The Impact of Mass Decompounding on Assessing the Value of Vehicle Lightweighting

by

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Abstract

Among consumers and manufacturers alike, there is an increasing realization about the need for fuel efficient vehicles. One effective way to accomplish this is through vehicle lightweighting, which can be achieved by material substitution, novel vehicle component design, and changes in processing.

Although primary vehicle mass reduction is often associated with additional costs to the automaker, a decision to lightweight may, depending on when in the vehicle development process the decision is taken, result in additional secondary mass savings such that the value derived from lightweighting is greater than the costs.

In this study, the concept of secondary mass savings, or mass decompounding, is developed using regression analysis. Moreover, the full, both primary and secondary, mass savings potential is assessed at different times in the vehicle development process. Lastly, powertrain and market trend modeling are employed to estimate the value of the compounded mass savings in terms of improved fuel economy and acceleration.

This methodology is applied to a collected vehicle dataset in order to generate a model by which the value of and the subsystem-specific amount of secondary mass savings may be easily estimated during the early stages of vehicle development. In summary, this analysis may be employed to evaluate the economic competitiveness of vehicle lightweighting options at different times in the vehicle development process.

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Chapter 1

Introduction

There is a growing interest in automotive weight reduction, which to a large extent stems from the need for improved fuel efficiency and reduced emissions. Improved vehicle efficiency can be achieved in a number of different ways, including through improved engine and transmission efficiency, reduced aerodynamic drag, and decreased rolling resistance. However, the most effective means of achieving improved fuel efficiency is deemed to be by reducing the overall weight of the vehicle.

Realizing the still considerable potential for vehicle lightweighting, the automotive industry has focused much attention on reducing the weight of the various vehicle subsystems and subcomponents. Additionally, weight reduction in one vehicle subsystem can often allow for the downsizing or lightweighting of other vehicle components. Hence, great secondary weight savings can be achieved, which result in even further benefits of and motivations for automotive weight reduction.

1.1 Automotive Weight Reduction

Automotive manufactures have made substantial progress in vehicle weight reduction over the last 25 years. During this time, the average weight of a new automobile in the U.S. has dropped from over 2200 kg to 1500 kg. This large reduction in weight has been brought about largely by the downsizing of vehicles and by the elimination of unnecessary vehicle features [1].

This approach, however, is no longer sustainable due to consumer demand for improved automobile characteristics. Improved occupant safety systems and features, increased interior space, supplementary comfort-oriented accessories, reduced noise and vibration, and additional exhaust purification equipment have added significant weight to the vehicle and forced automakers to turn to alternative lightweighting strategies to reach vehicle lightweighting targets.

1.1.1 Motivations for Automotive Weight Reduction

Managing the total mass of a vehicle is recognized as a critical task during the development of a new automobile; specifically, because of the numerous economic driving forces for minimizing or optimizing the gross vehicle mass of a vehicle [2-4].

First, the recent increases in the price of gasoline and the subsequent importance of fuel economy in the minds of car buyers have lead vehicle manufactures to place renewed emphasis on increasing fuel efficiency and, by extension, on weight reduction. It has been shown that while improvements of 10% in vehicle aerodynamics or rolling friction provide a 3% fuel economy improvement, that same magnitude of mass reduction provides a roughly 7% increase in fuel economy [5]. Other studies have suggested fuel economy improvements in the range of 2% to 8% for a similar decrease in vehicle mass [6]. This topic is of high interest to the automotive lightweighting community and will be discussed in detail in Section 2.3.2. In addition to having a measurable effect on fuel economy, vehicle mass reduction has been shown to positively impact other vehicle attributes, such as acceleration performance, cost, durability, and ease of assembly [7].

Second, increased market competition and consumer demand for high-feature, high-performance vehicles pose additional pressure on auto-makers to minimize the weight of vehicle components. Targeted weight reduction becomes especially important in light of the non-negligible mass increases associated with additional features such as rear passenger entertainment systems, trailer towing packages, and powered seats and windows, as well as with more powerful engines. Safety enhancement features that are desired by the consumer, such as side impact air bag systems, stability control, and anti-lock brakes, also add to the overall weight of the vehicle [8].

Third, auto-makers may perceive direct incentives in reducing vehicle weight. There are immediate benefits in that lighter vehicles will require less raw material and may therefore cost less to produce, but also long term benefits in that lighter cars may be more durable and result in fewer warranty claims [7].

Lastly, there are a number of societal and legislative pressures motivating automotive weight reduction. The preservation of the environment and in particular concerns about air pollution, smog, global warming, waste disposal, and depletion of natural resources has a high priority today. Accordingly, many individuals and interest groups seek to persuade auto-makers to produce lighter and more fuel efficient automobiles with reduced emissions.

One example of legislative pressure is the Corporate Average Fuel Economy (CAFE) standard. During the peak of the oil crises in 1975, the U.S. government enacted the CAFE standards as part of the Energy Policy and Conservation Act [9]. The intent of CAFE was to reduce U.S. reliance on foreign oil through prescribed increases in the fuel efficiency of vehicles. Compliance is measured by calculating the fuel efficiency of an auto-maker's product line by a sales-weighted average formula and financial penalties are imposed for failure to comply with the regulations. Recently, Congress passed a bill that raises the fuel economy standards from today's 27.5 miles per gallon (mpg) for cars and 20.7 mpg for trucks to a 35 mpg combined corporate fleet sales average by year 2020. Consequently, automakers will be forced to respond by actively pursuing ways to improve the fuel efficiency of their vehicles, for instance through vehicle weight reduction.

Alternatively, automakers may pay a penalty fee in lieu of meeting the CAFE standards. The current penalty for failing to meet CAFE standards is $5.50, per tenth of a mpg under the target value, times the total volume of those vehicles manufactured for a given model year [10]. Should the automaker's fleet average, on the other hand, surpass the established standard for a given year the firm earns CAFE "credits." The CAFE credits can be used to offset deficiencies in future years' CAFE performance.

In spite of the option to pay a penalty fee, the CAFE program has been shown to contribute positively to increasing the fuel economy of the U.S. light-duty vehicle fleet. The CAFE program has been particularly effective in keeping fuel economy above the levels to which it might have fallen otherwise, especially during the decline in gasoline prices in the early 1980 s [11]. In turn, the improved fuel economy has helped to reduce U.S. dependence on imported oil and to reduce carbon dioxide emissions. If the fuel economy had not improved, gasoline consumption has been estimated to be about 114% of what it is today [11].

There are also several international agreements that affect vehicle emissions, such as the Kyoto Protocol. In 1997, as part of the United Nations Framework Convention on Climate Control (UNFCCC), 36 developed nations agreed to reduce their greenhouse gas emissions by a combined amount of 5% from 1990 levels by the years 2008 to 2012 [12]. One of the six particularly targeted gases is carbon dioxide, which places further emphasis on the need for increased automotive fuel efficiency and greater weight reduction.

