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AESTHETIC-AERODYNAMIC DESIGN OPTIMIZATION OF A CAR GRILLE PROFILE WHILE PRESERVING BRAND IDENTITY

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ABSTRACT
The purpose of this study is to investigate how to combine the aesthetic quality with the engineering functionality in a design project while preserving the brand identity. It is aimed to develop a framework for decision making in the design of a specific product that can be used by designers simply and efficiently. The car front grille design is presented as the case study and the aerodynamic drag minimization is chosen as the functionality criterion of the design. A specific brand is selected to study its identity and a specific product associated with this brand is chosen to implement the approach. Finally, a framework is presented in the form of a table and a utility function which can be used to optimize the grille profile of the chosen vehicle multi-objectively.

Keywords: Aesthetics, brand identity, aerodynamic drag minimization, multi-objective optimization

1 INTRODUCTION
Market research has proved that aesthetic quality can function as a key success factor in a competitive market. Therefore, there have been many attempts by industrial and engineering designers to formulate and incorporate aesthetic intentions into their products in various industries. The other important aspect of the appearance of a product is the brand identity. Strong brands use certain design attributes or features in their products to differentiate them in the market place and also make them consistent with each other. Maintaining and promoting the brand identity is a crucial task for brand strategists [1].

1.1 Aesthetics
By definition, aesthetics, which has roots in the Greek word "aisthetika" or "aesthesis" [2, 3], is the study of the influence of a physical configuration or composition on the human sensation [4, 5]. With this definition, aesthetics covers not only the study of the visual characteristics of an object, but also the investigation of any of its aspects that can be perceived by the human senses [2]. However, in product design, the aesthetic studies are mostly focused on the visual attributes of the products.
The role and significance of aesthetics in several fields of product design have been investigated by various researchers. By the enhancement and standardization of the functionality of most products as a result of technological advances, manufacturers attempt to differentiate their products through distinctively eye-catching designs. Furthermore, as the manufacturing technologies develop, more sophisticated and exotic forms become manufacturable, and the aesthetic evaluation and improvement become more significant [6, 7].
In spite of the importance of the aesthetic aspects in the product design and development, the process of integration of aesthetic factors to the products has not been methodical sufficiently [8]. Aesthetics has been disregarded as a significant part of the systematic design research in many cases and mostly it has been based on the intuition and presumptions of the designers [7]. The major difficulty in incorporating the aesthetic judgments into the design process is the subjectivity of this discipline [8]. While various methods and tools enable researchers to quantify the various aspects of functionality of the products and also evaluate the associated human factors concerns such as safety, user friendliness and comfort, it is relatively difficult to quantify the aesthetic attributes of them [7].
Although the aesthetic quality is an issue in the design of any product, the degree of importance of visual attractiveness differs from one industry to another. Furthermore, it is highly dependent on the

characteristics of the target market. Many scholars have investigated the role and importance of aesthetics in the various industries. MacLennan [9] studied the significance of aesthetics in software engineering and proposed methods to promote and educate the aesthetic aspects of the software. Thorlacius [10], Tractinsky et al. [11] and Stenalt et al. [12] investigated the role of aesthetics in web design. Gauvreau [13] focused on the bridge design aesthetics with a case study approach. In the distinctive study undertaken by Bushnell [14], he examined the aesthetic dimensions of design of aerospace vehicles. According to his work, due to huge costs involved in any changes to the external configuration of the large civil aircraft, these vehicles are only styled by colour schemes and logos. Nevertheless, for the private aircraft market the situation is quite different, and customers are sensitive to the appearance of the aircraft. An interesting case was the general aviation aircraft Beechcraft Bonanza. The manufacturer company produced two versions of this aircraft which were different in the tail configuration. One of them had a conventional straight tail (T-tail), while the other one had a V-tail configuration. Despite the V-tail version having more fatal in-flight accidents than the other one, it was much more popular in the market [14, 15]. It has been said that the V-tail Bonanza was the most popular airplane in the world in its class [15], described as the "hottest airplane on the market [14]", as a consequence of its highly distinctive and striking styling at that time.

Among the various branches of industrial design, the automotive industry has been the most important field for research in aesthetics. Styling is described as "the over-riding issue in the automotive world [14]". Furthermore, the streamlining trend of vehicles, and specifically automobiles, has affected the design style of many products, even those that may not be designed for motion at all [16]. For these reasons, most research on product aesthetics has previously been focused on the automotive design industry.

