO2 input. Each test was performed over a 12-hour period, repeated every 4 hours in order to assess the effect of the set that occurs at the seat cushion due to the static weight applied to it.

5.1 Vibration Analysis

Vibration analysis of the standard foam seat cushion was accomplished using a linearly swept frequency sine wave (chirp signal) and a 1-inch step input. The chirp signal was implemented to determine the vibration characteristics via power spectral densities and transmissibility plots. The step input was implemented to define the damping properties of the seat cushion. The chirp and step inputs are previously defined in detail in Chapter 3.

5.1.1 Chirp Results

The power spectral density (PSD) of the base of the seat, shown in Figure 5-1, gives the frequency-weighted amplitude of vibration at each frequency form 0.5 to 10 Hz over the 12-hour test period for each 4-hour test. Similarly, the PSD measured on the seat cushion is shown in Figure 5-2. As expected, the results exhibit two modes of vibration typical of a two degree of freedom system. The frequency at each mode will become evident when observing transmissibility. The seat base displays an increased level of acceleration in the 2-4 Hz range and in the 8-10 Hz range. It is worth noting that the human body is quite sensitive to vibration in the 4-8 Hz range. The seat suspension has significantly reduced vibration in this range. The PSD of the seat cushion, however, shows that the foam seat cushion demonstrates much higher levels of acceleration in this 4-8 Hz range.
Figure 5-1. Power Spectral Density of Base Acceleration for Chirp Input (Foam Cushion)

Figure 5-2. Power Spectral Density of Seat Acceleration for Chirp Input (Foam Cushion)
Over time, the foam seat cushion does display some change in its power spectral density. From hour 0 to hour 4 the magnitude of vibration is increased at low frequencies and decreased at higher frequencies. This effect is significant in that the human body is much more tolerant to lower frequencies and increases in magnitude at these low frequencies generally translates to less comfort and more fatigue in a shorter amount of time. It should be recalled that fatigue is dependent on time, frequency, and magnitude. That is to say, increased magnitude between 4 - 8 Hz would result in a decreased time to reach a fatigue tolerance limit.

Figure 5-3 and Figure 5-4 respectively show the transmissibility from the floor to the seat base and from the seat base to the seat cushion. Both figures exhibit a natural frequency of approximately 1.5 Hz. As shown in Chapter 2, this is typical of a truck seat with a suspension. Also shown in the figures is that there is relatively no change difference in frequency response between the base and the seat. The seat suspension absorbs most of the gross input vibration from the floor and the dynamics of the dynamics of the seat cushion are comparatively negligible. Furthermore, the time tests had little effect on the dynamics of the seat suspension as shown by nearly identical responses from 0 -12 hours.

![Figure 5-3. Transmissibility From Floor to Seat Base (Foam Cushion)](image-url)
The transmissibility from the floor input to the seat cushion, referred to as cushion transmissibility, is shown in Figure 5-5. The seat cushion initially has a natural frequency of approximately 6 Hz. Over time there is a shift in natural frequency to about 6.8 Hz after 12 hours. This shift in natural frequency represents stiffening of the foam based seat cushion. It is known that when polyurethane foam is loaded it becomes compressed and over time begins to lose its resiliency. That is, it loses its ability to damp vibration. If the cushion were to become extremely stiff, it would act as a solid mass resulting in direct transmission of input vibration. The cushion also exhibits an increase in acceleration amplitude over time. As the cushion becomes stiffer the foam begins to lose its ability to decrease the magnitude of input vibration.

One of the metrics typically used when analyzing the effects of vibration on a given automotive seat is Seat Effective Amplitude Transmissibility (SEAT%). As previously discussed, SEAT% is a measure vibration transmitted from the floor through the seat weighted by factors of human tolerance to vertical vibration. The SEAT% values for the standard foam seat cushion are given in Table 5-1. The values are relatively constant for
the 12-hour tests, with an average value of 37.1%. Without comparison, these values are of little meaning. The use of SEAT% is better served by comparing one seat to another. A good baseline, however, is a hard board seating surface with no seat suspension, which would yield direct transmission of vibration and a SEAT% value of 100. Obviously the foam seat cushion along with the air-ride suspension acts as a much better seating surface.

![Figure 5-5. Transmissibility from Floor to Seat (Foam Cushion)](image)

**Table 5-1. SEAT% Values For Standard Foam Seat Cushion**

<table>
<thead>
<tr>
<th>Hour</th>
<th>SEAT %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>38.38</td>
</tr>
<tr>
<td>4</td>
<td>36.39</td>
</tr>
<tr>
<td>8</td>
<td>36.81</td>
</tr>
<tr>
<td>12</td>
<td>36.76</td>
</tr>
</tbody>
</table>
5.1.2 Step Results

The step response of the standard foam seat cushion represents the transient response, analogous to a vehicle driving over a pothole. As with the chirp input tests, the step response was examined every 4 hours over a 12-hour duration. Shown in Figure 5-6 is the step response of the seat base. The seat is heavily damped with a settling time of approximately 0.7 seconds. This is primarily due to the damper of the seat suspension, which dissipates most of the energy of the impact to the seat. More importantly we see that over time, the seat base shows relatively no change in its transient response with no change in peak response and settling time. Similar results are shown in the step response of the seat cushion, shown in Figure 5-7. The seat cushion does amplify the vibration transmitted from the seat base with an initial peak response of approximately 4 m/s$^2$. The settling time, however, is decreased to approximately 0.6 seconds relative to the seat base.

![Figure 5-6. Base Acceleration Time Response to a 1-inch Step Input (Foam Cushion)](image)

65
The main conclusion taken from the step response is that the seat suspension, particularly the damper, absorbs most of the impact from the step input. This is evident in the relatively small change in the base and seat transient responses. That is to say, in terms of vibration, the effects of sitting on the base of the seat with no seat cushion would not be much different than sitting on the seat cushion when exposed to sudden changes in road elevation. From common experience, however, it is known that sitting on a hard surface is very uncomfortable due to the high pressure that is created at the seated interface. It is for this reason that a pressure distribution analysis is necessary when evaluating a seat cushion in terms of comfort and fatigue.

### 5.2 Pressure Distribution Analysis

Pressure distribution analysis of the standard foam seat cushion is divided into two sections of chirp results and ISO2 results. The chirp signal was implemented to determine the identify pressure distribution performance over a range of frequency, for 0.5 to 10.5 Hz. The ISO2 input signal was used specifically to emulate the typical low

---

**Figure 5-7. Base Acceleration Response to a 1-inch Step Input (Foam Cushion)**
frequency, high amplitude road conditions experienced by heavy commercial trucks. The chirp and ISO2 input signal are previously defined in detail in Chapter 3.