An even more recent example is WP.29. Since 1958, Europe has had a coordinated set of regulations known as the United Nations/European Economic Commission (UN/EEC) Working Party on the Construction of Vehicles (WP.29). In 2000, however, an agreement signed by the governments of the United States, Canada, Japan, Germany, France, the United Kingdom, Russia, and the E.U., transformed WP.29 to a global entity known as the World Forum for Harmonization for Vehicle Regulations [13]. This international set of automotive standards, which includes restrictions on emissions of hydrocarbons, nitrogen oxides, and carbon monoxide released into the atmosphere during incomplete combustion of fossil fuels, may force all automakers to consider additional methods of weight reduction.

1.1.2 Methods of Automotive Weight Reduction

There are many different methods of automotive weight reduction, most of which fall into one of the following three categories: material substitution in favor of lighter or lower density materials, design changes aimed at optimizing, improving, or eliminating different vehicle components, and novel processing techniques. A few examples of automotive weight reduction technologies are listed in Table 1-1.

Table 1-1: Examples of targeted material substitution, design modifications, and novel processes that may be employed in vehicle lightweighting [14].

Lightweighting Technology
Material Substitution
High strength steel optimization of the body structure
Utilization of carbon fiber in the underbody
Switching to a die cast aluminum engine block
Design Change
Seat frame shape optimizations
Reduced engine wall thickness
Instrument panel optimization
Minimized feature tires and wheels
Body structure joint improvements
Suspensions shape optimization
Downgauging of the fuel tank
Novel Processing
Tailor-welded blanks for the closure panels
Aluminum super plastic forming

Material Substitution

The primary material for use in automobile body manufacturing has typically been mild steel, but manufactures are now investigating applications utilizing alternatives such as advanced high-strength steel (AHSS). AHSS is considered an enabler in terms of part shape and design optimization. Although inferior to mild steel, the formability of AHSS is superior to regular high strength steels. The improved formability permits designs that increase the vehicle mass efficiency by placing the materials where they are most effective at achieving performance requirements with minimum mass [15].

In addition to AHSS, other alternative materials such as aluminum, titanium, magnesium, and composite materials are also being looked to as a means for reducing vehicle mass. Although the mass-saving potentials of these materials have been long known to the auto industry, the lack of cost-competitiveness, as well as difficulties with parts production and assembly using these materials, has prevented them from being considered for large scale production vehicles. Today's higher fuel costs and increased emphasis on improving fuel economy, however, may be sufficient to offset the higher costs [5].

Design Changes

Downgauging, parts elimination, and other design changes that result in reduced material usage are also effective means of reducing the overall weight of the vehicle. Even parts consolidation may achieve this goal if it makes the constituent parts interface simpler, thus reducing the need for additional brackets, connectors, and other vehicle subcomponents.

One such example involves a hybrid bumper system, whose main components are the impact beam, the fascia, and the step pad. A hybrid bumper system is devised to combine the high strength and stiffness of steel with the design flexibility of thermoplastics. By integrating these parts and material properties, higher bending stiffness and reduced total mass can be achieved, while satisfying the structural requirements of the bumper system [16].

Novel Processing Techniques

Novel processing, manufacturing, and assembly techniques should also be considered when investigating lightweighting strategies. New processing techniques may help to reduce vehicle mass by enabling novel, more elaborate, and leaner designs. One example of a novel processing technique is tailor rolling technology, which presents the opportunity to reduce vehicle weight by varying the thickness of the steel in a continuous manner. This allows the material thickness to be adjusted exactly to meet the material performance required for the part [17].

1.1.3 Barriers to Automotive Weight Reduction

Although the motivations for and benefits of automotive weight reduction are plentiful, a number of barriers exist to the development of lighter, more stream-lined, and mass-efficient vehicles. First, consumers seem to value larger and more high-tech vehicles, which has resulted in a trend of increasing new vehicle weight in the U.S., as shown in Figure 1-1. A net increase of 1% annually has also been demonstrated in the weight of new European vehicles [4, 5].

Second, safety is a big concern. Although lighter-weight vehicles are engineered to be structurally equivalent and to meet the same structural requirements as their heavier counterparts, there is a common perception that lighter-weight vehicles are less safe [18].

Another limiting factor is the rate of development of new enabling technologies and strategies in the domain of lightweight materials, processing, and design. Without cost and resource effective means of achieving lighter vehicles, automotive mass reduction is not possible.

Lastly, a significant barrier to automotive weight reduction is the cost to the automaker. Unless vehicle lightweighting results in some kind of positive value proposition for the automaker, it is not likely to occur. Ultimately, the growing desire for lightweight designs must be balanced against economic considerations.

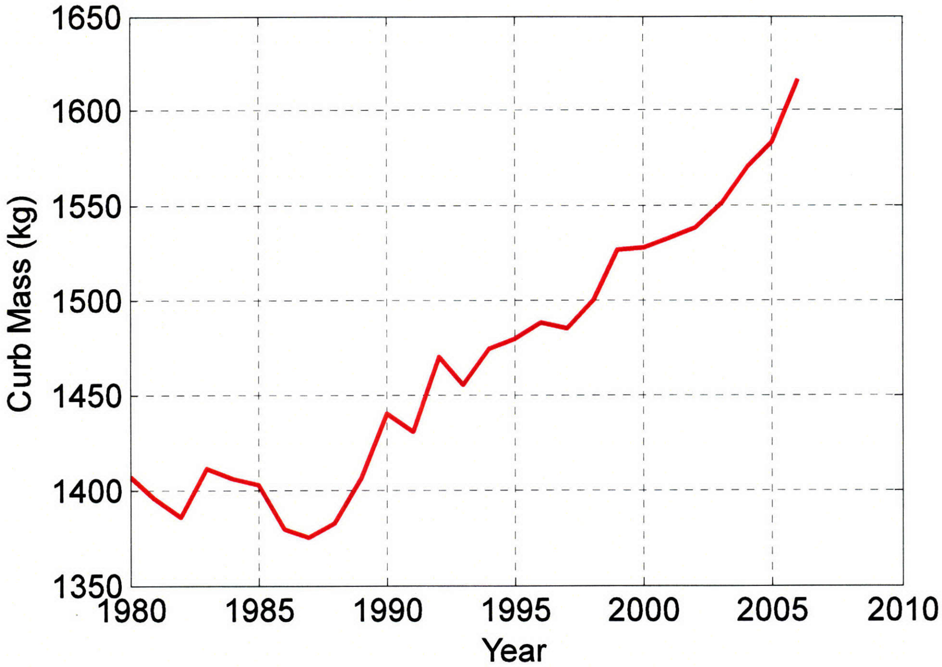


Figure 1-1: Increasing trend in automobile curb mass since 1980.

1.2 Importance of the Secondary Mass Effect

The current emphasis on reducing the weight of existing and new vehicle designs makes an understanding of the secondary effects of vehicle mass changes particularly important. If the full effects of vehicle lightweighting are to be realized and the full benefits are to be gained, it is essential to be able to identify and quantify the secondary mass that may be saved in the various vehicle subsystems or subcomponents as a result of primary weight reduction.

