

Mass Benchmarking Using Statistical Methods Applied to Automotive Closures

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ABSTRACT

Understanding the lightweighting potential of materials is important in making strategic decisions for material selection for a new vehicle program. Frequently benchmarking is done to support these decisions by selecting a reference vehicle which is believed to be mass efficient, then using the teardown mass data to set targets for the vehicle under design.

In this work, rather than considering a single benchmark vehicle or a small set of vehicles, we looked at a large sample of vehicles over a range of sizes and segments (approximately 200 vehicles). Statistical methods were used to identify mass drivers for each subsystem. Mass drivers are the attributes of the vehicle and subsystem which determine subsystem mass. Understanding mass-drivers allows comparisons across vehicle size, segments, and materials. Next, we identified those vehicles which had subsystems which were much lighter than the average after adjusting for mass drivers. This set was defined as mass-efficient designs. We then focused on the lightweighting gained by material selection for these mass-efficient designs.

This paper focuses on four body closures systems: side door, hood, decklid, and hatchback door. Results include the identification of mass drivers and predictive equations for closure structure mass for both average designs and mass efficient designs; The influence of material selection on mass for both average and mass-efficient designs; and observations on the diminished mass savings achieved at the system level when there is a mass savings due to material substitution at the structure level.

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1. INTRODUCTION

Benchmarking is the process of comparing systems or processes across an industry. Benchmarking provides a snapshot of industry performance and allows engineers to identify the range of performance for systems in the current market; to identify the current best performance (best in class); and to identify those design practices and technologies which lead to light weight designs [1, 2].

Knowledge provided by benchmarking allows better design decisions by using a base of facts. Our focus is on applying benchmarking to lightweighting during the product planning phase where targets are established for mass budgeting and strategic decisions are made on material selection. Benchmarking insures that the mass targets set are both competitive and achievable [3].

Often mass benchmarking is done with a one-at-a-time approach. A reference vehicle is selected which is believed to be mass efficient. The vehicle is then disassembled, parts weighted and analyzed, then the data used to set mass targets for a vehicle under design [4]. In this work, a statistical methodology was developed for mass analysis. Rather than considering a single vehicle or a small set of vehicles,

this method looks at a very large sample of vehicles over a range of sizes and segments. From this larger population, our assumptions on mass drivers and their influence on real vehicles may be tested via statistics [5]. We can then look at subsystems which are much lighter than the 'average' vehicle after adjusting for the mass drivers.

A difficulty in mass benchmarking is how to identify those designs which are mass-efficient, i.e. those which exhibit low mass. For example, consider the door-in-white mass for several vehicles shown in [Figure 1](#). There are several low mass doors compared to the others. We can ask: *Are these low mass doors good examples of efficient design, or are they low mass merely because they are the smaller sized doors, or doors of a specific material, or more recent models, or those with a specific door regulator that enables low mass, ...?*

In [Section 2](#) we describe a methodology to answer these questions, then in [Sections 3](#) and [4](#) we apply the methodology to several closure systems. Finally in [Section 5](#), we provide some observations on material selection.

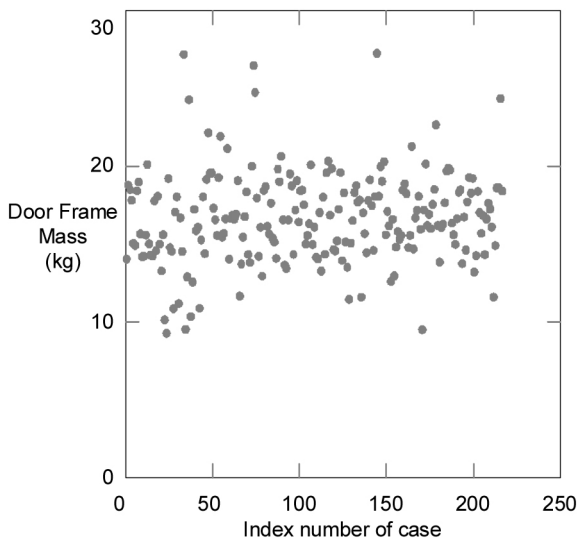


Figure 1. Door frame mass ordered by model name.

2. METHODOLOGY FOR STATISTICAL MASS BENCHMARKING

Consider the door mass variation shown in Figure 1 to be organized by source as shown in Figure 2.

