Res Eng Design (2008) 18:181–196
DOI 10.1007/s00163-007-0035-9

ORIGINAL PAPER

A methodology for creating a statistically derived shape grammar composed of non-obvious shape chunks

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Received: 1 September 2006 / Accepted: 29 May 2007 / Published online: 9 October 2007

Abstract A shape grammar is a production system that can be used to create new product designs. Traditionally, a product shape grammar's rules are created by a skilled person that understands the language of the design. In this paper the results of a principal component analysis of vehicles are used to create a vehicle shape grammar by basing the rules upon the determined shape relationships. The advantages are that: rules can be created according the results of a statistical analysis, and not according to a designer's subjective observations; class specific vehicles can be created with fewer rule applications; and those rule applications encourage divergent designs. Using the principal component analysis based shape grammar, unique vehicles are created to demonstrate the potential of statistically based concept creation for the generation of product forms.

Keywords Vehicle design · Design language · Principal component analysis · Shape grammar

1 Introduction

Vehicle designers have many tools at their disposal to help them in the creation of new vehicle concepts. Brands have established design languages that can be referenced on style sheets. Designers are trained to use their skill and intuition to bring potential designs to reality while respecting the established brand history and features for a product class. The understanding of vehicle differentiations is often based upon a general understanding of the vehicle form and established relationships between vehicle characteristics. This paper takes the results of a statistical analysis of vehicle forms as the design vocabulary for three vehicle classes. This vocabulary is then used as the basis for a vehicle shape grammar.

Shape grammars have been used as a computational design tool for representing design artifacts for over two decades. Shape grammars are a production system created by taking a sample of the whole for which one is trying to write a language (Stiny 1980). From this sample a vocabulary of shapes can be written that represent all the basic forms of that sample. By defining the spatial relationships between those forms and how the forms are related to each other, shape rules can be written. A shape rule consists of a left and right side. If the shape in the left side matches a shape in a drawing then the rule can be applied, and the matching shape changes to match the right side of the rule. The shape rules allow the addition and subtraction of shapes, which in the end are perceived as shape modifications. These shape rules, combined with an initial shape, produce a shape grammar that represents the language of the design (Stiny 1980). Shapes themselves can exist as points, lines, planes, volumes, or any combination thereof (Stiny 1980). All shape generation must start with an initial shape: a point, a coordinate axis, or some foundation from which to start the shape grammar. If the grammar is going to end, it can end with a terminal rule, which prevents any other rules from being applied after it. This forces there to be closure in the rule sequence. Alternatively, a design sequence can continue

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indefinitely and designs could be chosen at any point in the design process.

The method introduced here fundamentally changes the method of developing the shape grammar. Previously, the vocabulary of the design to be used as the foundation of the shape grammar was determined by the creator of the grammar. The creator of the grammar would look at the sample and subjectively derive the vocabulary. From that vocabulary, the rules would be formed based upon the creator's experience and intention. It is quite possible that two different persons looking at the same sample of shapes would create two very different shape grammars. In this work we introduce a method that uses a statistical analysis of product characteristics to determine relevant groupings of elements. These objective groupings are then used to create rules for the shape grammar.

Orsborn et al. (2006) developed a vehicle shape grammar based upon the existing vehicle classes of coupe, pickup, and SUV. 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. The forms for 15 coupes, 20 SUVs, and seven pickups were captured using four-control-point Bezier curves. The data collected from this sample was statistically analyzed in Orsborn et al. (2007). Principal component analysis was used to determine the fundamental characteristics within the individual vehicle classes of coupe, pickup, and SUV. Principal component analysis is a statistical method whereby an original set of related data is reduced in dimensionality to match the original data as closely as possible (Patel et al. 2006). Principal component analysis finds a set of new variables that are weighted averages of the original variables. The first principal component is a vector that captures most of the variation between the original variables. Each variable is then given a weight related to the vector. The weight describes the influence of that variable on the principal component. Based upon the weights of all the variables a percentage variance explained is calculated for the first principal component. The second principal component is described using a vector orthogonal to the first principal component. The analysis is repeated, returning different weights for the variables and a smaller percentage variance explained. In many applications, like vehicles, only a few principal components account for much of the differences in the objects and identify key elements that distinguish the objects.

The fundamental characteristics found through the principal component analysis of the vehicles at times differed from the traditional and expected feature definition, resulting in a deeper understanding of what features of an existing set of designs must differentiate one form from another (Orsborn et al. 2007). In this paper, the results from the principal component analysis are used to create a new shape grammar based upon these discovered shape relationships. The shape grammar is then used to create new vehicles. 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.

Table 1 Vehicle sample

	Coupes	SUVs	Pickups
1	Acura RSX	Acura MDX	Chevrolet Silverado
2	Audi TT	BMW X3	Dodge Ram
3	BMW M3	BMW X5	Ford F150
4	Chevrolet Cavalier	Chevrolet Suburban	Ford Ranger
5	Dodge Stratus	Ford Escape	GMC Canyon
6	Ferrari 456M	Ford Excursion	GMC Sonoma
7	Ferrari 612 Scaglietti	Ford Expedition	Toyota Tacoma
8	Ford Mustang	Ford Explorer	
9	Honda Accord	Hyundai Santa Fe	
10	Honda Civic	Kia Sportage	
11	Hyundai Tiburon	Land Rover Free Lander	
12	Mercedes Benz C	Land Rover Range Rover	
13	Mercedes Benz CLK	Mazda Tribute	
14	Mitsubishi Eclipse	Mercedes Benz ML	
15	Toyota Celica	Mitsubishi Montero	
16		Mitsubishi Montero Sport	
17		Porsche Cayenne	
18		Suzuki Grand Vitara	
19		Toyota Land Cruiser	
20		Toyota RAV4	

2 Vehicle data description

In Orsborn et al. (2006), vehicles were chosen from three known classes: coupes, pickups, and SUVs. The selection requirements were that each vehicle have an available blueprint that included the front, side and rear views. Each of the views must be isometric (or as 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. Table 1 indicates the sample vehicles for each class.

To maintain a reasonable degree of homogeneity within classes, all the vehicles chosen were from the 2003 model year. All the pickups chosen were extended cab models. The coupes were all standard coupes. Unusual forms, like the Volkswagen Beetle, were not included. Any vehicles

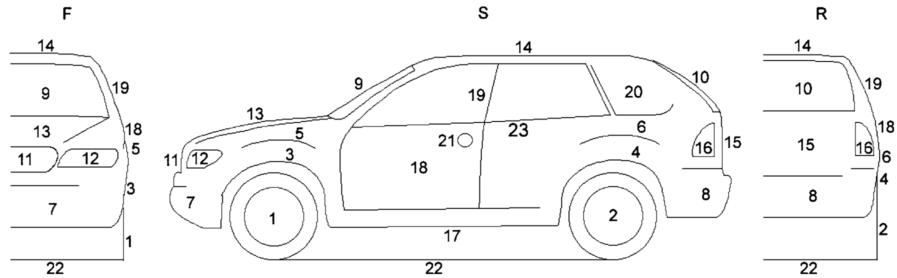


Fig. 1 Vehicle characteristics

considered to be anomalies in their class were not chosen. For example, the Infiniti FX35, while technically an SUV, has an unusual form with respect to most SUVs (Csere 2003). This vehicle was not included in the sample.

The intention of this paper is to apply our understanding of the foundational forms in vehicle classes through the creation and application of a vehicle shape grammar. The vehicle characteristics from Orsborn et al. (2006) were used, and will be discussed in detail 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 Fig. 1 for their locations on the 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) rear side window, (21) door handle, (22) ground, and (23) belt line.

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 will be built using a combination of the related characteristics: the hood, side windows, and trunk.

Each characteristic is defined by a curve or set of curves. These curves were captured manually through the following process:

1. A vehicle's blueprint was imported as an image plane into Alias DesignStudio.
2. Each characteristic was traced using Bezier curves (four control points), except tires and rims, which use circles.
3. The minimum number of curves were used to capture the characteristic accurately.
4. This was done for each of the three views: front, side, and rear.