### 5.2.1 Chirp Results

Pressure distribution analysis was performed using the chirp input in order to examine the performance of the standard foam seat cushion at multiple frequencies. Figure 5-8 displays the “movie-averaged” pressure maps along with objective metric values for each 4-hour test.

<table>
<thead>
<tr>
<th>Chirp Hour 0</th>
<th>Chirp Hour 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Chirp Hour 0" /></td>
<td><img src="image2" alt="Chirp Hour 4" /></td>
</tr>
<tr>
<td>Contact area = 164.32 in^2</td>
<td>Contact area = 165.28 in^2</td>
</tr>
<tr>
<td>Force = 97.59 lb</td>
<td>Force = 105.62 lb</td>
</tr>
<tr>
<td>Pcrms = 6.54 psi/s</td>
<td>Pcrms = 5.98 psi/s</td>
</tr>
<tr>
<td>aPcrms = 283.58</td>
<td>aPcrms = 288.90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chirp Hour 8</th>
<th>Chirp Hour 12</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3" alt="Chirp Hour 8" /></td>
<td><img src="image4" alt="Chirp Hour 12" /></td>
</tr>
<tr>
<td>Contact area = 165.76 in^2</td>
<td>Contact area = 166.24 in^2</td>
</tr>
<tr>
<td>Force = 107.29 lb</td>
<td>Force = 108.73 lb</td>
</tr>
<tr>
<td>Pcrms = 5.93 psi/s</td>
<td>Pcrms = 5.59 psi/s</td>
</tr>
<tr>
<td>aPcrms = 299.70</td>
<td>aPcrms = 290.73</td>
</tr>
</tbody>
</table>

**Figure 5-8. Foam Cushion Pressure Distribution Summary for Chirp Input**
The pressure maps show high concentrated pressure in the lower half of the cushion loading indentor. This region on the CLI represents the bony prominence of the ischial tuberocities of the human buttocks. It is widely known that high pressure at a bony prominence reduces blood flow to the surrounding tissue. Over extended time this can lead to extreme discomfort and eventually the onset of ischemia and possibly a pressure sore. The other consideration to be made is that when sitting the ischial tuberocities are made to support the majority load of the seated person. So the question becomes whether it is necessarily bad to experience high pressure in this region. This question will be addressed later in Chapter 7 when comparing the two types of seat cushions.

The contact area and force are constant which is to be expected due to the fact that the CLI does experience an increase or reduction in weight over time. The pressure change rate (Pcrms) values also change very little. As will be later discussed, the Pcrms value is highly dependent on the input since it is a measure of pressure change. In terms of area pressure change rate (aPcrms), there is a slight increase from hour 0 to hour 12. The metric aPcrms is a measure of pressure change with the incorporation of pressure distribution. Hence, increasing areas of high pressure would cause and increase in aPcrms even if the pressure change rate remained constant.

Increasing regions of high pressure are hard to decipher from the pressure maps given in Figure 5-8. However, increasing regions of high pressure become more apparent when looking at pressure occurrence as shown in Figure 5-9. This figure was created by calculating the average pressure of each cell for the duration of each test run. A histogram of these average pressures was created using 6 bins of 10-mmHg increments. The foam seat cushion displays a transfer of occurrences from smaller pressure ranges to a larger pressure ranges with significant shifts to the 80-100 and >100 mmHg pressure ranges. This can be explained when recalling the increase in stiffness of the foam cushion. Degradation of the foam is accompanied by an increase in mechanical stiffness. Over time this creates a harder cushion surface resulting in higher interface pressures. Furthermore, the increase in high pressure explains the increase in the aPcrms value over time.
The purpose of using the chirp input in evaluating pressure distribution was to observe the effects of frequency on interface pressure. The methods used for this evaluation are average pressure, pressure change rate, and seat percent distribution (SPD%). The average pressure for the 30-second duration of the chirp signal is shown in Figure 5-10. For each of the 4-hour tests, the average pressure remains at approximately 40 mmHg with fluctuations as high as 5 mmHg. There is no particular information taken from the average pressure data over time. However, when observing the pressure amplitude at varying frequency, the data appears to follow the trend of the seat power spectral density of Figure 5-2. This is expected when considering that, from Newton’s second law, pressure is proportional to acceleration.

Figure 5-11 shows the pressure change rate, dP/dt, for the chirp input test. Included in the figure are the Pcrms values for each test run. Pressure change is a function of the input; hence as the period of the chirp signal decreases the change in pressure increases accordingly. Since pressure is proportional to acceleration, Pcrms is directly proportional to the derivative of acceleration, or jerk.
Figure 5-10. Average Contact Pressure Over Time (Foam Cushion)

Figure 5-11. Dynamic Pressure Change Rate Over Time (Foam Cushion)
Seat Percent Distribution Percent (SPD%) is a measure of the pressure distribution relative to a seat cushion with equal pressure over the entire contact area. It is believed that a more evenly distributed interface pressure is desirable due to the fact that high pressure regions, particularly at bony prominences, are relieved. Observing SPD% over time demonstrates the ability of the seat cushion to maintain evenly distributed pressure in a dynamic environment. As previously mentioned, a lower SPD% value indicates a more evenly distributed seating surface.

Figure 5-12 demonstrates that the foam seat cushion is unable to maintain equal pressure distribution over time. The mean SPD% values are approximately 15% for each 4-hour test run, indicating that the pressures are 15% above perfectly evenly distributed pressure, for each 4-hour test run. As a comparison, static tests of a person seated on a hard board have resulted in values as high as 60%. The more important observation, however, is that the foam seat cushion displays high oscillations, especially in the high frequency regions. The magnitude of oscillation, however, is not significant unless presented relative to other seat cushions. This comparison will be made in Chapter 7.

![Figure 5-12. Seat Pressure Distribution Percent Over Time (Foam Cushion)](image-url)
### 5.2.2 ISO2 Results

The ISO2 input signal is representative of actual driving conditions of a heavy truck. This is particularly important when evaluating pressure distribution. Similar to the chirp pressure distribution results, this section includes a summary chart for the 12-hour ISO2 experiments as shown in Figure 5-13.