The secondary weight savings may be considerable and may help to turn the economic argument in favor of automotive lightweighting. Realizing the full, both primary and secondary, mass savings potential results in higher automotive mass- and fuel-efficiency, which translates into higher consumer value.

A detailed analysis of secondary mass savings necessitates a better understanding of the subsystem mass interdependencies and a quantification of the subsystem-specific mass decompounding effect. However, because of the complex nature of many of the factors and design considerations that govern vehicle weight, the specific details of how vehicle mass changes result in further vehicle mass changes are not well understood. Furthermore, the procedure to estimate the subsystem-specific secondary mass savings may be costly and time consuming, as large amounts of input data and design information about a specific lightweighting strategy may be required. Therefore, the approach taken in this study has been to collect the required and diverse sets of inputs and present a methodology by which the secondary mass savings may be easily estimated during the early stages of a vehicle development program.

1.2.1 Concept of Secondary Weight Savings

The concept of secondary weight savings derives from the qualitative understanding that "mass begets mass," which exists in many manufacturing industries [19]. As vehicle weight increases, the weight of tires, wheels, suspensions, brakes, steering, and structure must also increase to provide the same level of performance and function. Moreover, as vehicle weight increases, the engine size and drivetrain torque capacity need to increase to maintain equivalent acceleration performance and functionality.

This empirical effect has also been observed to work in reverse, allowing for secondary weight to be saved as a result of any primary weight reduction. For instance, following a primary weight reduction somewhere in the vehicle, the designs of all the other vehicle subsystems (tires, suspensions, powertrain, body structure) may be updated to account for the overall lighter vehicle. The lighter vehicle is associated with lighter loads, less friction and drag, and requires less power to be accelerated.

By establishing how the masses of the different subsystems of the vehicle depend on the total weight of the vehicle, it is possible to calculate and provide estimates of the amount of secondary mass that could be saved in any given subsystem following primary vehicle lightweighting.

1.2.2 Importance of Timing

A vehicle is an integrated set of subsystems, each made up of many individual components that go through stages of design, development, and validation. Generally, vehicle requirements define subsystem requirements, which in turn define component requirements. Components designed, developed, and validated to meet the top level requirements are combined into subsystems, which are developed and validated before coming together as a vehicle.

The complex interdependent tasks put pressure on design deadlines to ensure that the vehicle development project finishes on time. In particular, the design of certain subsystems must be locked in before that of certain other subsystem designs. For example, many components in the vehicle depend on the design details of the powertrain to be employed in the vehicle. Therefore, it is paramount that the powertrain design be fixed early on in the vehicle development process. Design decisions regarding other subsystems, such as exterior styling and finishing, however, do not play as important a role in impacting the design decisions of the rest of the vehicle and may therefore become locked in relatively later in the development process.

Since the secondary weight saving potential depends on the subsystem availability for re-engineering and design optimization, the vehicle development process timing becomes a key factor in quantifying the mass decompounding potential.

1.2.3 Cost and Value Proposition

As mentioned in Section 1.1.3, lightweighting can be expensive and the cost to lightweight often exceeds the economic value derived from primary lightweighting. When, on the other hand, the additional benefits of the secondary weight savings are taken into consideration, the cost and value proposition changes.

The cost to carry out primary lightweighting can be analyzed using a variety of different methods, included process-based cost modeling (PBCM). PBCM is a method that comprehends the technical requirements to run a process and attaches specific cost elements to each of the resources required. In doing so, it provides a means for estimating the costs of all inputs necessary to produce a part. Furthermore, because the cost is built up from the underlying resources and process requirements, the influence of changes to the production conditions, such as the production volume, on costs can easily be explored.

Also the cost of the secondary weight savings may be analyzed using PBCM. However, this is only possible if the details of the design changes that result in secondary weight savings are known.

The value of the secondary mass savings can be quantified using performance and market trend modeling. First, the mass-driven performance improvements, such as fuel economy and performance of the vehicle, may be analyzed through powertrain modeling. Second, the performance-driven increases in consumer value can be quantified using market modeling. In short, as the vehicle becomes lighter, its overall performance and by extension its associated consumer value increase.

1.3 Role of the Present Work

Based on the realization that a mass reduction in one subsystem can generate additional, secondary mass savings in other subsystems and thus help to sway the economic argument in favor of lightweighting, the present study was initiated in collaboration with leading automotive OEMs.

The "primary" weight savings is just a piece of the equation and is often insufficient (when considering the costs) to justify. But secondary weight savings could be significant and help to change the value proposition. A quantitative analysis of the magnitude of these secondary effects as well as of the influence of subsystem design deadlines in the vehicle development process are therefore needed to understand the full value of lightweight design strategies.

It is believed that a better understanding of secondary weight changes, both positive and negative, will be of importance during the early stages of vehicle planning and lightweighting. Furthermore, the cost and value proposition of mass decompounding is not well understood and will therefore be addressed explicitly in this study.

The goal is to be able to analytically determine and quantify the subsystem-specific secondary weight savings and to estimate their importance for vehicle lightweighting at different times in the vehicle development process.

1.3.1 Relationship to Prior Work on Secondary Weight Savings

To date, there are few publications on the topic of secondary mass savings, but some papers quote industry "rules of thumb," where the mass decompounding potential is expressed as a fraction of secondary to primary mass saved. Ten recent mass decompounding figures, ranging from as low as 23% to as high as 150% for sedan class automobiles, are summarized in Table 1-2. The quoted numbers imply that for every one kilogram of primary mass saved in the vehicle, an additional 0.23 kg to 1.50 kg, respectively, may be saved in secondary mass.

While these estimates may provide a very rough estimate of the expected amount of secondary mass that can be saved, they do not provide sufficient granularity or accuracy for more detailed vehicle mass prediction. Moreover, the large range in these numbers indicates that there is no consensus about how much secondary mass savings can be achieved. Therefore, in order to assist in vehicle benchmarking and mass target setting and to provide a valuable means for comparing different lightweighting options, estimates that specifically relate to vehicle class and subsystem type are needed.

One detailed set of approaches to mass prediction and estimation was discovered in literature pertaining to the aircraft and missile industries. There, physical relationships are used to predict the mass properties of each component of the craft, based on the requirements on performance, reliability, cost, and technical feasibility that the component needs to meet. One recent study outlines the method to measure the inertia properties of different subsystems in a vehicle. Knowing these properties allows for more accurate descriptions of the structural integrity requirements placed on each subsystem [20]. The systems engineering role in mass management is also emphasized to ensure that any changes in gross vehicle mass are communicated to and optimized for at the subsystem levels [21].

In a large automotive vehicle program, however, it is a challenging task to obtain all the necessary mass information to make decisions regarding potential weight savings on a per subsystem basis; moreover, the above approach does not directly lend itself to vehicle mass target setting and estimation in the early development phases.

