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A NEW APPROACH TO VEHICLE CONCEPT GENERATION: A STATISTICS-BASED METHOD FOR CREATING INNOVATIVE PRODUCT FORMS

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ABSTRACT

When creating vehicle concepts, designers often follow a common methodology. Initial sketches center around the flow of the vehicle, focusing first on curves that sweep from front to back. As the design progresses through the development stages these expressive curves are constrained into specific vehicle characteristics. By looking at vehicles in their final form much can be learned about how to create new vehicle concepts. For example, vehicle characteristics like the hood, bottom of the side windows, and trunk would be grouped together and represented in the initial concept by a belt line that sweeps the whole of the vehicle from front to rear. Experience, training, and human intuition are used by designers to understand how to represent the vehicle characteristics in initial concepts. The initial representation drives the vehicle towards its final form.

In this work we introduce a new method for vehicle concept creation based on a statistical analysis of similarities and differences in a vehicle class. Representative chunking of vehicle characteristics is determined through a statistical analysis of existing vehicles, not through human intuition. A sample of existing coupe vehicles is gathered. Each vehicle is decomposed into 22 vehicle characteristics, e.g. headlights. A minimum number of four-control-point Bezier curves that sufficiently capture the form of the characteristic are used. Through principal component analysis the control points, and thereby the curves, that differentiate the most between vehicles are chunked together. These statistically derived curve chunks, often unintuitive and non-obvious, but effective, are used as the foundation for creating new vehicle concepts.

A traditional conceptualization methodology limits the designer's exploration of the concept space by introducing curves in the same order. The method discussed here, based upon statistical chunking of curves, encourages the designer to deviate from tradition and thereby explore more of the design space. Additionally, since the curve chunks are based upon their influence on a sample set of designs, the designer is guaranteed to consider the most influential curves and their impact on conceptualization. In the method, the designer chooses a curve chunk and introduces the curves to the concept. Based upon which curves have already been drawn, the designer picks a new chuck and adds more curves to the concept. Thus, a concept flows from chunk to chunk until all the statistically derived curves have been introduced. The designer then fills in the rest of the curves and adds details as seen fit.

Keywords: Product Design, Principal Component Analysis, Shape Relationships, Curve Chunking

1 INTRODUCTION

Visually representing a product form is an art. Designers use many skills and techniques to explore new forms and communicate their concepts. A typical automotive designer, or stylist, would begin by positioning the wheels and then the rocker panel. The designer may then address the front of the vehicle and move towards the back [1]. Whatever the method, designers typically put the wheels on the ground and then build up from there. This methodology, enabling the designer to explore the form while ensuring that a vehicle is created, can limit the exploration of vehicle characteristic relationships. According the traditional method, certain characteristics have predefined spatial relationships, expected proportions, and are introduced in a certain order. In this paper we define the relationships between vehicle characteristics based upon a statistical decomposition. Then, we offer a new design methodology based upon these new relationships and demonstrate through an example. The result is a novel vehicle conceptualization process that is based upon a scientific definition of curve relationships.

Efforts to scientifically examine what some consider to be artistic expression, the design of the form of the product, have begun to emerge. Biederman [2] discusses how humans perceive shapes and decompose them into recognizable chunks. A chunk is a group of parts that have a recognizable relationship. These chunks are often based upon spatial relationships. McCormack and Cagan [3] simplified the representation of complex shapes by decomposing the shapes into mathematically simpler forms. Complex curves are decomposed into distinct subshapes composed of straight lines. Groupings of curves are decomposed into simple shapes, e.g. triangles. Prats, Earl, Garner and Jowers [4] take this methodology a step further and use it to understand simplified shapes with regard to style and product design. Their shape decomposition provides designers with a structured exploration of new forms. In this paper we look not at the intuitive, or learned, decomposition of a complex shape, but at the statistical decomposition of a complex shape (a coupe) into fundamental chunks. We do not consider how to take a complex shape and represent it with a simple shape, but how to break a complex shape into meaningful chunks of simpler shapes. Specifically, we use principal component analysis to identify element groupings that differentiate models within a product class.

Orsborn, Cagan, Pawlicki, and Smith [6] analyzed the exterior form of a sample of three types of existing vehicle classes. It was determined, in conjunction with a vehicle designer, which vehicle characteristics were most important for capturing the general form of the vehicle so that a potential consumer would recognize different vehicles and designers would have the freedom to develop new forms. The forms for fifteen coupes, twenty SUVs, and seven pickups were captured using four-control-point Bezier curves. The coupe data collected from Orsborn, et al., [6] is used as the foundation for the work described in this paper. Orsborn, Boatwright and Cagan [7] use principal component analysis, a statistical method in which relationships in a data set are determined through a weighted linear combination of the original variables [5], to determine the relationships within and between vehicle classes. This paper uses principal component analysis to determine the fundamental characteristics within one vehicle class, that of coupes, rather than using traditional designer heuristics to determine vehicle characteristics. These fundamental characteristics at times differ from the traditional and expected feature definition, resulting in a deeper understanding of what features of an existing set of designs differentiate one form from another. The results from this analysis, combined with the related methodology, can then be used by designers to create new vehicles. The designers can take the statistically-based curve chunking found in this paper as a foundation for new designs, rather than rely upon a traditional understanding of chunking curves according to vehicle characteristic and spatial relationships.

The combination of the results from the statistical measure and the new design methodology with an experienced product designer unleashes the full potential of the information through the statistics, the method, and the designer working in chorus. Although the focus of this paper is on vehicle design, the methods developed here are applicable to any class of physical products based on a consistent form language.