3 Principal component analysis based shape grammar

Orsborn et al. (2007) analyzed the vehicle data using principal component analysis. The vehicle classes were separated into their views and dimensions: y- and z-coordinate for front and rear views (horizontal and vertical, respectively), and x- and z-coordinate for side view (horizontal and vertical, respectively). The results produced chunks of curves that represented a percentage of the vehicle class explained. For example, Fig. 2 pictorially shows the results of the coupe front y principal component

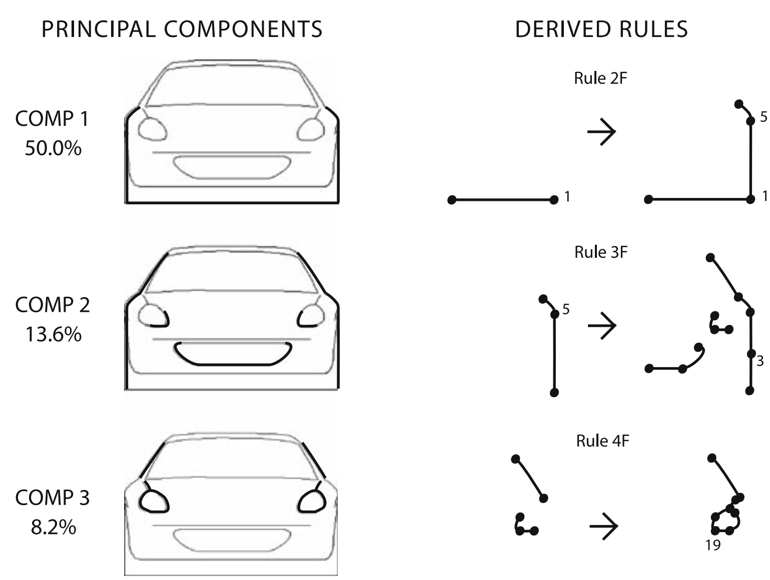


Fig. 2 Rule derivation example

Table 2 New rules from principal components

	Front	Side	Rear
Rule 1	Ground	Ground	Ground
Rule 2	Coupe Comp 1 Y	Echoes	Coupe Comp 1 Y
Rule 3	Coupe Comp 2 Y	Echoes	Coupe Comp 2 Y
Rule 4	Coupe Comp 3 Y	Echoes	Coupe Comp 3 Y
Rule 5	Coupe Comp 2 Z	Echoes	
Rule 6	Coupe Comp 1 Z	Coupe Comp 1 Z	Coupe Comp 1 Z
Rule 7	Coupe Comp 3 Z	Coupe Comp 2 Z	Coupe Comp 3 Z
Rule 8	Coupe Comp 4 Z	Coupe Comp 3 Z	
Rule 9		Coupe Comp 1 and 2 X	
Rule 10		Coupe Comp 4 Z	
Rule 11	Pickup Comp 2 Y	Pickup Comp 1 X	Pickup Comp 1 Y
Rule 12	Pickup Comp 1 Z	Pickup Comp 1 Z	Pickup Comp 1 Z
Rule 13	Pickup Comp 1 Y		
Rule 14	SUV Comp 1 Y		SUV Comp 1 Y
Rule 15	SUV Comp 2 Y		SUV Comp 2 Y
Rule 16	SUV Comp 1 Z	SUV Comp 1 Z	SUV Comp 1 Z
Rule 17		SUV Comp 2 X	
Rule 18	SUV Comp 2 Z	SUV Comp 2 Z	SUV Comp 2 Z
Rule 19		SUV Comp 1 and 3 X	
Rule 20	SUV Comp 3 Z	SUV Comp 3 Z	SUV Comp 3 Z

Table 3 Vehicle characteristics not completely described by principal components

	Front	Side	Rear
Coupe	Front windshield, front wheel well	Wheels, ground, fenders, wheel wells, hood, head light, front windshield, rear windshield, side window, rear bumper, door	Trunk, rear wheel well
Pickup	Head light, grill, front bumper	Front bumper, head light, hood, front tire, front wheel well, front windshield, side window, rear windshield, tail light, rear bumper, rear wheel well, rocker, rear tire, ground, door	Rear windshield, tail light, rear bumper, wheels, ground
SUV	Grill, head light, front windshield, front wheel well	Hood, front windshield, rear windshield, front wheel well, rear wheel well, wheels, ground, fenders, door, side window, handle	Rear windshield, ground

analysis using darkened curves. It should be noted that the vehicles were analyzed symmetrically about the longitudinal vertical plane, but are mirrored here for the sake of visualization. The top-left figure is the first principal component (Comp 1) and 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. This chunk is inserted as the right-hand side of Rule 2F. Then, the curves shared between Comp 1 and Comp 2 become the left-hand side of Rule 3F. The right-hand side inserts the curves in Comp 2 that were not part of Comp 1. The right-hand side of Rule 3F is the entire chunk shown in Comp 2. The process is repeated for Rule 4F. The curves shared by Comp 2 and Comp 3 compose the left-hand side of the rule and the curves chunked in Comp 3 are the right-hand side of the rule. In each instance the left-hand side of the rule is composed of curves shared with another chunk and the right-hand side is composed of the entire chunk. This just demonstrates one view of a rule. The side and rear views are also included in a single rule. These are derived in the same fashion. The methodology described here is used in the derivation of all the shape grammar rules.

The vocabulary for this shape grammar is based upon shape chunking that resulted from the principal component analysis. Because not every vehicle characteristic is contained within the principal component analysis (Table 3), additional rules will be created to fill in some of the empty

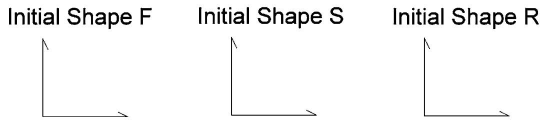


Fig. 3 Initial shape

spaces. This new shape grammar will be compared and contrasted with the original vehicle shape grammar from Orsborn et al. (2006).

The shape grammar rules use labels and makers. The markers (a dot) indicate the end of a four-control-point Bezier curve. The labels (a number) guide the rule application. While the intention of many shape grammars is to be elegant, the emphasis here is to show that shape grammar rules can be objectively derived from a principal component analysis. Table 2 lists the 20 shape grammar rules and their principal component composition. It should be noted that the groupings of the principal components provided a connected progression through the rules. By selecting principal components with related curves, a sequence was automatically created that maintained the shape relationships found through the principal component analysis. In most instances, the dominant principal components came earlier in the rule progression. There are some principal components that are not used in rules. This is because the curves that are chunked together already appear in another principal component. In the instance where one principal component shares all of its curves with another, the principal component is used which simplifies the rule progression. The rules are separated according the vehicle class, since this is how the vehicles were analyzed. We introduce the term echo in Table 2. An echo is when a certain shape is indicated in the front and rear views but not in the side view of the principal component analysis. The shape is "echoed" into the side view of the rule, for the sake of continuity.

The initial shape (Fig. 3) is a coordinate axis located on the ground at the center of the vehicle in the front and rear views and at the point where the front tire touches the ground in the side view.

Rule 1 (Fig. 4) inserts the ground, which also indicates the track width and the wheelbase. This rule is used as the starter for all vehicles. Though the ground is not an indicator in every vehicle class in every view, it was decided to be necessary as a foundation for generation of any vehicle creation.

3.1 Coupe rules

Rules 2–10 were derived from the principal components for coupes. If these rules are applied parametrically all the differentiating curves of a coupe will be created.

Rule 2 (Fig. 5) inserts the shoulder and width of the vehicle in the front and rear views, taken from Coupe Comp 1 Y in the front and rear. The rear fender is also inserted in the rear view and as an echo in the side view. Label 5 is added in as an echo in the side view.

Rule 3 (Fig. 6) inserts the chunks from Coupe Comp 2 Y in the front and rear views. The related echoes are added in the side view, along with the necessary labels. At this point it is difficult to see how a vehicle will form. But, these shape groupings are relevant in that they are taken directly from the principal component analysis.