1.2 Brand identity

Neumeier [17] defines a brand as "a person's gut feeling about a product, service or organization". By definition, the brand identity is the set of associations with the brand that should be preserved in the design of any product associated with that brand [1, 18]. Strong brands usually use certain design features in their products to make them recognisable in the market place from the products of other competitors and also to make them consistent with each other. Companies make effort to design products which are not only aesthetically attractive, but also hold distinguishing references to the character of the brand [19].

Although there are many factors that affect the identity of a brand, the visual characteristic of products associated with the brand are the crucial factors that affect the initial perception and judgement of the customer [1, 19]. Therefore, designing products with consistent visual attributes is critical to product design. 'Brand DNA' determines the visual elements that convey the brand identity of a product [6].

Most of the recent work on the brand identity in product design has been based on shape grammars [1, 20, and 21]. Karjalainen [19] studied the brand identity by introducing a semantic transformation from characteristics of the brand and a semantic attribution from user perception to design features. He presented a number of methods to evaluate the consistency of a product with the brand character.

2 CAR GRILLE DESIGN

From the industrial design standpoint, the grille is one of the most distinctive components of the body of a car which represents the brand of the vehicle. For this reason, grille is sometimes called the "brand identifier" of an automobile [22]. On the other hand, as a major functional part of an automobile exterior, the radiator grille should be designed watchfully to satisfy the aerodynamic, heat exchange and under-bonnet protection requirements as well as aesthetic and stylistic necessities. Therefore, it is a crucial design challenge in automotive design process to optimize the air inlet design multi-objectively.

From an engineering point of view, the front grille must guide the appropriate amount of air to the under-bonnet compartments to provide the engine with the necessary heat exchange. It is seen that in many vehicles the decorative grille design reduces the engineering functionality of the cooling system by causing 'stagnation pressure' loss, which is the representative of enthalpy [23].

2.1 Structure & Engineering Functionality

In automotive design, grilles are designed to achieve three major goals [24]:

1. To allow air to enter the under-bonnet systems for heat exchange;

2. To protect radiator and engine compartments against entrance of water, dust, debris and other external objects;
3. To represent the visual characteristics of the brand and improve the facial aesthetics of the vehicle.

Furthermore, cooling drag minimization is a major concern that should be examined thoroughly before design finalization and is the focus of this study. It should be noted since the front bumper is usually placed in line with the radiator, the intake splits into two upper and lower parts [23]. In this work, only the upper air inlet is considered as the "grille".

To investigate the influence of each of the above goals in grille design, it is necessary to look into the structure of the grille of a typical passenger car. Design of a grille for a specific car consists of designing the following features, as shown in Figure 1:

1. Grille profile or the shape of the grille frame;
2. Geometrical characteristics of the grille bars (grille bar pattern);
3. Geometrical characteristics of the background gridlines or "grille mesh" (not easily observable in many vehicles nowadays);
4. The suitable space for emblem installation (for vehicles with the emblem on the grille).

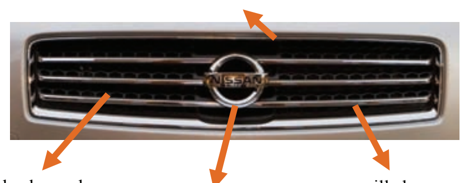


Figure 1. Components of a typical car grille

The design of each of the mentioned features can be investigated and modified separately to meet specific functionality or styling requirements. For example, grille mesh and bars are usually designed to make the flow satisfactorily turbulent to increase the time that the air particles are in the vicinity of the radiator, and consequently increase the quantity of dissipated heat [25]. As another instance, most older vehicles had sharp-edged intake apertures which resulted in separation of the flow from the edges and hence losses of stagnation pressure. Today, grilles are designed in such a way to not have any sharp edges and keep the flow attached as long as possible [23].

Among all the features highlighted, the frame shape or profile is the most distinctive characteristic for styling purposes. Also since this element directly determines the air flow inlet area, this case study will focus on the design of this feature.

2.2 Aerodynamic drag

From a styling viewpoint, all the various characteristics of the grille frame of a car, including the geometrical shape, bounded area, colour and material are important. However, from an aerodynamic standpoint, the bounded area is the dominant variable, since its variation changes the flow rate directly. As a result, the main task in the study of the aerodynamic considerations in the design of an inlet for an engine cooling system is to investigate the effects of the inlet area on the engineering performance. Although each of the three other features i.e. the grille bars, background mesh and even emblem affects the flow pattern, the frame shape has the most significant effect and consequently is the primary factor to study and optimize.

