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ANALYSIS OF METHODS FOR PREDICTING ACCURATE
ACCOMMODATION IN PASSENGER VEHICLES

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by

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ABSTRACT

The objective of this thesis is to assess and compare modern statistical methods of vehicle packaging design for the sake of improving accuracy. Accurate design of a vehicle’s packaging is critical for the safety and comfort of its user population while also being essential in keeping the costs of manufacturing low. An individual is deemed accommodated by a design if they can comfortably interact with it as they prefer. This study seeks to employ a method known as the Cascade Prediction Model in order to posture individuals in vehicle packages. The use of the Cascade Prediction Model in conjunction with a virtual fit test results in a lower overall accommodation rate compared to the rate intended by the current design standards put forth by the Society of Automotive Engineers. This implies that designs generated using the current methods likely accommodate a lower percentage of individuals than they predict. The results of this thesis suggest that the current Society of Automotive Engineers J standards should be revised in order to reflect modern methods that produce better recommendations in the packaging design process. By implementing an approach such as the Cascade Prediction Model, packages that accommodate the correct percentage of individuals can be designed.
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CHAPTER I
INTRODUCTION

The quality of interior packaging design is one of the most important aspects in improving safety, comfort, and manufacturing cost of a vehicle. For the purpose of this thesis, vehicle packaging is defined as the geometry of structures including the driver seat, pedals and visual obstructers in the interior of a vehicle. A common goal throughout the history of automotive design is the appropriate accommodation of a targeted group of potential drivers (Gragg, Yang, & Howard, 2012). A design that properly accommodates its intended users will yield a product that permits a select group of drivers to posture themselves for the safe and comfortable operation of the vehicle (Peacock & Karwowski, 1993). One of the biggest challenges that occurs in packaging design stems from the variability between humans (de Vries & Parkinson, 2014; Garneau & Parkinson, 2009; Reed, Manary, Flannagan, & Schneider, 2000).

Henry Dreyfuss is a key figure in the field of human factors and ergonomics who is credited with designing some easily recognizable products ranging from John Deere tractors and Honeywell thermostats to the classic Bell System telephones. Dreyfuss and his firm employed a fixed percentile manikin technique for modeling human anthropometry (Dreyfuss, 1966). While these manikin models have been used to design many of the products we use every day, they fail to consider the variability caused by differences in size and shape between people (Garneau & Parkinson, 2011). The sort of percentile-based manikin model that Dreyfuss contributed to the field became commonly deployed across industries, including automotive. An example can be found in the current rules for the Society of Automotive Engineers (SAE) Formula racecar design competition. The 2019 rules require that “The vehicle must be able to accommodate drivers of sizes ranging from 5th percentile female up to 95th percentile male” and that “Accommodation includes driver position, driver controls, and driver equipment” (“Formula SAE Rules 2019,” 2018). While these design principles can readily be found in the rules of a competition for college
students, they are not all that different from how SAE recommends the automotive industry lay out a vehicle.

SAE has maintained a collection of procedures for use in the development of vehicle design. Known as the SAE J standards, these procedures contain a subset of design guidelines that focus on vehicle interior packaging. Standards like J-941, which predicts driver eye location, and J-4004, which predicts driver seat position, are used to design packaging such that accommodation is maximized for a targeted population. In recent years, the packaging standards have been criticized for their outdated methods (Flannagan, Manary, Schneider, & Reed, 1998; Manary, Flannagan, Reed, & Schneider, 1998; Reed, 2005, 2013). While some of the standards have been modernized or replaced entirely, there is still an overarching issue with the methods of the current guidelines. The J standards have failed to account for the variability of physical measures such as height and mass, between individuals. By assessing measures of interest such as eye location and seat position individually, instead of in concurrence with other packaging measures, target accommodation statistics are likely not being met in reality (Moroney & Smith, 1972; Robinette & McConville, 1981).

This thesis investigates several packaging strategies including the percentile models used in the SAE J standards, and the driver posturing model known as the Cascade Prediction Model. Ultimately, the goal of this work is to show how the percentile-based methods currently used to design vehicle packaging likely overestimate accommodation rates for potential driver populations.
CHAPTER II
BACKGROUND AND LITERATURE REVIEW

In the field of human factors and ergonomics, a few major strategies are used in modeling for design. For statistical analysis, either univariate or multivariate methods are employed to determine the percentage of a population that will successfully interact with a design. *Univariate methods*, such as the percentile models addressed in Chapter I, break a larger design problem down into subproblems that are solved individually and superimposed on each other. *Multivariate methods* consider the entirety of the design problem simultaneously. In rare cases, univariate methods may be appropriate for design. Complexity added by an increased number of variables or poor correlation between variables, will diminish the performance of such univariate models (Robinette & McConville, 1981). This chapter discusses the current strategies employed by industry for the purpose of vehicle packaging design as well as the principles behind a proposed alternative.

2.1 Modeling Strategies Addressed

Vehicle packaging as discussed in this document, focusses on the driver seat’s horizontal and vertical adjustability as well as the location of a driver’s eyes within an automobile. A driver is considered *accommodated* by a vehicle package when they both fit in the design such that safety constraints and physical restrictions are not being violated, and can posture themselves in a way that they are comfortable. An example of such a physical restriction is the censoring of part of a driver population that would prefer to adjust their seat beyond the limits of the seat track. If a driver is unable to adjust the seat to a comfortable position because of the track limits, they are considered *disaccommodated*. The goal of this study is to address the effects that two differing models used in the design of vehicle packaging have on predicted accommodation.
The first model discussed is the current recommended practices set by The Society of Automotive Engineers for designing vehicle packaging. This group of J standards are a subset of SAE’s Ground Vehicle Standards which act as guidelines for the design of high quality and highly operable vehicles. The J standards relevant to this study consider seat adjustability and eye-location. While there are numerous other vehicle packaging design tools within the J standards, it is out of the scope of this project to include them. The Cascade Prediction Model (CPM) is the second technique being evaluated here. The CPM is a human posturing model that designates the highest priority to the prediction of hip and eye location for a driver (Reed, Manary, Flannagan, & Schneider, 2002).

There is a major difference in these models. The J standards are broken out into individual tools used for predicting specific measures such as hip and eye location for a population using the summary statistics of distributions describing the population’s physical measures. The CPM is used for predicting all of the measures of interest simultaneously for a single individual. Because the J standards evaluate variables either one at a time or in groupings (such as eye location along three axes) they poorly consider covariance between measures such as eye and hip location. The CPM considers this covariance by posturing each person individually. This feature can be exploited for use with a technique known as a virtual fit test (VFT) that individually checks each postured driver for proper accommodation on all measures (Garneau & Parkinson, 2011; Parkinson, Reed, Kokkolaras, & Papalambros, 2007).

2.2 Anthropometric Distributions, Preference and Vehicle Packaging

Human Factors and Ergonomics is a field that aims to improve the quality of products by applying knowledge of human physiological and biomechanical characteristics to the design process (“Definition and Domains of Ergonomics,” 2019). A subset of these characteristics, known as anthropometry, describe the physical measurements of people. A convenient quality of anthropometric measures is that they are typically either normally distributed, or easily transformed to be normally distributed (Peacock & Karwowski, 1993; Vasu & Mital, 2000). In populations of data, measures of length such as stature or hip height tend to be normally distributed naturally (Kroemer, Kroemer, & Kroemer-Elbert, 2010; Vasu & Mital, 2000). Measures involving mass will commonly need to be
mathematically transformed in order to be modeled with a Gaussian distribution (Kroemer et al., 2010; Lalonde, 2012; Reed, 2005). Modeling each anthropometric measure with the same type of distribution is critical as it allows them to be represented simultaneously (e.g. a dataset with two independent normally distributed variables whose sum are also normally distributed is considered bivariate normally distributed). The tails of these distributions are typically where design constraints come from.

When designing a vehicle interior, tradeoffs must be made between accommodation, cost and appeal (Peacock & Karwowski, 1993). Parkinson et al. (2005) suggest that it is unreasonable to design for accommodation of all users as costs become excessive when designs are made to meet the requirements of outliers. While it is cost prohibitive to design for total accommodation, a balance between cost and safety must be met for the majority of potential drivers. Reed et al. (2000) describe the importance of packaging design with respect to the proper fit of restraint and control systems. Proper design models need to accurately predict accommodation so that decisions regarding safety and cost can be made on a solid foundation.