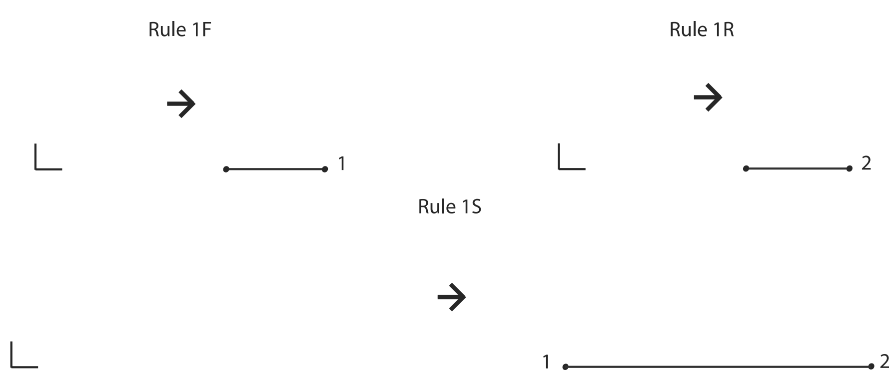
The right-hand side of Rule 4 (Fig. 7) inserts the additional shapes found in Coupe Comp 3 Y Front and Rear, which gives the chunking according to the indicated principal components. It also inserts the echoes of the curves in the side view.

Rule 5 (Fig. 8) adds in just the horizontal front bumper line and the related Label 9. This is based off Coupe Comp 2 Z Front and echoes on the side view.

Rule 6 (Fig. 9) links together all the Coupe Comp 1 Z views. Since all of these views share curves, they can be applied in one rule. Additional markers and labels are added for continuity.

Rule 7 (Fig. 10) uses Coupe Comp 3 Z for the front and rear and Coupe Comp 2 Z for the side. This combination of principal components is used because of the curves that are shared between them, not because of the percentage explained by the principal components.