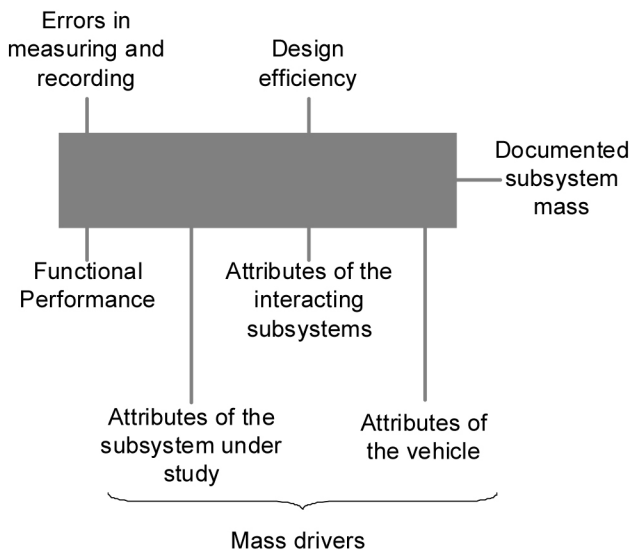


Figure 2. Sources of mass variation.

These sources include the differences in:

- Subsystem-Variation from door to door in the subsystem itself, such as door dimensions or materials.
- Vehicle attributes-Variation due to the type of vehicle the door is part of-passenger car, premium car, utility vehicle. This may reflect the performance levels required and content of the door system.
- Interacting subsystems-Variation in the door mass due to variation in the subsystems it interacts with. For example, the type door frame-to-body pillar construction.

- Door performance-Levels of functional performance, such as door sag stiffness or side impact deformation, may influence door mass.
- Due to chance-This source includes all unaccounted for influences, such as measurement or recording mistakes.
- Design efficiency-Some doors are better optimized than others and demonstrate good design. We would like to identify those doors with high efficiency, i.e. the mass-efficient designs.

We assume that all doors in the market perform at a similar level (an assumption we are forced to make as our database does not include performance data), and that measurement and recording errors are small. The remaining variation in mass is then due to the attributes (mass drivers) and to design efficiency. We can account for mass drivers as described below, and then we can identify the doors with much lower than expected mass as mass-efficient designs.

In this paper, we examine body closures-driver side door, hood, decklid, hatchback door-and use a statistical approach to mass benchmarking. The objective of this work was to identify those vehicles which exhibit exceptional mass efficiency with particular emphasis on materials used, and to estimate the mass reduction potential for aluminum and steel.

The source of data is the A2Mac1 AutoReverse database [6]. Since 1997, A2Mac1 has been providing benchmarking services to manufacturers and suppliers. The A2Mac1 teardown database contains data for 200+ vehicles. The database includes sedans (approximately 1/3 of the database), hatchbacks (approximately 1/2 of the database), and also SUVs, vans, convertibles, pick-up trucks, station wagons. Vehicles in this database were disassembled to the part level, the part photographed, weighed, dimensions measured, and a material category identified (ferrous, alloy, plastic). The database does not include performance information or material description at a grade or alloy level. The database is accessed through the internet.

The steps illustrated in Figure 3 were performed for each of the structural subsystems studied. In the next section we provide a detailed example for the side door subsystem, here we provide a general description of the overall methodology.

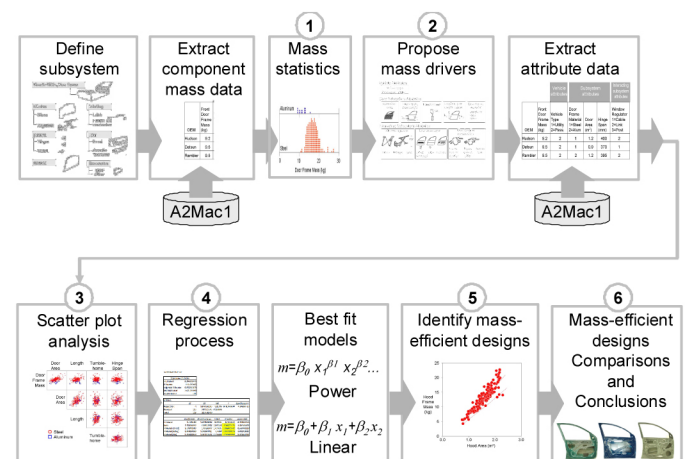


Figure 3. Mass benchmarking methodology.

The methodology begins by carefully defining the subsystem of interest and which parts are to be included. This definition should be based on a functional description of the subsystem to insure that like systems will be compared across vehicles. Mass data for this subsystem are then downloaded from the A2Mac1 database. Then the data are processed using the following steps:

1. First, we quantify mass statistics for the subsystem. These statistics included the mean, standard deviation, minimum and maximum mass unadjusted for vehicle type or subsystem attributes.
2. Next, we gain insight into mass drivers for each subsystem. Mass drivers are defined as attributes of the vehicle and subsystem which, to some degree, determine the subsystem mass [7]. In this work, a group of experts suggest attributes to test as potential mass drivers. Once these potential mass drivers are identified, the additional data is extracted from the database.
3. Scatter plot analysis is then done to visually gain insight into correlations among the potential mass drivers and system mass. This analysis provides insights into creating the regression model.
4. Regression is used to fit a model which estimates the subsystem mass based on the significant mass drivers.