Linear regression methods can be used to model anthropometric and non-anthropometric characteristics of individuals in a population. For instance, Reed developed a model that predicts driver eye location in heavy trucks and buses using linear regression (Reed, 2005). Regression equations that include measures of anthropometry and vehicle dimensions as predictors are used to calculate a dependent measure. An example of the implementation of such an equation is the prediction of some measure as a function of stature, seat height, and a stochastic component that is representative of variability unrelated to the predictors. The regression models take the form as shown in Equation 1, where $a$ is the intercept, $b$ and $c$ are coefficients, and $N(0, sd)$ is the stochastic term centered on zero, with a specified standard deviation.

\[
\text{measure} = a + (b \times \text{stature}) + (c \times \text{seat height}) + N(0, sd) \quad \text{Eqn 1}
\]

Reed et al. (1999, 2002) proposed a method for predicting the way a driver interacts with a vehicle package based on linear regression. It postures individuals using a process called the Cascade Prediction Model. By locating key points of the human body and then
backfilling with inverse kinematics, the CPM places individuals in a design. The methods of the CPM are different from those of the SAE J standards because the CPM positions the whole body. This enables the evaluation of accommodation for unique measures simultaneously via a virtual fit test. The J standards evaluate accommodation based on population data that specifically target a single measure of interest at a time. Multivariate methods such as a virtual fit test combined with the CPM (Reed et al., 2002) or de Vries and Parkinson’s (2014) model show that individuals are often accommodated on some measures such as hip breadth while being disaccommodated for other measures such as stature.

Other packaging techniques and tools have been developed and implemented in both the US and abroad. One such example is the boundary manikin “Jack” tool developed by the University of Pennsylvania. This model treats individuals as kinematic linkages that can be postured and evaluated for accommodation (Blanchonette, 2010). For a few univariate cases, the use of boundary manikins can be an effective method for determining accommodation; however, under most circumstances boundary manikins are problematic, especially when poorly correlated measures are compounded (Moroney & Smith, 1972). Simultaneous evaluation of poorly correlated variables incorrectly considers individuals to be disaccommodated across all measures (Robinette & McConville, 1981).

Patterns in user interaction with a design that cannot be explained or modeled with anthropometry, such as the difference in seat position for two people of identical shape and size, are considered preference. While unaccounted for in some of the current SAE standards, the CPM takes preference into consideration in order to improve accuracy (Reed et al., 1999, 2002). Linear regression models used in the proposed alternatives include a stochastic term that falls within a specified normal distribution (Parkinson & Reed, 2006, 2010). The residual variance from linear regression models is usually normally distributed about a mean value of zero and is considered user preference (Garneau & Parkinson, 2009). Including preference is useful in design and improves accuracy by developing information about populations that can’t be modeled with anthropometry. Preference is a form of variability unique to the population represented in an experimental setup, therefore, translating a model including preference from one target population to another without acquiring further data may pose difficulties (Garneau & Parkinson, 2009).
2.3 The Kick Scooter: A Case Study in Univariate and Multivariate Methods

The following is a case study that displays the methods and impacts of univariate and multivariate fit based models. A univariate model is defined by the way it considers each variable of interest separately, while a multivariate model will consider all of the variables simultaneously. The main purpose of using multivariate instead of univariate methods is the improved accuracy in predicted accommodation due to the inclusion of covariance between measures.

A classic univariate approach employed in modeling interaction with a vehicle design is the use of percentile models. A percentile model in its simplest form is one that is used to design for a single dimension at a time by selecting a specific range of percentiles as boundaries. An overall design is built by stacking up independent univariate models. Consider a simple kick scooter as shown in Figure 1.

![Figure 1: Kick scooter](image)

Should the design requirements for the scooter specify that 90% of a certain population be able to interact with the handlebar height and width successfully, an engineer may attempt to employ a percentile model. In this example it will be assumed that the height of the handlebars from the deck of the scooter should be equal to the height of the rider’s trochanter (the distance from the floor to a bony landmark at the top of the femur, in a standing position). This means that the design of the adjustability of the
handlebar height be equal to some range that contains 90% of the population’s trochanter height. In a case such as this, a designer may select the central 90% or 5th to 95th percentile range of users. This minimizes the adjustable height range for the purpose of manufacturing and material cost reduction. The same process can be carried out for the design of the handlebar width. For this, we assume that handlebar width is equal to a person’s bideltoid breadth (the width across shoulders). The engineer may believe that they have designed a set of handlebars that accommodates 90% of the population but in reality, it will fall short of this specification.

![Figure 2](image.png)

**Figure 2: Plot of accommodated individuals using a univariate percentile method with trochanteric height vs bideltoid breadth accommodated individuals**

Figure 2 is a plot of trochanteric height vs bideltoid breadth for a population of male military reservists pulled from the ANSUR II dataset (Gordon et al., 2014). The red points indicate persons not within the 5th and 95th percentile cutoff boundaries for both measures simultaneously. The green values indicate persons who are within these bounds and are considered accommodated. This color convention will be carried throughout the
The purpose of Figure 2 is to convey that while boundaries are made at the 5th and 95th percentile, capturing 90% of the population for each measure individually, there are 3,287 accommodated persons marked in green and 4,082 persons total. This suggests that only 80.5% of individuals can successfully use this design. The principle causing this difference in accommodation rate is the individual evaluation of poorly correlated variables. The correlation between bideltoid breadth and trochanteric height is 0.45. Had predictors with higher correlation been utilized, the accommodation could have been closer to the 90% goal. Take for example the predictors of trochanteric height and forearm to hand length which have a correlation 0.81, being used to predict handlebar height and width adjustability respectively.

**Figure 3: Plot of accommodated individuals using a univariate percentile method with trochanteric height vs forearm to hand length**

In Figure 3, it can be seen that forearm to hand length is a far better predictor of trochanter height than bideltoid breadth. In fact, the number of accommodated individuals in this case is 3,456 out of 4,082 total riders. This represents an 85%
accommodation rate. While forearm to hand length correlates well with trochanteric height, it does not make for a good rule-of-thumb predictor of handlebar width. If the scooter’s handlebar width could be estimated with a measure more highly correlated with trochanteric height, the univariate method would work better. Though without perfect correlation, percentile models will never be perfect.

There are numerous alternatives to the univariate methods discussed above. It may be apparent that in order to accommodate 90% of users in actuality, a balance of handlebar width and height adjustability exceeding 90% individually, must be met. There are a large number of combinations of boundaries that will produce an overall 90% accommodation rate. One method for balancing these variables is the use of a cost function (Parkinson et al., 2007). For example, if cost due to adjustability were a concern, a function could be produced that simultaneously minimizes the total adjustability and meets the 90% accommodation requirement.

A multivariate method could be as simple as two arbitrary adjustability limits that when combined, produce a total accommodation of 90%. For the scooter example, a combination of width adjustability of 138 mm and height adjustability of 182 mm do exactly this. Figure 4 is a plot similar to the previous accommodation plots with the new adjustability limits imposed. The new design will accommodate 3,665 persons from the ANSUR II male data. This represents 90% accommodation.
The univariate methods of the kick scooter case study are analogous to the methods that the SAE J-Standards utilize in order to predict accommodation for vehicle packaging. The J-Standards reviewed in this research are procedures that predict seat position and eye location separately. If the seat position and eye location variables are not perfectly correlated, then it is expected that the J-Standards will produce a predicted accommodation rate that is too high. Instead, a multivariate method such as the previous example should be employed in order to achieve a more accurate accommodation rate and potentially provide a secondary function such as minimizing expensive adjustability.
CHAPTER III
METHODS

In order to show the disagreement between the CPM and the current SAE J standards, a direct comparison of the two models, using data from NHANES III will be performed (National Health and Nutrition Examination Survey III, 1988-1994, 1994). By setting up the procedures of the CPM and a selection of the SAE J standards including J-941 and J-4004 in R, accommodation levels can be determined for the CPM and the combination of J standards. This head-to-head contrast is expected to demonstrate that increased adjustability is required to achieve the targeted level of accommodation or that the J standards overestimate accommodation.

In this study, any mention of the terms “weight” or “weighting” refers to statistical multipliers used to prioritize certain participants over others in order to reflect the targeted population accurately. The term “weight” is never used to address the force of gravity on an individual.

3.1 Anthropometric Data from NHANES III

The population used for the development of the models in this chapter is a collection of US citizens that consists of approximately 50% women and 50% men, ages 21 and older from 1988-1994. This group will be collected from the NHANES III dataset which is intentionally sampled in order to reflect the general non-institutionalized US population. This dataset was selected for the first comparison because it is the same data used in the J-941 standard. Variables used from NHANES III include stature, the ratio of stature to sitting height, mass, and BMI. Since there are very few individuals with incomplete data compared to the overall number of participants, missing data were handled by using mean substitution imputation. The six-year statistical weights included in NHANES III are used to mimic the entirety of the US population using the individuals surveyed. The procedure for acquiring data from the overall NHANES III data set is as follows:
1. NHANES III data with specified variables including participant number, age, gender, stature, ratio of stature to sitting height, mass and BMI from the years 1988 to 1994, are loaded into R. To do this, a MATLAB script is used to pull from the NHANES III PDF data tables and create an excel spreadsheet.