Fig. 4 Rule 1



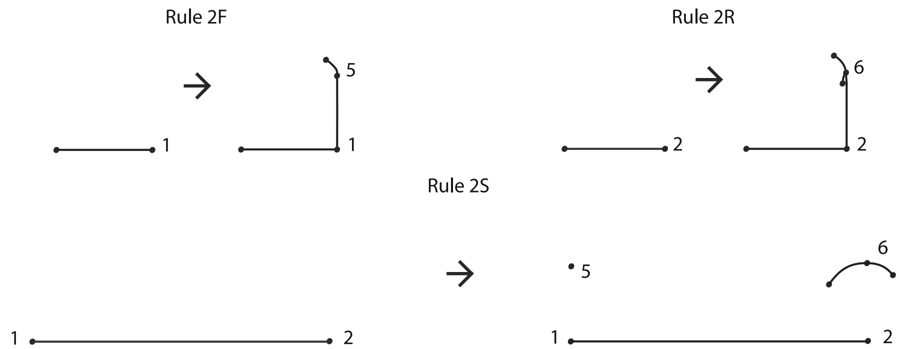


Fig. 5 Rule 2

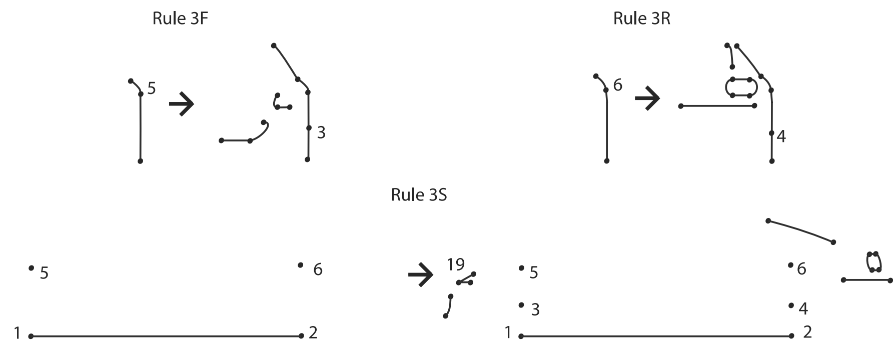


Fig. 6 Rule 3

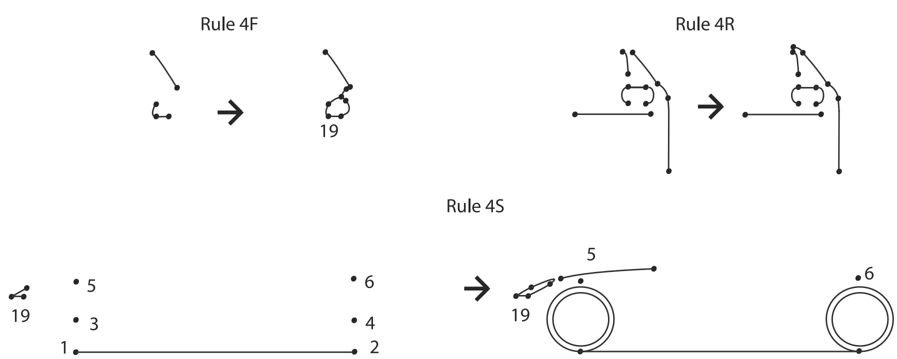


Fig. 7 Rule 4

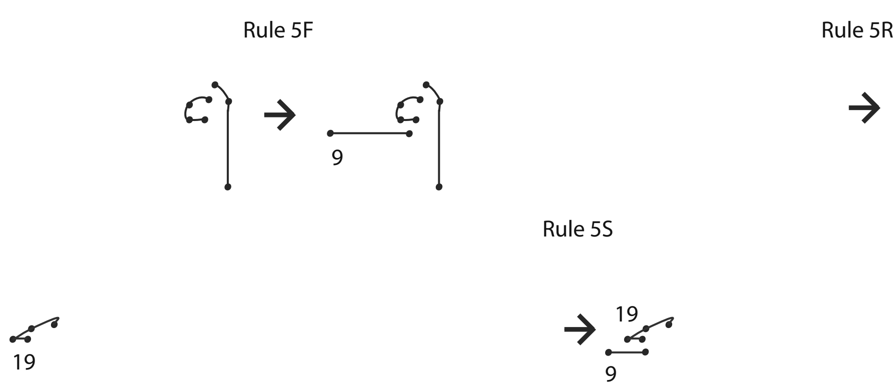


Fig. 8 Rule 5

Fig. 9 Rule 6

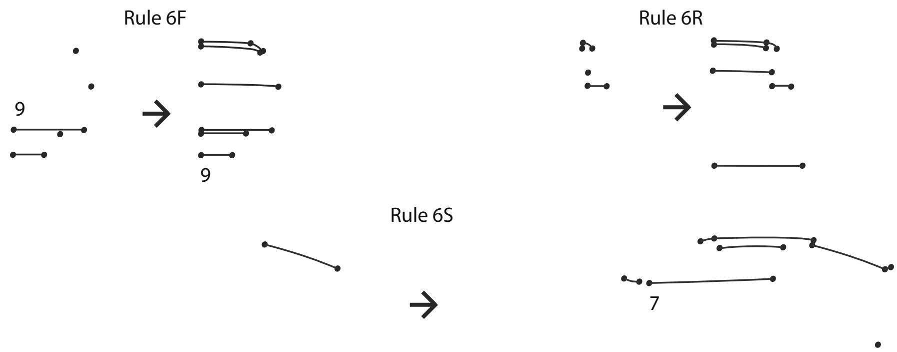


Fig. 10 Rule 7

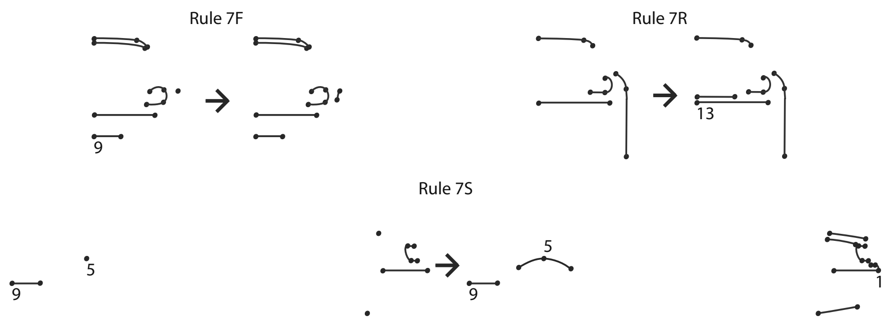


Fig. 11 Rule 8

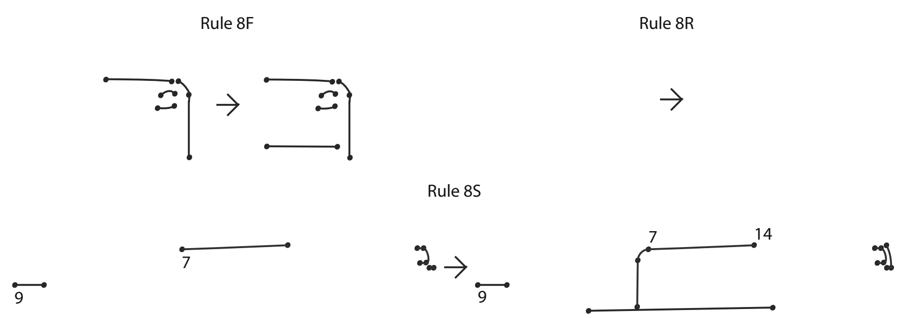
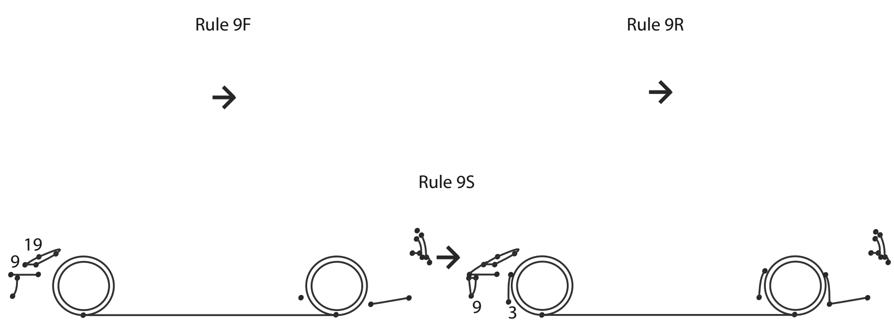


Fig. 12 Rule 9



Rule 8 (Fig. 11) combines Coupe Comp 4 Z Front and Coupe Comp 3 Z Side. A rear principal component is not used because all the curves explained by rear principal components have been created.

Now that all the front and rear curves found in the principal components have been created, Rules 9 (Fig. 12) and 10 (Fig. 13) add in the rest of the side chunks. Coupe Comp Side 1 and 2 X are combined in Rule 9 because they do not

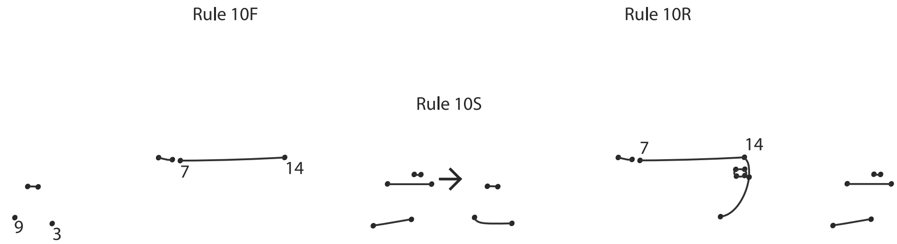


Fig. 13 Rule 10

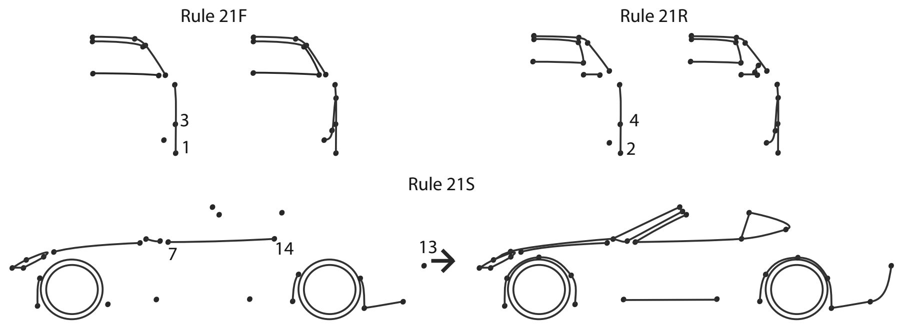


Fig. 14 Rule 21

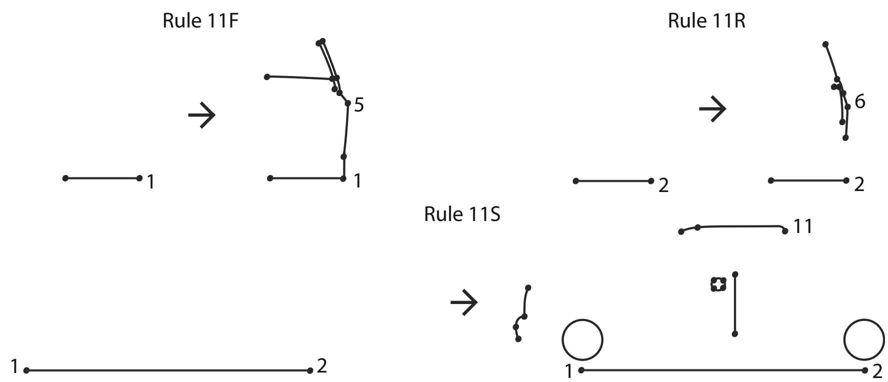


Fig. 15 Rule 11

overlap. Then, Rule 10 inserts part of the door, handle, and lower front bumper found in Coupe Side Comp 4 Z.

At this point, the vehicle is not completed since not all curves are contained within the principal component analysis criteria used. So, Rule 21 (Fig. 14) was created to insert the rest of the curves, the curves not chunked together through the principal component analysis (Table 3). After Rule 21 is applied, the shape modification rules (Fig. 27) can be applied to parametrically modify the shape of the vehicle. These will be discussed in more detail later.

3.2 Pickup rules

Rules 11–13 were derived from the principal components for pickups. There are less rules than that for a coupe due to the fact that there were fewer significant principal components for pickups found in Orsborn et al. (2007). Also, due to the similarities between pickups, the principal components from different views were more easily combined.

Rule 11 (Fig. 15) combines Pickup Comp 2 Front Y, Pickup Comp 1 Side X, and Pickup Comp 1 Rear Y. This rule is applied after Rule 1. It inserts seemingly disparate curves. The front and the rear view have some overlap, and the side view includes some of the curves indicated in the other views.

Rule 12 (Fig. 16) is more cohesive in the shapes that it shares between the views. This rule includes Pickup Comp 1 Front Z, Pickup Comp 1 Side Z, and Pickup Comp 1 Rear Z. These add the tops of most characteristics and indicate the general form of the vehicle.

Because the front view of pickups has one more principal component than the other views, Rule 13 (Fig. 17) adds in the rest of the curves in the front view, derived from Comp 1 Front Y.

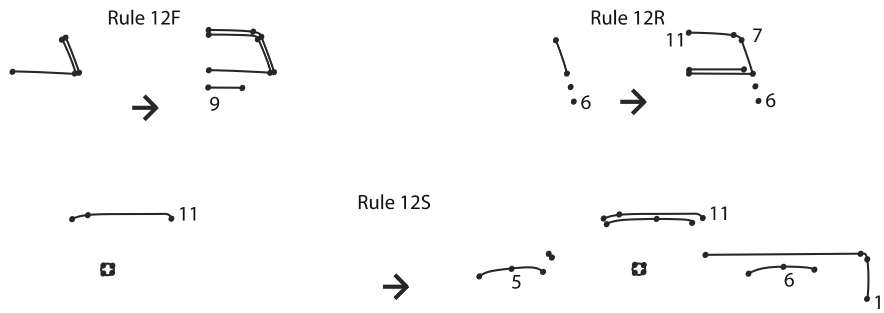


Fig. 16 Rule 12

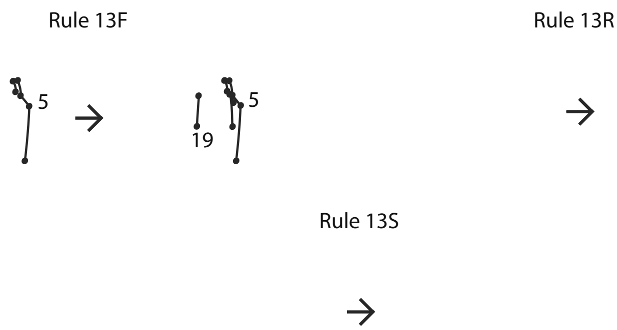


Fig. 17 Rule 13

After the application of these four rules, the vehicle is not yet complete. Rule 22 (Fig. 18) finishes off the characteristics that have been started, and adds in necessary curves to enable the completion of the vehicle. Finally, as in the coupe, the shape modification rules can be applied indefinitely to parametrically change the vehicle form.