2 VEHICLE FORM DESCRIPTION

The vehicles chosen for this study were all from the coupe class. The selection requirements were that each vehicle have a publicly available blueprint that included the front, side and rear views. Each of the views must be isometric (or as parametrically close as possible) and the three views should complement each other parametrically, i.e. the proportions in each view of the drawing is consistent with the actual vehicle. To maintain a reasonable degree of homogeneity within the class, all the vehicles chosen were from the 2003 model year. The coupes are all standard coupes. Any vehicles considered to be anomalies were not chosen, such as the Volkswagen Beetle. For the model year 2003, 31 coupe models were sold in the U.S. market. The sample is composed of 15 of these vehicles, accounting for 48% of the coupes. The 15 coupes are as follows: Acura RSX, Audi TT, BMW M3, Chevrolet Cavalier, Dodge Stratus, Ferrari 456M, Ferrari 612 Scaglietti, Ford Mustang, Honda Accord, Honda Civic, Hyundai Tiburon, Mercedes-Benz C, Mercedes-Benz CLK, Mitsubishi Eclipse, and Toyota Celica.

The intention of this paper is to understand the fundamental form relationships of a product class and to use that as a basis for a new design methodology which will encourage new form exploration. In order to easily analyze the form of the vehicle, it must be simplified. According to Ching [9], "In drawing the images we see or envision, we rely primarily on lines to visually communicate shape and form. The line therefore exists as the quintessential graphic element of drawing." Therefore it was chosen to represent each vehicle with sets of curves. Each set of curves describes a certain characteristic of the vehicle. A minimum number of curves is used to effectively represent the characteristic. Each curve is represented by a four control point Bezier curve. The only exception is the tires and rims, which are represented with circles.

The vehicle characteristics from Orsborn, et al. [6] were used, and will be summarized in this section. Through discussion with a vehicle designer, it was determined that the following vehicle characteristics are the most relevant for sufficiently describing the form of the vehicle (Refer to Figure 1 for their locations on a vehicle.): (1) Front Wheels, (2) Rear Wheels, (3) Front Wheel well, (4) Rear Wheel well, (5) Front Fender, (6) Rear Fender, (7) Front Bumper, (8) Rear Bumper, (9) Front Windshield, (10) Rear Windshield, (11) Grill, (12) Headlight, (13) Hood, (14) Roof, (15) Trunk, (16) Taillight, (17) Rocker, (18) Door, (19) Front Side Window, (20) Door Handle, (21) Ground, and (22) Belt line.

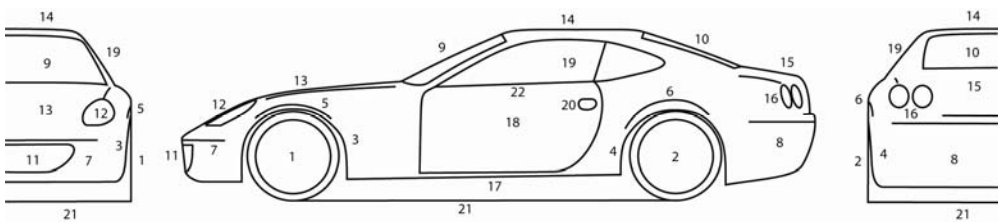

Figure 1 – Vehicle Characteristics

The belt line, which starts at the bottom of the A-pillar and runs along the bottom of the side windows to the trunk, is an important characteristic. There is no specific curve for the belt line, but it represented using a combination of the related characteristics: the hood, side windows, and trunk.

The coupe vehicle class was separated into its views (front, rear, side) and dimensions (horizontal and vertical): y- & z-coordinate for Front and Rear views (horizontal and vertical, respectively), and x- & z-coordinate for Side view (horizontal and vertical, respectively). The views and the dimensions were separated so that unrelated dimensions would not be analyzed together. As will be seen, many of the same curves are foundational regardless of the view or the dimension. The vehicles were assumed to be symmetric about the longitudinal vertical plane. Due to this, many horizontal curves in the front and rear views have a y-value of zero. All the curves were normalized according to their matching curves across the vehicle class, to prevent the analysis from being skewed towards larger shapes like hoods and roofs [5]. For example, in the Front view, y-coordinate for coupes, all the inner headlight curves were normalized against each other.

3 PRINCIPAL COMPONENT ANALYSIS OF DATA

According to the designers interviewed in [1], the characteristics of a vehicle are typically chunked according to spatial relationships. Designers put the ground and the wheels together, which sets the space for the vehicle. Traditionally, the proportions of the front and rear of the vehicle are crucial for its vehicle class. The side of the body and the front and rear corners are then introduced. The greenhouse is then added followed by details in the bumpers and wheel arches. It is seen that the representation of the vehicle is based upon the spatial relationship between the vehicle characteristics and follows a consistent pattern.

In this section we use a statistical method called principal component analysis to determine which characteristics compose the foundation for a class of vehicles. Through this principal component analysis we are able to chunk together the characteristics that form the foundation of a vehicle form. These chunks can then be used to intentionally create novel vehicles. This analysis and its results were first presented in [7] and are revisited here in detail.