2. Using R, entries that contain repeated 8’s (e.g. 8888) are replaced with “NA” as these represent missing data. Because there are few participants with missing data, the entries are imputed with the mean value of the remaining entries in the variable.

3. The remaining NHANES III data are narrowed to ages 21 and older

4. The data are then split into two groups, Nm (NHANES Male) and Nf (NHANES Female), that represent the data for each gender separately.

3.2 Example Vehicle Data

In order to compare accommodation levels for the CPM against the accommodation levels of the combined J standards, the models will be applied to multiple passenger vehicles. Design condition parameters for the example vehicles sourced from (Reed et al., 1999) include H30 (seat height), L6 (ball of foot reference point to steering wheel center), and L27 (seat cushion angle). As specific vehicle dimensions are not widely available to the public, values for the cowl and hood point locations with respect to the Ball of Foot and Accelerator Heel Point are estimates. In Chapter IV, is shown that these estimates are sufficient for the purpose of conveying the principles discussed in this thesis. The example vehicles are tabulated in Table 1. All variable definitions for vehicle measurements can be found in SAE Motor Vehicle Dimensions (“J1100 - (R) Motor Vehicle Dimensions,” 2009).

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>H30 (mm)</th>
<th>L6 (mm)</th>
<th>L27 (°)</th>
<th>Cowl Point (x,z) (mm)</th>
<th>Hood Point (x,z) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plymouth Voyager</td>
<td>326</td>
<td>504</td>
<td>14.0</td>
<td>(-80,750)</td>
<td>(-750,400)</td>
</tr>
<tr>
<td>Chrysler LHS</td>
<td>250</td>
<td>597</td>
<td>17.7</td>
<td>(-125,600)</td>
<td>(-1000,400)</td>
</tr>
<tr>
<td>Dodge Avenger</td>
<td>189</td>
<td>577</td>
<td>16.6</td>
<td>(0,480)</td>
<td>(-1000,350)</td>
</tr>
</tbody>
</table>
3.3 Vehicle packaging dimensions and critical locations

The following is a brief description of the dimensions and landmark points of vehicle packaging as discussed in this document. In a package, the x-axis describes the fore-aft location of a point with positive values being in the aft direction. For instance, a seat that slides backward and forward for adjustability does so along the x-axis. The origin of the x-axis is a point where the foot rests on the accelerator pedal called the Ball of Foot Reference Point (BOF). The z-axis points from the floor of the vehicle to the ceiling with its origin at the point where the heel of the foot on the accelerator meets the floor called the Accelerator Heel Point (AHP). The origin, landmark points, and vehicle dimensions referred to later in Chapter III are shown in Figure 5. Definitions of these variables are found in Appendix B.

![Diagram showing vehicle dimensions](image)

**Figure 5: Example vehicle dimensions**

3.4 Modeling Methods of SAE J-941

Field of vision is critical in vehicle packaging. One of the tools used in determining a driver’s field of vision is the SAE J-941 Eyellipse. This tool describes the predicted eye location for a specified percentage of a population, usually 95%, on one side of any tangent line drawn from the ellipse. The Eyellipse is useful as it shows how a population interacts with a package design’s visual obstructers such as the hood point and cowl point shown in Figure 5. The purpose of this section is to discuss the J-941 standard and provide a sample
calculation that develops the shape and orientation of the Eyellipse. Further information regarding the procedure and use of the Eyellipse can be found in SAE J-941 and SAE J-1100.

For this sample, the NHANES III data for the general United States population ages 21 and older, are used in conjunction with the vehicle package data from a Plymouth Voyager as described in Table 1. The following equations and procedure are referenced from SAE J-941 with further detail provided by Reed et al. (2005).

Figure 6: Principle axes of the Eyellipse

In order to determine the principle axes of the Eyellipse and the angle they make with the x-axis as shown in Figure 6, the variance-covariance matrix between the x-axis and z-axis predicted eye location ($x_{eye}$ and $z_{eye}$) data must be calculated. The variance-covariance matrix can be seen in Table 2.

Table 2: Variance-covariance matrix for predicted eye location

<table>
<thead>
<tr>
<th></th>
<th>$x_{eye}$</th>
<th>$z_{eye}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{eye}$</td>
<td>5664.8</td>
<td>1643.5</td>
</tr>
<tr>
<td>$z_{eye}$</td>
<td>1643.5</td>
<td>1349.2</td>
</tr>
</tbody>
</table>

From the variance-covariance matrix, the eigenvalues and eigenvectors as seen in Table 3 can be found. The first eigenvector is a linear combination of the predicted eye location variables that maximizes variance in its direction while the second eigenvector is a linear combination that is perpendicular to the first and accounts for as much remaining variance as possible.
Table 3: Eigenvalues and corresponding eigenvectors for the variance-covariance matrix

<table>
<thead>
<tr>
<th>Eigenvalues</th>
<th>λ₁</th>
<th>λ₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corresponding</td>
<td>-0.9475</td>
<td>0.3197</td>
</tr>
<tr>
<td>Eigenvectors</td>
<td>-0.3197</td>
<td>-0.9475</td>
</tr>
</tbody>
</table>

The first eigenvector describes the rotation of the first principle component’s axis (x’) away from the x-axis of the vehicle package. Equation 2 shows how this angle is calculated.

$$\theta = \arctan\left(\frac{-0.3197}{-0.9475}\right) = 18.65^\circ$$ \hspace{1cm} Eqn 2

This angle is used to rotate the predicted eye locations \(x_{\text{eye}}\) and \(z_{\text{eye}}\) into the x’ and z’-axes using Equations 4 and 5.

$$x_{\text{eye}}' = x_{\text{eye}} \times \cos(\theta) + z_{\text{eye}} \times \sin(\theta)$$ \hspace{1cm} Eqn 3

$$z_{\text{eye}}' = -x_{\text{eye}} \times \sin(\theta) + z_{\text{eye}} \times \cos(\theta)$$ \hspace{1cm} Eqn 4

The predicted eye locations are then centered by subtracting the mean value for both the \(x_{\text{eye}}'\) and \(z_{\text{eye}}'\) components from each point. This process creates the two most independent measures of predicted eye location by having maximized variance along new axes.

Two linear models are applied to these new measures. The first model predicts \(x_{\text{eye}}'\) as a function of stature, while the second model predicts \(z_{\text{eye}}'\) as a function of stature. Plots of these models can be seen in Figures 7 and 8. The adjusted R² value for the model fitted to \(x_{\text{eye}}'\) vs Stature is 0.5856 suggesting that there is reasonable evidence that predicted eye location in the x’ direction is significantly influenced by stature. This is not the case for \(z_{\text{eye}}'\). The R² value for the second linear model is 0.1116 which suggests low reliance on stature as a predictor. This concept leads into the procedure of the SAE J-941 standard where only the x’ Eyellipse axis length is directly related to the stature of the population. Since the z’ Eyellipse axis length is not influenced by stature, it is assumed that it can be solely modeled as normally distributed user preference.
Figure 7: Linear model fit to $x_{eye}$ vs Stature

$Eyex = -1026 + 0.6097 \times \text{Stature}$  
$R^2 = 0.5856$, RMSE = 51.49

Figure 8: Linear model fit to $z_{eye}$ vs Stature

$Eyz = -160.2 + 0.6951 \times \text{Stature}$  
$R^2 = 0.1118$, RMSE = 26.85
The next step in the J-941 standard’s procedure is locating a reference center point for the Eyellipse in the x-z plane, where H8 and L1 are the origins for their respective axes, and L6 and H30 are the vehicle parameters of Ball of Foot to Steering Wheel Center and Seat Height. This vehicle specific data is referenced from Table 1. Equations 5 and 6 are used to establish this reference point.

\[ x_{\text{reference centroid}} = L1 + 664 + 0.587(L6) - 0.176(H30) \quad \text{Eqn 5} \]

\[ z_{\text{reference centroid}} = H8 + 638 + H30 \quad \text{Eqn 6} \]

Once the reference center of the Eyellipse has been established, its axis lengths are taken into consideration. The axis lengths of the Eyellipse are directly related to percentile accommodations for a population. Care must be taken in calculating the length of the axes for a population of 50% women and 50% men, as male and female drivers have differing average stature, which causes their respective Eyellipse centers to differ. The first step in determining axis lengths is to calculate male and female eye location centroids in the x’ direction with the slope of the linear model given in Figure 7 and Equations 7 and 8,

\[ x'_{\text{male centroid}} = 0.6097(S_M - S_R) = 44.6 \text{ mm} \quad \text{Eqn 7} \]

\[ x'_{\text{female centroid}} = 0.6097(S_F - S_R) = -44.6 \text{ mm} \quad \text{Eqn 8} \]

where \( S_M \) and \( S_R \) are male and female mean stature, respectively, and \( S_R \) is the total population’s average stature. Standard deviations for the male and female component distributions are then calculated with the slope and RMSE of the linear model in Figure 7 and Equations 9 and 10,

\[ x'_{\text{male std dev}} = \sqrt{(0.6097)^2\sigma^2_M + (51.49)^2} = 68.62 \text{ mm} \quad \text{Eqn 9} \]
\[ x'_{female \ std \ dev} = \sqrt{(0.6097)^2 \sigma^2_F + (51.49)^2} = 66.99 \, mm \quad Eqn \ 10 \]

where \( \sigma_M \) and \( \sigma_F \) are the male and female standard deviations for stature.

