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EVALUATING SIMILARITY AND EXPLORING BRANDING IN VEHICLE STYLING USING FOURIER DECOMPOSITION

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1. Introduction

It can be said that, for certain products, appearance plays the primary role in creating appeal for potential consumers [Bloch 1995]. In addition many companies endeavour to develop and maintain an appealing brand as a further point of competition in the marketplace [Karjalainen et al. 2010], [Millman 2011]. Furthermore it is known that product appearance is one of the key mechanisms for communicating brand to potential consumers. Thus it can be said that product appearance or styling is an essential element in successful product design and marketing.

Research into the different features that constitute a product's appearance has shown that often certain features have a particular resonance with consumers in signifying the products origin. In practice designers may repeatedly use such features or 'visual references' to maintain the brand identity of products [Karjalainen 2003]. Thus during the design process there is the need to consider the appearance of such features and reach a compromise between designing products that look suitably novel and different while still maintaining a degree of similarity to previous and familiar products [Millman 2011], [Person et al. 2008]. Currently designers must rely on intuition and experience when faced with such evaluations. Thus assessing appearance with respect to brand can be a difficult and lengthy aspect of the design process which is further compounded by issues of subjectivity and personal bias.

A number of studies have been conducted relating to the relationship between branding and product appearance. Bloch [1995] presents a high level review of consumer response to form and proposes a model for ways in which designers can achieve the ideal appearance including references to brand. Person et al. [2008] discuss the compromises that exist when evaluating styling and proposing styling strategies. They propose approaches to guide decisions depending on type of product and its maturity. Sudjianto and Otto [2001] acknowledge the importance of distinctive branding and appearance with respect to platform sharing. The result of their research is a method to highlight dominant themes in appearance that may then be used to develop modules for product platform sharing while maintaining key distinctiveness. Karjalainen and Warell [2005] present a structured analysis of brand used to design products that maintain core visual elements/similarities that can be applied to signify brand to consumers. Ranscombe et al. [2011] propose a technique to decompose aspects of appearance to explore consumers ability to identify brand based on particular features in appearance. While these studies provide valuable approaches to analyse and inform appearance with respect to branding they are qualitative in nature. This paper attempts to extend previous research in the field to propose quantitative and thus more objective analyses to review branding in appearance by using Fourier decomposition.

Yannou et al. [2008] apply Fourier decomposition to develop algorithms that are used to create possible vehicle silhouette designs. In this paper the aim is to use Fourier decomposition to review

designs rather than create them and do so by assessing similarities in shape. Research led by Ramani [Hou et al. 2008], [Iyer et al. 2005], [Pu et al. 2005, 2006] reports a number of studies that adopt Fourier decomposition to assess similarity for the purpose of retrieving designs based on shape. Hence the research reported in this paper adopts similar techniques to assess similarity and subsequently review feature shapes exploring their similarity with respect to brand.
The paper begins by discussing the choice of vehicles for the product under investigation and the selection of the headlight as the feature to investigate in detail (section 2). Sections 3 and 4 propose the method for modelling headlight shape using Fourier series and the method to assess similarity. Similarities are then discussed with respect to brand and between novel headlight designs in section 5. Conclusions are made in section 6.

2. Subject matter: Vehicle headlights

The products investigated and the choice of features are now discussed, followed by the process used to generate the shapes of individual features that will be modelled and compared.

2.1 Vehicles used

Vehicles have been selected as the subject of this study as they are product often judged based on appearance. Furthermore vehicle manufacturers are some of the most notable brands in the world [Interbrand 2009]. Hence styling design of vehicles is of great significance to both consumers and manufacturers, thus they are an exemplary product type to use for assessment of brand and appearance. The vehicles selected for analysis have been chosen based on a particular brand (BMW) renowned for their distinctive styling [Karjalainen et al. 2010]. A number of competing brands have also been included for the purpose of comparison and exploring brand.

