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# APPLICATION OF ADVANCED LIGHTWEIGHT MATERIALS FOR OPTIMISATION OF FUNCTION AND WEIGHT IN VEHICLE PLATFORMS

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## Abstract

A major challenge currently facing the automobile industry is weight reduction. A reduction in vehicle mass will improve performance in critical areas, namely energy efficiency and reduced emissions. One obvious route to achieving this aim is to focus design approaches towards the use of advanced lightweight materials. This paper investigates the evolution of the industry and the use of advanced materials to reduce weight.

A flexible Quality Functional Deployment (QFD) tool is developed to ascertain the requirements of automotive body components, and formulate materials systems best suited to their fulfilment. Three discrete conceptual models are created using these materials systems that can be deployed by the automobile manufacture addressing lifecycle use and delivering functional improvement using advanced engineering materials in vehicle platforms.


## 1. Introduction

The demands placed upon the modern automobile include reduced weight, improved crash performance, increased fuel efficiency, recyclability, reduced energy use for manufacture, enhanced durability, and improved corrosion protection. The use of advanced materials, and selection methodology used, that will meet many of these demands. Improved performance has been achieved with materials such as aluminium in transmissions, engine blocks, and wheels. [1] However, the motor vehicle body structure makes up a high percentage of total vehicle mass as shown in figure 1. The targets set for reduction of green house gas emissions, figure 2, will also stimulate technological improvements. Specifically, advances in drive train technology should be coupled with lightweight materials selections to achieve these goals while maintaining crash safety and noise, vibration and harshness (NVH) standards.

It is clear though that improvements directed towards weight reduction will assist in achieving these future goals. To maximise the economic utility, light materials must also offer additional functional benefits. This paper presents a novel quality functional deployment (QFD) tool to assist in weight reduction while maintaining functional requirements. The tool uses material systems’ qualities to evaluate their fulfilment of the customer demands for the multiple component systems within automotive structures as opposed to the traditional QFD model of evaluating and benchmarking discrete designs to customer demands.

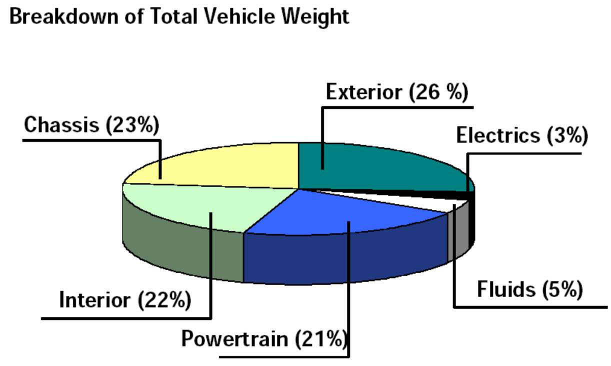


Figure 1. Breakdown of Total Vehicle Weight [2]

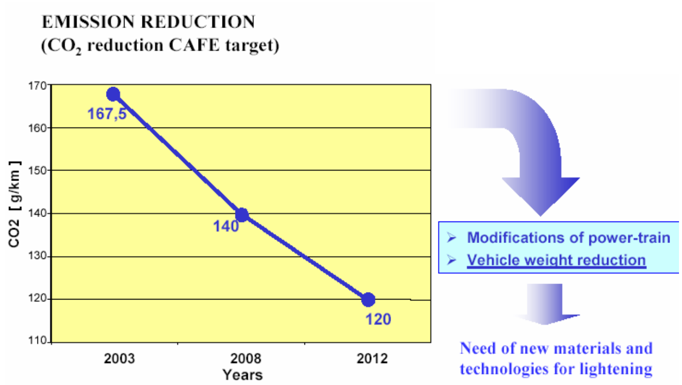


Figure 2. Emission Reduction (CO2) reduction CAFE Target) [3]

# 2. Automotive design challenges and lightweight materials

The current lean manufacturing environment tailored to react just-in-time to changing demands presents opportunities to address changing customer demands through use of new materials and technologies. In addition, the competitive marketplace has placed demands on manufacturers to maintain profitability on reduced production volumes for individual models by platform engineering – the practice of tying individualised vehicle styles, configurations and brands, to a common set of mechanical components interior architecture, and floorpans. This has also led to the death of independence for many lower-volume manufacturers unable to afford this expense [4]. The trend in diversification and reduced production volume during the 20$^{th}$ century is illustrated in figure 3.

Economic globalisation has also led to a greater transfer of vehicles from one manufacturing nation or region to another. Localised companies must diversify production or export to maintain economically viable volumes. The challenge for a geographically constrained small manufacturer is to diversify economically and improve export potential [5]. With a requirement to maintain volume within a globally competitive market largely free form artificial vehicle tariffs, localised manufacturers must capitalise on their ingenuity and resourcefulness to meet global environmental requirements while satisfying their traditional core customers [4, 5]. It is also a requirement to source continued revenues from relatively low volumes to invest for future product. In a world increasingly using lightweight materials to fulfil future design requirements, local manufacturers may capitalise on their status as low-volume, niche producers to create these diversified products [4, 6]. Maximising the advantages that new design and manufacturing methods can yield using lightweight materials economically can be achieved by optimally configuring components' materials systems to match vehicle functional and design requirements [4, 6].

