ABSTRACT

The Woodbridge Group continues to explore the role of the PUF cushion in the measured comfort of the entire seating system. In this investigation our expanded comfort analysis of 60 PUF cushions, currently in the market, is illustrated through statistical analysis and comparisons drawn between PUF front seat driver cushions designed in North America, Europe, and Japan. All of the cushions included in this study were obtained from production moulds using production chemistries.

A principal component analysis was conducted on sixteen different physical properties. In this manner we sought to reveal relationships not previously understood and subsequently allow for simpler interpretation. Using multivariate statistical methods all cushions, regardless of cushion type or origin, can be simultaneously analyzed. This analysis has revealed a number of critical foam characteristics. We have also identified those physical property tests that are highly correlated with each foam characteristic. Additionally, the analysis also facilitated the identification of three distinct cushion design philosophies as evidenced by cushions designed in North America, Europe, and Japan. Subsequently, differences in the PUF cushion design philosophies are illustrated.

The future directions based on this multivariate analysis are discussed. We show a scheme that illustrates the effective use of chemistry that seeks to manipulate those specific physical property tests that impacts those foam characteristics, which we hypothesize, alter comfort performance.

INTRODUCTION

Understanding the role of the polyurethane foam (PUF) cushion, in the overall comfort of the seating system, continues to be of significant interest to automotive manufacturers, seat assemblers, foam manufacturers, and raw material suppliers. Clearly, comfort of the PUF cushion has not been adequately defined and effectively judged by the ultimate customer, the end user. Therefore, defining comfort for the PUF cushion cannot take place until we can sufficiently quantify the end user reaction to various stimuli and translate a physical impression into a quantifiable number. In other words, we must quantify a feeling. However, before this can take place we must define the foam characteristics and subsequently measure comfort as a function of these foam characteristics. This has necessitated a survey of the current level of comfort provided by PUF cushions in the market place. In this investigation, 60 cushions have been obtained from PUF production facilities around the world. Those countries are Argentina, Brazil, Canada, England, Germany, Japan, Mexico, and USA. These cushions are currently used in vehicles manufactured by many of the major OEMs such as Audi, Bentley, BMW, Chrysler, Fiat, Ford, General Motors, Honda, Mitsubishi, Nissan, Peugeot, Porsche, Rover, Toyota, and Volkswagen.

With such a large number of cushions, and a high number of physical properties measured to fully characterize these cushions, the data analysis and comparison appeared monumental. To overcome this obstacle, a principal component analysis was conducted.

A principal component analysis is a multivariate statistical method that seeks to explain the variance-covariance structure through a few linear combinations of the original variables. Using principal component analysis we seek to explain as much of the total system variability using as few principal components as possible. Such an analysis seeks to reveal relationships that were not previously suspected and allow for interpretation that would not ordinarily result.

Each principal component identifies and explains a specific foam characteristic. In our research, we discovered four principal components that identify four foam behavioral characteristics. These four foam characteristics explain a large portion of the variation in the data set. Subsequently, we identified those physical
property tests that are highly correlated with each foam characteristic. We then named each of the said foam characteristics, and thus define comfort as a function of these four foam characteristics. This is illustrated through foam characteristic equations. Finally, we identify the highest correlated physical property tests in each foam characteristic.

The objective of this work was to critically assess cushions available globally and attempt to define PUF cushion comfort as a function of those critical foam characteristics. In addition, the statistical analysis has yielded an opportunity to identify regional differences and cushion design philosophies.

EXPERIMENTAL

Cushion Evaluation

Each cushion irrespective of its origin, OEM, or Tier 1, had its foam tested as identically as possible. For instance, all cushions were tested for IFD hardness at various deflections, e.g. 25%, 50%, 65% and for hysteresis loss, even if the part usually was tested for some other criteria. All cushions were thoroughly tested for many physical properties. We selected the ASTM D3574-95 and the JIS K6400 -1997 test procedures and examined all cushions using the protocols contained in these specifications. Samples from each cushion were tested for compliance with the FMVSS302 specifications as a matter of routine. In addition, we measured the cell count of the cushion surface and cores and ball rebound of both core and skin samples (ASTM and JIS test procedures).

In this contribution, we report the portion of our data that corresponds to sixteen physical property tests evaluated according to the ASTM D 3574-95 test protocol.