2.2 Features

Of the vehicles investigated, the headlights are the feature chosen for in depth investigation. This feature is selected as the headlights have been shown to be influential in consumer recognition of brand [Ranscombe et al. 2011]. The headlight shape is defined in accordance with the visual decomposition method also proposed by Ranscombe et al. previously used to test the influence of different features on recognition of brand. The method involves tracing the outline of features from high resolution photographs. The features are traced using chains of Bezier curves. Curve data can then be easily exported for further investigation. Figure 1 provides an example of the graphics features investigated and the result of the visual decomposition method.

Figure 1. Illustration of the vehicle photograph used and isolation of the feature to be investigated

3. Representation of curves using Fourier series

Having defined products and features to be investigated, the representation of features as closed planar curves in terms of a Fourier series is now considered. The interest here is in the case when the curve

represents the outer boundary of a feature. However the same approach has been applied to the description of the output paths of planar mechanisms [McGarva et al. 1993], [Singh et al. 2008]. In this latter case, the Fourier approach allows the closed curves to be normalized to remove the effects of translation, rotation and scaling, and hence generate (moderately sized) catalogues of mechanisms together with their output paths. This investigation process is adopted in this study.
The complex plane is used to represent a closed curve. It then takes the following form

$$z(t) = x(t) + iy(t)$$

where i is the square root of -1 and t is a parameter whose variation traces out the curve. It is convenient to assume that this parameter is normalized so that t runs between 0 and 1. In particular, this means that $z(0) = z(1)$.
The usual theory for a complex Fourier series shows that $z(t)$ can be represented as the doubly infinite series of the form

$$z(t) = \sum c_m \exp(2\pi imt)$$

where the dummy variable m passes between $m = -\infty$ and $m = +\infty$. The c_m are the Fourier coefficients which are constant values, normally non-real. These coefficients can be obtained from

$$c_m = \int \exp(-2\pi imt)\, z(t)\, dt$$

where the integral is over a full period, with the parameter going between t=0 and t=1. The zero-th coefficient c_0 is the fundamental, then coefficients c_1 and c_{-1} generate the first harmonic, coefficients c_2 and c_{-2} the second harmonic, and so on.
In use here, the closed curve is not provided as an explicit function. Instead it is obtained (by digitisation) in terms of a number of points around the curve, not necessarily equally spaced. This means that integration needs to be performed by some form of numerical procedure. Suppose there are N points round the curve

$$z_0, z_1, z_2, \ldots, z_{N-1}$$

and that this sequence is regarded as being circular so that z_k is the same as z_{k-N}. It is assumed that the curve follows a straight line (in the complex plane). Then the above Fourier coefficients are given by

$$c_m = \sum I_j$$

where the sum is between $j = 0$ and $j = N$-1, and I_j is the integral between the limits t_j and t_{j+1}. These latter limits are the values of the parameter t at the ends of the line segment (obtained by finding the proportion of the length of the curve to the appropriate point compared to the full length). It is straightforward to evaluate this last integral I_j exactly, assuming that z varies linearly.
The fundamental coefficient is the average position of all the points around the curve. It thus represents the centroid of the curve. Hence $z(t)$ - c_0 is a closed curve whose centroid lies at the origin of the complex plane. This represents the first step in a normalization process.
Now consider the part of the series formed by the first harmonic terms.