3.3 SUV rules

Rules 14–20 were derived from the principal component analysis of SUVs. The results from this analysis were much less linked than coupes or pickups. While the principal components provided some interesting results noted Orsborn et al. (2007), it proved to be difficult to build the rules in an order that gave the dominant principal components priority in that very few curves are shared between principal components. Where the principal components for coupes shared at least one curve (as demonstrated with Fig. 2), the principal components for the SUVs sometimes shared only a point. The rule order was established by necessity of the shared curves. Labels were added to help the progression of the shape grammar.

As before, Rule 1 must first be applied. Then Rule 14 (Fig. 19) inserts the outside of the vehicle in the front and rear views, derived from SUV Comp 1 Y front and rear.

Rule 15 (Fig. 20), derived from SUV Comp 2 Y front and rear, adds in additional features. The only connection found between these two principal components in the rear view was a single point indicating the beltline. This point was labeled to facilitate the curve insertion.

Rule 16 (Fig. 21) combines Comp 1 Z from all three views. Here, some curves are shared between views, but the vehicle still seems to be quite disjointed. Rule 17 (Fig. 22) only adds in curves to complete SUV Comp 2 X in the side view: the front of the door and part of the side window.

Rule 18 (Fig. 23) inserts in some additional curves, though the relationship between the front and rear is not easily inferred. The front bumper does show up in both the front and side views. Rule 19 (Fig. 24) inserts the front and rear details from SUV Comp Side X 1 and 3. The rear area accounts for much more the variation between SUVs, but these were joined to be concise.

Rule 20 (Fig. 25) pulls in Comp 3 Z in all three views. There are some similarities between views. After the application of this rule, the vehicle is almost entirely complete.

As with the other vehicle classes, the remaining curves need to be filled in. Rule 23 (Fig. 26) provides the means to

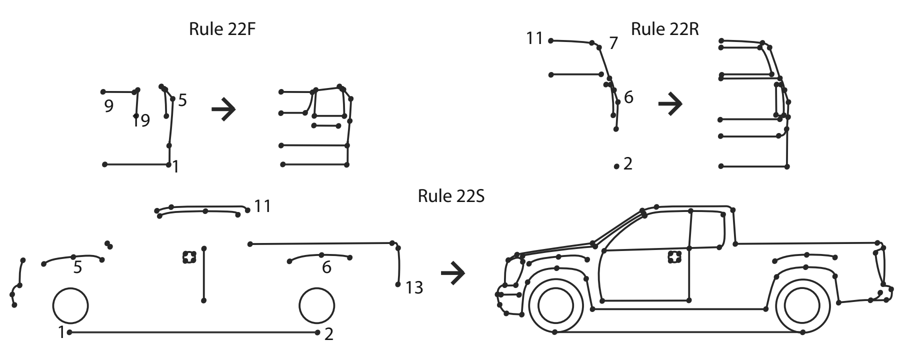


Fig. 18 Rule 22

Fig. 19 Rule 14

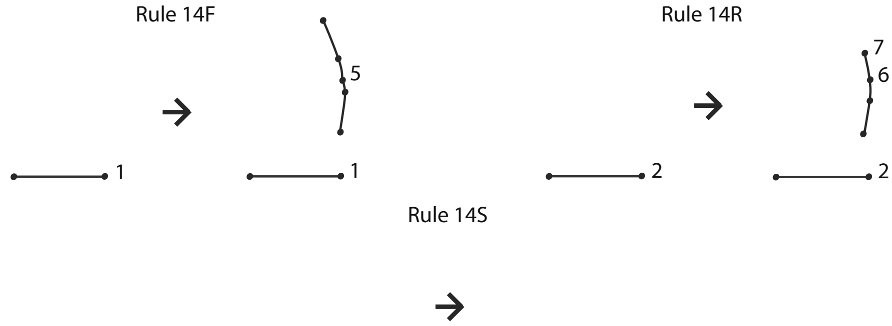


Fig. 20 Rule 15

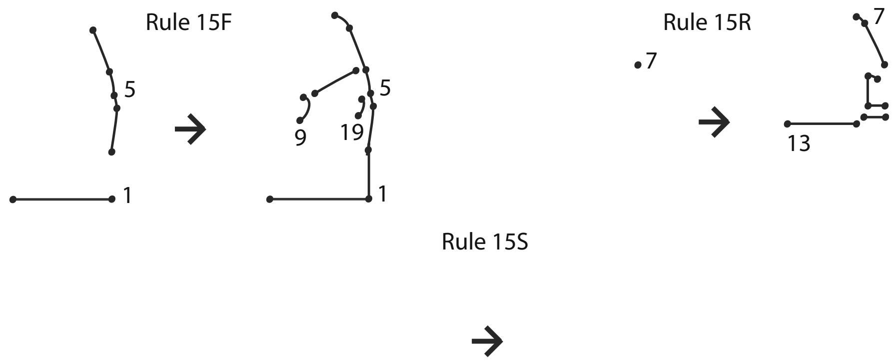


Fig. 21 Rule 16

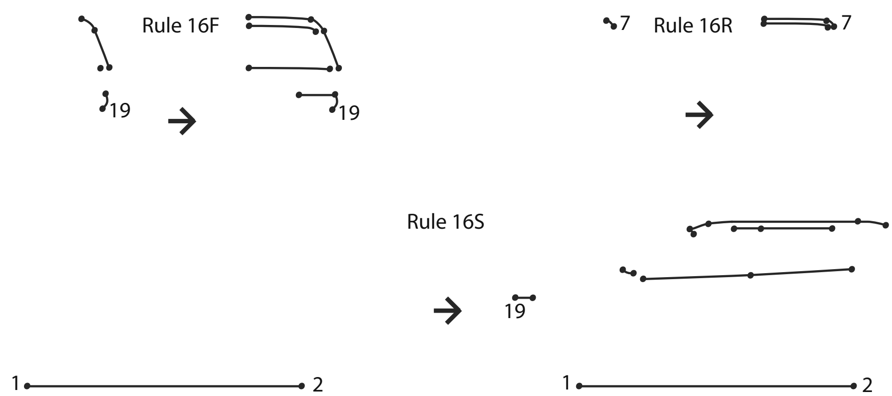
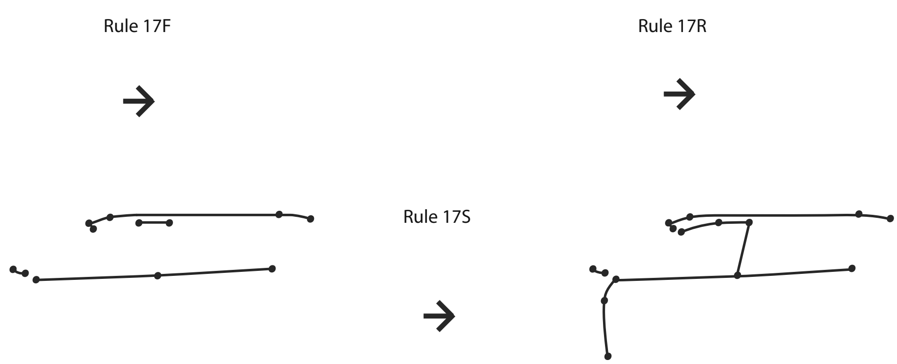