Physical Property Tests Evaluated

A principal component analysis was conducted on the following sixteen physical properties:

1. Foam Firmness/Hardness at 50% deflection
2. Support Ratio (65%IFD/25%IFD)
3. % Hysteresis Loss
4. Ball Rebound with Skin - ASTM method
5. Cushion Thickness via IFD measurement
6. Core Density
7. Natural/Resonance Frequency (νr)
8. Peak Transmissibility (A0)
9. Attenuation Frequency (νA)
10. Transmissibility at 6Hz (A6Hz)
11. % Height Loss (Dynamic Fatigue)
12. % IFD Loss (Dynamic Fatigue)
13. Tensile Strength
14. % Elongation
15. Tear Strength
16. 50% Compression Set

All cushions were tested in our Corporate Testing Laboratory in Woodbridge, Ontario after at least twenty-four hours of conditioning at 23 ± 2°C and 50 ± 2% R.H.

a) Indentation Force Deflection (IFD), Hysteresis Loss

In all cases, the cushion hardness was determined in the same manner irrespective of the automotive manufacturers specifications. Cushion hardness was determined using a 4200 series Instron equipped with series XII control software. The test was conducted at a crosshead speed of 50 mm/min with two 75% preflexes prior to a final compression of 65%. The IFD at 5, 20, 25, 50, and 65% strains as well as hysteresis loss were recorded. The support (sag) ratio was calculated from the IFD at 65 and 25% strain.

b) Physical Properties

Physical properties of all cushions were evaluated according to the ASTM D 3574-95 method. Ball rebound tests were performed on skin and core foam samples. Flammability was evaluated as indicated in the FMVSS302 specification.

c) Vibrational Transmissibility

In the transmissibility test, complete cushions are subjected to a load of 22.7 kg over an indenter foot area of 314cm². The load is then accelerated at a constant input acceleration, A0, of 0.2 G while stepping through a frequency regime from 1 to 16 Hz. The resulting or output acceleration, A, of the 22.7kg mass is also recorded. The transmissibility, A/A0, is then plotted as a function of frequency. The test is completed in 150 seconds. The natural or resonance frequency (νr) is thus obtained as well as the peak maximum at resonance A0. It is also possible to obtain the attenuation frequency (νA), i.e. the frequency at which the output vibrational amplitude, A, is equal to the input amplitude, A0. The transmissibility at 6 Hz (A6Hz) is also recorded. Some of the internal organs of the human body resonate at this frequency.

d) Dynamic Fatigue

The dynamic fatigue test was conducted as previously outlined by Cavender[7,8]. The dynamic fatigue test exposes the foam cushion to a 5 Hz perturbation having an amplitude of ±5% deflection after a pre-compression of 50%. Changes in load, creep, and height are monitored as a function of time and used to generate a composite number (Dynamic Fatigue Number) depicting the potential durability of a particular PUF cushion.

RESULTS AND DISCUSSION

Principal Components and their Mathematical Properties (see appendix for details)
Principal components are orthogonal, this simply means that any combination of principal components are not correlated. Given no correlation exists among the principal components, we can mathematically analyze each component independently. Since each principal component describes a specific foam characteristic, any inference we make is therefore specific to that foam characteristic. From this point, we interchangeably refer to principal components as foam characteristics. In Table 1, we show a foam characteristic correlation matrix. The foam characteristics are identified as FC1, FC2, FC3, and FC4. As expected the correlations are zero. Later, in the analyses, we will name each foam characteristic.

<table>
<thead>
<tr>
<th>FOAM CHARACTERISTIC CORRELATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC1</td>
</tr>
<tr>
<td>FC2</td>
</tr>
<tr>
<td>FC3</td>
</tr>
<tr>
<td>FC4</td>
</tr>
</tbody>
</table>

Table 1

Proportion of Variation Explained by Principal Component Analysis

In Table 2, we identify each foam characteristic as FC1, FC2, FC3, and FC4. Under each foam characteristic, there is a numerical weighting for each physical property test. This weighting quantifies that physical property tests contribution to that specific foam characteristic. Multiplying this weighting by the square root of the Eigenvalue for that foam characteristic tells us how correlated that physical property test is with the said foam characteristic.