Both a linear model, [Equation 1](#), and a power model, [Equation 2](#), are used:

$$\hat{m} = \beta_0 + \beta_1(\text{attribute}_1) + \beta_2(\text{attribute}_2) + \dots + \varepsilon \quad (1)$$

$$\hat{m} = \beta_0(\text{attribute}_1)^{\beta_1}(\text{attribute}_2)^{\beta_2} \dots \quad (2)$$

Where:

$\hat{m}$ =Estimated subsystem mass

β_i =Coefficients estimated by regression

Attribute_i =Value for mass driver i. For example, Door area.

ε =Residual error

5. After accounting for mass drivers, those subsystems with much lower than expected mass are identified. Each member of this set is reviewed to insure the lower mass is not due to errors in measuring or recording. (Refer back to [Figure 2](#) for the categories for sources of variation.) After passing this screening, these subsystems are taken to be mass-efficient designs and worthy of closer study.
6. Finally, we examine and compare the mass-efficient designs to understand the design features, material applications, and components which make these efficient. In this paper, we focus on comparisons of the mass-efficient steel designs with the mass-efficient aluminum designs.

3. EXAMPLE APPLICATION OF THE METHODOLOGY TO THE FRONT DOOR

In this section, we describe the application of this method for the front door as a detailed example. In [Section 4](#) we provide a brief description of results for other closures. The front door system

consists of the door frame, glass, linkages, door-side hinges, seals and trim, lock, mirror, and all mounting hardware. The door frame consists of the welded assembly of door inner and outer, window frame, door beam, and welded reinforcements as shown in [Figure 4](#).

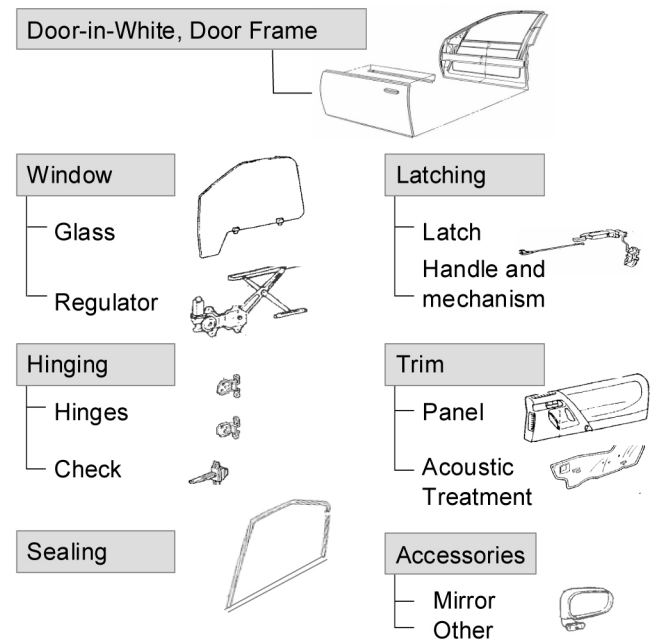


Figure 4. Definition of door system and door frame.

Subsystem mass and attribute data were extracted from the A2Mac1 database and loaded into a spreadsheet file. Each row of the spreadsheet contained data for one vehicle. An example of the abbreviated file for the door frame is shown in [Figure 5](#). The vehicle, subsystem, and interacting subsystem attributes are added after the initial analysis of door frame mass.

		Vehicle attributes	Subsystem attributes			Interacting subsystem attributes
OEM	Front Door Frame Mass (kg)	Vehicle Type 1=Utility 2=Pass.	Door Frame Material 1=Steel 2=Alum	Door Area (m ²)	Hinge Span (mm)	Window Regulator 1=Cable 2=Link 3=Post
Hudson	9.2	2	1	1.2	400	2
Datsun	9.5	2	1	0.9	370	1
Rambler	9.5	2	2	1.2	395	2

Figure 5. Example spreadsheet data organization.

Analysis of the Door Frame Structure

Once the door system mass data are loaded, the analysis follows the steps shown in [Figure 3](#).

In Step 1, descriptive statistics for door frame mass were generated using both Excel and Systat software [8]. These statistics, shown in [Figure 6](#), include mean, standard deviation, minimum, maximum, and

a dot-graph distribution for each material category (steel, aluminum). Note that these statistics, at this point in the analysis, were unadjusted for any attributes such as door area.