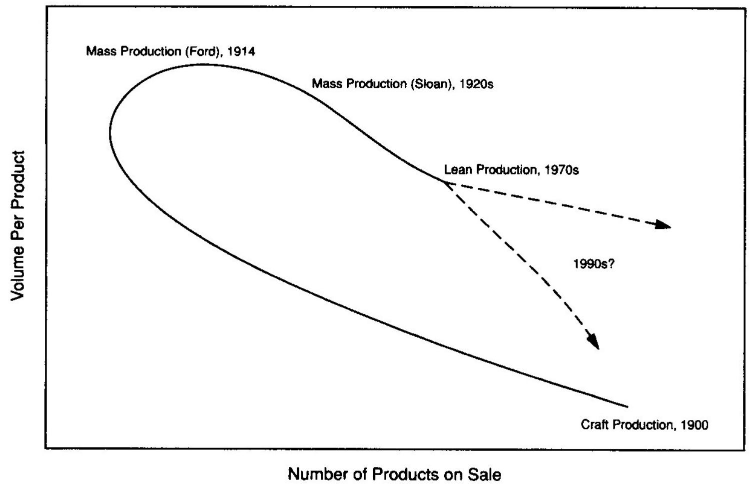


Figure 3. The progression of Product Variety and Production Volume in the Auto Industry [4]

# 3. Materials Selection

Although cost has possibly the single greatest factor affecting the selection of materials for automotive usage, the mechanical properties of the materials play a significant part in how much material is required to perform particular functions. The materials selection process should therefore focus on optimisation for weight and functional design requirements. The key properties for automotive bodies are density (ρ), tensile modulus (E) and tensile strength (σ). The absolute values for flexural modulus and strength of commonly used materials; steel, aluminium, polypropylene and fibre reinforced plastics (FRP) are shown in figure 4(a). The metals have the highest values with steel clearly superior for equal thickness. However, for automotive panels, comparison between materials on a weight for weight basis is more significant. Comparison of specific modulus and strength, that is $E/\rho^3$ and $\sigma/\rho^2$, in figure 4(b) shows that aluminium, FRP and PP become more attractive. The significance is that these materials will perform better than steel for equal weight.

It is important to note that, in addition to mechanical properties, design engineers need to consider other properties such as surface hardness, thermal conductivity, temperature and chemical resistance, and fatigue performance. These properties may also be optimised for functional performance across component systems and differing materials. The objective is to tailor materials systems most appropriate for functional use within automotive platforms. The parameters identified for measure relate most closely with the requirements for the delivery of low mass vehicle structures [6, 7].

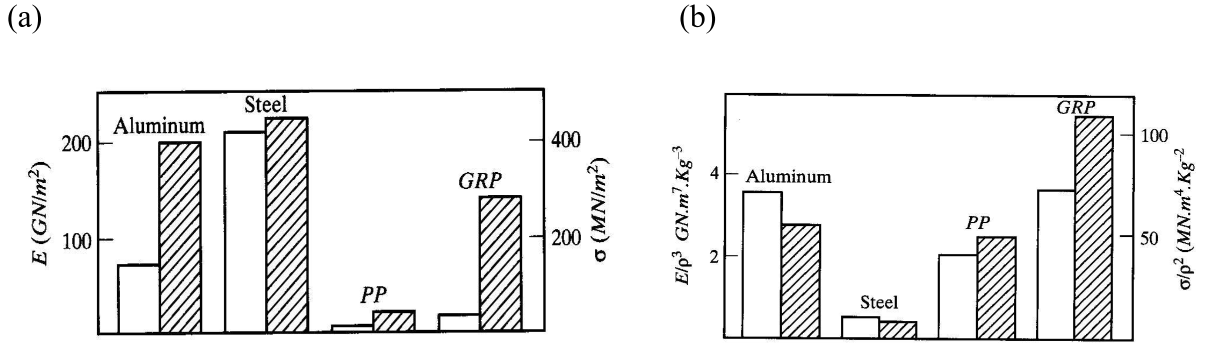


Figure 4. (a) Relative stiffness (open bars) and strengths (shaded bars) in flexure of equal thickness sheets from the materials. (b) Relative stiffness (open bars) and relative strengths (shaded bars) in flexure for sheets of equal weights from the materials. [7]

# 4. Quality Functional Deployment

The typical Quality Functional Deployment (QFD) tool is used to source and eliminate quality defects upon delivery of the product or service, and provides an opportunity to discover and quantify the customers' likes as well as dislikes within the design phase. The customer information is then transformed into quality characteristics that are used to implement appropriate solutions for the development of improved products or services [8]. QFD take up was centred within the manufacturing industry under the term value engineering and was used as a benchmarking tool to differentiate companies' products from their competitors [8]. By resolving quality issues and delivering products that exceeded the customers' expectations, the QFD method helped deliver products that could be delivered profitably within the consumer marketplace.