The centroid and standard deviation for the male and female predicted eye locations define a set of normal distributions that are used to calculate forward and rearward boundaries for the Eyellipse based on cutoff percentiles. Cutoff boundaries \( CM \) and \( CF \) are determined by solving Equations 11 and 12 iteratively.

\[
1 - q = 0.5 \Phi \left( \frac{CF - x'_{\text{male centroid}}}{x'_{\text{male std dev}}} \right) + 0.5 \Phi \left( \frac{CF - x'_{\text{female centroid}}}{x'_{\text{female std dev}}} \right) \quad Eqn \ 11
\]

\[
q = 0.5 \Phi \left( \frac{CM - x'_{\text{male centroid}}}{x'_{\text{male std dev}}} \right) + 0.5 \Phi \left( \frac{CM - x'_{\text{female centroid}}}{x'_{\text{female std dev}}} \right) \quad Eqn \ 12
\]

This forms the boundaries for the \( x' \)-axis of the tangent cutoff ellipse from the lower end of the female distribution to the upper end of the male. For this sample, \( CF = -128.7 \, mm \) and \( CM = 156.2 \, mm \). The cutoff percentile is represented by \( q \), and \( \Phi \) is the Gaussian distribution function. \( CM \) and \( CF \) are used to calculate the \( x \)-axis length as in Equation 13.

\[ x_L' = CM - CF = 285 \, mm \quad Eqn \ 13 \]

Since stature has been shown to be a poor predictor of eye location in the \( z' \) direction, the \( z \)-axis length of the Eyellipse is calculated with only the standard deviation of predicted eye location in the \( z' \) direction and Equation 14 where \( \Phi^{-1} \) is the inverse Gaussian distribution function.

\[ Z_L' = 27.87 \left( \Phi^{-1}(q) - \Phi^{-1}(1-q) \right) = 93 \, mm \quad Eqn \ 14 \]

Using \( \beta \) which defines the angle between the \( x \)-axis and the long axis of the seat track, the final center point of the Eyellipse is located by Equations 15 and 16.
\[ X_C = X_{\text{reference centroid}} + \frac{CF + CM}{2} \cos \beta \]  
\[ Z_C = Z_{\text{reference centroid}} + \frac{CF + CM}{2} \sin \beta \]

Eqn 15  
Eqn 16

The Eyellipse representative of the general US population with a 50/50 mix of men and women seated in a Plymouth Voyager can be seen in Figure 9. The Eyellipse appears to be located further rearward than the center of the point cloud. This is caused by the larger standard deviation of male eye location in the x’ direction which causes the boundaries CM and CF to be asymmetric.

Figure 9: J-941 Eyellipse for the NHANES III general US population seated in a Plymouth Voyager
3.5 Modeling Methods of SAE J-4004

In order to determine hip-point (H-Point) locations for the intended driver population in the vehicle package, J-4004 utilizes a univariate regression model similar to that of SAE J-941. The key difference in these models is that SAE J-4004 is used only to predict a single variable; seat position in the fore-aft direction. Equation 17 is used to calculate the location of the H-point reference location.

\[ x_{H-Point\ reference} = 718 - 0.24(H30) + 0.41(L6) \]  \hspace{1cm} Eqn 17

After the reference location is determined, Equations 18 and 19 are used to construct an interval containing 95% of individuals within the population by adding 124 mm in the aft-direction and subtracting 116 mm in the fore-direction. These values were referenced from confidence interval tables within the J-4004 procedure.

\[ x_{Fore\ H-Point} = x_{H-Point\ reference} - 116 \]  \hspace{1cm} Eqn 18

\[ x_{Aft\ H-Point} = x_{H-Point\ reference} + 124 \]  \hspace{1cm} Eqn 19

One limitation of the CPM model is that it deals specifically with seats that are only adjustable in the vertical direction. Because of this, the z-coordinate of the H-Point is always H30. Once the predicted H-Points are determined, they are ready to be compared to that of predicted H-Point locations given by the CPM using a virtual fit test.

3.6 Modeling Methods of the Cascade Prediction Model

The Cascade Prediction Model uses experimental data to create regression equations that posture an individual based on vehicle dimension and driver anthropometry inputs (Reed et al., 1999). Regression tables used in the CPM are given in Appendix A. By outputting a few points on the human body including ankle, hip, and eye location, the CPM gives key points the highest priority and the most accuracy when compared to its other outputs (Reed et al., 2002). Other variables predicted by the CPM include a group of angles that are used for the inverse kinematic backfilling of the rest of the model.
In order to use a dataset as close to the one implemented in the SAE J-941 and SAE J-4004 procedures as possible, some alterations to the original NHANES III data must be made. Since the data points missing for some measures are different across individuals than those of the missing points for stature, these points must be imputed in order to preserve the same stature data. The missing non-stature data will be substituted with the mean for the rest of the measure. This preserves a common set of data for stature while not significantly altering the summary statistics for the other measures.

Within the regression equations of the CPM, there is a root mean square error (RSME) term. This term represents the standard deviation of the residual error about the regression line. In Equation 20, RSME is used to model individual preference.

\[
\text{Random Preference} = N(0, RSME) \quad \text{Eqn 20}
\]

This random preference term is added to the regression equation for each individual within the population. This creates a point cloud that is bivariate normally distributed for each variable’s predicted location.

Once each individual has had the regression equations with random preference applied to their anthropometry, a group of postural measures are generated. The variables of high importance to this study include predicted H-Point, Hip, and Eye locations. The CPM can predict eye location with respect to either the BOF/AHP or the hip location. Reed et al. note that the indirect hip location method avoids issues involving seat track angles different from the angle used in building the model. In this study, the seat track angle is such that the two methods give nearly identical results, therefore, the direct method is used.

### 3.7 Comparison of Models

By determining locations of variables such as seat position (defined by H-Point location) and Eyellipse size and location, the SAE J standards are used to produce a comprehensive package model representing the NHANES III population. The CPM produces a similar package representing the individuals of NHANES III in a single procedure. The constraints developed by the J standards are then applied to the CPM model via a virtual fit test in order to determine which individuals are expected to be
disaccommodated. These constraints include the geometry of field of vision obstructers, and seat track limits as shown in Figure 10. The visual obstructers in this study are the cowl point (the last point at the bottom of the windshield that the driver can see over) and the hood point (the last point on the hood in the driver’s line of sight). In order to be considered accommodated, a driver’s predicted eye location must fall above both of the lines tangent to the lower half of the Eyellipse extending to the hood and cowl points. The lower of the two lines leads to a point on the ground that is considered safe visibility for at least 95% of drivers. For the seat track constraint, J-4004 has imposed limits represented by hashes in Figure 10. Drivers are deemed accommodated for seat position if their predicted H-Point falls between these limits.

![Figure 10: Constraints developed by the J standards](image)

In order to be considered accommodated for the entire design, a driver must have an eye location that is above both the hood and cowl point tangent lines and an H-Point that between the seat track limits imposed by J-4004. By determining accommodation status of each individual based on these constraints, the total accommodation level of the CPM is compared to that of what the SAE J standards are targeting.
In order to show proper employment of the J standards, their accommodation levels will first be analyzed individually. Figure 11 is a plot of accommodated individuals based solely on eye location. The target of the model is 95% accommodation. The virtual fit test of the CPM eye location data gives a 94% accommodation level based on J-941 alone. This value is considered adequate and will vary around 95% closely due to the stochastic nature of the CPM.