One study that addresses this issue was commissioned by the Auto/Steel Partnership [14]. This report models the subsystem-specific mass decompounding behavior using statistical regression analysis. The study employs mass data from 15 sedan vehicles to determine the subsystem-specific mass decompounding coefficients, which are presented in Table 1-3. The conclusions from the analysis suggest that 1.5 kg of secondary mass may be saved for every 1.0 kg of primary mass saved in the sedan vehicle.

The methodology proposed by the Auto/Steel Partnership study is interesting and appropriate; however, the statistical nature of the analysis warrants the use of a larger input dataset and a thorough investigation into the presence of any outliers. Moreover, in order to be able to predict secondary mass savings, it is important to breakdown the vehicle into its most basic subcomponents in order to decide which masses may or may not be subject to mass decompounding. Lastly, the study suggests a methodology for finding the expected value of the mass decompounding coefficient; however, the confidence bounds on the mass decompounding coefficient are not presented.

In order to address these points, the current study is based on an extended dataset of 52 vehicles. Careful statistical analysis is also performed to remove any misguiding outliers. Next, the mass decompounding potential of the vehicles is assessed on a very granular level in order to ensure consistent and accurate analysis. Moreover, the present study will take uncertainty into account in order to find the confidence bounds of the mass decompounding potentials. In addition, this study will incorporate the time-dependency of the mass decompounding coefficients and also discuss and asses the cost and value proposition of mass decompounding.

Table 1-2: Recently published studies that estimate the mass decompounding potential for automobiles.

Author	Association/Journal	Decompounding Potential
Bertram, M. [22]	International Aluminum Institute	23%
Zengen, K. H. [23]	European Aluminum Association	48-51%
Lovins, A. B. [24]	Rocky Mountain Institute	50%
Lorenz, D. [25]	Advanced Materials Research	50%
Das, S. [26]	Resources, Conservation, and Recycling	50%
Karabin, L. [27]	Automotive Aluminum	68%
Asnafi, N. [28]	Materials Processing Technology	50-80%
Malen, D. [14]	Auto/Steel Partnership	150%

Table 1-3: Subsystem-specific mass decompounding coefficients from the Auto/Steel Partnership study.

Subsystem	Decompounding Potential
Powertrain	67%
Body Structural	33%
Rear Suspension	22%
Tires & Wheels	12%
Front Suspension	9%
Braking System	7%
Bumpers	-
Body Non-Structural	-
Fuel & Exhaust	-
Steering	-
Electrical	-
Cooling	-
Closures	-

1.3.2 Research Objectives

The aim of this research is to suggest a methodology for considering secondary mass savings when analyzing the value of different lightweighting options. The secondary mass savings potential for the sedan vehicle category will be analyzed using statistical regression analysis. Furthermore, vehicle development timing data will be employed to determine the time-dependency of the mass decompounding potential. The value will be calculated in terms of mass-driven performance improvements and performance-driven consumer value increases at different times in the vehicle development process. The ultimate goal is to develop a tool that can support mass target decisions and provide guidance during the process of selecting and implementing different lightweighting options.

To achieve this aim, three key research questions have been addressed:

1. How can the subsystem-specific secondary mass savings be quantified?
   A quantification of the mass decompounding coefficients is important in order to advise designers on actual opportunities for lightweighting.

2. How does timing of the primary mass saving impact the potential for secondary mass savings?
   An understanding of how the timing of the primary mass saving impacts the potential for secondary weight savings is crucial for the assessment of the cost and value of lightweighting.

3. How can the value of secondary mass savings be measured? Specifically in terms of:
   - Mass-dependent vehicle performance improvements, such as acceleration time and fuel economy; and
   - Performance-driven consumer value increases.

An analysis of the value of lightweighting, taking secondary mass savings into account, is necessary because if there is no positive value proposition involved, the interest in secondary mass savings will be very low.

The findings from the above research questions will be combined into a spreadsheet model that can be employed to calculate the compounded value of lightweighting at different times in the vehicle development process, taking the subsystem-specific secondary mass savings into account

1.3.3 Thesis Outline

The work, alluded to in Section 1.2, consists of three parts that will be combined into one model: derivation of the mass decompounding coefficients, incorporation of the subsystem design timing, and assessment of value. The procedure for creating the model was established first. This task, outlined in Chapter 2, involved understanding the equations and necessary statistical methods needed to connect the separate parts. The collection, refinement, and transformation of the raw data were also part of this task. Next, the information was converted into an accessible format with an interface for easy definition and execution of case studies. This is explained in Chapter 3 together with a case study of different sedan vehicles, for facilitated interpretation of the results. Initial sensitivity studies were then conducted to assess the robustness of the model. These results are presented and discussed in Chapter 4. Next, an emphasis was put on improving the accuracy and user-friendliness of the model and some time was dedicated to the analysis of the model outputs (also Chapter 4). Lastly, the findings were summarized and presented in Chapter 5. The conclusions were drawn with a number of audiences in mind – including the academic, who may be interested in the modeling methodology, and the industry-oriented, who may be thinking about ways to evaluate and gain full benefit of lightweighting through secondary weight savings. Future work is also presented in Chapter 5.

Chapter 2

Analytical Approach

This chapter will outline the method used and data needed to construct the model; in particular, it will describe in detail the relationships that govern the secondary mass savings, timing, and cost and value calculations.

First, the data and the equations used to calculate the mass decompounding will be discussed. In this study, an empirical approach will be adopted to establish the relationship between the primary mass savings and the expected subsystem-specific secondary mass savings according to

$$\Delta\text{mass}_{\text{secondary}} = f\left(\Delta\text{mass}_{\text{primary}},\ \text{subsystem, vehicle category}\right) \tag{2.1}$$

Where $\Delta\text{mass}_{\text{primary}}$ and $\Delta\text{mass}_{\text{secondary}}$ are the primary and secondary mass changes, respectively, *subsystem* refers to the particular subsystems that are being considered for secondary mass savings, and *vehicle category* refers the sedan, SUV, cross over, or pick-up vehicle group. In this study, the mass decompounding analysis will be limited to the sedan vehicle category, but future studies could investigate how the secondary mass savings vary by vehicle category.

Second, the method used to incorporate the subsystem timing information will be explored. Data from the vehicle development process will be employed to obtain a time-varying mass decompounding potential. Consequently, this step in the analysis will add *time* as one of the independent variables in (2.1), yielding

$$\Delta\text{mass}_{\text{secondary}} = f\left(\Delta\text{mass}_{\text{primary}}, \text{ subsystem, time}\right) \tag{2.2}$$

for the sedan vehicle category.

Third, the process to assess the cost and value of the compounded mass saving will be discussed. In particular, value will be quantified using powertrain modeling, to calculate the mass-dependent performance improvements, and market modeling, to estimate the performance-driven consumer value increases. In this analysis, fuel economy and acceleration will be targeted as the key performance metrics. By fuel economy is meant the number of miles a vehicle can drive per gallon of gasoline and by acceleration the number of seconds it takes for the vehicle to accelerate from 0 to 60 miles per hour.