<table>
<thead>
<tr>
<th>PHYSICAL PROPERTY TEST CORRELATIONS</th>
<th>Hysteresis Loss</th>
<th>IFD Loss</th>
<th>Natural Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFD Loss</td>
<td>0.605</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>-0.496</td>
<td>-0.491</td>
<td></td>
</tr>
<tr>
<td>Attenuation</td>
<td>-0.511</td>
<td>-0.474</td>
<td>0.965</td>
</tr>
<tr>
<td>Thickness</td>
<td>-0.340</td>
<td>-0.384</td>
<td>0.803</td>
</tr>
<tr>
<td>Compression</td>
<td>0.590</td>
<td>0.384</td>
<td>-0.195</td>
</tr>
</tbody>
</table>

Table 3A

We must keep in mind that some physical property tests may measure more than one foam characteristic. When we consider explaining a physical property test with another we must not eliminate that physical property test until we have assured ourselves that it is not equal to, or

The first foam characteristic explains about 27% of all the variation in the data set. The second foam characteristic explains about 22%. The third, and fourth foam characteristics explain about 9 and 7% of all the variation in the data set respectively. In total, the first four foam characteristics explain 65% of all the variation in the data set.

Of interest are those physical property tests that are highly correlated with each foam characteristic FC1 through FC4. As such, we are interested in those physical property tests that have a correlation equal to, or greater than 0.6 with each foam characteristic. A correlation of 0.6 was chosen since we consider this a conservative cut-off correlation.

First Foam Characteristic – FC1

In Figure 1, we show a Pareto chart that illustrates the absolute magnitude of the correlation for each physical property test versus FC1. Hysteresis Loss is the highest correlated physical property test with FC1, r = 0.84. The remaining physical property test correlations are found in Figure 1.

Given Hysteresis Loss has the largest correlation, any physical property test that is highly correlated with Hysteresis Loss (r = 0.75 or greater) is a candidate for elimination. We call this the Primary Physical Property Testing Reduction Stage. This achieves data reduction and testing efficiency. In Tables 3A and 3B we show a correlation matrix for those six physical property tests having a correlation equal to, or greater than 0.6 as evaluated against FC1. We show IFD Loss as having the highest correlation, r = 0.60, with Hysteresis Loss. Given this does not meet our cut-off requirement, eliminating it from the analysis is not recommended.
greater than \( r = 0.6 \) with another foam characteristic. In this manner, we do not eliminate a physical property test that may explain another foam characteristic. When a physical property test measures more than one foam characteristic we call such a test a Dual Property Test.

Having identified Hysteresis Loss, IFD Loss, Natural and Attenuation Frequency, Thickness, and Compression Set as those physical property tests with correlations equal to, or greater than 0.6 we subsequently named the first and most critical foam characteristic Energy Dissipation\(^{(6)}\).

Second Foam Characteristic – FC2

In Figure 2, we show a Pareto chart that illustrates the absolute magnitude of the correlation for each physical property test versus FC2. IFD is the highest correlated physical property test with the second foam characteristic, \( r = 0.80 \). The remaining physical property test correlations are found in Figure 2.

Given IFD has the largest correlation, \( r = 0.80 \), any physical property test that is highly correlated with IFD (\( r = 0.75 \) or greater) is a candidate for removal. This again is the Primary Physical Property Testing Reduction Stage. In Table 4, we show a correlation matrix for those four physical property tests with a correlation equal to, or greater than 0.6 as evaluated against FC2. We show Tear Strength as having the highest correlation, \( r = 0.62 \), with IFD. Since this does not meet our cut-off requirement, there does not exist an opportunity to achieve data reduction and testing efficiency.

Table 4

<table>
<thead>
<tr>
<th></th>
<th>IFD 50%</th>
<th>Tear Strength</th>
<th>Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tear Strength</td>
<td>0.620</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>0.596</td>
<td>0.579</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>0.589</td>
<td>0.440</td>
<td>0.398</td>
</tr>
</tbody>
</table>

Regional Cushion Design Philosophies

At this point, we have defined the two most critical foam characteristics as Energy Dissipation and Strength. Collectively, they explain about 50% of all the variation in the data set. In this regard, we may use their principal component scores to illustrate cushion design philosophies.

In Figure 3, we plotted the principal component scores for Strength and Energy Dissipation. The horizontal axis represents Energy Dissipation. The lower the score, the higher the level of Energy Dissipation. Subsequently, the vertical axis represents Strength. A higher score corresponds to a higher Strength.