$$z_1(t) = c_1 \exp(2\pi it) + c_{-1} \exp(-2\pi it)$$

This can be re-expressed in the form

$$z_1(t) = \exp(i\alpha) [(r_1 + r_{-1})\cos(2\pi t + \beta) + i(r_1 - r_{-1})\sin(2\pi t + \beta)]$$

where

$$r_1 = |c_1|$$

$r_{-1} = |c_{-1}|$

$\alpha = [\arg(c_1) + \arg(c_{-1})]/2$

$\beta = [\arg(c_1) - \arg(c_{-1})]/2$

In the aforementioned expression for $z_1(t)$, the term within the square brackets gives an ellipse. Its centre lies at the origin of the complex plane and the lengths of its semi-major and semi-minor axes are $(r_1 + r_{-1})$ and $(r_1 - r_{-1})$ respectively. Multiplication by the complex exponential $\exp(i\alpha)$ acts to rotate the ellipse through an angle α anticlockwise.
Similar considerations apply also to the higher harmonic. The expression

$$z_m(t) \;=\; c_m \exp(2\pi imt) \;+\; c_{-m} \exp(-2\pi imt)$$

also represents the ellipse (centred at the origin) for the m-th harmonic. The principal difference is that this is traced out m times as the parameter t goes from 0 to 1.

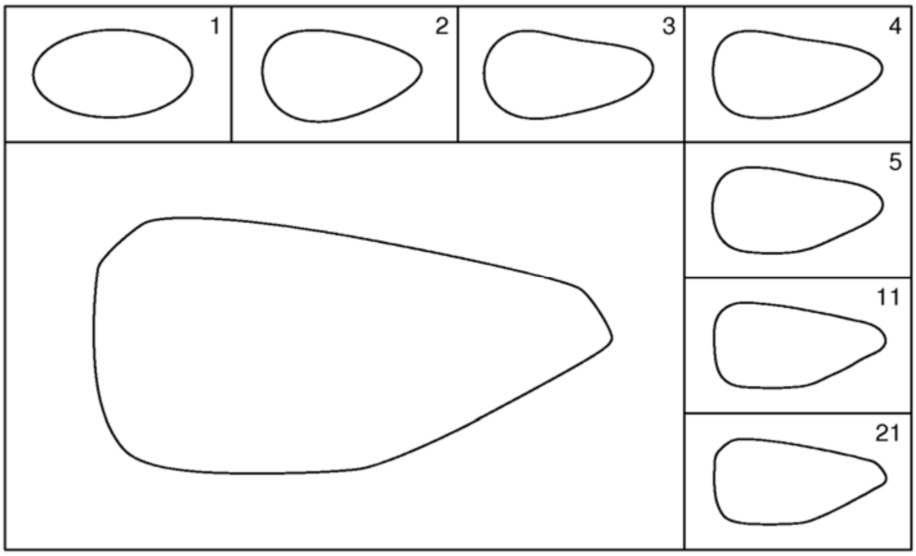

Figure 2. Decomposition of a closed curve

Table 1. Fourier coefficients for closed curve in figure

m	c_m	$\lvert c_m \rvert$
-21	-0.01158 + 0.00621i	0.01314
-11	0.01712 - 0.02887i	0.03356
-5	0.09865 + 0.13265i	0.16531
-4	-0.08979 - 0.23583i	0.25235
-3	-0.51542 + 0.92492i	1.05884
-2	-0.22353 + 0.44446i	0.49750
-1	-12.78437 + 4.67355i	13.61184
0	-42.20281 + 14.18186i	44.52193
1	-3.63522 - 1.50018i	3.93260
2	0.54845 + 0.94395i	1.09171
3	0.10747 - 0.10183i	0.14805
4	0.02722 + 0.34485i	0.34592
5	-0.02939 + 0.00412i	0.02968
11	0.00448 + 0.00212i	0.00496
21	-0.00290 - 0.00277i	0.00401

Figure 2 shows an example of the decomposition of a closed curve representing the outer shape of a car headlight. The main part of the figure is the full curve. The parts numbered 1 to 5 are formed by taking the partial sums of the first through to the fifth harmonics. It is clear that the original curve is increasingly well represented as the number of harmonics increases. Table 1 lists the complex Fourier coefficients of the fundamental and first five harmonics. It also includes the 11^{th} and 21^{st} harmonics which are also shown in Figure 2 as part of the sum of the harmonics up to and including 11^{th} and 21^{st} respectively. It is seen that the values of the moduli of these tend to decrease as for the higher harmonics.