<table>
<thead>
<tr>
<th>ISO2 Hour 0</th>
<th>ISO2 Hour 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="ISO2 Hour 0 Image" /></td>
<td><img src="image2" alt="ISO2 Hour 4 Image" /></td>
</tr>
<tr>
<td>Contact area = 139.68 in^2</td>
<td>Contact area = 137.28 in^2</td>
</tr>
<tr>
<td>Force = 97.69 lb</td>
<td>Force = 107.09 lb</td>
</tr>
<tr>
<td>Pcrms = 1.99 psi/s</td>
<td>Pcrms = 1.60 psi/s</td>
</tr>
<tr>
<td>aPcrms = 117.68</td>
<td>aPcrms = 109.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ISO2 Hour 8</th>
<th>ISO2 Hour 12</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3" alt="ISO2 Hour 8 Image" /></td>
<td><img src="image4" alt="ISO2 Hour 12 Image" /></td>
</tr>
<tr>
<td>Contact area = 138.00 in^2</td>
<td>Contact area = 140.80 in^2</td>
</tr>
<tr>
<td>Force = 107.28 lb</td>
<td>Force = 109.14 lb</td>
</tr>
<tr>
<td>Pcrms = 1.40 psi/s</td>
<td>Pcrms = 1.32 psi/s</td>
</tr>
<tr>
<td>aPcrms = 104.44</td>
<td>aPcrms = 123.52</td>
</tr>
</tbody>
</table>

Figure 5-13. Pressure Distribution Summary Chart for ISO2 Input (Foam Cushion)
High-pressure regions remain at the rear of the cushion loading indentor. Most of the load is supported by this ischial region of the CLI with two other points of high pressure near the lower thigh region. The Pcrms and aPcrms values are much lower than with the chirp input tests. This is due to the low frequency content of the ISO2 input.

Figure 5-14. Movie-Averaged Pressure Occurrences from Hour 0 through 12 (Foam Cushion)

Figure 5-14 displays, for the ISO2 experiments, a bar chart showing the occurrences of pressure in bands for each 4-hour movie-averaged file. From the figure, the occurrences of high pressure are increased relative to the chirp results. This is due to the fact that the ISO2 signal generates much higher amplitudes than the chirp signal causing the indentor to have greater inertia upon downward impact with the seat cushion. Again, the there is a noticeable shift in pressure to the ranges of 80-100 and greater.

Figure 5-15 shows the dynamic pressure change rate over time and Figure 1-16 shows the seat pressure distribution over time. The pressure change becomes smaller while the pressure distribution change rate becomes larger over time. This seems to indicate an inverse relationship; while the foam cushion is able to reduce the change in pressure, it is not able to maintain equally distributed pressure.
Figure 5-15. Dynamic Pressure Change Over Time (Foam Cushion)

Figure 5-16. Seat Pressure Distribution Over Time (Foam Cushion)
5.3 Summary

Extended duration testing of the standard foam seat cushion revealed that:

1. The foam cushion stiffens over a 12-hour time period,
2. This stiffening causes higher interface pressures between the seat and the seated person, particularly in the 80 – 100 mmHg range, and
3. The pressure distribution of the foam cushion displays high-pressure regions—on the order of 140 mmHg—located primarily at the ischial tuberocities.

Transmissibility plots and the measured step responses of the seat cushion revealed that the overall dynamics of the seat were dominated by the seat suspension. That is, the seat cushion is much stiffer than the seat suspension and therefore acts almost as a rigid link between the seat floor and seat cushion. Objective measures, such as SEAT% and Perms, were applied to the foam seat cushion for both a chirp input and an ISO2 input signal. Long-term changes of these measures were not significant, therefore no conclusion can be made. These objective measures, however, are more useful for comparing seat cushions. The following chapter, Chapter 6, applies the same objective analysis—as was performed with the standard foam seat cushion—to an orthotic air-inflated seat cushion.
6 Air-Inflated Cushion Analysis

This section presents the experimental results for the air-inflated seat cushion. Experimental results for the air-inflated cushion are divided into sections of vibration analysis and pressure distribution analysis. The results are presented in the same format as with the standard foam seat cushion in Chapter 5. Input signals used for vibration analysis included a chirp input and a step input. Input signals used for the pressure distribution analysis were the chirp input and the ISO2 input. Each test was performed over a 12-hour period, repeated every 4 hours in order to assess the effect of the long-term performance of the seat cushion.

6.1 Vibration Analysis

Vibration analysis of the air-inflated seat cushion was performed using a linearly swept frequency sine wave (chirp signal) and a 1-inch step input. The chirp signal was implemented to determine the vibration characteristics via power spectral densities and transmissibility plots. A 0.5 - 10.5 Hz range was chosen for the results included here, since this frequency range encompasses the main dynamics occurring at the seat suspension and seat cushions. The step input was implemented to define the damping properties of the seat cushion. The chirp and step inputs are previously defined in detail in Chapter 3.

6.1.1 Chirp Results

The power spectral density (PSD) as measured at the seat base and seat cushion are shown respectively in Figure 6-1 and Figure 6-2. The base of the seat experiences significant vibration in 2 - 4 Hz frequency range and in the 7 - 10 Hz range. In the critical range of 4 - 8 Hz—significant due to human resonance at these frequencies—the seat base experiences almost no acceleration. It is worth noting that vibration outside the range of 10 Hz is not considered because of the fact that heavy trucks typically do not experience vibration outside of this range. The frequency response of the base exhibits two modes of vibration typical of a two-degree of freedom system. Considering the response at the seat cushion, there is a broad spectrum of acceleration between 2 and 10
Hz. In both the frequency response of the base and the seat there is an exchange in energy from the low to the high frequency ranges. That is, as time increases the vibration magnitude at low frequencies increases while at it is reduced at higher frequencies. For the seat base this transfer in energy takes place at approximately 6 Hz, and at around 8.5 Hz for the seat cushion. This energy transfer is important due to the fact that the human body is typically more sensitive to vibration in the lower frequency ranges. Therefore, as acceleration magnitude increases, the time for a person to reach a fatigue induced tolerance limit will become shorter as opposed to increased high frequency magnitudes. As an example, the fatigue exposure limit for identical acceleration magnitude is approximately twice as long at 12.5 Hz compared to the 4 Hz.

![Figure 6-1. Power Spectral Density of Base Acceleration for Chirp Input (Air-Inflated Cushion)](image-url)
Figure 6-2. Power Spectral Density of Seat Acceleration for Chirp Input (Air-Inflated Cushion)

Figure 6-3 and Figure 6-4 respectively show the transmissibility from the floor to the seat base and from the seat base to the seat cushion. Both figures exhibit a natural frequency of approximately 1.5 Hz, which is typical response for a seat with a soft suspension (i.e., air ride). As discussed in Chapter 2, the seat suspension isolates frequencies above 2 Hz and also decreases the magnitude of vibration experienced by the driver. What is interesting about the transmissibility plots is that their response is nearly identical. This is the same result as seen with the standard foam seat cushion, which indicates that the dynamics of the seat suspension dominate the response of second-order system. The consequence of this effect will be discussed in later Chapter 7, which compares the performance of the two types of seat cushions.