First, the form of the following relationships will be investigated

$$\begin{gathered}\Delta\text{FE} = f\left(\Delta\text{mass}_{\text{total}}, \text{ powertrain}\right)\\ \Delta\text{ACC} = f\left(\Delta\text{mass}_{\text{total}}, \text{ powertrain}\right)\end{gathered} \tag{2.3}$$

where ΔFE and ΔACC are the changes in fuel economy and acceleration, respectively, and $\Delta\text{mass}_{\text{total}}$ is the sum of the primary and secondary mass savings. The variable *powertrain* refers to the specific combination of engine and transmission that is being modeled and could, for instance, distinguish between 4-, 6-, and 8-cylinder engines and manual vs. automatic transmission. For this study, the analysis will focus on three powertrain combinations typical to compact, midsize, and large sedan automobiles.

Second, market modeling will be employed to convert the changes in fuel economy and acceleration determined in (2.3) into consumer value

$$\begin{gathered}\Delta\text{value}_{\text{FE}} = f\left(\Delta\text{FE}, \text{ vehicle type}\right)\\ \Delta\text{value}_{\text{ACC}} = f\left(\Delta\text{ACC}, \text{ vehicle type}\right)\end{gathered} \tag{2.4}$$

where $\Delta\text{value}_{\text{FE}}$ and $\Delta\text{value}_{\text{ACC}}$ are the additional dollar values that the consumer is willing to pay for improvements in fuel economy and acceleration, respectively, for a particular *vehicle type*. Vehicle type refers to a subset of automobiles, in a particular vehicle category, such as the compact, budget, sport, or large type sedans. In the present study, which focuses on sedans, the analysis will be segmented into three mutually exclusive vehicle types: compact, midsize, the large. This choice of vehicle types will allow for seamless integration with the results from (2.3).

Lastly, to obtain a measure of the cost, the results of process-based cost modeling will be incorporated. Process-based cost modeling can be used to find the estimated cost of a lightweighting strategy according to

$$\Delta \text{cost}_{\text{primary}} = f\left(\text{design, material, processing, production volume, ...}\right) \tag{2.5}$$

where $\Delta \text{cost}_{\text{primary}}$ is the change in cost associated with performing vehicle lightweighting.

Chapter 2 will emphasize the logical connection between the three main parts, as illustrated in Figure 2-1. It will also lay the foundations for the work described in Chapter 3, where equations (2.1) through (2.4) will be combined into a model that can be used to find the net worth of lightweighting, taking secondary mass savings into account.

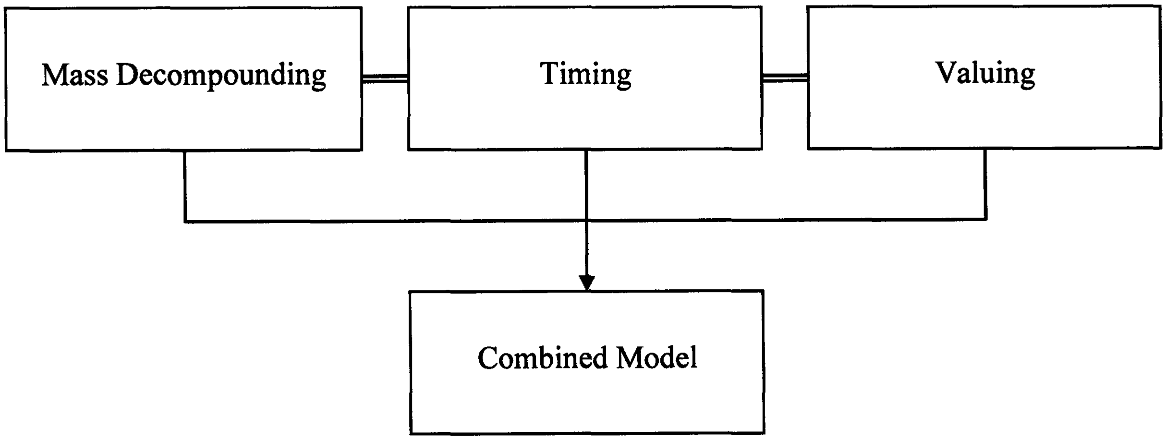


Figure 2-1: Overview of main model components and their interconnection.

2.1 Mass Decompounding

There are multiple methods that may be applied to obtain a measure of the subsystem-specific potential for mass decompounding. One approach might be to employ first principles to understand how reductions in gross vehicle mass affect the masses of the subsystems. To that end, mathematical models based on the subsystem inertial properties, such as the centre of gravity locations and the inertia tensors, could be built to explain the mass-dependent interaction forces between subsystems and to understand exactly how the masses of the various subsystems depend on each other. This approach might give accurate predictions of what could be achieved in theory; however, the inertial properties of a vehicle are almost impossible to compute [20], and the process to do so is time consuming and requires many inputs about the vehicle system. Moreover, due to the complex interactions of the parts and the numerous vehicle requirements that must be met, it may even be impossible to analytically understand all the necessary mechanical relationships, especially since some physical relationships can only be met through testing.

Another approach is to use empirical analysis to determine how the different subsystem masses are expected to change given a change in the overall weight of the vehicle. This may be done through statistical regression analysis of large sets of current vehicle mass data, which results in good estimates of what is currently done in practice. Once the analysis is complete, only a small number of inputs, specifically the change in total vehicle weight, are needed to determine the secondary mass savings. This is of importance, since successful lightweighting will invariably lead to a decrease in total vehicle mass.

There are also a few drawbacks to using statistical regression analysis. First, statistical analysis may be associated with larger uncertainties due to the inherent variance and covariance of the mass data. Furthermore, statistical approaches do not analyze causality. Consequently, the cause and effect or the underlying reasons for the secondary weight savings are not accounted for. Nonetheless, regression analysis provides an effective means of estimating the amount of secondary savings that may be gained in a subsystem given a primary lightweighting of the vehicle.

Based on the above reasoning, the empirical approach was chosen for this study and the method used to find the subsystem-specific mass decompounding potentials for the sedan class vehicle will be outlined here. The process involves finding the subsystem-specific mass influence coefficients from a processed mass dataset in order to subsequently estimate the mass decompounding coefficients for the vehicle subsystems. Some discussion will also follow regarding the covariance of the mass data and its impact on the results of the analysis.

2.1.1 Mass Dataset

The first step to statistically determine the subsystem-specific mass decompounding coefficients is to gather appropriate vehicle mass data. The dataset needs to be sufficiently specific and contain a sufficiently large number of observations to allow for general conclusions to be drawn. In particular, detailed and consistent subsystem mass information is needed.