Fig. 22 Rule 17



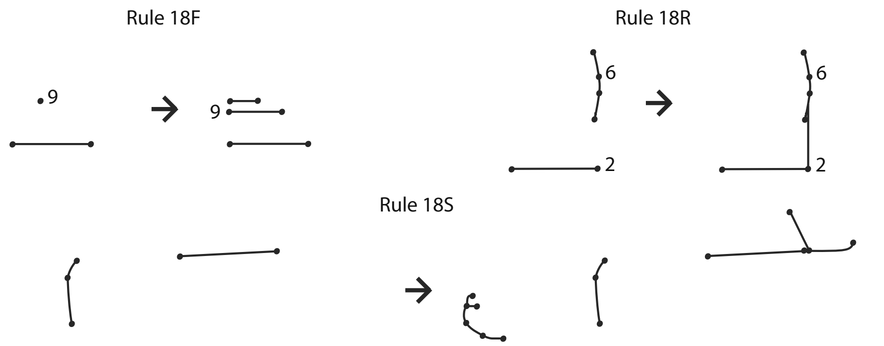


Fig. 23 Rule 18

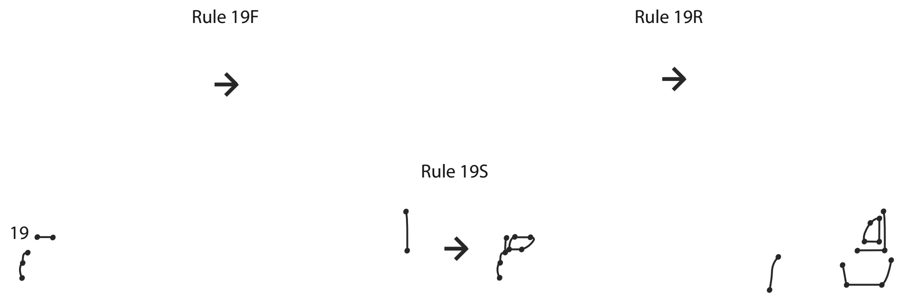


Fig. 24 Rule 19

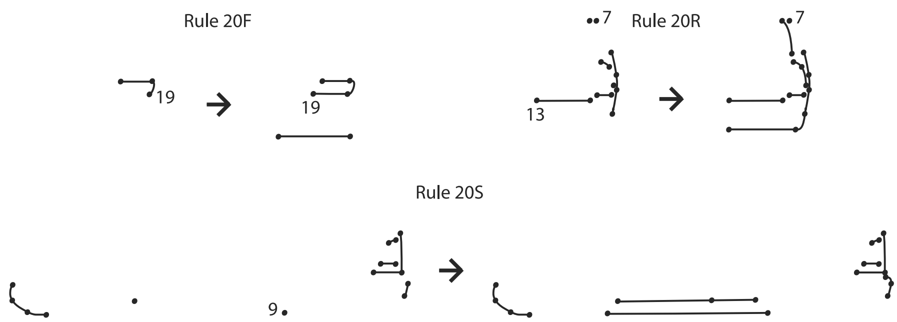


Fig. 25 Rule 20

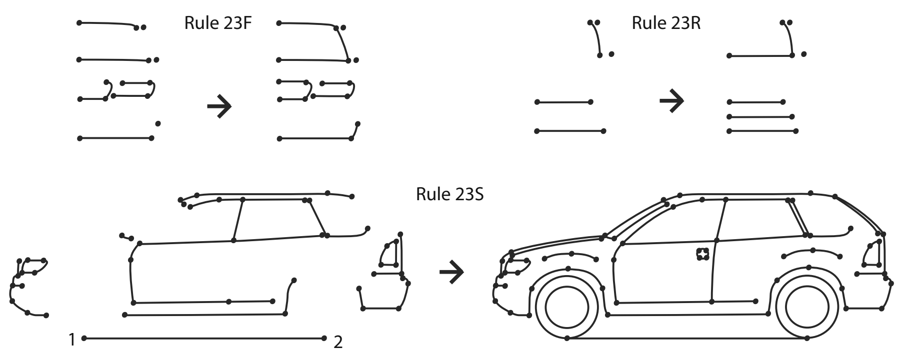


Fig. 26 Rule 23

fill in the rest of the characteristics. The shape modification rules may then be used to parametrically modify the vehicle.

3.4 Modification rules

The shape modification rules (Fig. 27) were first created for the vehicle shape grammar in Orsborn et al. (2006). These rules allow the chunks to be modified and can be applied to any curve in any view, as long as the curve still has its end point markers. There are constraints, in that a curve that exists in more than one view must necessarily have the same vertical dimension. The horizontal dimension in the front (or rear) and side views may not be the same. Rule A takes two curves and divides them into three similar curves. This is commonly used on fenders and wheel wells. Rule B changes two curves to one, or vice

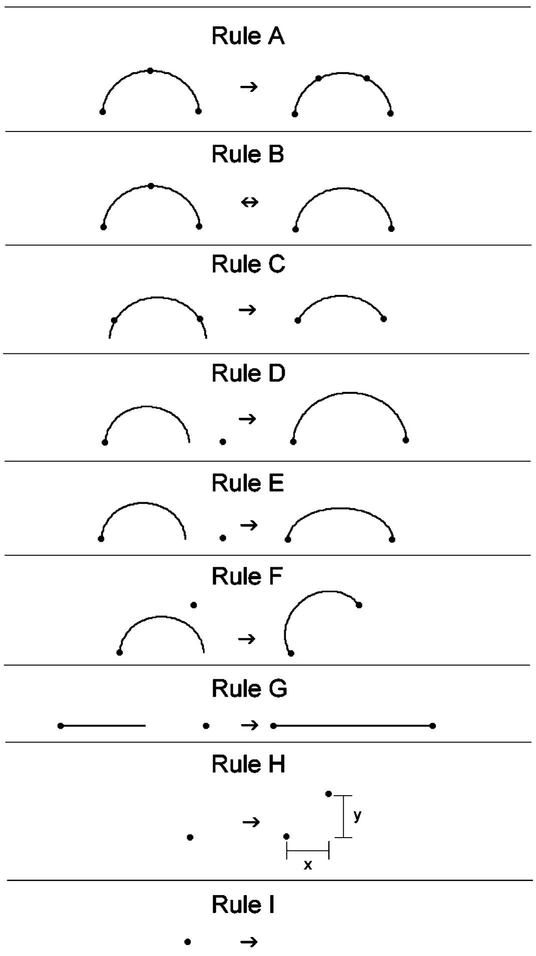


Fig. 27 Shape modification rules

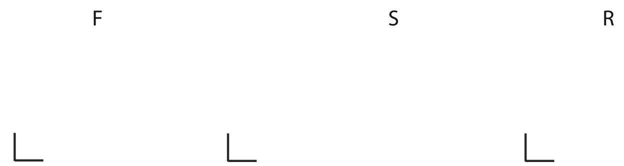


Fig. 28 Coupe build initial shape

versa. Rule C changes the arc through which a curve sweeps. Rule D scales a curve proportionally. Rule E scales a curve non-proportionally and is used quite frequently. Rule F rotates a curve about one end point. Rule G changes the length of a line. Rule H enables a labeled or non-labeled point to be moved. This rule must first be applied to relocate one or more endpoints of a curve before Rules C to G can be applied. This forces attached curves to remain attached at their endpoints throughout curve modifications. Rule H is also useful in the positioning of hoods, headlights and taillights. Rule I is the terminal rule and removes all end points of the curves. Once this rule is applied throughout the vehicle, no more rules can be applied and the vehicle design is completed.

4 Proof of concept

With the establishment of new shape grammar rules, vehicles may now be created. Three novel vehicles (one from each class of rules) will be shown, one of which will be discussed in detail. All three of these vehicles were drawn by hand, following the shape grammar rules. The shape grammar produces vehicles, but due to the chunking of the curves in the rules the design can easily be forced in an unusual direction if desired. It should be noted that if the shape grammar were to be used conservatively, it would produce very traditional looking vehicles, though it would require intention on the part of the designer. Control vehicles from each vehicle class were also derived to confirm the accuracy of the grammar.