The design engineering use of QFD is the delivery of the customer requirements into a numerically measurable set of objective engineering quality requirements. This is formulated within the House of Quality, fundamentally a comparative matrix of numerical relationships. Results from this process are used to benchmark existing products or services with those of competitors, or with upcoming developments [8]. Prototypes of these developments can be evaluated by potential customers within focus groups or interviews to ensure that the tool has delivered effective design solutions.

The strength of the tool is the removal of the ambiguity between customer desires, and manufacturing engineers' product delivery. Additionally the tool can identify key customer wants, key customers, and erroneous data sensitivities that are ultimately unimportant to the typical customer experience. However, the weakness of present tools lies in their inability to deliver clear numerical selection sensitivity to multiple product systems, multiple competitive choices, and the apparent sensitivities contained within these large-scale systems. This paper presents a novel QFD tool, outlined in the following sections, which can be used to evaluate the engineering parameters that the competing materials systems were able to fulfil successfully. It expands upon current QFD philosophy and methodology to address the issue of weight reduction and functionality for automotive body panels.

# 5. Novel QFD Tool – The Evaluated Systems Matrix

To select optimal materials systems for the delivery of high-function automotive components, a tool must be created that can evaluate a broad selection of materials systems while minimising the bias toward favourites. The novel tool created here is termed the Evaluated Systems Matrix (ESM) and is shown in figure 5.

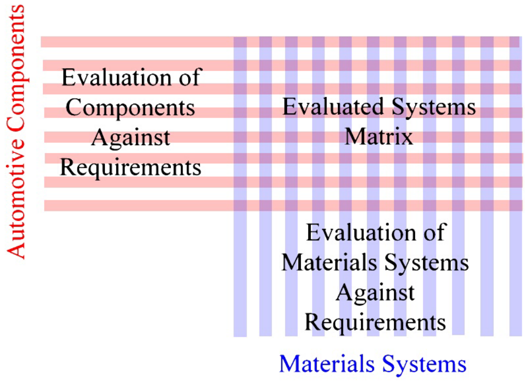


Figure 5. The Evaluated Systems Matrix

The measure of sensitivity of the functional requirements to the component systems evaluated is determined numerically. The sensitivity scoring system is shown in table 1. The Automotive Components section of the Evaluated Systems matrix therefore defines the relative importance of measurable, Yes/No, technical or quality attributes. The second, Materials Systems section, relates the materials to their fulfilment of the functional requirements. The functional requirements list may be as long as deemed necessary and may contain redundant requirements that may be useful upon expansion of the component systems evaluated.

Table 1. Sensitivity scoring system

| | **Sensitivity** | **Score** |
|---|---|---|
| Sensitivity of the component system to the engineering or quality parameter | Insignificant or none | 1 |
| | Low | 2 |
| | Medium | 3 |
| | Moderately high | 4 |
| | High | 5 |

An important consideration in this section is the *positive*, *negative* or *neutral* relationship between the functional requirements and the materials system. If one materials system has little or no relationship to the functional requirement, it is not evaluated in the matrix. If the relationship is positive i.e. the materials system contributes positively to the solution of the requirement, the numerical value (and column) is added to the Evaluated Systems Matrix. If the relationship is negative, i.e. the materials system contributes disadvantageously to the requirement; the numerical value (and column) is negated to the Evaluated Systems Matrix. This defines the Materials Systems section of the ESM.

In practice, any measurable functional requirement may be evaluated against any possible materials system. In this part of the study, 10 first tier components were evaluated. (This will be expanded to 25 first tier components for later analysis in later sections). The 10 components are listed in the first column of the Evaluated Systems Matrix given in Table 2. This matrix numerically states the relationship between the vehicle components and the functional requirements evaluated for the optimisation of function and weight. The attributes have been assigned numerical values in line with objectives. An example demonstrating this relationship is the bonnet component, numerically assigned 5 (high) for mass. This is due to its function (non structural closure), size (large), and location (high polar extreme in yaw). The component is numerically assigned 1 (insignificant) for deep draw due to the relative flatness and low geometric feature complexity required during stamping formation. These numerical values are assigned relative to the other component system values.

Table 2. Sensitivity of automotive body components in regard to performance, manufacturing, interchangability and functional criteria