Generally, Japanese front seat cushions have the highest level of Energy Dissipation followed by Europe then North America. Alternatively, European front seat cushions have the highest level of Strength, followed by Japan then North America.
In Table 5, we show the median results for Hysteresis Loss, Ball Rebound, Thickness, IFD, and Density for North American, European, and Japanese front seat cushions.

### MEDIAN PHYSICAL PROPERTY RESULTS

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>North America</th>
<th>Europe</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hysteresis Loss (%)</td>
<td>29</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>Ball Rebound (%)</td>
<td>49</td>
<td>51</td>
<td>58</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>68</td>
<td>74</td>
<td>93</td>
</tr>
<tr>
<td>IFD 50% (N)</td>
<td>295</td>
<td>380</td>
<td>345</td>
</tr>
<tr>
<td>Density (Kg/m³)</td>
<td>37</td>
<td>47</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 5

Each region has a different cushion design philosophy. We generally explain the high Energy Dissipation outcome for Japanese cushions by way of their larger cushion Thickness. The median Thickness difference between a Japanese and European cushion is 19 mm. Comparing the Japanese median Thickness to a North American cushion we notice a 25 mm difference. Alternatively, European cushions are 35 N and 85 N harder than Japanese and North American cushions.

### Third Foam Characteristic – FC3

In Figure 4, we show a Pareto chart that illustrates the absolute magnitude of the correlation for each physical property test versus FC3. Support Ratio is the highest correlated physical property test with FC3, \( r = 0.67 \). The remaining physical property test correlations are found in Figure 4.

Visually inspecting Figure 4 it is evident that no significant correlations exist with Support Ratio. Thus, an opportunity for Primary Physical Property Testing Reduction does not exist. We have named this foam characteristic Static Support.

### Fourth Foam Characteristic – FC4

In Figure 5, we show a Pareto chart that illustrates the absolute magnitude of the correlation for each physical property test versus FC4. Elongation is the highest correlated physical property test with FC4, \( r = 0.77 \). The remaining physical property test correlations are found in Figure 5.

Visually inspecting Figure 5 it is evident that no significant correlations exist with Elongation. Thus, an opportunity for Primary Physical Property Testing Reduction does not exist. We have named this foam characteristic Elasticity.

### Energy Dissipation and its Foam Characteristic Equation – FCE1.

\[
\text{FCE1} = 0.400z_1 + 0.374z_2 - 0.357z_3 - 0.351z_4 - 0.299z_5 + 0.295z_6 - 0.284z_7 - 0.264z_8 - 0.258z_9 - 0.161z_{10} - 0.160z_{11} - 0.059z_{12} + 0.034z_{13} + 0.014z_{14} + 0.015z_{15} - 0.008z_{16}
\]

As we illustrated earlier, Hysteresis Loss \( z_1 \), IFD Loss \( z_2 \), Natural \( z_3 \) and Attenuation \( z_4 \) Frequency, Thickness \( z_5 \), and Compression Set \( z_6 \), yield correlations in excess of \( r = 0.6 \). Therefore, these physical properties have the greatest effect on Energy Dissipation.
The Energy Dissipation coefficients are arranged in descending order. The standardized variables z1 through z16 are Hysteresis Loss, IFD Loss, Natural and Attenuation Frequency, Thickness, Compression Set, Ball Rebound, Density, A/Ao Peak, A/Ao at 6 Hz, Height Loss, IFD, Tear Strength, Elongation, Support Ratio, and Tensile Strength.

Before we illustrate the use of the Energy Dissipation equation, we must properly interpret the role of Natural and Attenuation Frequency in this equation. Given Natural and Attenuation Frequency are highly correlated, we will limit our discussion to Natural Frequency.

The transmissibility, $A/A_0$, is plotted as a function of the excitation frequency, which in our investigation begins at 1 Hz and ends at 16 Hz. The natural frequency we have referred to is the resonance frequency that corresponds to the peak maximum, $A_p$, at resonance. In order to avoid the disastrous effects resulting from the increased amplitude of vibration at resonance, the natural frequency of the system must be known and properly considered.