4. Method for exploring similarity

This section discusses the method used to represent a range of shapes and compare their similarities. The first section address the need to normalise the shapes. The second section describes the method used to compare shapes.

4.1 Normalization

One of the main advantages in using Fourier series to model and compare shapes is in the ability to do so outside the context of scale and position. In order to achieve this there is a requirement to normalise shapes such that they may be reliably compared. Naturally, the Fourier coefficients carry significance for the curve shape and it is possible to identify explicitly this significance for the fundamental and the first few harmonics. Thus allowing normalisation to be carried out by removing the effects of translation, rotation and scaling (that is the rigid body transforms) and hence just deal with the curve shape.

As a first stage the fundamental coefficient c_0 simply represents the centroid of the original closed curve. This merely gives the position in the plane where the curve lies and so does not influence the actual shape. Replacing coefficient c_0 by zero retains the shape of the curve and moves the centroid to the origin of the complex plane.

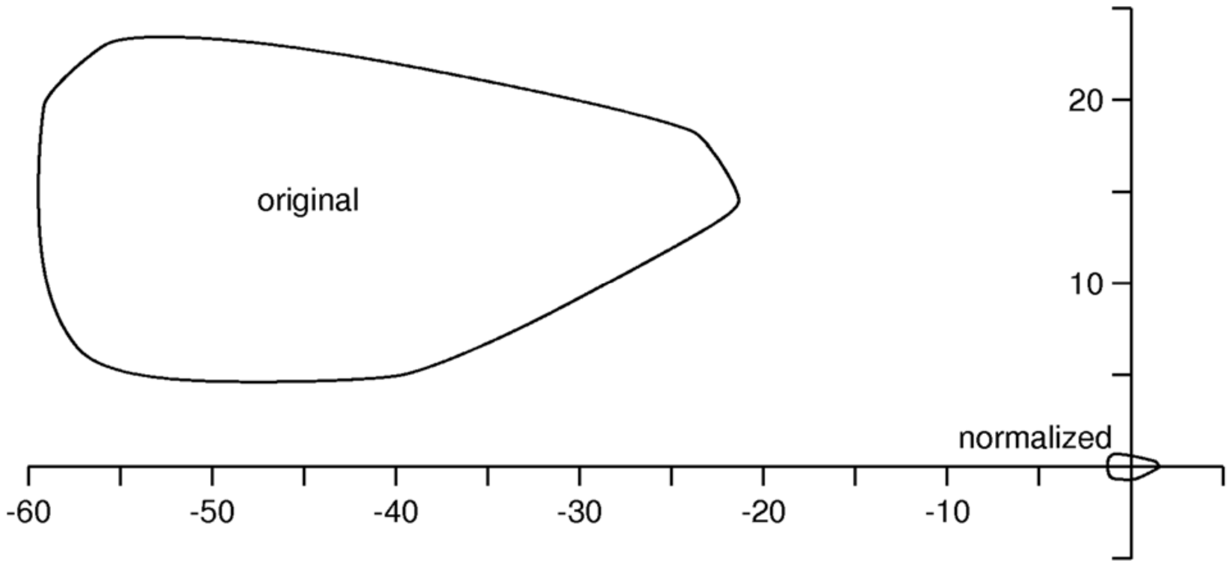

Figure 3. Normalisation of a closed curve

The first harmonic coefficients are c_1 and c_{-1}. Together these correspond to an ellipse in the complex plane with the major axis at angle $\alpha = [\arg(c_1) + \arg(c_{-1})]/2$ to the real axis. If all of the Fourier coefficients are multiplied by $\exp(-i\alpha)$, then the entire closed curve is rotated about the origin. This means that the major axis for the ellipse of the first harmonic is aligned with the real axis. Again this leaves the shape of the curve unchanged but turns its “widest part” in the direction of the real axis.