Figure 6-5 shows the cushion transmissibility for each of the 4-hour experiments. The cushion transmissibility, as measured from the seat base to the seat cushion, initially shows a natural frequency of about 6.1 Hz. Over time there is a shift in resonant frequency to approximately 6.6 Hz. Furthermore, the magnitude increases approximately 7%. This effect is representative of the stiffening of the air-inflated cushion.
Figure 6-3. Transmissibility from Floor to Seat Base (Air-Inflated Cushion)

Figure 6-4. Transmissibility from Floor to Seat Cushion (Air-Inflated Cushion)
Figure 6-5. Transmissibility from Seat Base to Seat Cushion (Air-Inflated Cushion)

Values of seat effective amplitude transmissibility (SEAT%) are given below in Table 6-1. SEAT% is one of the comfort metrics used to analyze the vibration transmitted through the seat from the floor while also considering human tolerance levels. Considering these values, the air-inflated seat cushion has a slight change in weighted transmissibility from hour 0 to hour 12. It appears, however, that after 4 hours the cushion loading indentor settles into the air-inflated cushion and the SEAT% values reach a steady state of approximately 39%.

Table 6-1. SEAT% Values for Chirp Input (Air-Inflated Cushion)

<table>
<thead>
<tr>
<th>Hour</th>
<th>SEAT %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>35.92</td>
</tr>
<tr>
<td>4</td>
<td>39.98</td>
</tr>
<tr>
<td>8</td>
<td>39.12</td>
</tr>
<tr>
<td>12</td>
<td>39.08</td>
</tr>
</tbody>
</table>
6.1.2 Step Results

The step responses of both the seat base and the seat cushion, shown respectively in Figure 6-6 and Figure 6-7, demonstrate no change over the 12-hour test period. The seat base has a settling time of approximately 0.7 seconds while the seat cushion reaches steady state in approximately 0.6 seconds. Hence, the air-inflated seat cushion is able to reduce the time of transient response relative to the input base. Even though the dynamics of the seat suspension highly influence the response, the seat cushion still plays a role in determining the transient response. The air-inflated seat cushion is constructed of interconnected air cells, which creates additional damping to the overall system. As one air cell is loaded the air is transferred from to a neighboring cell. This is analogous to placing a series of springs and dampers between the base and the seated person.

Figure 6-6. Base Acceleration Time Response to a 1-inch Step Input (Air-Inflated Cushion)
6.2 Pressure Distribution Analysis

Pressure distribution analysis of the air-inflated seat cushion is divided into two sections; chirp results and ISO2 results. The chirp signal was implemented to determine the identify pressure distribution performance over a range of frequency, for 0.5 to 10.5 Hz. The ISO2 input signal was used specifically to emulate the typical low frequency, high amplitude road conditions experienced by heavy commercial trucks. The chirp and ISO2 input signal are previously defined in detail in Chapter 3.

6.2.1 Chirp Results

Figure 6-8 provides a summary of the pressure distribution analysis for the chirp input signal. The figure includes movie-averaged pressure maps, corresponding contact area and force, and comfort metrics Pcrms and aPcrms.
<table>
<thead>
<tr>
<th>Chirp Hour 0</th>
<th>Chirp Hour 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact area = 193.12 in^2</td>
<td>Contact area = 194.08 in^2</td>
</tr>
<tr>
<td>Force = 97.74 lb</td>
<td>Force = 102.37 lb</td>
</tr>
<tr>
<td>Pcrms = 7.72 psi/s</td>
<td>Pcrms = 6.62 psi/s</td>
</tr>
<tr>
<td>aPcrms = 163.17</td>
<td>aPcrms = 152.40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chirp Hour 8</th>
<th>Chirp Hour 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact area = 192.64 in^2</td>
<td>Contact area = 193.76 in^2</td>
</tr>
<tr>
<td>Force = 106.46 lb</td>
<td>Force = 108.48 lb</td>
</tr>
<tr>
<td>Pcrms = 6.73 psi/s</td>
<td>Pcrms = 6.57 psi/s</td>
</tr>
<tr>
<td>aPcrms = 165.01</td>
<td>aPcrms = 170.26</td>
</tr>
</tbody>
</table>

Figure 6-8. Air-Inflated Cushion Pressure Summary Chart for Chirp Input

Referring to the movie-averaged pressure maps, the air-inflated seat cushion demonstrates the ability to more evenly distribute pressure throughout the heavily loaded regions of the cushion loading indentor. This is expected due to the inherent nature of a
confined fluid which, when loaded, will transmit pressure undiminished in all directions. Distributing pressure can be beneficial in that it relieves high-pressure regions that can lead to regionally decreased blood flow.

Figure 6-9 shows the change in pressure occurrence from hour 0 through hour 12. Each cell of the movie file was averaged to form a composite movie averaged pressure map. This pressure map was divided into six pressure regions to determine the shift in pressure over time. The figure shows that there are no pressures greater than 100 mmHg for any of the experiments, which is a direct result of the more evenly distributed pressure. There is a shift in pressure range but it is primarily confined to the 40 - 60 mmHg pressure range. The additional pressure in this range is taken from the 0 - 20 mmHg pressure range. As discussed in Chapter 2, keeping pressure below a threshold value of 60 mmHg greatly reduces the occurrence of ischemia.

![Figure 6-9. Movie-Averaged Pressure Occurences from Hour 0 Through 12](image)

84
Figure 6-10 shows the average contact pressure for the chirp input. The average contact pressure remains at approximately 40 mmHg for each of the 4-hour tests. The pressure amplitude over time is comparable to the power spectral density of Figure 6-2, which shows the weighted amplitude of acceleration at each frequency. This is expected due to the fact that the pressure is proportional to acceleration.

![Figure 6-10. Average Contact Pressure Over Time (Air-Inflated Cushion)](image)

Figure 6-11 and Figure 6-12 respectively show the pressure change rate and seat pressure distribution percentage over the 30-second interval of the chirp input signal. As expected, the pressure change rate increases with increasing frequency. The seat pressure distribution percent (SPD%) only exhibits slight fluctuations. Compared to the foam seat cushion, the air-inflated cushion provides a more evenly distributed pressure over a larger surface, while maintaining a lower rate of pressure change during the run.
Figure 6-11. Dynamic Pressure Change Rate Over Time (Air-Inflated Cushion)

Figure 6-12. Seat Percent Distribution Over Time (Air-Inflated Cushion)
6.2.2 ISO2 Results

The pressure distributions presented in this section are typical of what would be found with actual road conditions. As shown in Figure 6-13, the air-inflated seat cushion is able to maintain a more evenly distributed pressure profile for a longer duration.