3.1 Background Description of Principal Component Analysis

The motivation for using principal components analysis is that it provides a method to project a larger dimensional set of data into a smaller set of dimensions, where the smaller set of dimensions captures as much information content as possible from the original space [5]. In our application, principal components will project a large set of complex curves of the vehicle into a smaller set. In mathematical terms, the original data can be represented by $n \times p$ matrix **X**, where *n* is the number of observations in the data and *p* is the number of variables (dimensions). The goal is to define a smaller set of variables or dimensions that approximates the data, an *r* dimensional subspace where $r < p$. With principal components analysis, the new set of variables $Y_1, Y_2, \ldots Y_r$ are linear combinations of the original data set **X**, where

$$\mathbf{Y}_i = \mathbf{a}_i^T\mathbf{X}. \tag{1}$$

To preserve as much information content about the original data as possible, the $\mathbf{a}_i$ are selected such that they maximize the sample variance in the new space $\mathbf{a}_i^T\mathbf{S}\mathbf{a}_i$, where **S** is the sample covariance matrix of X,

$$\mathbf{S} = \frac{1}{n-1}\sum_{i=1}^{n}(\mathbf{x}_i - \overline{\mathbf{x}})(\mathbf{x}_i - \overline{\mathbf{x}})^T \tag{2}$$

$$\text{and } \overline{x}_i = \frac{1}{n}\sum_{j=1}^{n} x_{ij} \ . \tag{3}$$

The first principal component is defined as the linear combination $\boldsymbol{Y}_1 = \boldsymbol{a}_1^T\boldsymbol{X}$ of the original variables that maximizes the value $\mathbf{a}_1^T\mathbf{S}\mathbf{a}_1$, subject to the constraint $\mathbf{a}_1^T\mathbf{a}_1 = 1$ for reasons of identification. The solution to this problem is simply the eigenvector $\mathbf{a}_1^T$ that corresponds to the largest eigenvalue of **S** [10]. The second principal component is similarly defined and must maximize the value $\mathbf{a}_2^T\mathbf{S}\mathbf{a}_2$ subject to the constraints $\mathbf{a}_2^T\mathbf{a}_2 = 1$ and $\mathbf{a}_2^T\mathbf{a}_1 = 0$, in that $\mathbf{a}_2$ is orthogonal to $\mathbf{a}_1$. Similar to the solution for $\mathbf{a}_1$, the solution is the eigenvector $\mathbf{a}_2$ that corresponds to the second largest eigenvalue of **S**. The pattern continues: the j^{th} principal component is the linear combination

$$\mathbf{Y}_j = \mathbf{a}_j^T\mathbf{X}, \tag{4}$$

where $\boldsymbol{a}_j$ maximizes the sample variance subject to constraints $\mathbf{a}_j^T\mathbf{a}_j = 1$ and $\mathbf{a}_j^T\mathbf{a}_i = 0$, $(i < j)$. In such a fashion, the variance of the j^{th} component is maximized after accounting for all previous components.

3.2 Principal Component Analysis Usage Example

A description of the principal component analysis and the method of extraction of foundational shapes will now be discussed with an active example: the analysis of the front view, y-coordinate (horizontal) for coupes, which is seen in the top of Figure 2. The principal components were found for each coordinate, view, and vehicle class from the data set in Section 2. Each principal component simplifies the description of the data through a vector. The data analyzed here is the normalized value of a control point for a specific curve that is part of a characteristic. Each control point is assigned a weight based upon its relationship to the principal component vector, the lower the absolute value of the weight the closer to the descriptive vector. For example, door curve 2 control point 1 was assigned a weight of 0.139, the highest value of any control point. This means that the first principal component is being described firstly by this control point. The second highest weight, 0.136, is assigned to the first control point for the 3rd curve of the front fender. This continues on for every single one of the 388 control points. But, a single control point is not enough to determine whether a curve should be included due to the fact that many of the weights are within a percentage of each other. Because a curve is defined by four control points, it was determined beforehand that for a curve to be included in the chunking, at least 2 control points from that curve must be included. It was found through the analysis that an isolated control point rarely appeared; for most important curves, the weights on the individual control points were of similar magnitudes.

Since only the dominant curves are of interest, only the top 10% of the weights with the highest absolute value are considered. The control points associated with these weights are then considered, like the two mentioned above. It was found that in the top 10%, most of the control points for a specific curve would be found. To continue the example, the first principal component for the front view y-coordinate of coupes was dominated by the following curves: Door 1 (upper part of front of door), Door 2 (lower part of front of door), Door 3 (bottom of door), Front Wheel Well 2 (front part of wheel well), Front Fender 1 (front fender crease), Front Fender 3 (outside of fender), Ground 2 (track width), Front Tire and Front Rim. From the front view (top of Figure 2) these curves all blend together. They can then be summarized by a single aspect of the form: the width of the body and the track. In some principal components, as will be discussed later in detail, the curves do not group together so intuitively. These provide insight into non-obvious shape relationships which are used as the foundation for the vehicle design methodology.

Each principal component describes a percentage of the variation associated with the original variables. In our example, the first principal component explains 50% of the variation between the coupes in the front view and horizontal coordinate. This has been summarized as the width of the body, which means that the width of the body and track of the vehicle accounts for 50% of the variation between coupes in the front view horizontal coordinate.

Describing the product form through Bezier curves, and thereby through control-points, does not account for some of the curve continuity that is inherent in vehicle design. Swamy, Orsborn, Michalek and Cagan [12] have demonstrated a method in which the description of the curves is modified to account for these continuities. While theirs is a simplified application, future work will consider how to extend this to more complicated forms such as entire vehicles.

3.3 Kaiser's Criterion

This evaluation was done for each coordinate and view, a total of 6 separate analyses. Fourteen principal components were found for the coupe views and coordinates. The percentage of variance explained was calculated for each principal component. It was determined which principal components dominated based upon Kaiser's Criterion [11]. According to Kaiser's Criterion, the threshold for relevant principal components is determined by the percentage of variance explained. If the total number of principal components is X, then principal components that are retained must describe at least $(1/X)*100\%$ of the variation between the original variables. For example, with the front view, y-coordinate there were fourteen principal components. But, after three principal components the percent variance explained dropped below $1/14 * 100\% = 7.1\%$, the threshold determined by Kaiser's Criterion.