	Alum	Steel
N of Cases	16	201
Minimum	9.2	10.8
Maximum	15.5	27.2
Range	6.3	16.4
Average	11.7	17.0
Std. Dev.	1.8	2.6

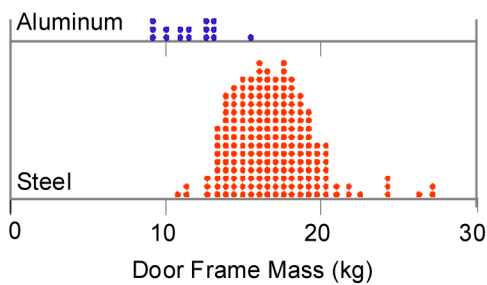


Figure 6. Descriptive statistics for door frame population.

Consideration of these descriptive statistics can offer some insight as to the range of mass variation seen in the market, and also facilitate identification of outliers so that they may be checked for error.

As can be seen from the figure, there are relatively few aluminum doors in the database, however there is a clear difference in mass between steel and aluminum. At this point the outliers seen in this plot were investigated for possible elimination based on any special causes which would make them unrepresentative of the population.

In Step 2 of Figure 3, attributes believed to have strong influence on the subsystem mass were identified by an expert team. Based on this engineering judgment, several attributes were hypothesized which may drive subsystem mass. For the door frame, those attributes are illustrated in Figure 7.

The attributes were categorized as follows:

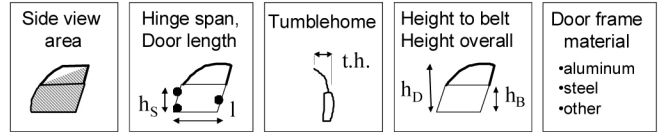
- Subsystem attributes-These include overall size of the door as described by the area, the hinge span and overall length due to the potential influence on door sag performance, tumblehome due to package influence on door width, height due to influence on door frame stiffness, and finally door frame material.
- Attributes of interacting subsystems-These include window regulator type and door beam type as these may drive mass into the door frame by requiring different mounting structure, and door-to-pillar construction due to the influence on the door frame area.
- Attributes of the vehicle system-These include type of vehicle-Utility or Passenger car-due to the influence on the performance

requirements of the door frame and thereby the door frame mass. Note that each system under study-door, hood, decklid, hatchback door-will have a unique set of attributes.

Vehicle Attributes

Vehicle type
Passenger, Utility

Door Subsystem Attributes



Interacting Subsystem Attributes

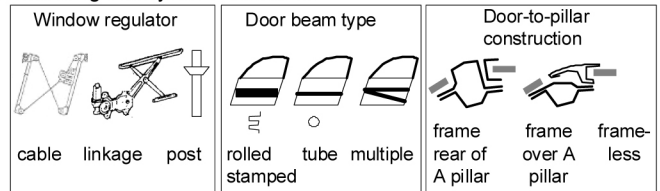


Figure 7. Attributes tested as mass drivers.

Once the potential attributes were identified, attribute data were extracted from the A2Mac1 database.

In Step 3 of Figure 3, we used a scatter plot matrix-SPLM- to visualize relationships between attributes which are quantified by continuous numbers. These plots were used to look for patterns between door frame mass and each attribute, and also to informally look for correlations between attributes. These latter correlations were used in the next step in fitting a descriptive equation to the data.

Figure 8 illustrates the SPLM for the door frame. Each square in the matrix is an x-y plot with the origin in the lower left corner. The x axis attribute is identified by the column label, the y axis by the row label. The full range of data for each attribute is shown in each graph. Specific numerical labels for each axis are not required as we are only looking for patterns in the data when using the SPLM.

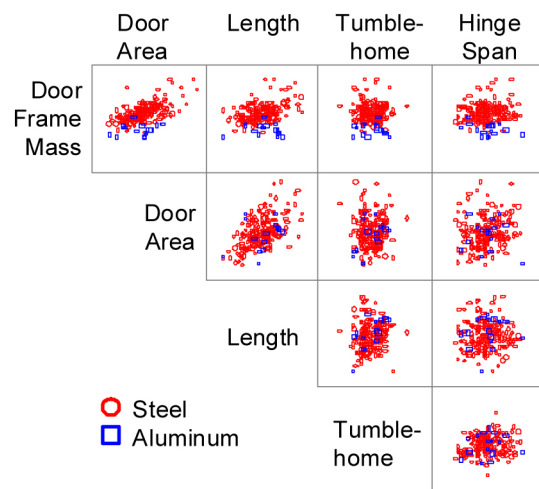


Figure 8. Scatter plot matrix for continuous attributes.