<table>
<thead>
<tr>
<th>ISO2 Hour 0</th>
<th>ISO2 Hour 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="0.png" alt="Image" /></td>
<td><img src="4.png" alt="Image" /></td>
</tr>
<tr>
<td>Contact area = 152.96 in²</td>
<td>Contact area = 155.36 in²</td>
</tr>
<tr>
<td>Force = 106.43 lb</td>
<td>Force = 111.87 lb</td>
</tr>
<tr>
<td>Pcrms = 2.12 psi/s</td>
<td>Pcrms = 1.83 psi/s</td>
</tr>
<tr>
<td>aPcrms = 49.45</td>
<td>aPcrms = 65.34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ISO2 Hour 8</th>
<th>ISO2 Hour 12</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="8.png" alt="Image" /></td>
<td><img src="12.png" alt="Image" /></td>
</tr>
<tr>
<td>Contact area = 156.32 in²</td>
<td>Contact area = 156.16 in²</td>
</tr>
<tr>
<td>Force = 114.02 lb</td>
<td>Force = 116.60 lb</td>
</tr>
<tr>
<td>Pcrms = 1.81 psi/s</td>
<td>Pcrms = 1.76 psi/s</td>
</tr>
<tr>
<td>aPcrms = 51.35</td>
<td>aPcrms = 66.65</td>
</tr>
</tbody>
</table>

Figure 6-13. Air-Inflated Cushion Pressure Summary Chart for ISO2 Input
Also noticed is a greater contact area than with the standard foam seat cushion. The foam cushion provided a contact area of around 140 in$^2$, while the air inflated cushion provides around 155 in$^2$. This is due to the fact that that the air cushion is constructed such that it conforms to the individual shape of the body, thus providing increased contact area. Increased contact area lowers the average pressure by supporting additional forces.

Movie averaged pressure occurrences for each 4 hour test are given in Figure 6-14. As time increases, occurrence of pressure in the 40 - 60 mmHg pressure range is increased, with only slight increases in the 60 - 80 mmHg range. This increase comes at the expense of lower occurrence of pressure in the 0 - 20 mmHg range. There are no occurrences in the extremely uncomfortable region of greater than 100 mmHg. Dynamic pressure increase is typical for any seating surface over extended periods of time due to the stiffening effect of the seat cushion. That is, the cushion becomes harder and thus generates higher interface pressures. Increasing pressure, however, only becomes a major concern when it is above 60 mmHg, as discussed in Chapter 2. The air-inflated cushion confines pressure shifts below this threshold value.

![Figure 6-14. Movie Averaged Pressure Occurrences from Hour 0 through 12 (Air-Inflated Cushion)](image-url)
The pressure change rate for each 4-hour test is shown in Figure 6-15. As expected, due to the frequency content, there is considerably less change than with the chirp signal. The air-inflated seat cushion demonstrates a decreasing trend in Pcrms over time. In terms of seat performance, a lower Pcrms value has been correlated with less discomfort.

\[ \frac{dP}{dt} \text{ (mmHg/s)} \]

![Graph showing dynamic pressure change over time](image)

**Figure 6-15. Dynamic Pressure Change Over Time (Air-Inflated Cushion)**

The seat pressure distribution, shown in Figure 6-16, demonstrates the ability of the air-inflated seat cushion to maintain evenly distributed pressure over time. Taking a mean value of the dynamic SPD% would give an overall idea of pressure distribution. In Chapter 7, Dynamic SPD% is one of the metrics used to compare the foam and air-inflated cushions.
6.3 Summary

Extended duration testing of the air-inflated seat cushion revealed that:

1. The air-inflated seat cushion does not stiffen substantially over time,
2. There are increases of interface pressure but they are limited to the 40 - 60 mmHg pressure region, and
3. The air-inflated seat cushion demonstrates the ability to distribute pressure evenly, hence alleviating high pressure at the ischial tuberocitities.

Similar to the foam cushion tests, the seat suspension dominated the dynamics of the overall seat system. This effect is expected when considering that the seat cushion, when loaded has a very small static deflection compared to the seat suspension. Static deflection is directly proportional to the stiffness. Hence, compared to the spring and
damper of the suspension, the cushion is much more stiff and acts as a rigid body between the seat cushion and the cushion loading indentor.

The objective comfort metrics used to evaluate the seat cushion did not have much significance when applied solely to the air-inflated seat cushion. Chapter 7 alleviates this problem by comparing the experimental results of both the air-inflated seat cushion and the standard foam seat cushion.
7 Comparative Analysis

This section presents a comparative analysis of the standard foam seat cushion and the air-inflated seat cushion. The comparative analysis draws from the experimental results of Chapters 5 and 6 in a manner that illustrates the main differences between the two cushion types. These differences are primarily illustrated using current objective methods of comfort evaluation such as SEAT% and Perms. The two new methods, aPerms and SPD%, are also used for comparative purposes. The results are divided into two main categories: 1) the vibration results measured by accelerometers that were described earlier, and 2) pressure distribution maps measured by the body pressure measurement system (BPMS). The vibration results will be mainly used to evaluate the damping characteristics of the two types of seat cushions, and also examine their dynamic degradation over time. The pressure distribution maps will be used to evaluate the dynamics of each seat cushion at the interface with the human body.

7.1 Vibration Analysis

To examine the stiffening effects of each seat cushion over time, a 12-hour test was performed. A chirp test was conducted in 4-hour intervals over a period of 12 hours. The results were that both seat cushions displayed stiffening over time that was revealed by an increase in natural frequency. Figure 7-1 and Figure 7-2 respectively show the cushion transmissibility of both seat cushions with increased time along with the corresponding resonant frequency for each 4-hour test. The seat cushions displayed almost identical resonant frequency and magnitude values for the initial test at hour 0. The foam cushion, however, displayed more stiffening over time, revealed in the shift in natural frequency. Considering a CLI mass of approximately 50 kg, the foam cushion’s stiffness increased 17% while the air-inflated cushion increased 12% over the total 12-hour period. Also, as demonstrated in Figure 7-3, the resonant frequency of the foam cushion does not appear to level off, even within the 12-hour test frame. In fact, the foam cushion exhibits a trend of further stiffening even after 12 hours.
Figure 7-1. Vertical Cushion Transmissibility (Seat Acceleration Divided By Base Acceleration) for the Standard Foam Cushion;

Figure 7-2. Vertical Cushion Transmissibility (Seat Acceleration Divided By Base Acceleration) for the Air-Inflated Seat Cushion
To evaluate damping of each seat configuration, the step response was evaluated as shown in Figure 7-4. A step input simulates common road disturbances such as sudden changes in road elevation. The step response of a given system is a valuable method for evaluating the damping properties of the system. Damping can be thought of as the ability of a seat cushion to quickly reduce vibrations from a transient input to zero.