Vehicles are complicated shapes composed of many curves that can be formed in innumerable ways. The principal components capture this variation. The high percentage of variance explained indicates the success of this method in portraying the multitude of curves with a simplified principal component. A summary of the dominant principal components, their percent influence, and composition is shown visually in Figures 2 – 10. A detailed discussion of the front view is listed in Table 2. These will be discussed in detail in Section 4. For the complete results refer to [7].

Table 2 – Coupe Front Principal Components

	VAR.	COUPE FRONT Y	VAR.	COUPE FRONT Z
COMP 1	50.0%	width of body, track	41.0%	top & bottom of grill, top of roof, cowl, horizontal front bumper line, top of front windshield
COMP 2	13.6%	width of body & greenhouse, outside & bottom of grill, inside & bottom of headlight	11.8%	shoulder, wheel size, inside & top & bottom of head light, horizontal front bumper line, outside of fender
COMP 3	8.2%	headlight, inner hood line, width of greenhouse	10.6%	horizontal front bumper line, bottom & top & outside of head light, top of roof, top of fender, top of front windshield, bottom of grill
COMP 4			8.4%	bottom & top of head light, bottom of front bumper, width of body, cowl, wheel size
COMP 5			7.4%	width of greenhouse, head light, width of body, wheel size, cowl, horizontal front bumper line
TOTAL	71.8%		79.2%	

4 RESULTANT CURVE CHUNKING

As indicated in Table 2, the first three principal components for the front view y-coordinate (horizontal) explain 71.8% of the variance and are composed of curves shown in Figure 2. In Figure 2, 50.0% of the differences between the coupes in the front view and y-coordinate was accounted for in principal component 1 (Comp 1), composed of the body width and track width (highlighted with thicker lines). An additional 13.6% is accounted for in Comp 2, composed of the width of the greenhouse and body, the inside and bottom of the headlight and all except the top of the grill. While the width of the body and the greenhouse may be intuitive, the relationship between only part of the headlight and the grill is not obvious. Figure 3 shows the Comp 2 curve chunking on four of the sample vehicles: Audi TT, Ferrari 456M, Ford Mustang, and Toyota Celica. It can be seen from these line drawings that the chunking of these curves produces a different representation for each vehicle. Without isolating the curves in this way, the differences between these four coupes would not be as obvious. Results like these can be taken into consideration by the designer when creating new concepts. Comp 3, another 8.2% explained, is composed of the whole headlight, the inner hood line and the width of the greenhouse, as seen in Figure 2.