To gather the subsystem mass information, vehicle teardown centers at large North American automakers were consulted. At the teardown centers, automakers reverse engineer their opponents' most recent vehicles in order to discover design details, down to the weight and production cost of the smallest subcomponents of the vehicle [29]. Vehicle teardown studies are a way for the automakers to understand how their competitors' vehicles are manufactured and assembled and to gain ideas about how to save money on and reduce the weight of vehicle subcomponents. Insights gained from teardown studies also help executives make long-term strategic decisions about future technologies. For instance, a tear down of the 2004 Prius played a role in GM's decision to target hybrid development in trucks and buses, instead of in sedans, while focusing its innovation efforts on fuel cells [29].

A full teardown takes about six weeks [29]. First, all the vehicle's dimensions are measured, such as the bumper height and the distance from the driver's eyes to the steering wheel. Next the car is disassembled into its smallest subcomponents. Each part is analyzed, named, and weighed. Finally, all the information is entered into a vehicle mass data file for future use.

For the purposes of this study, such data files were obtained for 52 sedans, 2007 to 2008 year models. The data files contain mass information at a granularity of about 250 to 260 subcomponents per vehicle. The files were consolidated and a master data table containing all the mass information for each of the 52 vehicles was created.

The main advantage of obtaining mass data from this source is that the data are detailed and include mass information for vehicle subcomponents at a sufficiently granular scale to allow for facilitated processing, grouping, and mass decompounding analysis. Moreover, these mass data files already exist at the automakers which precludes the need to institute a new mass data collection procedure.

In order to make additional inferences about the mass data, vehicle attribute information was also compiled for each vehicle. The vehicle attribute information was gathered from public as well as auto-industry specific sources. A summary and breakdown of common vehicle attributes for the collected dataset are shown in Table 2-2 and in Table 2-1.

Table 2-1: Minimum, maximum, and average values of price, acceleration, and fuel economy for the collected vehicles.

Attribute	*Average*	*Min*	*Max*
Price	$29,000	$13,700	$60,000
Acceleration (sec)	7.53	5.33	10.15
Fuel Economy (mpg)	21.11	15.93	25.60

Table 2-2: Overview of the spread of the 52 collected vehicles across common attribute categories.

Number of Cylinders	*Frequency*
Four	10
Six	32
Eight	10
Planview Area (m^2)	*Frequency*
$< 8\ \text{m}^2$	7
$< 9\ \text{m}^2$	36
$< 10\ \text{m}^2$	11
Drivetype	*Frequency*
Rear wheel drive	19
Front wheel drive	33
Transmission	*Frequency*
Manual	11
Automatic with manual override	20
Automatic	21

2.1.2 Subsystem Breakdown

The next step in the process to quantify and understand the mass decompounding effect was to analyze the distribution of mass across the various subsystems of the vehicle. This was done by classifying each vehicle subcomponent into larger categories or subsystems.

There are many different ways in which the vehicle subcomponents can be categorized, including by function, by parts-commonality, and by spatial orientation. For this study, a functional classification system was adopted for two reasons. Firstly, the mass data sheets from the tear down centers provide subsystem mass information organized by sub-function. Secondly, the decision-making process about vehicle design is oftentimes based on the functional characteristics of the vehicle rather than other breakdowns. In collaboration with engineers in the automotive industry, a mass breakdown into thirteen major functional subsystems was decided upon, as presented in Table 2-3. Table 2-3 also displays the percentage of curb mass – the sum of all the subsystem masses – made up by each subsystem.

Table 2-3: Functional subsystem breakdown and average percentage of curb mass made up by each functional subsystem.

Subsystem	Curb Fraction
Structure	25%
Interior	12%
Engine	11%
Suspensions	10%
Closures	10%
Tires & Wheels	6%
Fuel & Exhaust	6%
Transmission	6%
Exterior	5%
Electrical	3%
HVAC	3%
Steering & Brakes	2%
Info & Controls	1%

More information about the breakdown and the subcomponents contained in each functional subsystem can be found in Table 2-4.

Table 2-4: Detailed information about the subsystem mass breakdown and vehicle subcomponent breakup used in the study, outlining the main vehicle subcomponents included in each subsystem.

Exterior	Transmission
Windshield	Manual Transmission
Window	Automatic Transmission
Fascia	Tires & Wheels
Impact Bar	Tires
Grille	Wheels
Energy Absorber	Wheel Trim
Suspensions	Engine
Front Suspension	Engine
Rear Suspension	
Structure	Interior
Full Frame	Instrument Panel
Mounts	Seats
Body Structure	Airbags
Fuel & Exhaust	HVAC
Air Cleaner	Heating
Exhaust System	Ventilation
Fuel Tank	Air Conditioning
Steering & Brakes	Closures
Steering Shaft	Fenders
Steering Column	Door
Park Brake	Hood
Brake Apply	Decklid
Electrical	Info & Controls
Sensors	Switches
Generator	Speakers
Battery	Antenna
Power Converter	Entertainment System

2.1.3 Subsystem Mass Dependency on Gross Vehicle Mass

In order to estimate the secondary mass savings potential, it is important to separate the structural, or load-bearing, subsystem mass from the non-structural subsystem mass. Exclusively the subsystem mass that bears a physical relationship to the overall weight of the vehicle will be affected by lightweighting and, by extension, subject to mass decompounding. For instance, as gross vehicle mass (GVM) increases, only the masses of certain subcomponents of the vehicle, such as the impact bar and the energy absorber, need to increase to sustain the loads of the heavier vehicle. Correspondingly, these same subcomponents, which are deemed to have a dependency on GVM, are also believed to be associated with secondary mass savings, when the overall weight of the vehicle is reduced. The masses of the non-GVM dependent subcomponents, however, are believed to remain constant during vehicle lightweighting. Examples of such subcomponents include the seats, the doors, and the instrument panel of the vehicle.

As alluded to above, GVM is employed as the independent parameter in determining the mass-dependence of the functional subsystems. GVM, as opposed to any other measure of vehicle weight, such as curb mass, was selected because of the theory that every vehicle component is designed to carry the loads of the vehicle when it is at its heaviest, including not only the weight of the subsystems, but also the weight of the passengers and the cargo. GVM is defined as

$$GVM = \text{curb mass} + \text{passenger mass} + \text{cargo mass} \tag{2.6}$$

The curb mass is the sum of the masses of the vehicle subsystems, including both the GVM-dependent and the non GVM-dependent mass. The passenger mass can be found by multiplying the passenger rating for each vehicle by the dummy weight of 68 kg, which is used to estimate passenger weight in the auto industry. Lastly, the cargo mass can be estimated from a regression equation that uses an average density of cargo to convert cargo volume into cargo mass

$$\text{cargo mass} = 0.155 \cdot (\text{cargo volume}) + 4.20 \tag{2.7}$$

where cargo mass and cargo volume are measured in kilograms and liters, respectively.

In classifying the subsystem mass dependency on GVM, each constituent subcomponent was reviewed in collaboration with automotive mass engineers and classified as either GVM-dependent or non GVM-dependent. Next, the GVM-dependent mass-fraction was found for each subsystem. As an example, this process is illustrated in Table 2-5 for one of the subsystems, the Steering & Brakes. Moreover, to give an overview, the amount of GVM-dependent mass per subsystem, averaged across the entire dataset, is summarized in Table 2-6.