Figure 11: Accommodation of the NHANES III general US population seated in a Plymouth Voyager based on J-941 only

Figure 12 is a plot of accommodated individuals based solely on H-Point location. The target of the model is 95% accommodation. The virtual fit test of the CPM H-Point location data gives a 94% accommodation level based on J-4004 alone. Once again, this value is considered adequate and will also hover around 95% because of the stochastic nature of the CPM.
Figure 12: Accommodation of the NHANES III general US population seated in a Plymouth Voyager based on J-4004 only

Figure 13: Accommodation of the NHANES III general US population seated in a Plymouth Voyager based on both J-941 and J-4004 simultaneously
Figure 13 is a plot of accommodated individuals based on both predicted eye and H-Point location. The virtual fit test of the CPM eye and H-Point location data gives a 89% accommodation level based on both J-941 and J-4004. Compared to the standards evaluated on their own, this represents roughly a 5% decrease in accommodation rate. Zooming in on just the eye location portion as in Figure 14, shows the cause of the reduced accommodation rate. The large point marked in blue is an individual whose eye location is suitable for J-941 but wants to adjust her seat to a position that falls outside of the J-4004 limits. There are numerous individuals who are disaccommodated in the same way shown in this plot. There are also a number of individuals who can position their seat correctly but fall below the sight lines.

Figure 14: Zoomed Accommodation of the NHANES III general US population seated in a Plymouth Voyager based on both J-941 and J-4004 simultaneously
CHAPTER IV
DEMONSTRATION STUDIES

In this chapter, the methods described in Chapter III are utilized in a series of case studies that vary both the population and vehicle dimensions entered into the models. By varying these inputs, it is expected that the J standards overestimate accommodation levels regardless of variation in factors such as age, fitness or automobile design. The studies considered here are meant to both give further examples of the techniques used in the univariate and multivariate models and show a trend in the overestimation caused by the SAE J standards.

4.1 Variations in Population

The methodologies of the CPM and SAE J standards as fleshed out in Chapter III are done so using a population that is specified by SAE J-941. More specifically, a set of individuals from NHANES III that are twenty-one years and older are used for the example calculations. NHANES III, however, is a dataset useful for describing a population of the entirety of United States citizenry from the years of 1988-1994. Since packaging engineers employ these methods in order to design for highly specific target demographics, this section will detail the variation of factors within the more current NHANES 2015-2016 continuous survey (National Health and Nutrition Examination Survey, 2015-2016, n.d.). A broad population representing all of the United States citizens will first be analyzed. Individuals with a body mass index (BMI) considered obese will then be evaluated. This section will conclude with the analysis of an elderly population.
4.1.1 NHANES 2015-2016 Continuous Survey

The NHANES continuous survey runs in two-year cycles in order to provide-up-to-date data that representative of the current United States population. A major benefit of the continuous survey is a change in methodology that oversamples populations that are distinct minorities such as people of Latin American descent or the elderly. The purpose of this oversampling is to give a higher resolution to the measures describing these subpopulations. The oversampling methods are brought back into the correct proportions via the statistical weighting of each individual. NHANES 2015-2016 is the most up-to-date continuous survey data as of the time of this document’s preparation.

The first case being considered in this chapter is similar to that of the methods shown in Chapter III with the exception of the 2015-2016 continuous survey data being used to describe the overall population. This is a general United States population that is roughly 48% men and 52% women ages 20 and older. A comparison of summary statistics from NHANES III and NHANES 2015-2016 can be seen in Table 4. The main difference in these populations is the increase in BMI across men and women. Since stature is roughly the same (within 4 mm) for both sexes across NHANES III and NHANES 2015-2016, it is implied that the population has increased in mass.

<table>
<thead>
<tr>
<th></th>
<th>Mean Stature (mm)</th>
<th>Standard Deviation of Stature (mm)</th>
<th>Mean $\text{BMI (kg/m}^2\text{)}$</th>
<th>Standard Deviation of BMI $\text{kg/m}^2\text{)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NHANES III</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ages 20 and up</td>
<td>Males 1756</td>
<td>73.3</td>
<td>26.6</td>
<td>4.83</td>
</tr>
<tr>
<td></td>
<td>Females 1618</td>
<td>69.2</td>
<td>26.4</td>
<td>6.31</td>
</tr>
<tr>
<td><strong>NHANES 15-16</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ages 20 and up</td>
<td>Males 1752</td>
<td>76.6</td>
<td>29.1</td>
<td>6.06</td>
</tr>
<tr>
<td></td>
<td>Females 1615</td>
<td>70.6</td>
<td>29.7</td>
<td>7.60</td>
</tr>
</tbody>
</table>

An issue arises when inputting the data from the NHANES continuous survey into the CPM. The CPM requires sitting height as a predictor for its regression equations. Because the NHANES continuous survey does not include sitting height in its list of measures, the sitting height for the individuals in the dataset must be synthesized. Using
stature as a predictor, a linear model was built from the ANSUR II military reservist data discussed in Chapter II. Stature was selected as the sole predictor because it correlates well with the sitting height data in ANSUR II and is included in the NHANES 2015-2016 dataset. The linear models for use in synthesizing sitting height data are found in Equations 21 and 22.

\[
\begin{align*}
\text{Male Sitting Height} &= 206 + 0.406 \times \text{Stature} \quad R^2 = 0.61 \quad \text{Eqn 21} \\
\text{Female Sitting Height} &= 216 + 0.393 \times \text{Stature} \quad R^2 = 0.58 \quad \text{Eqn 22}
\end{align*}
\]

Following the methods of sections 3.3 through 3.6, Figures 15 through 17 were generated. Figures 15 and 16 show that while design for 95% accommodation based solely upon the J-941 or J-4004 standards alone produce good results with 94% and 93% accommodation respectively, the virtual fit test utilized in conjunction with the CPM model shows a reduction in predicted accommodation to 88% as displayed in Figure 17.

Figure 15: Accommodation of the NHANES 2015-2016 general US population seated in a Plymouth Voyager based on J-941 only
Figure 16: Accommodation of the NHANES 2015-2016 general US population seated in a Plymouth Voyager based on J-4004 only

Figure 17: Accommodation of the NHANES 2015-2016 general US population seated in a Plymouth Voyager based on both J-941 and J-4004 simultaneously
4.1.2 Impact of High Body Mass Index on the Models

In this subsection, we will narrow the NHANES 2015-2016 data to exclude non-obese individuals in order to investigate the effects of obesity on the models. According to the United States Centers for Disease Control and Prevention, an individuals with a BMI of 30.0 or greater are considered obese (“Centers for Disease Control and Prevention: About Adult BMI,” 2017). Figures 18 through 20 convey the same difference in accommodation of individuals as previously discussed. Figures 18 and 19 show that design for 95% accommodation based solely upon the J-941 or J-4004 standards alone produce good results with 94% and 96% accommodation respectively. The virtual fit test utilized in conjunction with the CPM model shows a reduction in predicted accommodation to 90% as displayed in Figure 20.

![Figure 18: Accommodation of the obese NHANES 2015-2016 US population seated in a Plymouth Voyager based on J-941 only](image)
Figure 19: Accommodation of the obese NHANES 2015-2016 US population seated in a Plymouth Voyager based on J-4004 only.

Figure 20: Accommodation of the obese NHANES 2015-2016 US population seated in a Plymouth Voyager based on both J-941 and J-4004 simultaneously.
4.1.3 Impact of Old Age on the Models

Similarly to the previous subsection, here we will consider the effects of old age on the methods of the J standards and the CPM. For the purpose of this study, individuals from NHANES 2015-2016 65 years and older, will be considered of old age. Figures 21 and 22 show that design for 95% accommodation based solely upon the J-941 or J-4004 standards alone produce good results with 94% accommodation for J-941 and 95% for J-4004. The virtual fit test utilized in conjunction with the CPM model shows a reduction in predicted accommodation to 90% as displayed in Figure 23.

Figure 21: Accommodation of the elderly NHANES 2015-2016 US population seated in a Plymouth Voyager based on J-941 only
Figure 22: Accommodation of the elderly NHANES 2015-2016 US population seated in a Plymouth Voyager based on J-4004 only

Figure 23: Accommodation of the elderly NHANES 2015-2016 US population seated in a Plymouth Voyager based on both J-941 and J-4004 simultaneously
4.2 Variations in Vehicle Dimensions

Up to this point, each of the comparisons between the J standards and the CPM have been made on dimensions representing a Plymouth Voyager. In this subsection, an additional two vehicle configurations will be considered. The differing dimensions for these configurations include H30, L6, L27, and the hood and cowl point coordinates. These dimensions are found in Table 1. The population used for the virtual fit test for each configuration will be that of the NHANES 2015-2016 general US population whose summary statistics are found in Table 4.

In the following subsections, the principle of overestimated accommodation due to the use of univariate methods carries throughout regardless of changes in vehicle dimensions. This, combined with the results from the previous section suggests that the cause of this overestimation is placed solely on poor correlation between predicted hip and eye location variables.