Damping, in its various forms will slow the motion of a mass supported by a cushion. If the damping is heavy, oscillatory motion will not occur; the system is over-damped. If the damping is light, oscillation is possible and thus the system is under-damped. A critically damped system is one in which the amount of damping is such that the resultant motion is on the borderline between the two cases mentioned\(^{10-11}\). When vibration is damped, less energy is transmitted to the mass. That energy is captured and dissipated by the cushion, and thus the cushion becomes the damper.

In the following equation, we compare undamped motion vs. damped motion.

$$\tau_{\text{max}} = \frac{\tau}{(1 - 2\delta^2)^{0.5}}$$

$\tau_{\text{max}}$ = Excitation period at resonance  
$\tau$ = Natural period of the system  
$\delta$ = Damping Factor

In the expression, we find that the period, $\tau_{\text{max}}$, is that excitation period that corresponds to the natural period of the system, $\tau$, when $\delta = 0$. This occurs when the frequency of the excitation is equal to the natural frequency of the system. In this case, the amplitude of the vibration transmitted to the mass, on the cushion, will increase dramatically. Through damping we can control and reduce this effect. As the damping factor increases the denominator in the expression decreases and the time required to complete one cycle becomes larger. Therefore, the mass will move slower, the peak amplitude will be reduced, and we eliminate the undesirable effects that occur at resonance. Overall, less energy is transferred to the mass since some of the energy is dissipated by the cushion.

In the Energy Dissipation equation, z3 and z4 correspond to Natural and Attenuation Frequency. We notice that each has a negative sign. This is the result of an inverse transform that was applied to the frequency data to ensure normality. Therefore, a large z3 or z4 variable corresponds to a small Natural and Attenuation Frequency.

If we want to minimize the energy transmitted to a driver the Natural and Attenuation Frequency experienced by the driver should be reduced. We attempt to do this by
increasing the damping factor of the foam. If we increase cushion resiliency, it will result in a low Hysteresis Loss, lower IFD loss, and most likely a lower Compression Set. However, this may not make the cushion a better damper but will shift the peak amplitude to a lower resonance frequency. In addition, by increasing cushion Thickness, the peak amplitude will be reduced and this will reduce the energy transmitted to the driver. Thus, the occupant should experience a more comfortable ride.

In this investigation, the highest Energy Dissipation result was -4.8. This cushion had the following standardized variable results, z1= -1.75, z2= -1.88, z3= 0.48, z4=0.59, z5=1.13, and z6= -1.88. This corresponds to a Hysteresis Loss of 18%, an IFD Loss of 15%, a Natural and Attenuation Frequency of 5 and 7 Hz respectively, a Thickness of 102 mm, and a Compression Set of 7%.

**Strength and its Foam Characteristic Equation – FCE2**

\[
FCE2 = 0.426*z1 + 0.422*z2 + 0.399*z3 + 0.348*z4 - 0.305*z5 - 0.300*z6 - 0.242*z7 - 0.204*z8 - 0.141*z9 + 0.131*z10 + 0.117*z11 + 0.098*z12 - 0.086*z13 + 0.086*z14 + 0.030*z15 - 0.027*z16
\]

Since IFD (z1), Tear (z2) and Tensile Strength (z3) and Density (z4) yield correlations in excess of \( r = 0.6 \), these physical properties have the greatest effect on Strength.

The Strength coefficients are arranged in descending order. The standardized variables z1 through z16 are IFD, Tear and Tensile Strength, Density, Attenuation and Natural Frequency, Thickness, Compression Set, Support Ratio, Elongation, A/AoPeak, Height Loss, Hysteresis Loss, Ball Rebound, A/Ao at 6 Hz, and IFD Loss.

If, for example, we desire high Strength we must achieve a high FCE2 result. This requires a high IFD, Tear and Tensile Strength, and Density. In this investigation, the highest Strength had the following standardized variable results, \( z1=3.28, \ z2=1.77, \ z3=1.48, \ z4=1.64. \) This corresponds to an IFD of 600 N, a Tear and Tensile Strength of 360 N/m and 250 kPa respectively, and a Density of 60 kg/m³.

**Static Support and its Foam Characteristic Equation – FCE3**

\[
FCE3 = 0.565*z1 + 0.455*z2 + 0.356*z3 - 0.310*z4 +0.248*z5 + 0.232*z6 - 0.211*z7 + 0.163*z8 + 0.154*z9 +0.122*z10 - 0.099*z11 - 0.098*z12 - 0.063*z13 +0.027*z14 - 0.027*z15 + 0.010*z16
\]

Support Ratio (z1) has a correlation in excess of \( r = 0.6 \). This physical property has the greatest effect on Static Support.