Figures 28–41 show the rule-by-rule progression of a coupe build. Four things should be noted. First, each view is indicated by its initial (F = front, S = side, R = rear), just as in the rules. Second, the front and the rear views are symmetric, so only half of the vehicle is constructed. The vehicle will be mirrored for the final design. Third, many curves are initially only seen in one view, though it may finally exist in more than one view. When the curve is added to a view, it will parametrically match its related curve in another view. For example, the bottom of the front bumper is inserted in the front view with Rule 8. It is not inserted in the side view until Rule 9 when the front wheel well is started. These will match, to keep the continuity of the design. Finally, the allowable parametric ranges for the curves are taken from Orsborn et al. (2006). Not all curves fall within these ranges, but a general consistency is kept. If a designer were to completely ignore the allowable parametric ranges derived for the specific vehicle classes, the resulting designs would be much more fanciful.

Figure 28 shows the Initial Shape, a coordinate axis in each view. Figure 29 is the application of Rule 1, which sets the wheel base, the track width, and inserts the ground.

Figure 30 is the application of Rule 2. Since this is a parametric shape grammar, the curves are stretched to interesting positions. This starts a framework for the rest of the vehicle, since each rule follows linearly. Figure 31 is the application of Rule 3. The front and rear views begin to take form, while the general dimensions of the side view are established. At any point, if the designer were not satisfied with the particular positioning of a curve, it could be modified using the shape modification rules. This is not done in this application.

Figure 32 is the application of Rule 4, the finishing of the headlight, the insertion of the wheels, and the insertion of the outside hood curve. This begins to more clearly

Fig. 29 Coupe build Rule 1

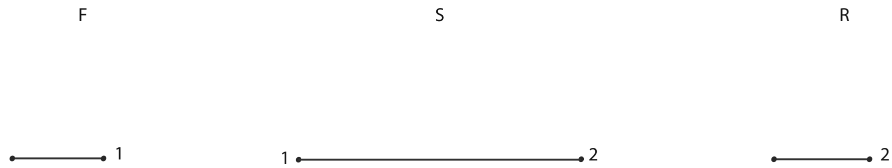


Fig. 30 Coupe build Rule 2

Fig. 31 Coupe build Rule 3

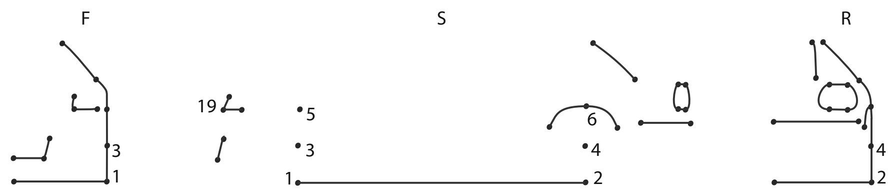


Fig. 32 Coupe build Rule 4

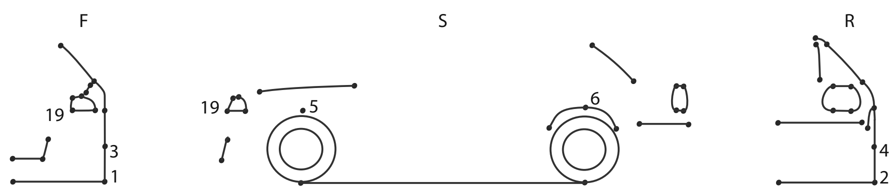


Fig. 33 Coupe build Rule 5

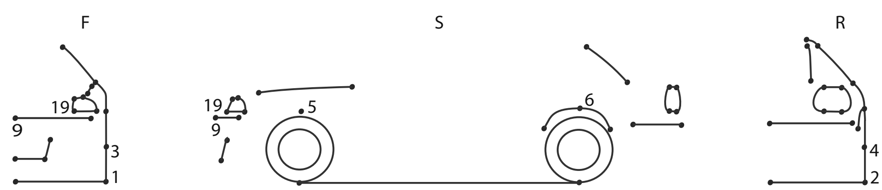


Fig. 34 Coupe build Rule 6

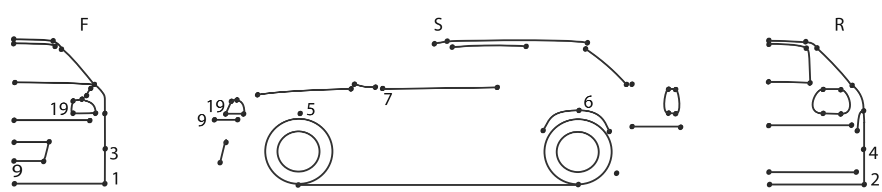
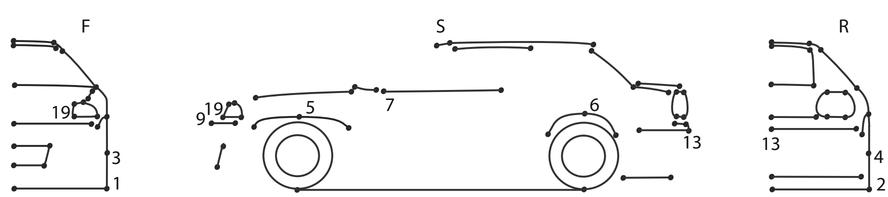


Fig. 35 Coupe build Rule 7



establish where the beltline and the cowl will be. Figure 33 is the application of Rule 5, where the horizontal front bumper line is inserted.

Figure 34 is the application of Rule 6. The greenhouse is more established through the insertion of the roof and part of the belt line. Rule 7 (Fig. 35) inserts the front fender and starts to establish the rear bumper in the side view. Rule 8 (Fig. 36) puts in the front of the door, the trunk, and the rocker, which gives a sense of the final dimensions. From this point on, the rules are just filling in details which the

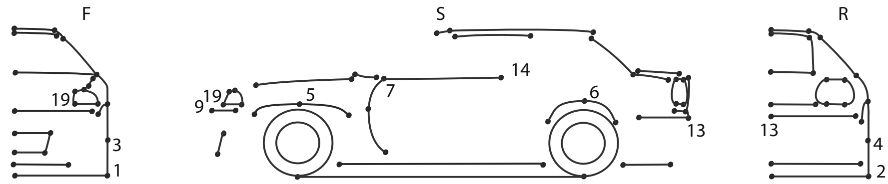


Fig. 36 Coupe build Rule 8

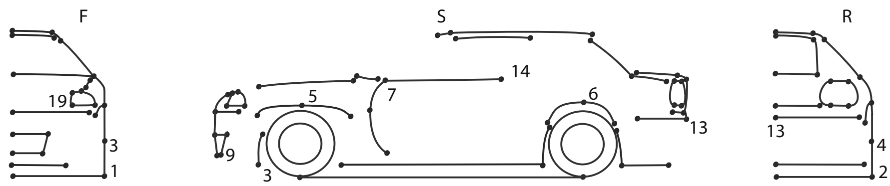


Fig. 37 Coupe build Rule 9

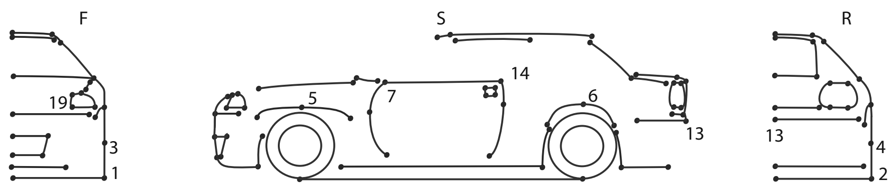


Fig. 38 Coupe build Rule 10

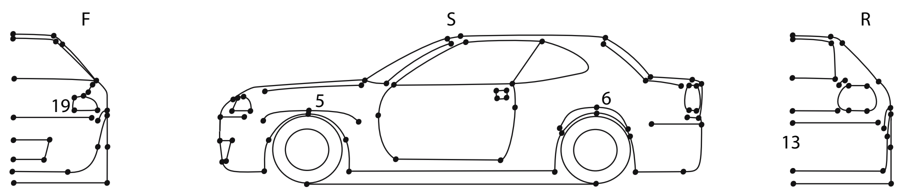


Fig. 39 Coupe build Rule 21

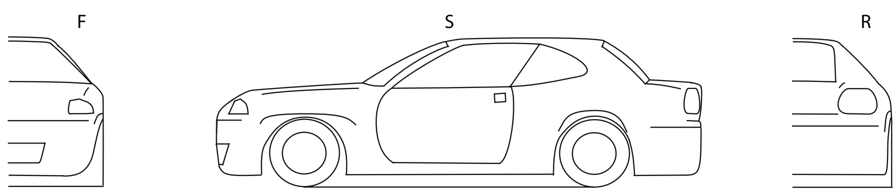


Fig. 40 Coupe build Rule I

principal component analysis has found to be connected. The general form of the vehicle has been established.