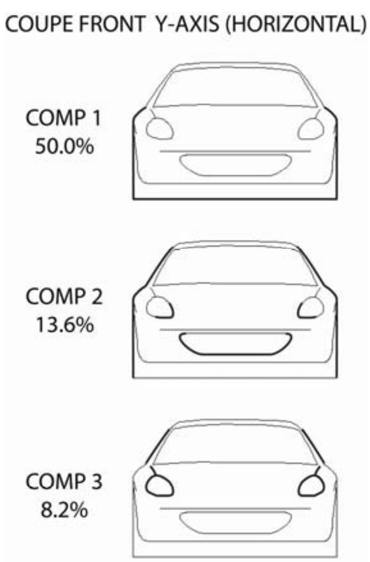

Figure 2 – Coupe Front Y-Axis Principal Components

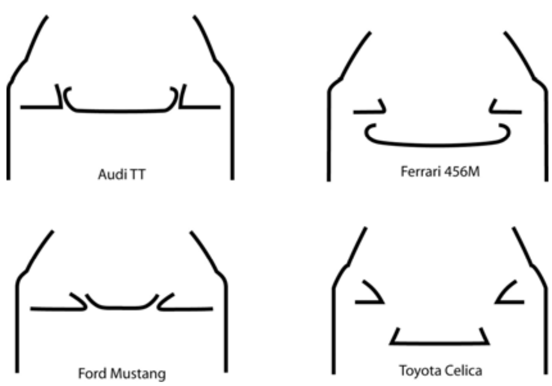

Figure 3 – Comparison of Coupe Front Y-Axis Comp 2

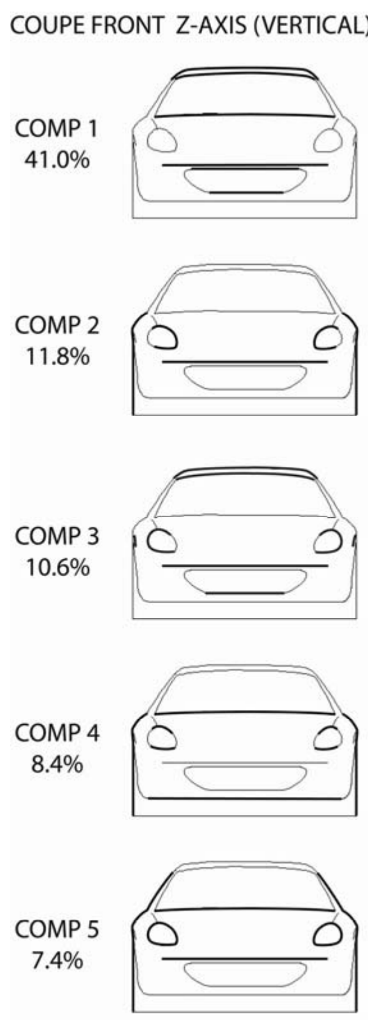

Figure 4 – Coupe Front Z-Axis Principal Components

Figure 4 shows the principal components for coupes front view vertical coordinate which are detailed in Table 2. This is the largest number of principal components for all views and coordinates, in that Kaiser's Criterion was not met until after five principal components. Since principal components 2 – 5 have such a low percentage, it means that the summarization of this view and coordinate is not easily simplified. Comp 1 explains 41.0% of the variance in this view and coordinate through the top of the vehicle, the top of the windshield, the cowl, the top and bottom of the grill, and the horizontal front bumper line. Many of the significant characteristics are quite intuitive and, as will be shown later, are repeated across all the vehicle classes. An additional 11.8% is explained in Comp 2 through the shoulder and fender, the wheel size, most of the headlight, and the front bumper's horizontal accent line. It should be noted that the headlight and the shoulder appeared also in the principal components for the same view horizontal axis. Their repetition here indicates that they, with their related characteristics, are important fundamental curves for coupes. Comp 3 is composed of the top, outside, and bottom of the headlight, the bottom of the grill, the horizontal front bumper accent line, the fenders, the top of the windshield and the top of the roof. Comp 4 repeats some of the previous curves, in a new grouping, and adds in the bottom of the front bumper. Finally, Comp 5 gathers some of the previous curves, brings in the whole headlight, and adds in the greenhouse. The significance of the greenhouse is that it also ties the two coordinate directions together for this view. The significance of the curve chunking in their various principal components will be used as the foundation for the new vehicle conceptualization methodology introduced in Section 5.

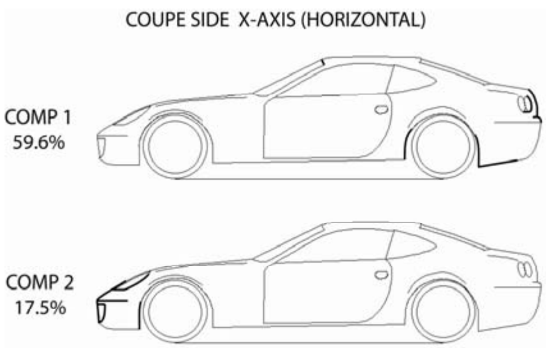

Figure 5 – Coupe Side X-Axis Principal Components

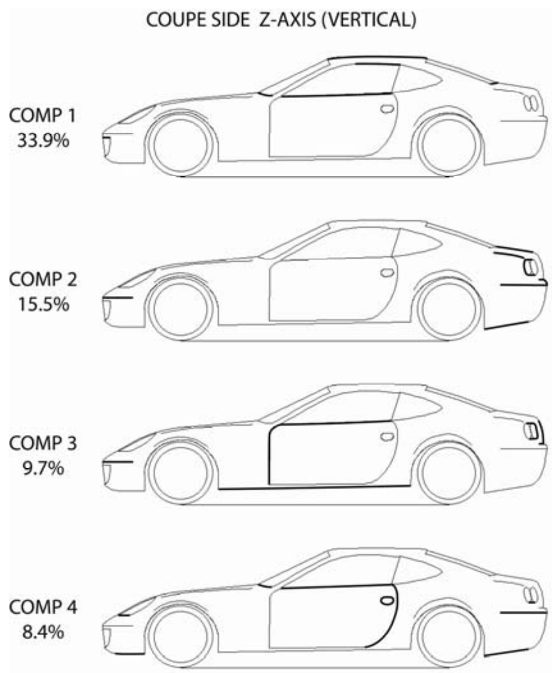

Figure 6 – Coupe Side Z-Axis Principal Components

Figure 5 shows the principal components for coupe side view x-coordinate. In this instance, there are only 2 principal components that fall within Kaiser's Criterion. Surprisingly, over half (59.6%) of the differences between coupes in this view and coordinate is explained by the rear and bottom of the trunk, half of the taillight, the top of the front windshield, the top and bottom of the rear bumper, and just part of the rear wheel well. This chunk is not at all intuitive and offers some insight into the differences between coupes. Comp 2, 17.5%, is composed of nose curves: the headlight, the front bumper, grill, the front of the hood, and the front edge of the front wheel well. Since this chunk is focused on one area of the vehicle, a vehicle designer can be certain that choices made in the form of the nose will have a strong influence on the design of the vehicle when viewed from the side.

The first principal component for coupe side view z-coordinate (Figure 6) ties together the top of the grill, the bottom of the windshields, the top and bottom of the side window, and the top of the roof, to explain about a third of the variation between coupe in this view and coordinate. The relationship between these curves is somewhat obvious, but will be utilized by a vehicle designer in the methodology. Comp 2 is split between the horizontal front bumper line, the taillight, the horizontal crease, top, and bottom of the rear bumper, and the top and outside curves of the trunk.

Again, it is not obvious that these very distant curves would chunk together to account for 15.5% of the differences between coupes in this view and coordinate. In Comp 3, the horizontal front bumper line, part of the taillight and the rear of the trunk are brought together. The addition of the rocker and the front and top edges of the door ties this chunk to Comp 1 of this view. Finally in Comp 4, which accounts for 8.4% of the variation between coupes, the chunk repeats the cowl, the top of the side door, and parts of the rear bumper and taillight. The addition of the rear of the door, the door handle, the bottoms of the headlight and front bumper form connections to other principal components in the side view.

Figure 7 shows the composition of the principal components for the rear view, y-coordinate of coupes. Comp 1 explains half (50.9%) of the variation through the width of the body, the fenders, the track width and the wheel size. This is quite similar to Comp 1 in the front view, which is understandable. The consistency between these two views further verifies this method of chunking together fundamental shapes through principal component analysis. Comp 2 chunks together the width of the body and greenhouse with details that are rear view specific: the taillights, the horizontal rear bumper crease, and the outside of the rear windshield. This, again, echoes the principal components in the front view. Comp 3 explains an additional 7.4% by grouping together the curves from Comp 2, minus the bottom of the taillight and adding the outside of the roof. The relationship between these chunks will facilitate the use of this information by the designer.