4.2.1 Chrysler LHS

The Chrysler LHS configuration has a decreased seat height (H30) and an increased BOF-to-steering wheel distance (L6) over the Plymouth Voyager. This causes individuals to sit both lower and further back along the x-axis. This is apparent when comparing Figures 24 through 26 with Figures 15 through 17. Figures 24 and 25 show that design for 95% accommodation based solely upon the J-941 or J-4004 standards alone produce good results with 95% accommodation for J-941 and 92% accommodation for J-4004. The virtual fit test utilized in conjunction with the CPM model shows a reduction in predicted accommodation to 88% as displayed in Figure 26.
Figure 24: Accommodation of the NHANES 2015-2016 general US population seated in a Chrysler LHS based on J-941 only

Figure 25: Accommodation of the NHANES 2015-2016 general US population seated in a Chrysler LHS based on J-4004 only
4.2.2 Dodge Avenger

The Dodge Avenger configuration has a decreased seat height (H30) from both the previous models and a BOF-to-steering wheel distance (L6) that is close to that of the LHS. This causes individuals to sit lower but in a similar x-axis position to the LHS. Figures 27 and 28 show that design for 95% accommodation based solely upon the J-941 or J-4004 standards alone produce good results with 94% accommodation for J-941 and 95% accommodation for J-4004. The virtual fit test utilized in conjunction with the CPM model shows a reduction in predicted accommodation to 90% as displayed in Figure 29.
Figure 27: Accommodation of the NHANES 2015-2016 general US population seated in a Dodge Avenger based on J-941 only

Figure 28: Accommodation of the NHANES 2015-2016 general US population seated in a Dodge Avenger based on J-4004 only
4.3 Real World Application

The purpose of this section is to provide a realistic analysis of the design of the previous example vehicles using a ground view requirement determined by the US military. The analysis will be done using a combination of military requirement MILSTD-1472 and J-4004, and will be subsequently checked for accommodation with the CPM and a virtual fit test. The main difference between this section and previous sections in Chapter IV is that the previous sections were based on vehicle configurations with the assumption that the standards had already met ground view safety constraints. According to MILSTD-1472, a driver must be able to see a point on the ground 3 meters in front of the vehicle. In this example we will use the vehicle information found in Table 1. The goal is to layout the sight lines and seat track limits based on the ground view regulation put forth by the military and the SAE J-4004 standard. The CPM and virtual fit test will then be implemented in order to check for the multivariate accommodation rate. Recommendations regarding changes in the design of the vehicles will then be made in order to improve
multivariate accommodation to at least 95%. The population used in this example is that of the NHANES 2015-2016 general US population.

The first step in this process is to determine the orientation of the sightlines. The location of the front of the vehicle and distance from the ground to the AHP are listed for each vehicle in Table 5. These data were obtained by measuring side view images (Appendix C) of the vehicles using the image processing software ImageJ.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Front of vehicle along x-axis (mm)</th>
<th>AHP to ground distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plymouth Voyager</td>
<td>-1,225</td>
<td>395</td>
</tr>
<tr>
<td>Chrysler LHS</td>
<td>-1,420</td>
<td>390</td>
</tr>
<tr>
<td>Dodge Avenger</td>
<td>-1,245</td>
<td>510</td>
</tr>
</tbody>
</table>

Since regulation requires a distance of 3 meters, our configuration will require the driver to be able to see a point on the ground at -4,225 mm for the Plymouth Voyager, -4,420 mm for the Chrysler LHS, and -4,245 mm for the Dodge Avenger along the x-axis. The location of the ground view point will be at -395 mm, -390 mm, and -510 mm for the Voyager, LHS, and Avenger respectively, along the z-axis. Sightlines from the ground view point to the hood and cowl points will then be drawn and the CPM predicted eye and H-Point locations will be checked for accommodation.

The first vehicle being reviewed is the Plymouth Voyager. As seen in Figure 30, the sightline from the ground view point to the cowl point runs above much of the eye location data. This causes a reduction accommodation to 61% that could mostly be resolved by increasing H30. With an increase in H30 of 30 mm, the bottom of the Eyellipse is made nearly tangent with the cowl point sightline which allows for around 84% accommodation. In order to further increase the accommodation rate, the seat track adjustability limits can either be widened or H30 can be again increased. For this example, the seat track adjustability is increased by 30 mm and H30 is further increased by 10 mm. Univariate accommodation for each measure comes to 97% for both eye location and seat track adjustability. As seen in Figure 31, the multivariate accommodation is 95%. While these changes would help to increase accommodation to the proper levels, they may not be feasible. This will be addressed at the end of this section.
Figure 30: Accommodation of the NHANES 2015-2016 general US population seated in a Plymouth Voyager based on both MILSTD-1472 and J-4004

Figure 31: Accommodation of the NHANES 2015-2016 general US population seated in a Plymouth Voyager based on both MILSTD-1472 and J-4004 with altered H30 and seat track adjustability limits
The next vehicle being reviewed is the Chrysler LHS. As seen in Figure 32, the sightlines from the ground viewpoint to the hood and cowl points run above some of the predicted eye location data. It is close to being tangent with the Eyellipse though. With no adjustments made, this design is expected to accommodate around 82% of individuals. In order to further increase the accommodation rate, the seat track adjustability limits can either be widened or H30 can be increased. For this example, the seat track adjustability will be increased by 25 mm and H30 will be further increased by 20 mm. Univariate accommodation for each measure comes to 98% for eye location and 97% for seat track adjustability. As seen in Figure 33, the multivariate accommodation is 95%.

Figure 32: Accommodation of the NHANES 2015-2016 general US population seated in a Chrysler LHS based on both MILSTD-1472 and J-4004
The final vehicle being reviewed is the Dodge Avenger. As seen in Figure 34, the sightline from the ground view point to the hood point runs above most of the predicted eye location data as with the Chrysler LHS. This causes a dramatic reduction accommodation to 8% that could mostly be resolved by decreasing the height of the hood point. With a decrease in hood point height of 45 mm, the bottom of the Eyellipse is made nearly tangent with the hood and cowl point sightlines which allows for around 80% accommodation. In order to further increase the accommodation rate, the seat track adjustability limits can either be widened or H30 can be increased. For this example, the seat track adjustability will be increased by 20 mm and H30 will be increased by 28 mm. Univariate accommodation for each measure comes to 98% for eye location and 97% for seat track adjustability. As seen in Figure 35, the multivariate accommodation is 96%.
Figure 34: Accommodation of the NHANES 2015-2016 general US population seated in a Dodge Avenger based on both MILSTD-1472 and J-4004

Figure 35: Accommodation of the NHANES 2015-2016 general US population seated in a Dodge Avenger based on both MILSTD-1472 and J-4004 with altered hood point, H30, and seat track adjustability limits
It is apparent in these examples that small changes made to package dimensions have the ability to greatly increase accommodation rates in a population. While it is tempting to lay the blame of the disaccommodation rates on the designers, it must be kept in mind that there are other constraints that can make changes for the purpose of increased accommodation more difficult. For example, the height of the roof is likely to be a limiting factor for cars such as the Chrysler LHS and Dodge Avenger as they are intended to be much shorter vehicles than those such as the Plymouth Voyager. A low roof height may prevent seat height (H30) from being increased as a tall individual’s head may hit the roof. In the case of the Plymouth Voyager, the vehicle has such a short nose (distance from the origin to the front of the vehicle along the x-axis) that most individuals can see over both the hood and cowl points without increased seat height (H30). It may also be apparent that the Voyager is a van which has a taller roof than that of the sedan type vehicles. Another limiting factor for adjustability may come from the leg room of the seats behind the driver’s seat. If the driver’s seat track limits are expanded, the leg room behind the seat will be encroached upon. In the case of the Voyager, the entire vehicle is designed to be spacious while the LHS and Avenger have less room available for increased adjustability. Any added adjustability given to the seat track limits for these sedans will most certainly cause discomfort to individuals seated in the back of the car. Since package designers must consider factors such as these, appropriate accommodation rates may not always be able to be met.
CHAPTER V
DISCUSSION AND CONCLUSIONS

The purpose of this research was to analyze and compare multiple statistical methods of vehicle packaging design in order improve accuracy in future models. The analysis of the various configurations presented clear results regarding over-estimated accommodation based on current modeling practices. The following sections discuss the general results, the limitations of the material in this study, and recommendations for future methods.

5.1 General Observations and Discussion of Results

The head-to-head comparison of the CPM with the selection of J standards consistently showed a decrease in predicted accommodation. While the J standards were successful in producing approximately 95% accommodation for each procedure (J-941 and J-4004) individually, they fell short when the individuals being tested were considered disaccommodated across both standards as soon as they were disaccommodated by one. This was the case when applied to populations that spanned varying demographics and secular trends.

The purpose of Chapter IV was to convey the effect that changing vehicle dimensions and population attributes had on the comparisons made. It showed that the concept of over-estimated accommodation due to the use of univariate methods purveyed throughout the virtual setups regardless of changes made to the vehicle and population data.