The Static Support coefficients are arranged in descending order. The standardized variables z1 through z16 are Support Ratio, A/Ao Peak, Hysteresis Loss, Elongation, Thickness, IFD, Ball Rebound, Tensile Strength, A/Ao at 6 Hz, Tear Strength, Height Loss, Density, IFD loss, Natural and Attenuation Frequency, and Compression Set.

To achieve a large FCE3 result, a high Support Ratio is required. In this investigation, the highest FCE3 result corresponds to a Support Ratio of 4.19.

$$FCE4 = 0.726z1 - 0.535z2 - 0.191z3 + 0.175z4 - 0.168z5 - 0.152z6 + 0.133z7 - 0.129z8 + 0.122z9 - 0.083z10 + 0.057z11 + 0.056z12 + 0.060z13 + 0.037z14 + 0.027z15 + 0.022z16$$

Since Elongation yields a correlation in excess of $r = 0.6$, this physical property test is considered the most significant.

The Elasticity coefficients are arranged in descending order. The standardized variables $z_1$ through $z_{16}$ are Elongation, Support Ratio, Height Loss, Ball Rebound, IFD Loss, $A/A_o$ at 6 Hz, Compression Set, $A/A_o$ peak, Density, IFD, Tensile Strength, Hysteresis Loss, Tear, Natural Frequency, and Attenuation Frequency, and Thickness.

To achieve a high FCE4 result, a high Elongation is required. In this investigation, the highest FCE4 result did not correspond to the highest Elongation. However, it was within the top 15 cushions. In this equation, Support Ratio ($z_2$) had the second highest coefficient. Although it had an absolute correlation result of $r = 0.57$ it was large enough to impact the overall FCE4 result. This illustrates how a specific physical property can be used to explain the desired foam characteristic result.

Summary and Conclusions

We have illustrated a procedure that groups physical property tests into distinct foam characteristics by way of their principal components.

We used the first and second foam characteristics, Energy Dissipation and Strength, and plotted their principal component scores to illustrate regional cushion design philosophies. This illustrates the various comfort philosophies that exist globally and shows how comfort is perceived differently by OEMs in different regions of the world.

We have illustrated the foam characteristic equations for Energy Dissipation, Strength, Static Support, and Elasticity. In this manner, we have shown how to quantify the impact, on the foam, by changing different physical properties. According to FCE1, a low Hysteresis Loss may be offset by a large IFD Loss that may not produce the desired Energy Dissipation result. Subsequently, the net Energy Dissipation effect may be zero. This example illustrates the usefulness of the foam characteristic equations.

We have introduced a method that seeks to change specific foam characteristics in a consistently scientific manner. We show how to target cushion comfort requirements in each market and how to design cushion comfort specifically to fit the desired application of the customer through the foam characteristic equations.

We have defined future chemical research in a manner consistent with the makeup of each foam characteristic and described those physical properties that influence each foam characteristic. This research will use customer ride evaluations to confirm our hypothesis that comfort is a function of foam characteristics. We have outlined this approach in Scheme 1.
Future Investigation

Hysteresis Loss, IFD Loss, Natural and Attenuation Frequency, Thickness, Compression Set, IFD, Tear and Tensile Strength, Density, Support Ratio, and Elongation have the largest impact on Energy Dissipation, Strength, Static Support, and Elasticity. The remaining challenge is to determine those chemical functions that cause these physical properties to change in a way that motivates changes in Energy Dissipation, Strength, Static Support, and Elasticity. The advantage of using this approach is the simplicity in designing a statistical experiment and administering a ride evaluation. Having identified four foam characteristics, a $2^4$ factorial experiment can be designed and the sixteen cushions may be subjected to ride evaluation. The objective will be to test the hypothesis that the evaluated comfort is a function of Energy Dissipation, Strength, Static Support, and Elasticity. Ultimately, we will quantify the customer's reaction to changing foam characteristics thus quantify comfort.

ACKNOWLEDGMENTS

We would like to thank our colleagues in the Woodbridge Group for their help in obtaining the cushions evaluated in this study. The cushions were tested in our Corporate Laboratory under the guidance of Tuan Le.