Older domestic vehicles used 'unducted' or 'free-flying [23]' cooling systems, while most cars now have 'partly-ducted' or 'intake-ducted' arrangements. A ducted system prevents 'flow spillage' around the radiator. 'Fully ducted' cooling systems are used only on race cars [23, 26].

The effect of inlet and outlet area sizes on the engine cooling and overall aerodynamic drag of road vehicles has been investigated by various researchers using analytical, numerical and experimental methods and tools. Soja and Wiedemann [27] investigated the drag due to the cooling flow using the conversation laws for mass, momentum and energy. Barnard [26] studied the sizing and location of

inlet and outlet openings both analytically and experimentally. Using linear momentum balance for steady flow, he showed theoretically that the inlet area is not a significant factor in the cooling drag formation, confirmed by wind tunnel tests. Although the induced drag (due to vortices) was not considered in this method, it is still a useful technique to find the qualitative contribution of each design parameter to the cooling air drag.
In the following section, based on Barnard's work on the cooling drag [26], the linear momentum balance is used to find the factors affecting the performance of the intake. Subsequently, some discussion and critics on the previous works are given. Finally, a decision is made on how to optimize the inlet area aerodynamically for a typical domestic car as a part of multi-objective optimization.

2.2.1 Analytical Aerodynamics of a Typical Cooling System

A typical ducted cooling system of a commercial car with the outlet on the bonnet is depicted in Figure 2. Assuming the vehicle is cruising at the velocity V_∞, where the ambient pressure is P_∞, the outlet and inlet apertures are planar and unique and the velocity and pressure distributions on them are uniform [28], a control volume is then chosen which begins in free stream conditions far in front of the vehicle and ends at the outlet surface. The general linear momentum balance equation can be expressed in the following form [29]:

$$\frac{\partial}{\partial t}\iiint_{V} \rho \boldsymbol{V} d\mathcal{V} + \iint_{S} (\rho \boldsymbol{V}.\boldsymbol{dA})\boldsymbol{V} = -\iint_{S} p\boldsymbol{dS} \tag{1}$$

In the above equation, ρ, $\mathbf{V}$, $\mathcal{V}$, S, $\mathbf{A}$ and p represent density, velocity vector, volume, surface, area vector and pressure, respectively. From Eq. (1), it is possible to find the drag force due to cooling system as a function of physical and geometrical variables. For cruise condition, the flow is steady and as a consequent the first term is zero. By taking the x component of Eq. (1) and assuming that the flow is incompressible, the drag force due to cooling system can be written as [26, 27]:

$$D_c = \dot{m}(V_\infty - V_O \cos\theta_O) - A_O(P_O - P_\infty)\cos\theta_O \tag{2}$$

In this equation D_c is the drag force due to cooling system, $\dot{m}$ is the mass flow rate through the duct, P_∞ and V_∞ are the free stream flow pressure and velocity respectively, P_O and V_O are the flow speed and pressure at the outlet respectively, A_O is the outlet area and θ_O is the acute angle between the horizontal axis shown in Figure 2 and the outlet surface. Applying the continuity equation ($\rho VA = const.$) to the duct between the radiator and the outlet surface, the air speed at the outlet can be expressed as:

$$V_O = (A_c/A_O)V_c \tag{3}$$

Where V_c is the air approach speed to the radiator core and A_c is the radiator core area. Barnard non-dimensionalized Eq. (2) by the free stream dynamic pressure ($\frac{1}{2}\rho V_\infty^2$) and the frontal area of the vehicle A_f, and obtained the following equation for the drag due to cooling coefficient [26]:

$$C_{DC} = 2\frac{V_c}{V_\infty}\frac{A_c}{A_f}\left(1 - \frac{A_c}{A_O}\frac{V_c}{V_\infty}\cos\theta_O\right) - C_{pO}\frac{A_O}{A_f}\cos\theta_O \tag{4}$$