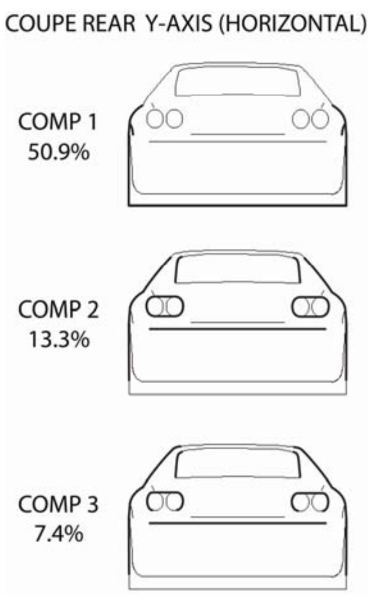

Figure 7 – Coupe Rear Y-Axis Principal Components

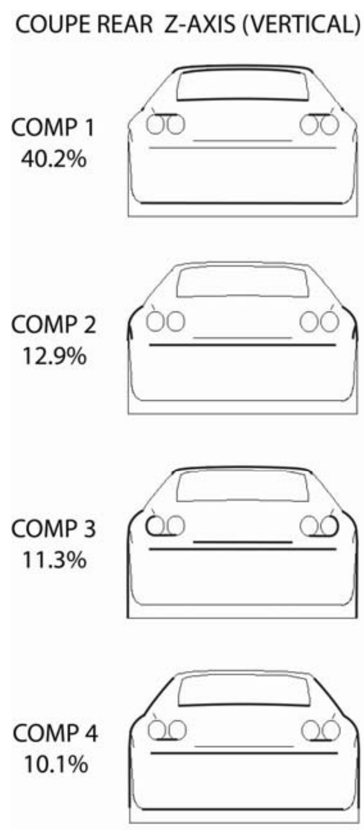

Figure 8 – Coupe Rear Z-Axis Principal Components

Figure 8 shows the four principal components for the rear of coupes in the vertical direction. The first principal component chunks together the top of the roof, the top and bottom of the rear windshield, the top of the taillight, the bottom of the rear bumper, and the belt line for an explanation of 40.2% of the variation. This is similar to the chunking for Comp 1 in the front view, vertical direction. Comp 2 includes the shoulder and the horizontal bumper line, like the front view. It also draws in the fender. Comp 3, for 11.3%, combines the roof, the trunk, the horizontal bumper crease, the shoulder, the outside and bottom of the taillight, and the wheel size. Finally, Comp 4 combines the previous characteristics in a new chunk with the bottom of the rear windshield, the bottom of the taillight, the horizontal crease and bottom of the rear bumper, and the shoulder. It also adds in the width of the body and greenhouse, to tie it into the principal components for the horizontal direction.

These vehicle characteristics are the fundamental characteristics within the coupe vehicle class. It is interesting to note that while some of the chunking of the characteristics is quite intuitive (i.e. the width of the vehicle in the front and rear views), some of them are non-obvious (i.e. the bottom and outside of the grill and inside and bottom of the headlight in the front view). Many of the characteristics that stand out in a certain view are significant in both the horizontal and vertical directions. This indicates that these characteristics are fundamental to the vehicle class. These fundamental characteristics and their chunking will now be used as the basis for new product conceptualization.

5 NEW VEHICLE CONCEPTUALIZATION METHODOLOGY

The new conceptualization methodology takes the curve chunkings represented in Section 4 and presents them as suggested steps in the drawing process for new vehicle conceptualization. Orsborn, Cagan and Boatwright [8] present a formal shape grammar based upon the principal component chunking. The formal shape grammar is necessary for the computational implementation of these forms. What we are introducing here is a less formal methodology that designers can merge with their current conceptualization technique, such as those discussed in [1]. Designers, by constraining themselves to the non-intuitive statistically-derived curve chunkings, will force themselves to explore new forms and curve relationships. The finished line drawing can then be used, if desired, as a foundation for further concept refinement.

The intention of the methodology is for the designer to consider the statistically-derived curve chunks as the product form is conceptualized. By visiting the derived chunkings in Section 4, the designer can intentionally take into account unintuitive curve relationships during conceptualization. As the design progresses, the designer compares what curves have already been created with respect to the curve chunkings. New curves are then introduced based upon these curve relationships.