The step response of the two seat configurations offered little difference between the two seats, in terms of their peak response and settling time. This indicates that the air-inflated cushion that we tested has a comparable damping characteristic to the foam cushion that was used in the study. The similar damping characteristics indicate that air-inflated seat cushions is able to damp out transient motions at the cushion, which are caused by large seat suspension travel, as effectively as the foam cushions that are commonly used in most truck seats.
In order to compare the two cushions using SEAT%, which was described earlier, the ISO2 input is used. The results shown in Figure 10 indicate that the air-inflated seat cushion is only 6% better than the foam cushion.

![Figure 7-4. Vertical Seat Acceleration Response to a 1-inch Step Input](image)

\[ \Delta = 6\% \]

![Figure 7-5. SEAT% for Air-Inflated and Foam Seat Cushions](image)
The reason was this small difference between the two seats can be attributed to the fact that SEAT% is based on acceleration measurements on the seat, which are strongly dominated by the seat suspension. This can be seen in Figure 7-6, which shows that seat cushions had very little effect on the resonant frequency or on the frequency at which isolation occurs. The seat suspension absorbs most of the gross input vibration from the floor and the dynamics of the seat cushions are comparatively negligible. As intuitively may be apparent, for seats with soft suspensions—such as the one that we used in this study—the vibrations measurements on the seat cushion are strongly influenced by the seat suspension, and the seat cushion plays only a minor role in those measurements. Therefore, using acceleration on the seat cushion alone does not allow for assessing the dynamic effect of the seat cushion on what is perceived by the driver; or more precisely, the dynamic interface between the cushion and the seated person. This indicates that a metric such as SEAT% may not be suitable for comparing different classes of cushions, although it would be quite valid for studying seats with different types of suspensions. As such, we will resort to other metrics, namely those that are based on the pressure distribution on the seat cushion, which will be discussed next.

Figure 7-6. Vertical Transmissibility (Base Acceleration Divided By Floor Acceleration and Seat Acceleration Divided By Floor Acceleration); (a) Standard Foam Cushion (b) Air-Inflated Cushion
7.2 Pressure Distribution Analysis

The pressure distribution analysis will include comparing the histogram of the pressure distribution between the seat cushion and the cushion loading indenter (CLI), as well as the following three measures that were discussed earlier:

- SPD%
- Pcrms
- aPcrms

The measurement of the interface pressure between the CLI and seat cushion was made using the body pressure measurement system (BPMS). These measurements show the fundamental difference between a foam and air-inflated cushion. They further show that pressure on the body cells at the seated region. (Some argue that ultimately this is the measure that counts the most.)

The air-inflated cushion is based on the application of Pascal’s law, which indicates that a confined fluid will transmit applied pressure uniformly. Figure 7-7 demonstrates this effect. The foam cushion shows areas of high pressure not found in the air-inflated cushion pressure distribution profile. The air-inflated cushion demonstrates the ability to more uniformly distribute the applied load as predicted by Pascal’s law. The lower pressures are also, in part, due to increased contact area.

The relative pressure distributions can be compared quantitatively using the static SPD% values. Figure 7-7 shows that the air-inflated cushion yields approximately 50% more uniformly distributed pressure distribution than the foam cushion. The question is whether evenly distributed pressure is better or worse. Research on maximum pressure tolerance (MPT) supports the spatial summation theory and suggests that, above a critical pressure, a force distributed over a larger area is less discomforting than the same force concentrated in a small area [19]. Furthermore, research in seat comfort has confirmed correlation of uniform distribution and perceived comfort [20]. Aside from the issue of pressure distribution, lower pressures are always more desirable in terms of long-term tissue integrity. Since uniform pressure distribution is one way to alleviate high
pressures, one is able to infer that a lower SPD% value indicates a less fatiguing, thus healthier seat cushion.

<table>
<thead>
<tr>
<th>Contact Area (in²)</th>
<th>Static SPD%</th>
<th>Peak (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>179</td>
<td>19.48</td>
<td>144</td>
</tr>
<tr>
<td>207</td>
<td>12.99</td>
<td>89</td>
</tr>
</tbody>
</table>

Figure 7-7. Static Interface Pressure Distribution; (a) Standard Foam Cushion (b) Air-Inflated Cushion

From previous vibration analysis, there was an increase in cushion stiffness over time. These effects and how they correspond to comfort and fatigue, however, were not evident from Figure 7-1 through Figure 7-3. An analysis of pressure occurrence over time shows that the increase in cushion stiffness results in higher interface pressures, as shown in Figure 7-8 and Figure 7-9. These figures present a histogram of the average pressures for each cell for the entire test cycle in 6 pressure bands. Both seat cushions show a shift of pressure distributions from the lower band to the higher bands. The foam cushion, however, exhibits a more significant shift to the 80 – 100 and >100 mmHg pressure ranges. Pressure shifts for the air-inflated seat cushion are mostly confined to the 40 – 60 and 60 – 80 mmHg pressure ranges. As previously discussed in Section 2.2.3, it is important in terms of tissue health to limit pressure exposure above 60 mmHg. It is evident that the air-inflated seat cushion performs significantly better in performing this task.
Figure 7-8. Pressure Occurrences From Hour 0 Through Hour 12 (Foam Cushion)

Figure 7-9. Pressure Occurrences From Hour 0 Through Hour 12 (Air-Inflated Cushion)
The results shown in Figure 7-8 and Figure 7-9 directly correlate to the cushion stiffening effect that was discussed earlier in Figure 7-1 through Figure 7-3. Together, these figures show the effect of the cushion stiffening over time on what the driver would feel.

Figure 7-10 shows the dynamic SPD% of both seat cushion types and Figure 7-11 displays the averaged SPD% over the entire 8 second test run. As with the static case, the air-inflated seat cushion displays more evenly distributed pressure. Also, the distribution remains relatively constant compared with the high changes associated with the foam cushion. The mean value of the SPD% for the entire run indicate a 36% improvement resulting from the air-inflated cushion, as compared to the foam cushion. This means that air-inflated cushions would better distribute the pressures at the cushion interface with the driver—in our case, by as much as 36% percent. Of course, a more evenly distributed pressure contour at the seated person could result in more comfort and less fatigue, although further testing is needed to quantify this benefit.

![Figure 7-10. Comparison of Dynamic Seat Percent Pressure Distribution (SEAT%)](image-url)
Figure 7-11. Comparison of Averaged Dynamic SPD%

Figure 7-12 shows the pressure change rate of the two cushions, as measured by $P_{crms}$ values. Figure 1-13 compares $P_{crms}$ for each cushion type. The results show a smaller $P_{crms}$ for the air-inflated cushions than the foam cushion. The percent difference between the two cushions (i.e., 8%), however, is smaller than what we observed in SPD% earlier and what $aP_{crms}$ will indicate in results that we will discuss next. This smaller difference is due to the fact that $P_{crms}$ is ultimately a measure of the rate of change of pressure on the cushion. The results in Figure 7-12 indicate that the rate of change of pressure is slightly lower for the air-inflated cushion.