We would also like to thank Doug Cavender and Brian Neal of Lyondell Chemical Company, West Virginia for supervising and reporting the vibrational transmissibility and dynamic fatigue investigations.

REFERENCES


APPENDIX

Principal Component Analysis Method

Principal components are specific uncorrelated linear combinations of p random variables $X_1, X_2, \ldots, X_p$. These linear combinations represent a new coordinate system. These new axes represent the directions with maximum variability and provide a simpler and more descriptive illustration of the covariance structure. Principal components depend on the covariance matrix $\Sigma$ or the correlation matrix $\rho$, of $X_1, X_2, \ldots, X_p$. In this analysis, the variables had different scales of unit measure. As such, sample principal components are not invariant with respect to changes in the scale of measure. Therefore, the scales of measure have been standardized. Standardization is accomplished by constructing the data matrix of standardized observations and subsequently deriving the sample correlation matrix $R$. 
Given a random vector \( \mathbf{X} = [X_1, X_2, \ldots, X_p] \) from which we can derive the correlation matrix \( \rho \), we can extract the Eigenvalues, \( \lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_p \geq 0 \), which represent maximum variability. By constructing uncorrelated linear combinations of the measured characteristics, we account for much of the variation in the data set. The sample principal components of the standardized observations are given by the matrix \( R \). If \( z_1, z_2, \ldots, z_p \) are standardized with correlation matrix \( R \), the \( i \)th principal component score is,

\[
y_i = e_i^T z_i = e_1 z_1 + e_2 z_2 + \ldots + e_p z_p
\]

\( i = 1, 2, \ldots, p \)

The sample variance is,

\[
(\hat{y}_i)^2 = \lambda_i, \quad i = 1, 2, \ldots, p
\]

The sample covariance is,

\[
(\hat{y}_i, \hat{y}_k) = 0, \quad i \neq k
\]

The total sample variance (standardized) is,

\[
\text{tr} (R) = \hat{\lambda}_1 + \hat{\lambda}_2 + \ldots + \hat{\lambda}_p
\]

The correlation of a component within a said principal component is,

\[
r_{y_i z_k} = e_{ki} \sqrt{\hat{\lambda}_i}, \quad i, k = 1, 2, \ldots, p
\]

A rule of thumb suggests retaining only those sample principal components whose variance \( \lambda_i \) are greater than unity or, only those which, individually, explain at least \( 1/p \) of the total variance. This rule should not be applied blindly.

**Principal Component Sample Calculation**

The first (E1), second (E2), third (E3), and fourth (E4) Eigenvectors are shown. They were derived from the sample correlation matrix \( R \). Each of the coefficients in an Eigenvector column represents a weighting assigned to each of the physical property tests, for each principal component PC1, PC2, PC3, PC4. Given these coefficients are scalar, we normalize each to insure an Eigenvector multiplied by it’s transpose yields a unit length of one. In this manner we do not weight or favor one principal component over another.

Multiplying the transpose of the first Eigenvector, a 1x16 vector, by a 16x1 column vector made up of the standardized physical property tests yields -3.2286 for PC1. This is the first principal component’s score for a single cushion. The remaining principal component scores for PC2, PC3, and PC4 are -0.1591, -1.1950, and 0.4318. Given 59 different cushions remain, there are an additional 59 principal component scores.

**PHYSICAL PROPERTY TEST EIGENVECTORS**

<table>
<thead>
<tr>
<th>Physical Property Test</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
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<tbody>
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<td>Thickness</td>
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<td>-0.242</td>
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<td>-0.059</td>
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<td>Density</td>
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<td>Tear Strength</td>
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<td>Compression Set 50%</td>
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<tr>
<td>Natural Frequency</td>
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<tr>
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<tr>
<td>A/Ao at 6 Hz</td>
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<td>0.030</td>
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<tr>
<td>Height Loss</td>
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<td>-0.063</td>
<td>-0.168</td>
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</table>

(Note: weights rounded to three decimal places)

**STANDARDIZED PHYSICAL PROPERTY RESULTS FROM A SINGLE FRONT SEAT CUSHION**

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<tr>
<th>Physical Property</th>
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<tr>
<td>IFD50</td>
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<td>A/Ao at 6 Hz</td>
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<tr>
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