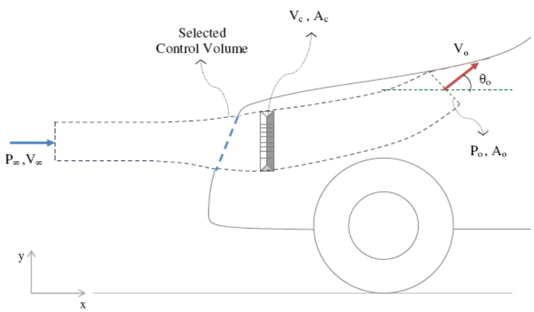


Figure 2. A typical ducted cooling system with the outlet on the bonnet (reproduced from Soja and Wiedemann [27])

As the above equation shows, the inlet area does not affect the drag due to cooling system theoretically. Barnard wind tunnel experiments confirmed this analytical conclusion. Nevertheless, the inlet area has an indirect influence on the aerodynamic efficiency of the cooling system. As depicted in Figure 3, in a subsonic diffuser, increasing the divergence angle has a limit. In the inclination angles larger than the limit value, due to adverse pressure gradient and consequently the tendency of air flow to separate from the walls and move in the backward direction, the diffusion efficiency decreases [26, 30].

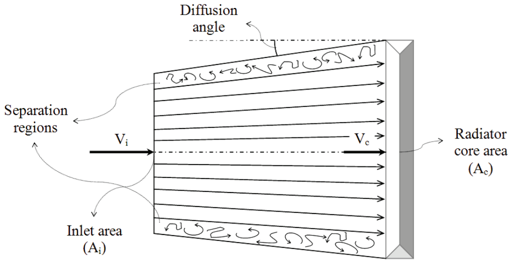


Figure 3. Divergent duct between the inlet aperture and the radiator core

From the analysis, it is evident that a larger inlet area would allow us to decelerate the flow more gradually and prevent probable separation from the walls of the duct. In other words, it is possible to avoid the reverse flow due to the adverse pressure gradient by increasing the inlet area [26].

2.2.2 Results

It can be concluded that although the inlet area is not important theoretically in an ideal diffusion duct of a typical cooling system, it is beneficial to choose a large inlet area to reduce the probability of separation. On the other hand, a large inlet area increases the air flow rate which obviously improves the cooling process. As a consequence, maximizing the inlet area for a domestic car with a ducted cooling system is advantageous from the standpoint of engineering functionality.

In the current automotive design trend, stylists tend to design front-ends for cars with small inlet areas [26]. This tendency is in contrast with the aerodynamic drag optimization criteria. Hence, it is a challenge to maximize the intake area while preserving the aesthetic quality and the brand identity.

3 CASE STUDY: A SPECIFIC BRAND

Among several automotive companies around the world, some of them have had more well-defined and enduring brand visual characteristics during different decades which have had diverse design trends. For this study, the brand Mercedes-Benz, one of the most successful brands in preserving and improving these characteristics, was chosen to investigate the grille design case. After a historical investigation on the various products of this company to capture the common design specifications of the grilles, a particular product of a specific class and model year was chosen to carry out a multi-objective design study.

3.1 Historical Investigations and Development of a Model

To find the design cues of the Mercedes grilles, a range of different models from 1930 to 2008 were investigated and their grille profiles were modelled using the design and drafting package AutoCAD, and the major dimensions were measured. Since the core visual attributes of a strong brand should be found in any of its designs, the vehicles were chosen from different classes: from urban sedans and SUVs to sports cars and from delivery vans to troop carriers. Finally, a general pentagonal model for the Mercedes grille profile was developed by fitting them in the suitable polygons. This pentagonal profile can be altered to produce all the investigated grille profiles with a good approximation. This profile is depicted in the left side of Figure 4. This profile model represents the inner borders of the grille frame, where the flow passes through. It should be mentioned that in some models of Mercedes, the grille profile has a considerable curvature or angle in the upper border, but in most cases it is negligible compared with the inclinations of the side and lower borders and can be approximated by a straight line.

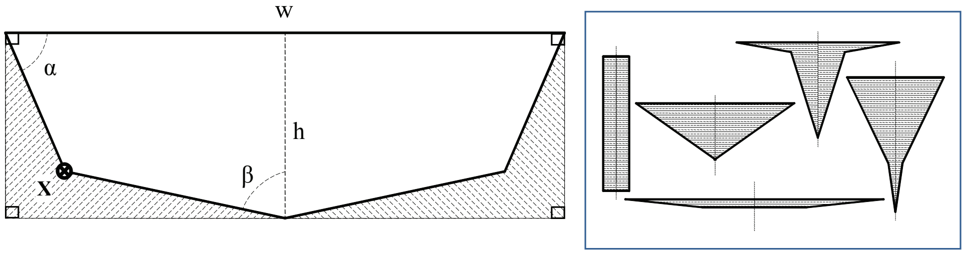


Figure 4. Left: a general model for Mercedes front grille; right: a number of inconsistent profiles generated by the model

In Figure 4, the point X is the “floating point” the location of which determines the values of angles α and β. In other words, for a predetermined aspect ratio (w/h), the grille profile will be determined by placing the point X in the left rectangle.