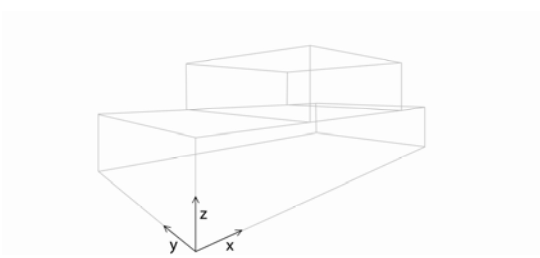

Figure 9 – ¾ View Two-box

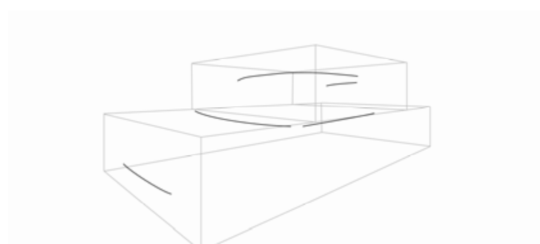

Figure 10 – Side Z Comp 1

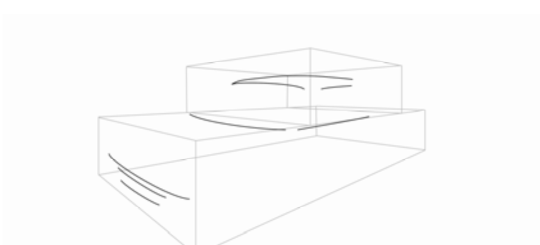

Figure 11 – Front Z Comp 1

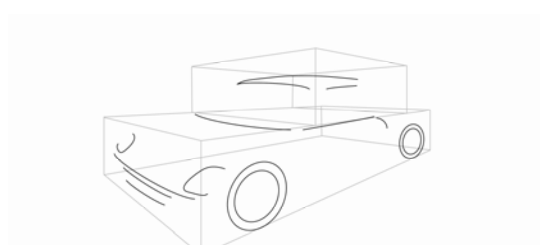

Figure 12 – Front Z Comp 2

This methodology will now be explored through an example. Some designers prefer to conceptualize with side elevations, and some prefer perspective [1]. Presume that we have been requested to create a coupe concept, based upon a two-box. A two-box is called such because the vehicle form is based off of two boxes: a lower one for the body and an upper one for the greenhouse. We initially set up the ¾ view two-box in two-point perspective (Figure 9). This sets the framework for the vehicle, which is based upon the decision to create a coupe. The designer can then chose to start with any one of the curve chunkings shown in Figures 2, 4-8. In this instance, the curves that appear in the Side Z Comp 1 chunking (Figure 6) are chosen randomly. There is, obviously, some flexibility as to how the designer applies the curves to the initial form. The cowl is often a starting point and the vehicle already begins to take shape as seen in Figure 10.

Since the cowl, the roof and part of the grill have already been drawn, the designer decides to continue with the curves from Front Z Comp 1 (Figure 4), which build upon the existing curves. Now, the grill, front bumper, and front windshield begin to take a definite shape (Figure 11).

The designer wants to show the width and stance of the vehicle, so the shoulder and wheels are introduced. These curves are based upon the chunking in Front Z Comp 2 (Figure 4) which builds upon the already existing horizontal front bumper curve. Part of the headlight is also introduced, which more clearly defines the front end of the vehicle (Figure 12).

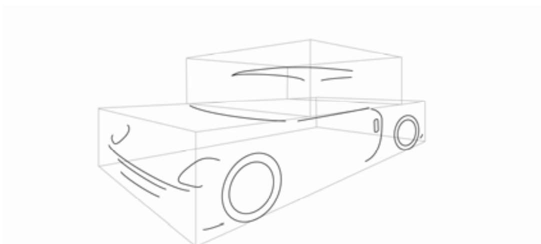

Figure 13 - Side Z Comp 4

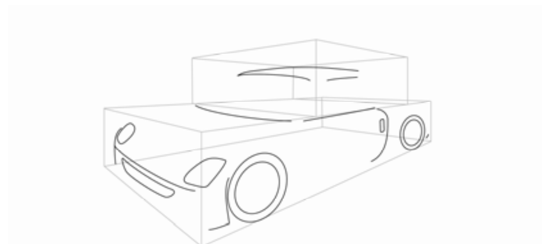

Figure 14 - Side X Comp 2

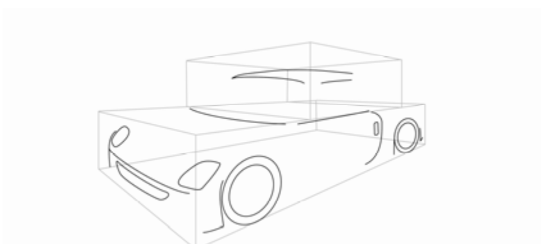

Figure 15 – Side X Comp 1

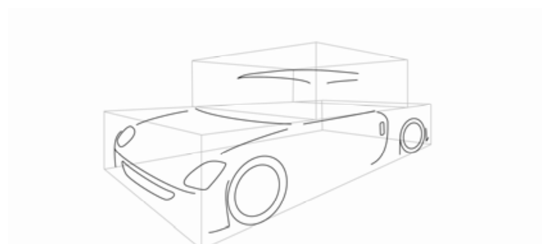

Figure 16 - Front Y Comp 3

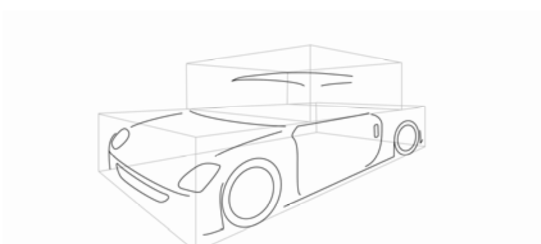

Figure 17 – Side Z Comp 3

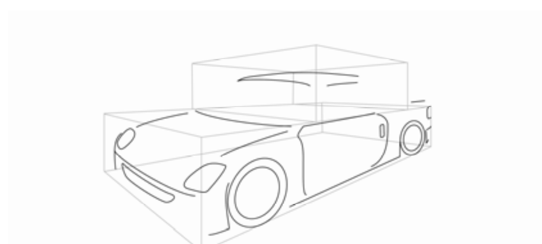

Figure 18 – Side Z Comp 2

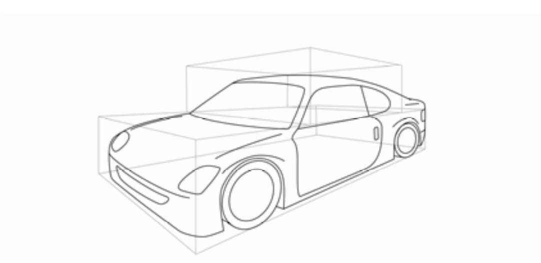

Figure 19 – Non-Chunked Curves

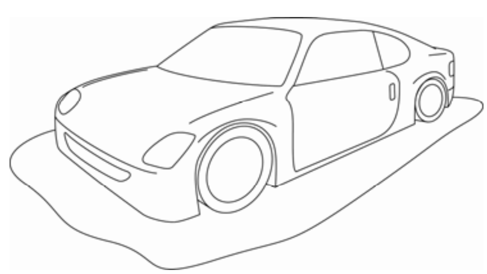

Figure 20 – Final

To further build upon the width and stance of the vehicle, part of the door and the front and rear lower bumpers are added (Figure 13), all of which are chunked from Side Z Comp 4 (Figure 6). Including the curves from Side X Comp 2 (Figure 5) brings closure to the grill and headlights while forming part of the front bumper and front wheel well (Figure 14). Most of the curves from Side X

Comp 1 (Figure 5) are already in the drawing. By considering this chunking, the rear wheel well begins to take shape (Figure 15).