As can be seen in Table 2-6, 66% of total vehicle curb mass was classified as GVM-dependent. The remaining non-GVM dependent mass was made up in large by the Interior, Info & Controls, Closures, Fuel & Exhaust, and HVAC subsystems, which were judged to have no dependency on GVM. This implies that the masses of these subsystems do not necessarily need to change as a result of a change in GVM. On the other hand, large fractions of the masses of the Suspensions, Engine, Tires & Wheels, Transmission, Structure, Electrical, and Exterior subsystems were classified as having a physical relationship with the overall weight of the vehicle. These eight subsystems will be important for subsequent analysis of the mass decompounding potential of the sedan class vehicle.

Table 2-5: Determination of GVM-dependent subsystem mass and mass-fractions for the Steering & Brakes subsystem on the subcomponent level.

Steering & Brakes	GVM-dependent?	Subsystem-Mass Fraction
Front Steering	Yes	21%
Steering Intermediate Shaft	Yes	0%
Rear Wheel Steering	Yes	0%
Steering Column	Yes	36%
Front Brake Corner	Yes	2%
Rear Brake Corner	Yes	0%
Park Brake	Yes	11%
Brake Apply	No	13%
Brake Modulator	Yes	0%
Brake Pedals	No	9%
Brake Pipe/Hose/Tube	No	10%
Perimeter Cradles	No	0%
Front Crossmembers	No	0%
Rear Crossmembers	No	0%
GVM-dependent Mass Fraction		*70%*

Table 2-6: Subsystem-specific GVM-dependent mass fractions averaged across the collected vehicle mass dataset.

Subsystem	GVM-dependent Mass Fraction
Suspensions	100%
Engine	99%
Tires & Wheels	99%
Transmission	96%
Structure	86%
Steering & Brakes	70%
Electrical	37%
Exterior	21%
Interior	0%
Info & Controls	0%
Fuel & Exhaust	0%
Closures	0%
HVAC	0%
Total	66%

2.1.4 Ordinary Least Squares and Covariance of the Mass Data

As established in the previous Section, eight of the thirteen functional subsystems are judged to contain GVM-dependent mass. The next step in the analysis is to explore that dependency in more detail and to find the functional form of the equations that can be used to predict subsystem mass changes.

First, GVM emerges as a necessary explanatory variable in light of the overall goal to estimate the secondary mass savings from reductions in total vehicle mass. Therefore, the aim is to express subsystem mass as a function of GVM. However, this method raises some concern about the impact of other vehicle attributes and functional parameters on subsystem mass. In particular, it was questioned whether engine torque and planview area of the vehicle might be more important than lightweight designs in estimating the masses of the vehicle subsystems. In other words, it was believed that the fits of subsystem mass with GVM might be poor because of the additional effect of vehicle size and performance.

One way to account for this and to separate out the effects of changing torque and planview area on subsystem mass is segmentation. For instance, the mass data could be segmented into different planview area classes or by cylinder number. Nevertheless, as can be seen in Table 2-2, the mass dataset was judged to contain too few observations to yield satisfactory outcomes for statistical regression analysis when segmented. The samples resulting from subdividing the mass data into different functional parameter classes were not judged to be statistically significant representations of the total population and any conclusions drawn from statistical analysis of these samples might not be accurate.

Another approach to address the effect of numerous explanatory variables is to perform multiple regression analysis. Examination of the subsystem mass data indicates a mostly linear relationship between the subsystem masses and the proposed independent variables GVM, torque, and planview area. The linear relationships suggest that ordinary least squares (OLS) would be an effective method for capturing the functional dependencies of the subsystem masses on GVM, planview area, and torque.

OLS is a standard linear regression procedure that aims to minimize the sum of the squared residuals – the error between the true values and the model predictions. OLS estimation applies to a linear regression model of the form

$$Y_i = a_0 + a_1 X_{1,i} + a_2 X_{2,i} + \ldots + a_k X_{k,i} + \varepsilon_i \tag{2.8}$$

where Y_i is the i^th^ observation of the dependent variable, $X_{n,i}$ and a_n are the i^th^ observation and the regression coefficient of the n^th^ independent variable, respectively, and ε_i is the residual.

In order to be able to apply OLS, the assumptions of OLS must be satisfied. The five standard assumption of OLS are [30]:

- There is no correlation between explanatory variables and residuals, i.e.

  $\operatorname{cov}\left(X_{n,i}, \varepsilon_i\right) = 0$.

  Failure of this assumption results in biased estimates of the coefficients of the explanatory variable.

- The expected or mean value of the residuals equals zero, i.e. $E\left(\varepsilon_i\right) = 0$.

  Failure of this assumption results in biased estimate of the constant term.

- Residuals are homoskedastic, i.e $E\left(\varepsilon_i^{\,2}\right) = \sigma^2 = \text{constant}$.

  Failure of this assumption results in inefficient estimate and biased tests of the hypotheses.

- Residuals are independently distributed, i.e. $E\left(\varepsilon_i \cdot \varepsilon_j\right) = 0$.

  Failure of this assumption results in inefficient estimate and biased tests of the hypotheses.

- Explanatory variables are independent (no multicollinearity), i.e. $\operatorname{cov}(X_n, X_m) = 0$.

  Failure of this assumption results in inefficient estimate and biased tests of the hypotheses.

To ensure accurate application of the OLS method, the data was tested for each of the above five assumptions and found to satisfy the first four. The fifth assumption, however, is violated due to high correlation between the explanatory variables.

When a correlation coefficient between the independent variables is greater than 0.7, multicollinearity is identified as a potential problem [31]. Multicollinearity is an artifact of non-orthogonal predictor variables, which yields regression coefficients that are less reliable and have larger standard errors. Moreover, when the input variables are highly correlated, the presence of one input variable in the multiple linear regression model may mask the effect of another input variable, thus reducing its relative statistical significance and explanatory power. As shown in Table 2-7, the correlation coefficient between GVM and planview area is 0.75 and that between GVM and torque is 0.81; consequently, given the current set of independent variables, multicollinearity could reduce the accuracy of the analsyis.

One method that can be employed to address multicollinearity and to weed out highly correlated predictor variables is stepwise regression. Stepwise regression is a technique for choosing the variables to include in a multiple regression model. Forward stepwise regression starts with no model terms. At each step it adds the most statistically significant term, i.e. the one with the highest F-value, lowest p-value, or other measurement statistic, until the addition of another explanatory variable worsens the fit of the equation [32].

When stepwise regression was employed to model the present data, different sets of explanatory variables were selected for different subsystems. Moreover, due to the high correlations between GVM and torque and between GVM and planview area, GVM was rarely selected at the same time as either torque or planview area; therefore, GVM was not guaranteed to be one of the predictor variables.