It is expected that as the number of design variables increases, the difference in predicted accommodation will also increase. This is due to the fact that individuals will have more opportunities to fall outside of the boundaries set by the J standards for some measures while being accommodated by others. A multivariate replacement would correct
for this issue by creating constraints for individuals that were postured and checked for fit individually.

5.2 Limitations

There are two critical limitations within this study. First, considering a limited set of measures focusing on hip and eye location in the x-z-plane is not practical for the full design of a vehicle package. Second, the CPM, relies on experimental data with serious limitations of its own. While not affecting the principles of this thesis, it is recommended that these limitations be addressed in a potential replacement to the current SAE methods.

Looking towards the future, a multivariate model for use in designing vehicle packaging will need to consider far more than just seat position and eye location. The combination Cascade Prediction Model and virtual fit test offered as an alternative to the current J standards are able to replace much more than just J-941 and J-4004. As can be seen in Appendix A, the CPM is able to predict much more posturing information including ankle, knee and spinal angles.

Should a future model incorporate the remaining posturing information, it will need more in depth data regarding the physical measures of the population being postured. The CPM places the most importance on the prediction of eye and hip location using stature, sitting height, BMI and a few vehicle measures (Reed et al., 2002). The regression equations used for posturing the rest of the body with respect to the hip and eye location output joint angles between kinematic sections of the body. The length of segments between the joints whose angles are predicted by the CPM are required for the inverse kinematic backfilling procedure. For example, knee angle is predicted in Table 5 of Appendix A. In order to locate the knee in the x-z-plane using this angle, it is necessary to know the distance from the ankle to the knee and the distance from the knee to the hip. The anthropometric measures in the NHANES surveys do not generally have this much detail. An alternative such as the ANSUR II data may be appealing because of the comprehensive data that it offers. Because ANSUR II is a military survey, it is not representative of the general US population. The best option may be to synthesize the missing data for an NHANES set using regression equations built from ANSUR II data. So long as the linear
regression models fit their respective data well, the measures lacking from NHANES could be accurately synthesized for the population.

A comprehensive multivariate model for packaging design would need to consider the postured individual and their interaction with all of the important components of the package. This would require that the model be extended into three dimensions by including measures along the y-axis. Suppose that the placement of the vehicle’s pillars is being considered in relation to field of vision. In the x-y-plane, each of the eyes will make an angle with the roof pillars as seen in Figure 36. Similar to how the cowl and hood points act as visual obstructers, so do the roof pillars. Since J-941 includes calculations that produce an Eyellipse for each eye in this plan view, the multivariate replacement would also need to predict eye location in the x-y-plane. Further, the replacement model would need to account for all important measures in three dimensions.

![Figure 36: Field of vision lines in the plan view](image)

While the CPM effectively models the entirety of the human body in the x-z-plane, it faces several limitations. Reed et al. (2002) note that their study was performed using experimental setups that did not include vehicles with manual transmissions. The presence of a clutch pedal can change the way in which people posture themselves. This is apparent in Equation A2 of J-941 as the location of the reference centroid for the placement of the Eyellipse is dependent on a term changes based on the transmission type. Since there are
still vehicles being produced with manual transmissions, the replacement to the J standards would need to include a method for design that took transmission type into account. This would not apply to electric vehicles because they lack transmissions altogether.

Another critical limitation that Reed et al. (2002) note is the exclusion of vehicles that have both vertical and horizontal seat adjustment. The inclusion of vertical adjustment will greatly impact numerous measures that are predicted by the CPM. For example, Eye location along the z-axis would become more spread out than currently predicted. the replacement model would need to include vertical seat adjustment since many vehicles being produced today include it.

Lastly, the CPM study was performed using only five vehicles (Reed et al., 2002). In order to provide a higher level of accuracy for a wider range of vehicles, it is expected that further data would need be collected including a higher number of more modern vehicles.

5.3 Recommendations

The results of this research show that the current methods employed by the Society of Automotive Engineers for the design and analysis of accommodation levels in passenger vehicle packaging overestimate accommodation. By utilizing outdated univariate techniques that consider individuals to be made up of measures all within the same percentile, the J standards predict a higher accommodation rate than multivariate methods do. Skilled designers have long known about the shortcomings of univariate methods but have worked to mitigate the problem by implementing rules-of-thumb. This is not a sustainable practice. The lack of an accurate method leads to flawed vehicle packaging designs and will continue to do so until it is replaced with a more modern approach. A comprehensive multivariate model should be developed in order to precisely design for appropriate accommodation of the entire human body within a complete three-dimensional vehicle package. By running a more in-depth study similar to that of the CPM, a model could be developed to posture individuals in modern vehicles that include manual and automatic transmissions.

The fully postured bodies generated by the replacement model could be used for the purpose of laying out the constraints of a package. Design such as seat track limits,
steering wheel adjustability and roof height could be balanced via a multivariate design procedure such as the cost function of the kick scooter example given in Section 2.3. This comprehensive model would produce highly accurate accommodation statistics and precise packaging design for specified populations.
BIBLIOGRAPHY


### APPENDIX A: CPM REGRESSION TABLES

#### Table 6: Regression Models

<table>
<thead>
<tr>
<th>Intercept of Regression Equation</th>
<th>Stature in mm</th>
<th>Sitting Height divided by Stature</th>
<th>Seat Height (H30) in mm</th>
<th>Steering Wheel to Ball of Foot in the x-direction (L6) in mm</th>
<th>Seat Cushion Angle (L27) in degrees</th>
<th>R² adj</th>
<th>Root Mean Square Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hipx reBOF</td>
<td>84.8</td>
<td>0.4659</td>
<td>-430.1</td>
<td>-0.1732</td>
<td>-0.4479</td>
<td>-1.04</td>
<td>0.78</td>
</tr>
<tr>
<td>Hip-to-eye angle</td>
<td>-72.7</td>
<td>0.00642</td>
<td>115.7</td>
<td>0</td>
<td>0.0147</td>
<td>0.11</td>
<td>0.2</td>
</tr>
<tr>
<td>Eycz reBOF</td>
<td>-836.6</td>
<td>0.5842</td>
<td>916.6</td>
<td>-0.1559</td>
<td>0.6101</td>
<td>0</td>
<td>0.71</td>
</tr>
<tr>
<td>Eyez reAHP</td>
<td>-267.1</td>
<td>0.3122</td>
<td>679.9</td>
<td>1.0319</td>
<td>0.0292</td>
<td>0</td>
<td>0.89</td>
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<tr>
<td>Eyez reHIP</td>
<td>-916</td>
<td>0.1187</td>
<td>1347.2</td>
<td>0</td>
<td>0.1563</td>
<td>1.15</td>
<td>0.23</td>
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<tr>
<td>Eycz reHIP</td>
<td>-261.5</td>
<td>0.3336</td>
<td>675.8</td>
<td>0</td>
<td>-0.0544</td>
<td>0</td>
<td>0.72</td>
</tr>
<tr>
<td>Ankle x reBOF</td>
<td>-300.2</td>
<td>0.04</td>
<td>467.6</td>
<td>0.1764</td>
<td>0.1358</td>
<td>1.3</td>
<td>0.32</td>
</tr>
<tr>
<td>Ankle x reAPedal</td>
<td>46.1</td>
<td>-0.0466</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.05</td>
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<tr>
<td>Ankle z reAHP</td>
<td>8.4</td>
<td>0.0312</td>
<td>0</td>
<td>0.1236</td>
<td>0</td>
<td>0.55</td>
<td>0.25</td>
</tr>
<tr>
<td>Knee angle</td>
<td>69.1</td>
<td>-0.0071</td>
<td>61.3</td>
<td>-0.0321</td>
<td>0.0829</td>
<td>-0.59</td>
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<tr>
<td>Head angle</td>
<td>-156.2</td>
<td>0.00919</td>
<td>137.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
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<td>Neck angle</td>
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<td>-0.01197</td>
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<td>0</td>
<td>0.0109</td>
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<td>0.04</td>
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<tr>
<td>Thorax angle</td>
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<td>0.00497</td>
<td>45.2</td>
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<td>0.0128</td>
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<td>Abdomen angle</td>
<td>-94.5</td>
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<td>0.0222</td>
<td>0</td>
<td>0.09</td>
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<td>Pelvis angle</td>
<td>-16.3</td>
<td>0.0102</td>
<td>90.2</td>
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<td>0.0177</td>
<td>0.39</td>
<td>0.04</td>
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</table>