| **Column** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **First Tier Component** | **Mass** | **Structural Strength** | **Polar Inertia (Yaw)** | **Polar Inertia (Roll)** | **Susceptibility to Low Speed Impact** | **Susceptibility to Medium Speed Impact** | **NVH Importance** | **Deep Draw Stamping** | **Geometric Features** | **Require to Weld** | **Interchangability (Fashion)** | **Standard Model Interchangability** | **Corrosion Issues** | **Best Practice Replacement** | **Validity of Fashion Implementation** | **High Cost Core Component** |
| **Bonnet** | 5 | 1 | 4 | 3 | 3 | 5 | 3 | 1 | 2 | 2 | 3 | 3 | 3 | 4 | 3 | 2 |
| **Front Wheel Arch (skin)** | 3 | 2 | 4 | 2 | 5 | 5 | 1 | 4 | 4 | 1 | 3 | 4 | 4 | 5 | 4 | 2 |
| **Front Doors** | 3 | 3 | 1 | 2 | 3 | 4 | 3 | 2 | 4 | 3 | 3 | 4 | 3 | 3 | 2 | 3 |
| **Rear Doors** | 3 | 3 | 1 | 2 | 2 | 3 | 3 | 2 | 4 | 3 | 3 | 3 | 3 | 3 | 2 | 3 |
| **Bootlid** | 4 | 2 | 4 | 3 | 3 | 4 | 2 | 3 | 3 | 2 | 4 | 3 | 2 | 3 | 3 | 2 |
| **Roof** | 4 | 4 | 1 | 5 | 1 | 1 | 3 | 2 | 1 | 3 | 1 | 2 | 2 | 2 | 2 | 2 |
| **Parcel Shelf** | 3 | 4 | 2 | 3 | 1 | 1 | 4 | 4 | 4 | 5 | 1 | 3 | 1 | 2 | 1 | 3 |
| **Boot Floor** | 3 | 3 | 4 | 2 | 1 | 3 | 4 | 4 | 3 | 5 | 1 | 5 | 4 | 2 | 1 | 4 |
| **Radiator Brace** | 2 | 3 | 5 | 2 | 3 | 4 | 2 | 5 | 4 | 4 | 1 | 5 | 2 | 3 | 1 | 2 |
| **Front Bulkhead** | 4 | 5 | 1 | 2 | 1 | 1 | 5 | 5 | 5 | 5 | 1 | 4 | 2 | 1 | 1 | 5 |

The materials systems selected for evaluation in this study cover are currently used for manufacture of vehicle structures; plastics (PP), aluminium, fibre reinforced composites and steel. They could be used in sheet form or made into sandwich constructions such as fibre-metal or polymer metal laminates. They also cover a wide range in materials cost and in manufacturing practices. The materials systems have been evaluated in their commonly manufactured states. Upon consideration of the ESM, materials with a significant negating effect upon a quality parameter can be considered for optimisation to remove this barrier for selection, either by altering the materials composition as is the case of composites or alloys, or by its manufacturing method or geometry in the case of plastics or composites. Additionally the benefit an objective evaluation of the present system status quo is conducted by the inclusion of current practice steel manufacture. This system is also evaluated in combination with sandwich structures in the same manner to that of the other materials systems to observe any derived benefit, usually for component systems requiring high stiffness and superior NVH properties.

## 6. Multi-System Processing – The Solution Matrix

The advantage of the Evaluated Systems Matrix is its ability to evaluate between large-number multiple systems of components, multiple quality measures and multiple materials selection. For this study, twenty-five components were evaluated over sixteen quality parameters and eight materials systems. The optimised materials systems and the optimal component systems are presented in the Solution Matrix in figure 6. The Solution Matrix is a sum of the ranked scores from the individual Component System/Material System analysis derived from the ESM. For each component, the optimised material is that for which the highest ranking is achieved within the Solution Matrix. Other high ranking material systems are valid in actual application, as they may complement the adjoining component systems more fully. An examination of the materials systems within the Solution Matrix yields the component systems that best utilise the functional qualities those materials display.