Of the (revised) coefficients, c_1 and c_{-1}, it can be assumed that c_1 has the larger modulus. If this is not the case, then all pairs of coefficients c_m and c_{-m} are interchanged. This has the same effect as changing the sign of the parameter t and hence does not alter the shape of the curve that is traced out.

The next stage in the normalization is to divide all the Fourier coefficients by $|c_1|$. This acts as a scaling factor on the entire curve and so does not change its shape, only its overall size. The resultant value of $|c_{-1}|$ is then a measure of how close to a circle the curve is: the smaller its value, the more circular the curve.

The combination of the first harmonic terms now takes the form $\exp(i\beta)$ and $|c_{-1}|\exp(-i\beta)$. The effect of changing the parameter t to $(t + \beta/2\pi)$ is the same as multiplying each coefficient c_m by $\exp(-im\beta)$. Once again, this parameter change does not affect the curve shape. It allows the coefficients c_1 and c_{-1} to both be taken as real, with the former equal to unity.

Thus normalization can be undertaken which eliminates the effects of:

- position of the curve in the plane
- rotation of the curve about its centroid
- direction in which the curve is traced out
- curve size
- starting point for tracing out the curve

Of these points, only the first, second and fourth relate to the actual geometry. The other two only relate to changes in the parameterisation. Figure 4 shows the effect of normalising an example curve.

4.2 Comparing shapes

Having defined the method for representing and normalising shapes, this section considers the use of the normalized Fourier coefficients as a means for assessing the degree of similarity between two shapes (represented as close curves). Suppose there are two curves C_i and C_j whose normalized Fourier coefficients are $c_m^{(i)}$ and $c_m^{(j)}$ respectively. Define the "distance" between the curve as the following expression

$$d(C_i, C_j) = \sqrt{[\Sigma \, | c_m^{(i)} - c_m^{(j)} |^2]}$$

where the sum takes m over a range of values (possibly infinite). Since the moduli of the coefficients is taken, this range can be restricted and for the examples used here m is taken to run between -32 and +32. (Note that this "distance" is not a metric in the usual sense: the distance between a curve and itself is zero, and the distance is symmetric, but it does not satisfy triangle inequality.) The distance can be used as a measure to assess whether two shapes are similar: the smaller their distance apart, the more similar they are.

5. Results and discussion

Results from modelling headlight shapes using Fourier series and comparing similarity of shapes are now discussed. Figure 4 and Figure 5 show the BMW range headlights and those from competing brands and novel concepts for headlights respectively.