The Front Y Comp 3 chunking provides the outer hood curves (Figure 2) which bring more form to the hood and the front of the vehicle (Figure 16). The side door and the rocker fill in the width of the body (Figure 17), both of which are chunked in Side Z Comp 3 (Figure 6). Side Z Comp 2 (Figure 6) chunks together the rear bumper, outside trunk curve, and part of the taillight. These curves bring form and features to the rear of the vehicle (Figure 18).

The curve chunking does not include every single curve in the form, but just the curves determined to be foundational by the principal component analysis. The designer must then fill in the rest of the form (Figure 19). Figure 20 shows the rest of the curves added, the perspective frame removed, and some grounding added.

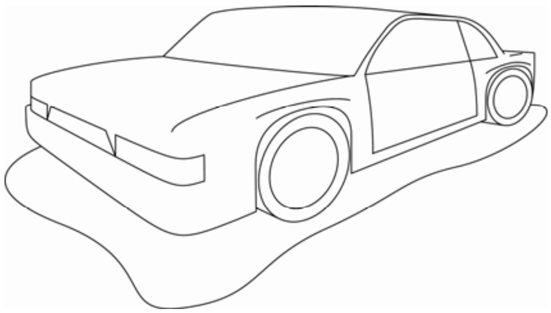

Figure 21 – Concept 2

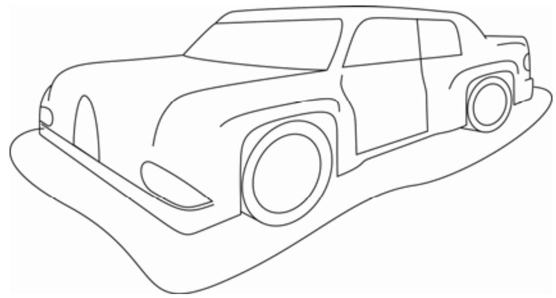

Figure 22 – Concept 3

Figures 21 and 22 are additional examples of coupes created using the above methodology. They both started with the same 2-box (Figure 9), but proceeded to introduce different curve chunks in a unique order to encourage divergence in the design exploration. Their distinctness in design, from each other and the concept in Figure 20, demonstrates the flexibility of the methodology when used to explore product conceptualization.

While the vehicle concepts produced may not be completely novel, the intention of this example was to show how the product conceptualization process can be guided. By specifically addressing statistically-derived (sometimes unintuitive) curve chunkings, the designer can explore the design space in ways not previously considered in traditional conceptualization techniques. Though there is no single conceptualization method, a more traditional method would have started with the two-box and then placed the wheels first. The wheels would have then set the stance and proportions for the rest of the vehicle. The belt line and other curves would be added with the intention of accenting the horizontal sweeping of the vehicle to make it appear sporty. In the primary example, the proportions (e.g. the roof height, belt line and nose position) are set by the positioning of certain curves (Figures 10 and 11) before the wheels are included. This did not detract from the sportiness of the vehicle, but caused the designer to consider seemingly secondary features, like the roof height. When added, the wheels accented the stance and proportions that were already beginning to take form.

A traditional vehicle conceptualization methodology follows a linear approach in the introduction of curves. This, unintentionally, limits the designer’s ability to explore the design space. A principal component analysis of a set of designs provides insight into which curves are related to each other according to their influence on the set of designs. These curve chunks are then the medium the designer uses to conceptualize. By choosing which chunks to introduce to the concept and when, the designer is able to explore non-obvious curve relationships and their effect on the vehicle concept. This facilitates the exploration of the design space and provides a means for the designer to conceptualize vehicles that may not have been considered through a traditional method.

A further benefit of this methodology is that educators can teach it to design students as a consistent way to explore the design space for a mature product class. Additionally, persons that may not be trained designers can explore conceptual product forms by following this methodology.

6 CONCLUSIONS

In current practice, initial new product concepts are created based upon a learned methodology, experience, and intuition. While this has proven, historically, to produce interesting new products, the method itself constrains the designer's exploration. A new method, based upon statistically-derived curve chunkings, provides an opportunity for designers to see unintuitive relationships between curves, which in turn can effect the form exploration.

By simplifying the representation of a class of products (in this case, vehicles) with four-control point Bezier curves, the product forms can be defined by the values for the control points. These values can then be analyzed using statistical tools, such as principal component analysis, to determine what are the fundamental curves that describe the product class. Principal component analysis chunks together these curves according to the percentage difference of the class that is explained. These curve chunks can then be addressed specifically by the designer as new product forms are conceptualized.

An informal drawing method ties together traditional methods with a focus on the curve chunks derived from the principal component analysis. Subjective product conceptualization methods can be augmented, or replaced, with this scientifically based method. This method provides a means for form exploration and formalizes how product concepts can be explored. Potential new forms begin to emerge as a designer observes the relationships between the chunked curves and begins to take these relationships into account during the new product form conceptualization.

7 ACKNOWLEDGEMENT

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