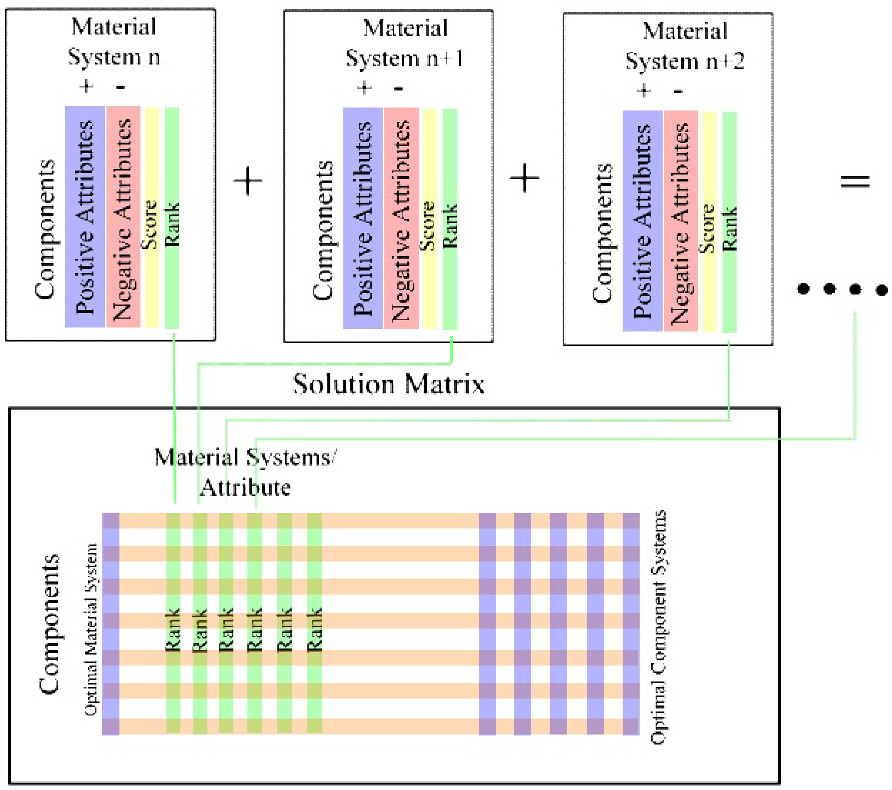


Figure 6. The Solution Matrix

The methodology remains valid for various initial problems, though best suited to large multi-system environments. Key to the tools functionality is the appropriateness of relating the multiple quality attribute to the same range of material system options or equally valid solution implementation i.e. manufacturing method. The matrices formed may be several-fold greater than those illustrated here, though computational methodology would be required to keep account for the formed solution matrix [8]. The example used appears to be a comfortable limit for hand calculation. An important factor in any Quality Functional Deployment exercise is the accuracy of the original data. Here, the numerical allocation of component/quality sensitivity is of great importance, along with the allocation of the positive/negative relationship of quality to material system. Individual organisations conducting the same quality experiment should be free to select their own numerical data, though the methodology should remain valid. A further variation on the ESM and Solution Matrix is the inclusion of scaling parameters, whether applied to individual quality, such as cost, or during the Positive Attribute phase of the Solution Matrix

# 7. Results

The resultant data from the Evaluated Systems Matrix and Solution Matrix, applied to the original automotive project brief, provides a guide to the selection of materials systems for the optimisation of weight and function in vehicle platforms. A summary of the solution matrix for all 25 components systems analysed is shown in table 3. These solutions are unmodified, that is modifications to materials attributes or introduction of scaling factors has not been performed. The results in table 5 are highlighted according to the criteria in table 4.

The formulation of two solution sets formed from the tool will be examined. In the instance of a material system or attribute, sandwich construction is illustrated due to its inclusion in both subsets. Within the ESM, the quality criteria deemed as positive to the use of sandwich construction are columns (1) mass, (2) structural strength, (6) susceptibility to medium speed impact, (7) NVH importance and (16) high cost core component. Those quality criteria deemed as negative are columns (8) deep draw stamping, (9) geometric features and (10) require to weld. The numerical relationship within the nominated quality columns for each component is added or negated accordingly. The resulting scores for each component are ranked from 1–25 and tabulated within the Solution Matrix illustrated in table 3. This process is continued for all attributes or materials systems to be evaluated. For any one material system, an examination of the material column within the Solution Matrix will indicate component systems, by highest rank, demonstrating the greatest potential gain from its application. For the sandwich construction system these are shown to be bonnet (1), roof (2), and front subframe (2) respectively. These are systems for which low weight and high stiffness are priorities.

Secondly, the materials selection process for the bonnet and roof components is illustrated. For each of these components, the numerical relationship to the quality criteria within the ESM in table 2 is evaluated, and, as for the materials systems or attributes, ranked scores are tabulated within the Solution Matrix, table 3. An assessment of each component row reveals, via the highest rank, the materials system most suited to fulfilling the quality criteria demanded by that component. In the case of bonnet and roof it is aluminium and composite respectively, with equally a high preference for sandwich construction. The comparatively high ranks of other materials indicate the validity of selecting alternates due to other possible considerations. In the conceptual model (A) developed for this project, figure 7, both these components were considered desirable for early substitution with lightweight materials, evidenced from the high rankings in the low mass attribute column within the Solution Matrix. Generally, the favourable components observed within the materials column will correspond with the optimum system as observed from the components' perspective.