Figure 37 (Rule 9) establishes the wheel wells and closes up the nose of the vehicle. Figure 38 is the application of Rule 10, which finishes the bottom of the front bumper and most of the door. Rule 21 is applied in Fig. 39. This is the addition of the curves noted in Table 2 that were not determined to be fundamental by the principal component analysis. There is the opportunity for a little parametric manipulation, especially with the side window. In general, the vehicle is done.

Now that all the principal component analysis rules have been applied, the shape modification rules must be used for any further changes. In this example, only Rule I is applied (Fig. 40) which removes all the markers and remaining labels. Figure 41 shows the final design with the front and rear views mirrored. This unique looking coupe was created not only through the purposefulness of the designer, but through the application of rules that inserted the characteristics in a non-obvious order. By making certain choices early on in the design process, later curve insertions were forced to fill in the spaces, pushing the extents of the design language.

Figure 42 shows the final pickup design after the appropriate rules have been applied and the front and rear views have been mirrored. Because of certain choices early in the rule applications, the vehicle has an unusually large C-pillar, and a very thin A-pillar. Figure 43 shows an SUV final design, after the application of the appropriate rules, then Rule I which removed all the left over markers, and a mirroring of the front and rear views. Here, the vehicle was designed intentionally with stiff geometry, in contrast to

Fig. 41 Coupe build final

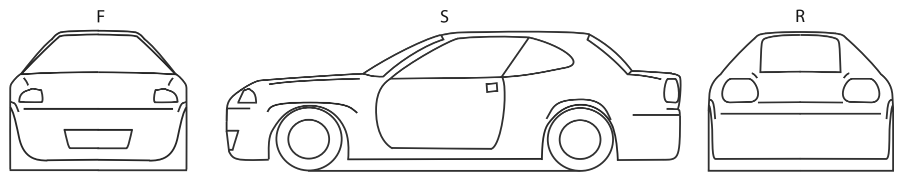


Fig. 42 Pickup build final

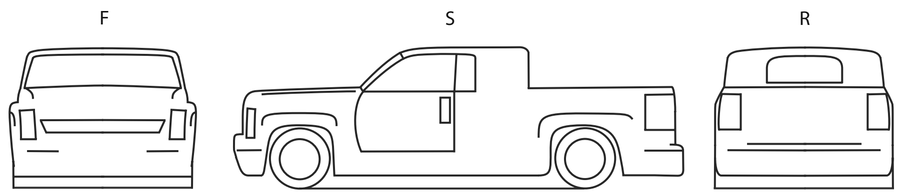
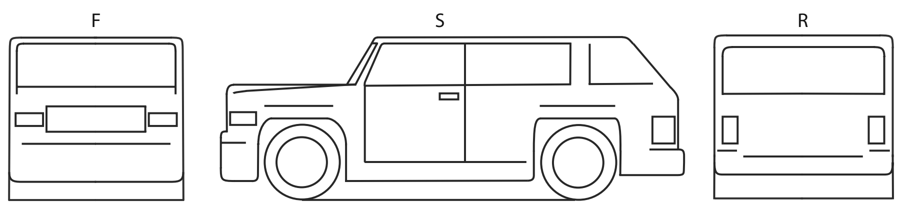


Fig. 43 SUV build final



the many curvy SUV forms that are being introduced in 2007. By making certain curves more linear in the first rule applications, it forced the later rules to fill in spaces with equally linear curves. Again, the final design is a result of early choices by the designer that cause a repercussion as more rules are applied.

5 Two different vehicle shape grammars

The vehicle shape grammar in Orsborn et al. (2006) was created with the intention of creating cross-over vehicles. The rules were written in a way that kept functional characteristics grouped together. This enabled characteristics from different vehicle classes to be inserted into a single vehicle. In general, at least 40 rule applications were required to create a vehicle. Vehicle classes were defined by class specific characteristics (i.e., pickup beds) and allowable parametric ranges for curves that kept them class specific.

The vehicle shape grammar derived in this paper from the results of the principal component analysis combined the representative curves in foundational chunks. This enabled a vehicle to be created with fewer rule applications, but also with less flexibility. The pickup seen in Fig. 42 was created using only six rule applications. The same vehicle created in the original vehicle shape grammar would have taken over 40 rule applications. The limitation of the new shape grammar is that the vehicles are constrained within their class, with respect to the placement of novel features, i.e., a pickup bed cannot be inserted on a coupe. While this result is good for making class specific vehicles, it limits the ability to create vehicles not in either of the three original vehicle classes of coupe, pickup, and SUV. The original vehicle shape grammar can create vehicles of any vehicle class through the combination of the appropriate rules. For example, a hatchback can be created by combining coupe and SUV rules.

The rules in the new shape grammar are also linear in application, i.e., Rule 4 follows Rule 3. In the original vehicle shape grammar, several of the rules could be applied recursively, limited only by the amount of space available between two characteristics. This enabled the insertion of a feature multiple times, like the horizontal line in the front bumper. All the vehicles produced with the principal component analysis shape grammar are limited to the fixed number of characteristics, i.e., one horizontal line in the front bumper. While this removes some of the creative divergence encouraged through the addition of features, the general form of every vehicle within these three vehicle classes can still be captured.

The advantage of the new shape grammar is that implementation is much faster. There are fewer rules to choose from at each step and it takes fewer rules overall to generate a final design. When implemented by hand, as was done for the examples in this work, the time savings is noticed. If implemented computationally for design exploration, the time savings should be substantial. Since design exploration is not encouraged solely upon the rule applications, it is more dependant upon parametric differentiation.

Both shape grammars can take advantage of the parametric ranges defined for these three vehicle classes in Orsborn et al. (2006). The allowable parametric ranges for the curves can still be pushed to the limits, thereby enabling the vehicles to fall outside their strict vehicle class definitions. This was demonstrated in the creation of the coupe which resulted in the vehicle in Fig. 41. Since both shape grammars share the shape modification rules, a designer is not limited to an initial design, but can continue to modify the curves until a desired form is produced. The parametric manipulation of designs, through the shape modification rules, provides the means for the designer to explore the design space and push the designs beyond the traditional parametric ranges.

Both of these shape grammars were derived from the same vehicle sample of coupes, pickups, and SUVs. The original vehicle shape grammar (Orsborn et al. 2006) contained 70 rules which were manually derived from a large vocabulary. The result was a shape grammar that could capture the entire language of automobiles, not just the three vehicle classes from which it was derived. The vehicle shape grammar introduced in this paper consists of 32 rules, a much smaller vocabulary, which were derived from the results of a principal component analysis. The new shape grammar can only create parametrically diverse vehicles from the three sample vehicle classes. Though the new shape grammar is not as robust as the original shape grammar, it is a first step toward the automation of shape grammar creation.

6 Conclusions

Historically, a person had to be trained in how to create shape rules in the most concise way through observation and insight that still captures the minimal vocabulary needed to describe a language thoroughly. By using the results of a principal component analysis, the shape rules can be derived from the curves chunked together in each principal component. These rules are not based upon the insight of a human, but upon the chunks established statistically. In this instance, non-obvious shape rules were created from the results of the principal component analysis of three vehicle classes. Through the application of this principal component analysis shape grammar, three unique vehicles were shown and many more can be created.

In this method we introduced a first step toward an automation of the derivation of shape grammar rules. A sample of the forms of a product class, captured using Bezier curves, can be analyzed using principal component analysis. Shape grammar rules can be created directly from the results of the analysis by sequencing principal components that share curves. These rules, along with a rule that inserts any curves that are not highlighted through the principal component analysis, can be used to create product class specific forms.

Acknowledgments Funding for this research was partially provided by the National Science Foundation under grant DMI-0245218 and by General Motors.

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