Although this profile model for Mercedes grilles is sufficiently inclusive to be used to generate most designs of the company from 1930 to date, it can determine many profiles which are completely inconsistent with the other products of the brand. A number of inconsistent profiles are shown in the right side of Figure 4. Therefore, it was necessary to constraint the model to generate only brand-consistent designs. In other words, the possible locations for the point X had to become restricted more. Because of its symmetry, it was sufficient to consider only half of the model, as depicted in Figure 5. This rectangle was the “initial design space” that the floating point X could move anywhere inside it. By drawing the diagonal of the rectangle, a border for the location of point X was formed. The angles α and β corresponding to this border were named critical angles, α_c and β_c, respectively. For a specific aspect ratio w/h, the values of critical angles are:

$$\alpha_c = \tan^{-1}(2/(w/h)) \quad (5)$$

$$\beta_c = \frac{\pi}{2} - \alpha_c \quad (6)$$

Figure 6 (left) shows the grille profile for different values of α and β relative to their critical values. By investigating the grille profiles of the same vehicles which were used to develop the model and determine the initial design space, it became obvious that when α and β are less than or equal to their critical values (points X_2 and X_3 in Figure 5), the generated profile will be inconsistent with the Mercedes brand image.

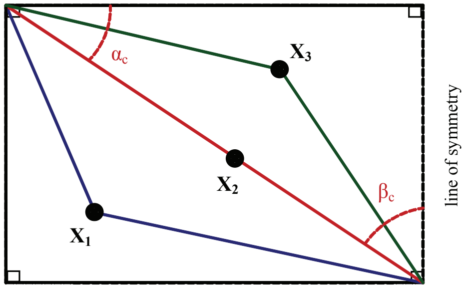
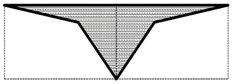
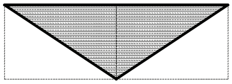
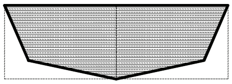
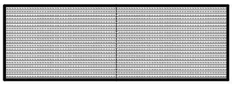


Figure 5. Critical angles and floating point in the initial design space

It should be noticed that to have a closed profile, the angles α and β should be simultaneously greater, equal or less than their corresponding critical values. As a result, the only possible combination of the angles α and β is when they are both greater than their critical values (point X_1 in Figure 5). The final design space for placing point X is shown in the right side of 6.

Our historical investigations showed that in the early designs of Mercedes-Benz vehicles, the grille aspect ratio was often very small, typically between 0.6 and 1. For many years this aspect ratio remained between 1 and 3 for most products of the company, but from the 1970s they have had aspect ratios usually more than about 2, sometimes up to about 5.5.

Profile	Geometrical Specifications
	$\alpha < \alpha_c$ $\beta < \beta_c$
	$\alpha = \alpha_c$ $\beta = \beta_c$
	$\alpha > \alpha_c$ $\beta > \beta_c$
	$\alpha = \alpha_{max}$ $\beta = \beta_{max}$

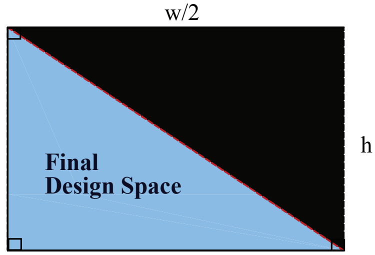


Figure 6. Left: various profiles and their geometrical specifications; right: the final design space

In the next section of this study, it was needed to choose a specific vehicle (with determined grille aspect ratio) to investigate how much the current grille design is desirable and functionally efficient and how it is possible to change its profile to achieve a more pleasing and functional grille.