Figure 7-12. Comparison of Pressure Change Rate
The last measure that is used for comparing the two cushions is $aPcrms$, which was described earlier. The $aPcrms$ accounts for the pressure distribution across the seated area. A larger contact area results in a lower $aPcrms$ value. The results shown in Figure 7-14 indicate that the air-inflated cushion yields a much more favorable pressure distribution, by as much as 58%. The subjective field-testing that has been conducted in an un-published study shows a direct correlation between the $aPcrms$ numbers and ride comfort. The results of that study show that the lower the $aPcrms$ is the higher the seat cushion is rated in subjective evaluations for both comfort (short time exposure) and fatigue (long-time exposure).

Figure 7-13. Comparsion of Pcrms for Foam and Air-Inflated Cushion

Figure 7-14. Comparison of $aPcrms$ between Foam and Air-Inflated Cushion
8 Conclusion and Future Research

This chapter summarizes the work performed in this thesis. In addition, the results of testing are discussed with respect to the research objectives set forth in Chapter 1. The chapter ends with a description of the recommendations of future work that should be performed in the field of fatigue research with regards to seat cushion performance.

8.1 Summary

A comprehensive comparison between an air-inflated seat cushion designed for truck seats and a commonly used foam cushion was provided, in order to highlight the differences in the dynamic properties of the two cushions and how they could affect driver comfort and fatigue. A single axis test rig, specially designed and built for truck seat testing, was used to conduct the tests necessary for comparing the dynamic performance of the cushions. Different types of tests were used to evaluate various aspects of each type of cushion; in terms of their response to narrow-band (single frequency) dynamics, broadband input of the type that is commonly used in trucking industry for testing seats, and a step input for assessing the damping characteristics of each cushion. The tests were conducted over a twelve-hour period—in four-hour intervals—in order to measure the changes that occur at the seat cushion over time and assess how these changes can affect the metrics that are used for evaluating the cushions.

The tests indicated a greater stiffening of the foam cushion over time, as compared with the air-inflated cushion that showed almost no change in stiffness when exposed to a static weight for twelve hours. Furthermore, pressure measurements at the seat showed higher-pressure concentrations for the foam cushion at the bony prominences of the seated person—namely, the ischial regions—as compared to the air-inflated cushion. The air-inflated cushion exhibited a much more evenly distributed pressure map between the cushion and the test object, and it provided lower pressures at the ischials. This is expected to contribute to more driver comfort, for both short hauls and extended driving ranges.
A series of tests aimed at evaluating the damping properties of each cushion showed both cushions to have nearly identical damping properties. The damping property is important for settling the bouncing up and down on the cushion that can occur during driving, due to large motions across the seat suspension. This indicates that air-inflated cushions can provide more comfort to the driver without causing any more bouncing up and down on the seat.

![Figure 8-1. Percent Improvement Offered by an Air-inflated Seat Cushion in Comparison with a Foam Cushion, using Different Metrics](image)

Other methods used for evaluating the dynamic properties of the two seat cushions included those recommended by studies in the past, as well as new techniques that were developed specifically for this study. The new techniques, named “SPD%” and “aPcrms” for the purpose of this study, were formulated such that they can best highlight the dynamic differences between different types of seat cushions, and their effect on driver comfort. The results, summarized in Figure 8-1, show that the air-inflated seat cushion can provide significant improvements in pressure distribution between the seat cushion and the driver, therefore providing a more comfortable ride and causing less fatigue.
8.2 Future Research

The purpose of the work presented in this thesis was primarily focused on evaluating the performance of foam seat cushions in comparison with air-inflated seat cushions. Evaluation was performed using current objective metrics, such as SEAT\% and Pcrms, for evaluating comfort and fatigue. Upon testing with these metrics, it was determined that they were not sufficient for highlighting the differences between the two cushion types. Therefore, two new methods, aPcrms and SPD\%, were introduced that were able to show significant discrepancy. The problem is that these new metrics have not been correlated with subjective evaluation and therefore only educated inference could be made regarding comfort and fatigue.

As previously discussed, comfort is generally associated with the short-term sensation of sitting while fatigue is associated with the long-term affects of driving. Furthermore, comfort and fatigue have been shown to have little relationship to one another. That is, a seat that is initially comfortable may cause more fatigue over time. Current research has identified several objective measures for evaluating a seat cushion for comfort but there is yet no measure of fatigue.

It should be the goal of future research to obtain objective measures of fatigue with regards to truck seats and seat cushions. The objective methods of evaluation presented here represent a background for such research. The requirement will be to correlate these new metrics with subjective evaluation. Such research would provide the seat manufacturer with objective evaluation tools that could be easily implemented to determine the level of fatigue that a particular seat or seat cushion would provide. Although the single axis test rig is quite effective for establishing the fundamental aspects of this study due to its simplicity, it represents a test condition that can differ from practice. In order to bridge this gap and yet maintain the test repeatability that can be enjoyed in a laboratory environment, we propose to perform a series of tests with a multi-axis rig that includes a fully furnished semi-truck cab. The proposed test rig should include the semi-truck cab that will be placed on four air springs in a manner such that the suspended cab will have nearly the same dynamic frequencies as what is commonly measured on a truck. Two hydraulic actuators will be used such that the heave, pitch, and
roll motions of the cab can be excited selectively. The input to the cab can range from simple, pure tune waves for exciting the cab (and therefore the seat) at a single frequency, to field-measured excitations for subjecting the seat to inputs experienced in practice. Other inputs that can be considered include step input for measuring seat response to sudden bumps, and chirp signals that measure the seat response to a range of input with different frequencies. The seat measurements made for the cab tests will be similar to those mentioned earlier for the single-axis seat tests. Other transducers may be used on the cab in order to determine the cab response and its interaction with the seat system.

In order to establish a correlation between the two test rigs, the tests performed with the cab rig should initially include the same indenter that was used for the single-axis rig tests. Subsequently, one should perform a series of tests with human subjects, according to the following guidelines:

- Using multiple test subjects hired from among local truck drivers who are of various gender, age, weight, height, and experience,
- Performing a series of tests with the human subjects in multiple test sessions,
- Dedicating each test session to a different aspect of the study,
- Mainly performing tests that will help evaluate the response of the test subjects to different types of seat designs, and
- Documenting the effectiveness of the selected methodologies in predicting fatigue.