#### Table 7: Regression Models for H-Point

<table>
<thead>
<tr>
<th>Intercept of Regression Equation</th>
<th>Stature in mm</th>
<th>Body Mass Index in kg/m²</th>
<th>Seat Height (H30) in mm</th>
<th>Steering Wheel to Ball of Foot in the x-direction (L6) in mm</th>
<th>Seat Cushion Angle (L27) in degrees</th>
<th>R² adj</th>
<th>Root Mean Square Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hipx reHp</td>
<td>-131.5</td>
<td>0.0482</td>
<td>-2.667</td>
<td>0</td>
<td>0.01375</td>
<td>0.49</td>
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<tr>
<td>HipzreHp</td>
<td>-143.4</td>
<td>0</td>
<td>2.009</td>
<td>0.07</td>
<td>0.1375</td>
<td>0.49</td>
<td>0.4</td>
</tr>
</tbody>
</table>
# APPENDIX B: VARIABLE DEFINITIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Stature</td>
<td>The standing height of an individual</td>
</tr>
<tr>
<td>-</td>
<td>Sitting Height</td>
<td>The distance from the top of the head to the surface on which a person is sitting</td>
</tr>
<tr>
<td>-</td>
<td>Cowl Point</td>
<td>A point on the exterior windshield glazing surface at the highest height of the Cowl, Hood, or exterior component *</td>
</tr>
<tr>
<td>-</td>
<td>Hood Point</td>
<td>The last visible point on the hood from the driver’s line of sight</td>
</tr>
<tr>
<td>AHP</td>
<td>Accelerator Heel Point</td>
<td>The heel of shoe location on the floor at the depressed floor covering *</td>
</tr>
<tr>
<td>BMI</td>
<td>Body Mass Index</td>
<td>The body mass divided by the square of stature</td>
</tr>
<tr>
<td>BOF</td>
<td>Ball of Foot</td>
<td>A point on the lateral centerline of the shoe 203 mm from the heel *</td>
</tr>
<tr>
<td>CF</td>
<td>Female Boundary of the Eyellipse</td>
<td>The fore-most boundary of the Eyellipse along the x’-axis with respect to the reference centroid</td>
</tr>
<tr>
<td>CM</td>
<td>Male Boundary of the Eyellipse</td>
<td>The aft-most boundary of the Eyellipse along the x’-axis with respect to the reference centroid</td>
</tr>
<tr>
<td>H30</td>
<td>Seat Height</td>
<td>The vertical distance from SgRP to the AHP *</td>
</tr>
<tr>
<td>H8</td>
<td>Accelerator Heel Point z-axis Coordinate</td>
<td>The distance from the z-axis origin to the AHP (H8=0 in this study)</td>
</tr>
<tr>
<td>L1</td>
<td>Ball of Foot x-axis Coordinate</td>
<td>The distance from the x-axis origin to the BOF (L1=0 in this study)</td>
</tr>
<tr>
<td>L27</td>
<td>Seat Cushion Angle</td>
<td>The angle of the cushion line from horizontal *</td>
</tr>
<tr>
<td>L6</td>
<td>Ball of Foot Reference Point to Steering Wheel Center</td>
<td>The longitudinal distance between the BOF and the steering wheel center *</td>
</tr>
<tr>
<td>q</td>
<td>Eyellipse Cutoff Percentile</td>
<td>The percentile for determining the percentage of users on either side of the tangent lines drawn from the Eyellipse</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
<td>The standard deviation of the residual error from a regression model</td>
</tr>
<tr>
<td>SF</td>
<td>Average Female Stature</td>
<td>-</td>
</tr>
<tr>
<td>SgRP</td>
<td>Seating Reference Point</td>
<td>A unique H-point established by the manufacturer as the design seat reference point *</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Sm</td>
<td>Average Male Stature</td>
<td>-</td>
</tr>
<tr>
<td>Sr</td>
<td>Average Reference Stature</td>
<td>The average of combined male and female stature</td>
</tr>
<tr>
<td>X&lt;sup&gt;’&lt;/sup&gt;female centroid</td>
<td>Female Eye Centroid x’-axis Coordinate</td>
<td>The female Eye Location Centroid in the x’-axis with respect to the reference centroid</td>
</tr>
<tr>
<td>X&lt;sup&gt;’&lt;/sup&gt;female std dev</td>
<td>Standard Deviation of Female Eye Location along the x’-axis</td>
<td>-</td>
</tr>
<tr>
<td>X&lt;sup&gt;’&lt;/sup&gt;male centroid</td>
<td>Male Eye Centroid x’-axis Coordinate</td>
<td>The male Eye Location Centroid in the x’-axis with respect to the reference centroid</td>
</tr>
<tr>
<td>X&lt;sup&gt;’&lt;/sup&gt;male std dev</td>
<td>Standard Deviation of Male Eye Location along the x’-axis</td>
<td>-</td>
</tr>
<tr>
<td>X&lt;sub&gt;Aft H-Point&lt;/sub&gt;</td>
<td>Aft Seat Track Limit</td>
<td>The x-axis location of the aft-most seat track limit based on H-Point percentiles from J-4004</td>
</tr>
<tr>
<td>X&lt;sub&gt;C&lt;/sub&gt;</td>
<td>Final Center Coordinate of Eyellipse along the x-axis</td>
<td>The location of the center of the Ey ellipse in the x-axis with respect to the BOF</td>
</tr>
<tr>
<td>X&lt;sub&gt;eye&lt;/sub&gt;</td>
<td>Eye x-axis Coordinate</td>
<td>The eye location from BOF in the x-axis predicted by the CPM</td>
</tr>
<tr>
<td>X&lt;sub&gt;eye’&lt;/sub&gt;</td>
<td>Eye x’-axis Coordinate</td>
<td>The eye location from the mean in the x’-axis rotated by θ</td>
</tr>
<tr>
<td>X&lt;sub&gt;Fore H-Point&lt;/sub&gt;</td>
<td>Fore Seat Track Limit</td>
<td>The x-axis location of the fore-most seat track limit based on H-Point percentiles from J-4004</td>
</tr>
<tr>
<td>X&lt;sub&gt;H-Point Reference&lt;/sub&gt;</td>
<td>Reference H-Point Location along the x-axis</td>
<td>The x-axis location of the reference H-Point for the purpose of locating the seat track limits</td>
</tr>
<tr>
<td>X&lt;sub&gt;L’&lt;/sub&gt;</td>
<td>Length of Ey ellipse along the x’-axis</td>
<td>The difference of CM and CF along the x’-axis</td>
</tr>
<tr>
<td>X&lt;sub&gt;reference centroid&lt;/sub&gt;</td>
<td>Eyellipse Reference Centroid x-axis Coordinate</td>
<td>The x-axis location of the reference centroid for the purpose of locating the Ey ellipse</td>
</tr>
<tr>
<td>Z&lt;sub&gt;C&lt;/sub&gt;</td>
<td>Final Center Coordinate of Eyellipse along the z-axis</td>
<td>The location of the center of the Ey ellipse in the z-axis with respect to the AHP</td>
</tr>
<tr>
<td>Z&lt;sub&gt;eye&lt;/sub&gt;</td>
<td>Eye z-axis Coordinate</td>
<td>The eye location from AHP in the z-axis predicted by the CPM</td>
</tr>
<tr>
<td>Z&lt;sub&gt;eye’&lt;/sub&gt;</td>
<td>Eye z’-axis Coordinate</td>
<td>The eye location from the mean in the z’-axis rotated by θ</td>
</tr>
<tr>
<td>Z&lt;sub&gt;L’&lt;/sub&gt;</td>
<td>Length of Ey ellipse along the z’-axis</td>
<td>A normal distribution of driver preference</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Definition</td>
</tr>
<tr>
<td>------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$z_{\text{reference centroid}}$</td>
<td>Eyellipse Reference Centroid $z$-axis Coordinate</td>
<td>The $z$-axis location of reference centroid for the purpose of locating the Eyellipse</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Eyellipse Angle with respect to Seat Track Angle</td>
<td>The added tilt to the Eyellipse downward from horizontal caused by angled seat tracks ($\beta = 18.6^\circ$ in this study)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of Rotation of Principle Axes</td>
<td>The angle defined by the first eigen vector of the var-cov matrix for the predicted eye locations given by the CPM</td>
</tr>
<tr>
<td>$\sigma_F$</td>
<td>Standard Deviation of Female Stature</td>
<td>-</td>
</tr>
<tr>
<td>$\sigma_M$</td>
<td>Standard Deviation of Male Stature</td>
<td>-</td>
</tr>
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* As defined by SAE J-1100
APPENDIX C: VEHICLE DIMENSIONS

Figure 37: Dimensions for Plymouth Voyager

Figure 38: Dimensions for Chrysler LHS
Figure 39: Dimensions for Dodge Avenger

Image Sources:

Plymouth Voyager
http://bestcarmag.com/makes/Plymouth/Voyager

Chrysler LHS

Dodge Avenger