3.2 Implementation of the model

In this section, a specific vehicle was chosen to implement the model on its grille profile. The selected vehicle, the 2008 Mercedes-Benz C-Class, and the half profile of its grille along with the major angles and dimensions are depicted in Figure 7. The aspect ratio of this profile was about 4.92 and the angles α and β were approximately 73.0° and 84.6° respectively. For this aspect ratio, the critical angles α_c and β_c would be 22.1° and 67.9° respectively, according to Eq. (5) and (6). The area bounded by this profile was about 84.5% of the rectangle which is shown by the dashed lines in Figure 7.

In the next stage, the goal was to investigate the effects of any change of current profile within the entire allowable design space. Preserving the same aspect ratio as in the current grille, it was purposed to examine the desirability and functionality of various possible and brand consistent designs.

To obtain a set of allowable designs, the design space was discretized by dividing the domain of each variable (angle) into equal intervals. As shown in Figure 8, the domains of α (22.1° to 90°) and β (67.9° to 90°) were divided into 6 and 4 parts, respectively. The intersection of each α line with each β line determined a location for the floating point X. Each of these 24 points, shown in Figure 8 by the intersection signs, represents a profile design.

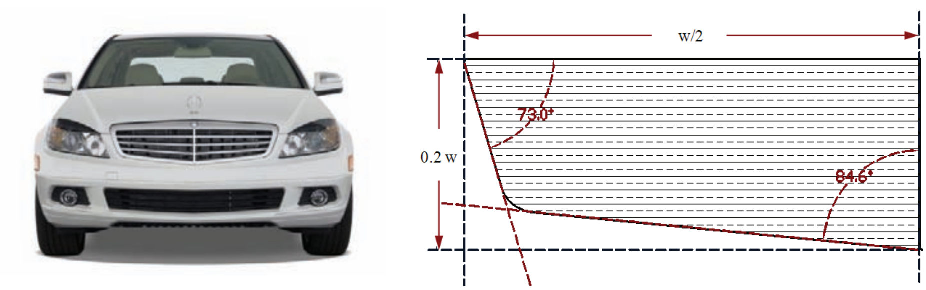


Figure 7. The chosen vehicle for case study and the half profile of its grille

The front views of the vehicle with the generated grille profiles were drawn and a number was assigned to each design. Also the current design and the critical design (profile with the critical values for α and β) were added to this table. Although it was previously described that the critical profile is not an acceptable design, it was aimed to capture the opinions of respondents about it in the following survey. In addition the current design was included in this set to evaluate it and find out if it could be improved.

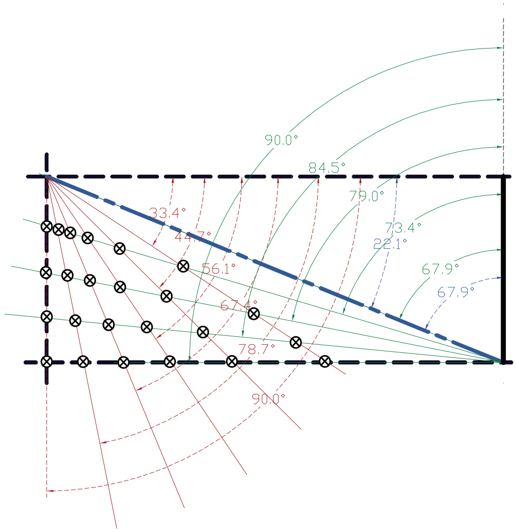


Figure 8. Discretization of the design space and creating design alternatives

Throughout this project there was an awareness that any essential changes in the design of any parts of a product should be accompanied by appropriate modifications in other elements. Particularly in vehicle design, the bodylines, grille, headlights, bumper and fenders form an integrated design that means that any changes to components can result in consequential changes in the other components [31, 32] .Nevertheless, the aim of this case study was to investigate the consequences of changes of grille profile of a specific "designed vehicle" to find out if any enhanced profile could be substituted on the same vehicle. Therefore, in this work the designs of other elements were preserved while changing the grille profile according to the proposed model.

To measure the relative aesthetic desirability of each design, an online survey was designed, based on the 26 alternatives, as shown in Figure 9. The survey was presented to 27 engineering undergraduate and graduate students from different countries. All the respondents were between 18 and 34 years old. They were asked to rate the appearance of each vehicle independently.