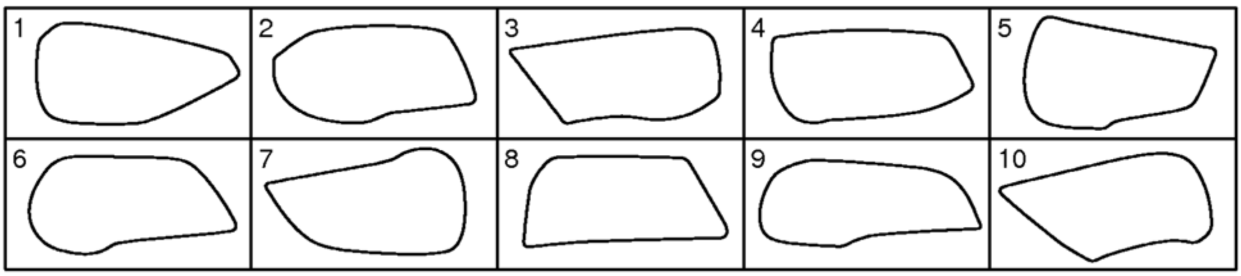

Figure 4. BMW headlights modelled using Fourier series and normalised

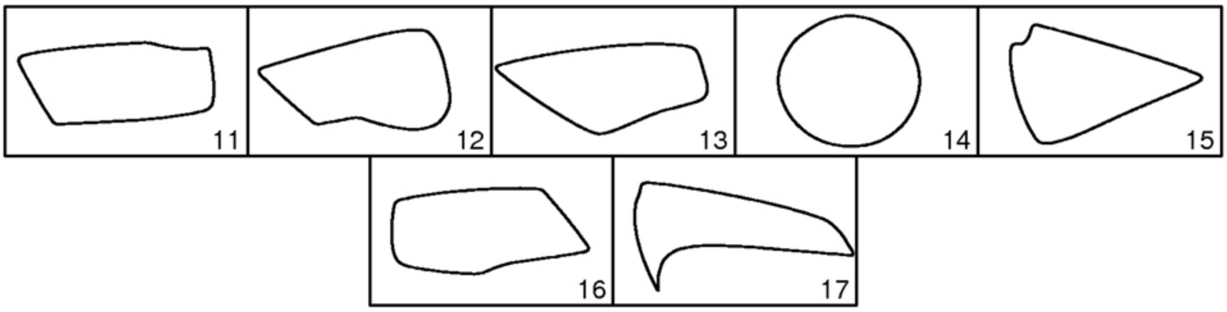

Figure 5. Headlights from competing brands (11-15) and novel concepts (16-17) modelled using Fourier series and normalised

5.1 Similarities within the BMW range

The distances between all pairs of these ten shapes have been evaluated and are shown in the main part of Table 2.

Table 2. "Distances" between normalized headlight shapes

	1	2	3	4	5	6	7	8	9	10	av
1	0.000	0.116	0.157	0.083	0.068	0.112	0.193	0.149	0.143	0.175	0.095
2	0.116	0.000	0.116	0.064	0.127	0.061	0.127	0.091	0.119	0.101	0.041
3	0.157	0.116	0.000	0.096	0.168	0.153	0.083	0.174	0.167	0.078	0.093
4	0.083	0.064	0.096	0.000	0.105	0.079	0.133	0.111	0.118	0.119	0.035
5	0.068	0.127	0.168	0.105	0.000	0.133	0.191	0.164	0.181	0.185	0.112
6	0.112	0.061	0.153	0.079	0.133	0.000	0.177	0.067	0.089	0.151	0.068
7	0.193	0.127	0.083	0.133	0.191	0.177	0.000	0.185	0.208	0.079	0.121
8	0.149	0.091	0.174	0.111	0.164	0.067	0.185	0.000	0.105	0.172	0.098
9	0.143	0.119	0.167	0.118	0.181	0.089	0.208	0.105	0.000	0.173	0.108
10	0.175	0.101	0.078	0.119	0.185	0.151	0.079	0.172	0.173	0.000	0.100
av	0.095	0.041	0.093	0.035	0.112	0.068	0.121	0.098	0.108	0.100	0.000

Table 2 shows that the shapes are all within 0.2 units of each other. In order to compare each shape with a "typical" headlight (from this class of shapes), the average of the Fourier coefficients for each harmonic m is formed. This represents an average of the ten shapes. The distances of each of the ten original shapes from the average is shown in the last row and last column of Table 1. This shows that all ten are within 0.11 units of the average, in turn giving a numerical value for the distance range of the BMW headlights.

With respect to similarities within the range this shows that no two headlights are more similar than the rest. The highest similarity is 0.061 between 2 and 6 which is unsurprising as they are both most similar to the mean.

The headlights which differ the most from the average and also from most of the other shapes are 5 and 9. These are some of the larger vehicles in the range (an SUV and saloon GT) suggesting that these larger vehicles have a more distinctly styled headlight. It should also be noted that these two headlights also differ dramatically from one another too.

5.2 Similarities with respect to the competition

The ten headlight shapes considered so far all come from a range of cars produced by the same brand. Now consider the seven additional designs shown in Figure 5. Of these, the first five are from current production vehicles; the last two are new concepts.