Table 3. Summary of the Solution Matrix

| **Rank** | **Attribute** | | | **Materials System** | | | | |
|---|---|---|---|---|---|---|---|---|
| **Component** | **Low Mass** | **Flexible** | **High Strength** | **Sandwich Construction** | **Plastics** | **Aluminium** | **Composites** | **Steel** |
| **1. Bonnet** | 1 | 2 | 4 | 1 | 2 | 1 | 3 | 24 |
| **2. Front wheel-arch skins** | 2 | 1 | 1 | 10 | 1 | 2 | 14 | 25 |
| **3. Front Doors** | 15 | 3 | 4 | 4 | 4 | 10 | 20 | 15 |
| **4. Rear Doors** | 15 | 8 | 8 | 9 | 7 | 10 | 17 | 20 |
| **5. Bootlid** | 2 | 3 | 8 | 9 | 3 | 2 | 5 | 23 |
| **6. Roof** | 4 | 18 | 17 | 2 | 20 | 4 | 1 | 15 |
| **7. Parcel Shelf** | 13 | 18 | 17 | 24 | 20 | 24 | 14 | 8 |
| **8. Boot Floor** | 8 | 13 | 14 | 14 | 10 | 15 | 20 | 6 |
| **9. Radiator Brace** | 4 | 3 | 4 | 25 | 4 | 15 | 20 | 12 |
| **10. Front Bulkhead** | 20 | 24 | 17 | 14 | 17 | 25 | 25 | 1 |
| **11. Front wheel-arch inners** | 4 | 7 | 1 | 9 | 25 | 10 | 10 | 10 |
| **12. Front Strut mount** | 15 | 13 | 8 | 23 | 10 | 19 | 20 | 6 |
| **13. Cant Rail** | 8 | 17 | 17 | 14 | 14 | 5 | 3 | 21 |
| **14. Roof Members** | 15 | 18 | 17 | 14 | 23 | 13 | 2 | 12 |
| **15. Rear Side Panel** | 8 | 8 | 8 | 4 | 6 | 5 | 5 | 21 |
| **16. Sills** | 20 | 13 | 14 | 19 | 19 | 7 | 9 | 15 |
| **17. Rear Bulkhead** | 20 | 24 | 17 | 9 | 22 | 19 | 7 | 8 |
| **18. Floor Pressing** | 20 | 18 | 17 | 4 | 14 | 19 | 24 | 3 |
| **19. Floor Braces** | 25 | 18 | 17 | 14 | 24 | 23 | 10 | 2 |
| **20. Dashboard Beam** | 8 | 11 | 8 | 19 | 17 | 18 | 17 | 11 |
| **21. Front Subframe** | 8 | 11 | 4 | 2 | 7 | 15 | 24 | 3 |
| **22. Rear wheel arch Inners** | 4 | 13 | 14 | 19 | 10 | 7 | 7 | 15 |
| **23. Rear Bumper Beam** | 13 | 8 | 8 | 9 | 13 | 13 | 10 | 15 |
| **24. Front Bumper Beam** | 8 | 3 | 1 | 4 | 7 | 7 | 14 | 14 |
| **25. Transmission Tunnel** | 20 | 18 | 17 | 4 | 14 | 15 | 17 | 3 |

Table 4. Solution Matrix Criteria

| | Attribute | Sandwich Construction | Material System |
|---|---|---|---|
| Dark shading | Top three (1–3)components requiring quality attribute | Top 1/3 rd (1-8) favourable to sandwich construction | Most favourable material system for component |
| Light shading | Second group of three (4-6) components requiring quality attribute | Second 1/3 rd (9-17) favourable to sandwich construction (neutral) | Additional favourable materials for component (within 3 of rank of most favourable) |

Overall, the results in table 3 indicate that the preferential usage of lightweight materials is focused on first ten components. The case for the inclusion of steel components is indicated by a priority selection of the material in key areas, notably in the floor assemblies. This does not indicate that steel is the single optimum material, as with all systems evaluated; the top selected material indicates the preference for the materials fulfilment of the quality requirement *ahead* of the other material systems. Also indicated, in green, are alternate material systems that could be used as alternatives where adjoining systems become more complimentary in doing so. Some anomalies may at first appear present, for example the preference for an elastic, plastic, sandwich front bumper beam. In reality, this is the solution which best fulfils the quality attributes compared with competing systems, namely high deformation before failure, low mass and high stiffness.

It should be noted that the criteria in Table 4 have been set out as a guide only, and have been provided as a quick visual assessment of the various systems under comparison and may be configured depending on the preferences and requirements of the initial quality exercise. The QFD tools is a guide only, and may be overruled, though the final data is only a reflection of the accuracy on the input data and the careful preparation of the quality experiment.

# 8. Conceptual Models

The vehicular basis used for conceptual models was the Ford Motor Company of Australia Falcon model. The Falcon occupies the large D-E segment, and is manufactured in Victoria, Australia with annual volumes of approximately 120,000 including sedan, wagon, long wheelbase (LWB), utility and sport utility vehicle (SUV) configurations. A majority of annual production volume is sold within Australia, whilst only small volumes are currently exported to New Zealand and South Africa. Therefore, the Australian market and its manufacturers such as Ford Australia face the issues discussed in section 2.

The following represent three conceptual models developed using the novel QFD tool. The models are differentiated by an implementation timeframe.

- Conceptual Model (A). Key components of visual differentiation applied to limited volume high-end variant of Falcon platform. Used in applications where positive attributes are of most benefit and where there is less market sensitivity to cost. Timeframe: 12-24 months.

- Conceptual Model (B). Most closures and key components within Body-in-White (BIW) engineered in conjunction with platform development phase for implementation across broader higher end variant of Falcon. Use of favourable materials system to increase viability for lower volume product variants. Timeframe: 48-60 months.

- Conceptual Model (C). Fully developed model including majority of BIW and closures. Model includes a wide range of diversified product variants viable at low to medium volumes and responsive to market changes. Timeframe: 72-120 months.

The three conceptual models and the key components selected for lightweight materials design are illustrated in figures 7-9.