Ultimately, the future tests should be aimed at the methods that hold the highest degree of promise for the field-testing that will be the final stage of research.
REFERENCES


APPENDIX A

CALIBRATION AND TEST PROCEDURES

A.1 Tekscan BPMS Calibration/Equilibration

To ensure repeatability of pressure measurements, it was necessary to follow rigorous procedures when Calibrating and Equilibrating the pressure measurement pads. Calibration and Equilibration of the Tekscan pressure pad was performed before each test, according to the following procedure:

1. Place pressure pad into calibration unit.
2. Apply 3.0-psi uniform pressure for 2 minutes to allow air to escape from pad and for conditioning purposes (conditioning helps to lessen the effects of drift and hysteresis).
3. Equilibrate at 3.5, 2.5, 1.5, and 0.5 psi.
4. Increase pressure slowly from 0.5 to 3.5 psi while checking for uniform pressure.
5. Calibrate at 3.0 and 1.0 psi.

A.2 Test Procedure

Similar to pressure measurement, experimental procedures were used to ensure test repeatability. Dynamic tests were conducted according to the following procedure:

1. If testing foam cushion proceed to Step 6. Open quick-flow valve and inflate ROHO overlay test cushion to 40 mmHg using 0-2 psi air regulator.
2. Place overlay on the seat-testing rig on top of foam cushion.
3. Place Tekscan pressure pad on top of seat cushion.
4. Load the CLI on the cushion as prescribed in Section 2.4. Location of CLI is checked by measuring the distance of the polyurethane mold from the back and side of the truck seat.
5. If testing air-inflated cushion, check and adjust pressure to 38 mmHg. Close quick-flow valve.

6. Excite actuator at 5 Hz, 0.25” amplitude for approximately one minute to allow the CLI to settle into the seat.

7. Perform a static pressure mapping.

8. Perform tests using chirp, ISO2, and step inputs and record pressure, displacement, and acceleration data.

9. If testing air-inflated cushion, open quick-flow valve and check static pressure.

All tests for this report were conducted over a 12-hour time period at 4-hour intervals. Static measurements pressure measurements were also recorded before each dynamic test.
APPENDIX B

MATLAB SOURCE CODE FOR CALCULATING APCRMS

clear all
fileloc1 = uigetfile('*.txt','Select movie-averaged file');
[data1] = textread(fileloc1,'%f'); %read into Matlab
average 1 movie-averaged file
fileloc2 = uigetfile('*.txt','Select movie file');
[data2] = textread(fileloc2,'%f'); %read into Matlab whole
movie file

num_rows = 42; %pad consists of 42 rows and 42 columns of
pressure sensing cells
num_cols = 48;
N = input('Enter number of frames for movie file: ');
n = num_cols*num_rows;
fs = input('Enter sampling frequency (frames per second): ');
T = N/fs; %time window
dt = 1/fs; %sampling rate
df = 1/T; %sampling frequency
t = 0:dt:(N-1)*dt; %time vector

mnu = menu('Specify Pressure Units (PSI or
mmHg)','PSI','mmHG');
convert = 51.715; %1 psi = 51.715 mmHg
if mnu == 1
    X = reshape(data2,n,N)*51.715; %convert to units of mmHg
elseif mnu == 2
    X = reshape(data2,n,N); %remains units of mmHg
end

avg = mean(X,2); %average value of each cell over entire
duration of test run
stdev = std(X,0,2); %standard deviation
stdev3 = 3.*stdev;
limit = avg+stdev3; %upper limit of acceptable pressure
I1 = find(data1>=40 & data1<60); %find cells with average
pressure between 40 and 60 mmHg
areal1 = length(I1)*0.16; %total area of I1
I2 = find(data1>=60 & data1<80); %find cells with average
pressure between 60 and 80 mmHg
area2 = length(I2)*0.16;  %total area of I2
I3 = find(data1>=80&data1<100);  %find cells with average
  pressure between 80 and 100 mmHg
area3 = length(I3)*0.16;  %total area of I3
I4 = find(data1>=100);  %find cells with average pressure
  >100 mmHg
area4 = length(I4)*0.16;  %total area of I4

%calculate dP/dt for each pressure range
if length(I1)==0
  delta1 = 0;
else
  for i = 1:length(I1)
    I11 = find(X(I1(i),:)<limit(I1(i)));
    t1 = 0:dt:(length(I11)-1)*dt;
    delta1(i) =
    sqrt(1/N*sum((diff(X(I1(i),I11))./diff(t1)).^2));
    clear I11 t1
  end
end

if length(I2)==0
  delta2 = 0;
else
  for i = 1:length(I2)
    I22 = find(X(I2(i),:)<limit(I2(i)));
    t2 = 0:dt:(length(I22)-1)*dt;
    delta2(i) =
    sqrt(1/N*sum((diff(X(I2(i),I22))./diff(t2)).^2));
    clear I22 t2
  end
end

if length(I3)==0
  delta3 = 0;
else
  for i = 1:length(I3)
    I33 = find(X(I3(i),:)<limit(I3(i)));
    t3 = 0:dt:(length(I33)-1)*dt;
    delta3(i) =
    sqrt(1/N*sum((diff(X(I3(i),I33))./diff(t3)).^2));
    clear I33 t3
  end
end

if length(I4)==0
  delta4 = 0;
else
    for i = 1:length(I4)
        I44 = find(X(I4(i),:)<limit(I4(i)));  \\
        t4 = 0:dt:(length(I44)-1)*dt;      \\
        delta4(i) = sqrt(1/N*sum((diff(X(I4(i),I44))./diff(t4)).^2));
        clear I44 t4
    end
end

%Pcrms for each pressure range
avgPcrms1 = mean(delta1)/51.715; % 1 psi = 51.715 mmHg
avgPcrms2 = mean(delta2)/51.715;
avgPcrms3 = mean(delta3)/51.715;
avgPcrms4 = mean(delta4)/51.715;

%areaPcrms for each pressure range
areaPcrms1 = 1*(mean(delta1)/51.715)*area1; % 1 psi = 51.715 mmHg
areaPcrms2 = 2*(mean(delta2)/51.715)*area2;
areaPcrms3 = 3*(mean(delta3)/51.715)*area3;
areaPcrms4 = 4*(mean(delta4)/51.715)*area4;

%comfort index value
ci = (areaPcrms1+areaPcrms2+areaPcrms3+areaPcrms4)
Vita

Thomas Michael Seigler was born on October 13, 1975 in Greenville, South Carolina where his parents still live today. Michael graduated from Travelers Rest High School in Travelers Rest, South Carolina. He attended Clemson University where he obtained his Bachelor of Science degree in mechanical engineering in May of 2000. In August of 2000, he began his graduate studies at Virginia Polytechnic Institute and State University, where he worked in the Advanced Vehicle Dynamics Laboratory. In May of 2002 he earned his Masters degree in mechanical engineering and went on begin PhD studies at Virginia Tech.