Table 3. “Distances” between new shapes and average of original shapes

	av	11	12	13	14	15	16	17
av	0.000	0.072	0.120	0.130	0.285	0.167	0.063	0.290
11	0.072	0.000	0.127	0.104	0.328	0.192	0.105	0.293
12	0.120	0.127	0.000	0.150	0.285	0.268	0.157	0.370
13	0.130	0.104	0.150	0.000	0.357	0.235	0.148	0.340
14	0.285	0.328	0.285	0.357	0.000	0.298	0.320	0.521
15	0.167	0.192	0.268	0.235	0.298	0.000	0.180	0.312
16	0.063	0.105	0.157	0.148	0.320	0.180	0.000	0.264
17	0.290	0.293	0.370	0.340	0.521	0.312	0.264	0.000

Table 3 shows the comparisons between the competing brands headlights (11-15) and the novel concepts (16 and 17). These comparisons suggest that the three shapes from existing cars (shapes 13, 14, 15) are significantly different from the original ten. Headlights 11 and 12 are within a similar ‘distance to the BMW average as other BMW headlights. In consideration of the brand of the headlights it should be noted that the more similar shaped headlights (11 and 12) are from Audi and Mercedes Benz vehicles, both of which are direct competitors to BMW. The headlights which differ more are from Ford, Porsche and Toyota models which are not direct competitors.

Of the new concepts, the first was designed with the intention of being more ‘conservative’ in order to fit within the current BMW range while the second concept is more far reaching. This is reflected in the distance from the BMW mean where it can be seen that the 1st concept (16) is particularly close to the average (Table 2) while the 2nd concept (17) is clearly very different.

6. Conclusions

A study was conducted to investigate similarities in vehicle styling and explore brand. This was achieved by creating a method to model the outline of vehicle headlights using Fourier series which also involved normalisation of curves. This then facilitated comparison of models and calculation of the similarity of the shape of features. Comparisons were then further explored by investigating the similarities within the BMW brand as well as those between BMW and competing brands. Finally the potential of the method as a design support tool was demonstrated using two novel concepts assessed for their similarity with respect to the current BMW range.

From the results it is possible draw a number of conclusions on the use of the method and the relationship between shape and brand. When looking at results for the BMW range it is possible to see a high level of similarity (low difference from the average) suggesting that all of the BMW headlights investigated are similarly distinctive. Headlights demonstrated as being the most different are those of the X5 and GT 5 Series, both distinctly larger vehicles. Thus it is contended that due to the nature of these vehicles a slightly different shape/aesthetic is adopted to that of the saloon cars.

With respect to the competing brands it can be seen that direct competitors have the same degree of similarity to the BMW average as the BMW vehicles. Thus, it is contended that within this part of the market the headlight design is quite similar, while other brands not in such direct competition are more distinct, in particular the Porsche.

Considering the brands with respect to the BMW design strategy, the study shows that the BMW headlights are relatively indistinct from direct competitors, and thus not the major signifier of the BMW brand. Indistinctiveness from direct competition suggests that the BMW headlight shapes subscribe to an ‘archetypal’ form for their part of the market. In terms of possible design strategy this presents an opportunity to become more distinctive using a differing design, or alternatively the range could be made more similar and coherent. These strategies are represented in part by the novel concepts. Concept 1 in effect represents a proposal that tends to the BMW average while concept 2 represents an example of a distinctive shape.

In terms of the use of Fourier series in investigating similarity, results show that it can successfully be used to objectively show similarities and differences between shapes. While the objectivity of the method is one of the main advantages of this approach it is noted that it does remove features from their context within the overall product ‘aesthetic’ or ‘gestalt’. Thus it is concluded that, while objective insights are valuable, they are best used in consideration of other features and the product as a whole. Further work would likely include the development of the method proposed to consider complete appearance as well as features in isolation.

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