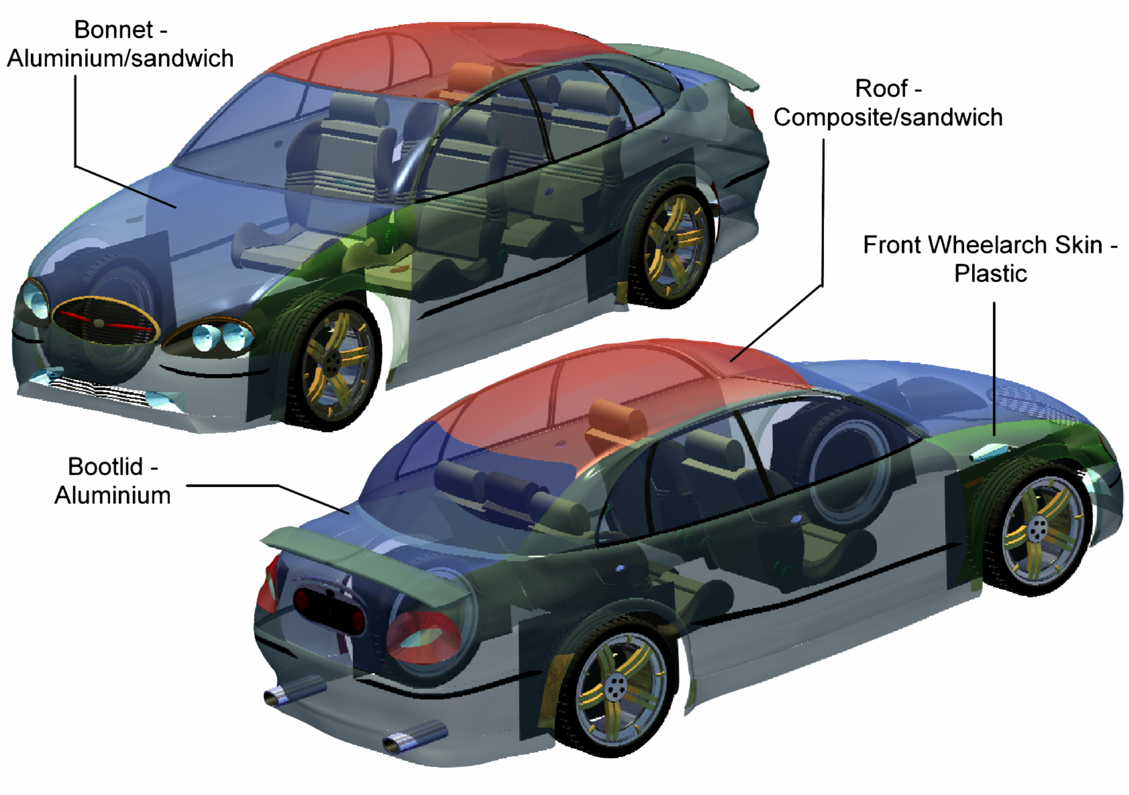


Figure 7. Ford Falcon Conceptual Model A.