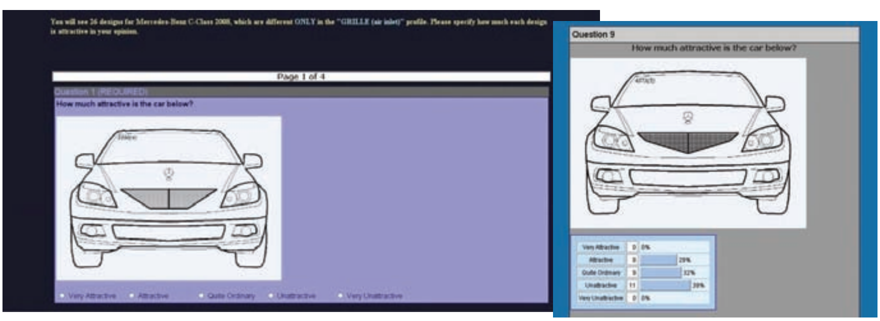


Figure 9. Screenshot of a question of the designed online survey and an example result

The survey provided the necessary information to rate the aesthetic quality of each design. A percentage from 0 to 100 with 25 percent increments was given to each level of desirability, with 0 and 100 being very unattractive and very attractive respectively. Finally, an average percentage of aesthetic preference was obtained for each design as listed in Table 1. The survey showed that for the preferred design according to the respondents the α and β angles were 56.1° and 84.5° respectively. It is shown along with the current design in Figures 10.

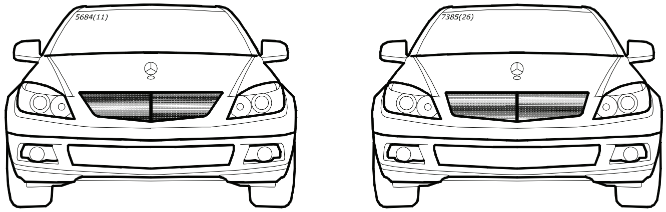


Figure 10. Left: the most attractive design: α =56.1° and β = 84.5°; right: the current design: α =73.0° and β = 85.2°

3.3 Results

The results showed that the current design was among the four most attractive designs, but still it could be modified to further enhance the appearance of the vehicle. It is interesting to note that for two of the four most popular designs the inner edges of the headlights are approximately parallel to the adjacent edges of the grille frame, although the most attractive one and the current design do not have this characteristic. As a result, designing parallel edges for the headlights and grille can result in a harmonious and aesthetically pleasant design.

At this stage, the task was to rate the aerodynamic functionality of the current and generated designs, based on the conclusion that a large intake can be advantageous to prevent separation of the flow in the inlet duct. The final results are shown in Table 1. This table can be used in the early stages of the design process to inform decisions for the grille profile.

The utility function to be maximized was written in the following form:

$$U_O = U(f_{Aesth}) + U(f_{Aero}) =$$
$$w_{Aesth} * f_{Aesth}(\alpha,\beta) + (1 - w_{Aesth}) * f_{Aero}(\alpha,\beta)$$

Subject to the constraints

$$\alpha_c < \alpha < \frac{\pi}{2} \qquad \& \qquad \beta_c < \beta < \frac{\pi}{2} \tag{7}$$

where f_{Aesth} and f_{Aero} are the aesthetic and aerodynamic objective functions respectively, $U(f_{Aesth})$ and $U(f_{Aero})$ denote the utility functions corresponding to them, and U_o represents the overall utility function. w_{Aesth} is the weighting factor associated with the aesthetic objective function, and α_c and β_c are the critical angles as defined by Eq. (5) and Eq. (6).

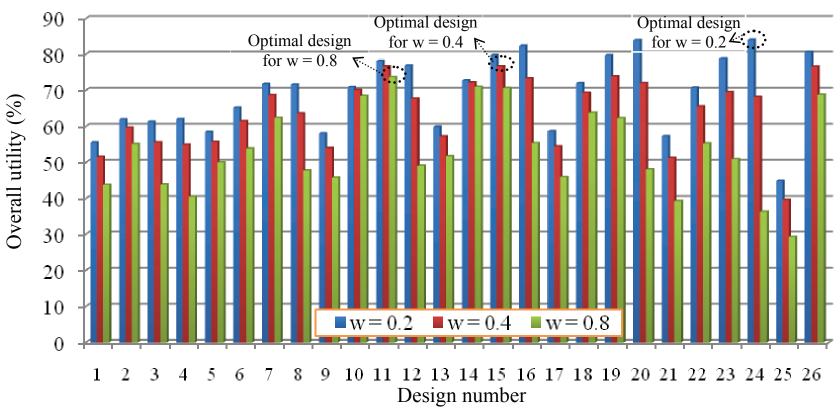
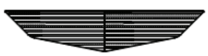
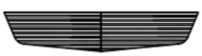
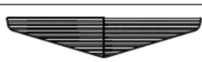
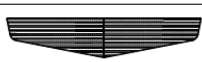
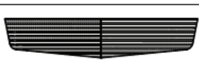
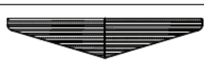
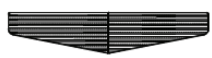
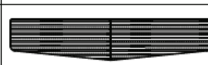
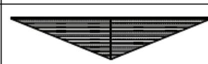
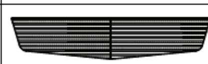


Figure 11. The optimal designs associated with three different values of w = w_{Aesth}

After selecting a value for w_{Aesth}, it will be possible to find the optimal design corresponding to that w_{Aesth} using Table 1 and the utility function. Selecting or estimating the appropriate weighting of each objective function is a task that should be done by the design team in the early design stages. As examples, the optimal designs associated with three different values of $w = w_{Aesth}$ are shown in Figure 11.

Table 1. Aesthetic preference and aerodynamic functionality for various grille profiles

No.	$\alpha_{(deg)}$	$\beta_{(deg)}$	Grille Profile	Aesthetic Preference (%)	Aerodynamic Functionality (%)
1	33.4	73.4		39.8	59.4
2	33.4	79.0		52.8	64.3
3	33.4	84.5		38.0	67.2
4	33.4	90.0		33.3	69.2
5	44.7	73.4		47.2	61.3
6	44.7	79.0		50.0	69.1
7	44.7	84.5		59.3	74.9
8	44.7	90.0		39.8	79.5
9	56.1	73.4		41.7	62.1
10	56.1	79.0		67.6	71.7
11	56.1	84.5		72.2	79.7
12	56.1	90.0		39.8	86.2
13	67.4	73.4		49.1	62.6
14	67.4	79.0		70.4	73.4
15	67.4	84.5		67.6	82.8
16	67.4	90.0		46.3	91.4
17	78.7	73.4		41.7	62.9
18	78.7	79.0		61.1	74.8
19	78.7	84.5		56.5	85.6
20	78.7	90.0		36.1	95.9
21	90.0	73.4		33.3	63.3
22	90.0	79.0		50.0	76.0
23	90.0	84.5		41.7	88.1
24	90.0	90.0		20.4	100
25	22.1	67.9		24.1	50.0
26	73.0	85.2		64.8	84.6

4 CONCLUSIONS AND FUTURE WORK

4.1 Conclusions

Making a trade-off between form and function has been a permanent challenge in product design for many years. While engineers attempt to improve the technical aspects of a product, stylists intend to enhance its aesthetic quality while preserving the brand identity.

In this study, the car front grille which is known as the brand identifier of the vehicle was selected to design and carry out a case study. Aerodynamic drag minimization was selected as the functionality aspect of design and was investigated theoretically. By choosing a specific brand to focus on, a historical study was accomplished to determine an initial design space for the front grille. Further investigations revealed the constraints that are imposed on the grille design by the brand identity. Applying these constraints to the initial design space determined the final design space. A specific vehicle of a specific class and model was chosen from the products of the company to implement the design model developed in practice. The design space for the chosen vehicle was drawn and discretized to generate a set of alternative designs. In the next step, an online survey was designed and carried out using the generated designs and the current design to capture the opinions of a group of respondents about the aesthetic quality of each design. Finally all the designs were rated on their appearance, and it was concluded that the current design is among the most attractive. Finally, we obtained a table along with a utility function that can be used to design the most appropriate grille profile for the new generations of the chosen vehicle.

4.2 Future work

In the survey part of this study, the respondents were a small group of engineering students who were asked to answer to a short survey. To improve the current research, it will be fruitful to design a more comprehensive survey and conduct it in a larger and more diversified group of people to capture their opinions and preferences.

With necessary modifications, the approach of this project can be used to optimize the grille profile or similar feature for products of other companies. Many brands have grilles which have significant curves in their profile, so it is not possible to model them by a few straight lines accurately. In these cases, the profile should be represented using curved models such as Bezier curves (see [31]). Also the same approach can be used to make a trade-off between form and function in design of other parts of a car such as headlights and mirrors.

Future work could extend the approach by including other functionality aspects of the grille design such as heat transfer rate and protection ability in order to find the optimum solution given a wider range of parameters for the grille profile.

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