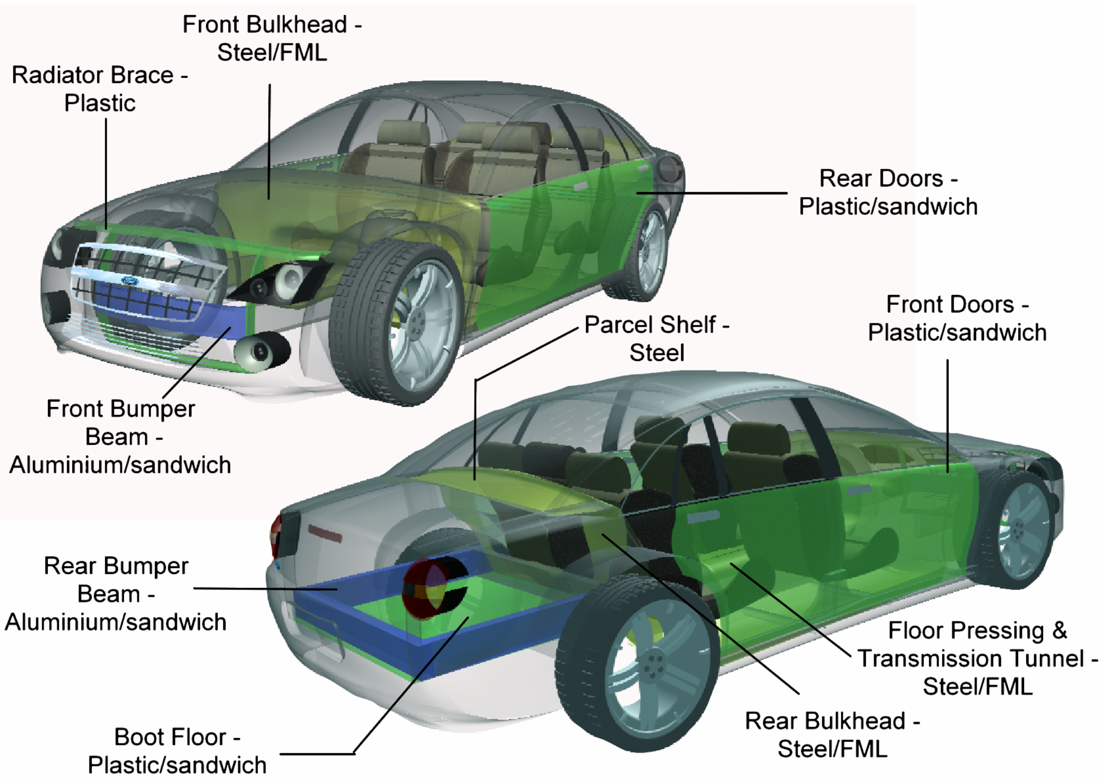


Figure 8. Ford Falcon Conceptual Model B.

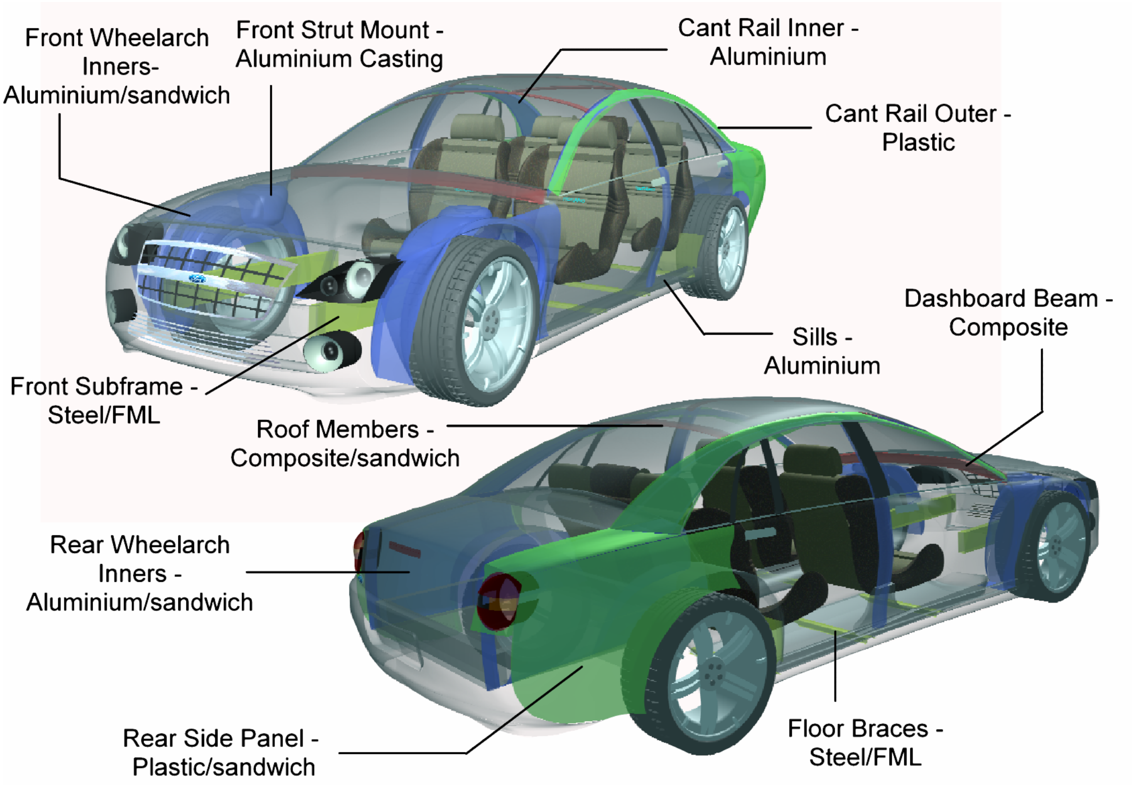


Figure 9. Ford Falcon Conceptual Model C.

# Conclusion

A major challenge for the automotive industry is to reduce mass and consumption while maintaining functionality. The use of advanced lightweight materials should to reduce mass should also provide functional improvement. Therefore, an understanding of which material properties are important, and how they can best be utilised, will enable viable design to help minimise weight, cost and consumption.

The Quality Functional Deployment tool presented in this paper has been designed to offer a broad evaluation of multiple component systems and materials. It uses material systems' qualities to evaluate their fulfilment of the customer demands for the multiple component systems within automotive structures as opposed to the traditional QFD model of evaluating and benchmarking discrete designs to customer demands.

The Evaluated Systems Matrix provides a method of evaluating these systems numerically against the quality attributes. Data obtained from the Solution Matrix offers objective selection criteria for the application of specific materials systems. The value of the tool lies in the flexibility of analysis, the reading of the data allowing complementing systems. The tool is not exclusive to the illustrating case study, and is equally applicable to other multi-system quality problems.

Upon selection of optimised systems three discrete conceptual models have been created to illustrate the implementation of the lightweight materials technologies offering the highest positive benefit and lowering potential risk. They offer an example of the use of Quality Functional Deployment tools to provide the optimisation of weight and function within vehicle platforms.

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