As can be seen in Table 2-7, the subsystem mass of the Engine correlates strongly with torque. Consequently, the stepwise regression methodology would select torque rather than GVM as the statistically significant explanatory variable. The Transmission subsystem, on the other hand, was found to have a stronger correlation with planview area than with GVM, hence planview area rather than GVM would be selected as the independent variable by the step-wise regression method.

Due to the need to maintain GVM as a predictor variable and in light of the fact that using just GVM still gives good results, it was decided to exclude engine torque and vehicle planview area from the set of predictor variables and to perform ordinary least squares regression analysis on the entire dataset using GVM as the independent variable

$$\begin{aligned} \text{Engine Mass}_i &= \alpha_{eng} + \beta_{eng} GVM_i + \varepsilon_{eng,i} \\ \text{Transmission Mass}_i &= \alpha_{transm} + \beta_{transm} GVM_i + \varepsilon_{transm,i} \\ \text{Suspensions Mass}_i &= \alpha_{susp} + \beta_{susp} GVM_i + \varepsilon_{susp,i} \\ \ldots &= \ldots \end{aligned} \tag{2.9}$$

In other words, a projection of the hypothesized multiple linear regression model, onto the plane defined by subsystem mass and GVM, was employed in determining the subsystem-specific regression coefficients β_{eng}, β_{transm}, β_{susp}, etc.

This transformation of the data from a multi-dimensional space into a two-dimensional space does not invalidate the ensuing mass decompounding analysis; however, it does increase the apparent lack of fit in the regression models [32]. The lack of fit is demonstrated by larger coefficients of determination, R^2, and larger residuals, as will be described in more detail in the following sections.

Table 2-7: Correlation coefficients for the dependent and suggested independent variables; orange and red boxes indicate a correlation greater than 0.50 and 0.70, respectively.

	GVM	*Torque*	*Planview Area*	*Structure*	*Engine*	*Suspensions*	*Tires & Wheels*	*Transmission*	*Steering & Brakes*	*Electrical*	*Exterior*
Gross Vehicle Mass	1.00										
Torque	0.81	1.00									
Planview Area	0.75	0.66	1.00								
Structure	0.44	0.25	0.47	1.00							
Engine	0.75	0.85	0.60	0.17	1.00						
Suspensions	0.57	0.48	0.20	-0.17	0.55	1.00					
Tires & Wheels	0.47	0.55	0.43	0.39	0.48	0.04	1.00				
Transmission	0.46	0.37	0.71	0.59	0.23	-0.23	0.36	1.00			
Steering & Brakes	0.58	0.52	0.70	0.15	0.44	0.10	0.16	0.44	1.00		
Electrical	0.62	0.36	0.54	0.20	0.42	0.45	-0.02	0.23	0.61	1.00	
Exterior	0.54	0.56	0.34	-0.13	0.56	0.85	0.08	-0.14	0.14	0.45	1.00

In Table 2-7, several interesting correlations may be noted; in particular, the positive correlation between the Structure and Transmission subsystems, and the negative correlation between the Transmission and Suspensions subsystems. These correlations indicate that on the average the mass of the Structure subsystem increases when the mass of the Transmission increases, while an increase in the mass of the Transmissions is likely to lead to a decrease in the mass of the Suspensions, and vice versa. Similarly, a positive correlation exists between the Suspensions and the Exterior, while the correlation is negative between the Exterior and the Structure subsystems. In other words, the mass of the Suspensions generally increases as the mass of the Exterior subsystem increases, while the mass of the Structure decreases. This interplay between the subsystem masses suggests an intricate design decision trade-off, which may prescribe that if, for instance, the Exterior and Suspensions of a vehicle are relatively strong and heavy, the mass of the Structure subsystem may be lightweighted. However, this leads to a discussion of causality, which, as described earlier, may not be adequately explored using statistical approaches.

2.1.5 Mass Influence Coefficients

After having processed the initial mass dataset and established the functional form of the subsystem mass equations (2.9), it is possible to proceed with the mass decompounding analysis.

The mass decompounding potential of a vehicle can be described as a function of the mass influence coefficients, γ_i, of the GVM-dependent subsystems. The mass influence coefficients can be thought of as the incremental increase in GVM-dependent subsystem mass per unit increase in GVM, and can be expressed by the following equation

$$\gamma_i = \frac{d\left(\text{GVM-dependent subsystem}_i \text{ mass}\right)}{d\left(\text{GVM}\right)} \tag{2.10}$$

where i refers to a particular functional subsystem. As shown in (2.10), all subsystem-specific mass influence coefficients may be found from OLS regression analysis of the GVM-dependent subsystem masses against GVM.

The regression coefficients resulting from OLS, however, are very sensitive to the presence of outliers, as outliers may significantly skew the end results [33]. Therefore, before determining the subsystem-specific regression coefficients, an outlier detection process was established. In particular, any observation occurring outside of the 95% prediction interval [34]

$$\begin{aligned} 95\%\ \text{P. I.} &= \hat{z} \pm t_{\alpha,v} \cdot \sqrt{V(\hat{z})} \\ V(\hat{z}) &= \frac{1}{n} + \left[\frac{(x-\bar{x})^2}{\sum (x-\bar{x})^2} \right] \cdot s^2 \\ s^2 &= \frac{\sum (z-\hat{z})^2}{n-p} \end{aligned} \tag{2.11}$$

where $t_{\alpha,v} = t_{0.05,51} = 2.01$, $n = 52$, and $p = 2$, was identified, classified as an outlier, and removed from the dataset. An outlier occurring in any subsystem was removed from the entire dataset and excluded from all subsequent analysis. Some observations may appear as outliers in multiple subsystems. As shown Table 2-8, a total of seven outliers was detected using this methodology.

Table 2-8: Number of observations occurring outside of the 95% prediction interval, and by extension classified as outliers, for each subsystem.

GVM-dependent Subsystem	Number of Outliers
Structure	1
Engine	0
Suspensions	2
Tires & Wheels	1
Transmission	1
Steering & Brakes	2
Electrical	1
Exterior	0
Total	7

The processed mass dataset, excluding outliers, is displayed in Figure 2-2 to Figure 2-9 for the eight GVM-dependent subsystems. The remaining five subsystems were shown to not have a physical relationship with GVM and are therefore not included in the subsequent mass decompounding analysis. For comparison, the original dataset, without any outliers removed, is presented in Appendix A.

In Figure 2-2 to Figure 2-9, four graphs are displayed for each relevant subsystem. The two top graphs show the scatter of subsystem mass vs. GVM together with the OLS best-fit line, (2.8), in solid red and the 95% prediction intervals, (2.11), in solid green. Additionally, the 95% confidence interval [35]

$$\begin{aligned} 95\%\ \text{C. I.} &= \hat{\gamma} \pm t_{\alpha,v} \cdot \sqrt{V\left(\hat{\gamma}\right)} \\ V\left(\hat{\gamma}\right) &= \frac{s^2}{\sum x^2 - \left(\sum x\right)^2 / n} \end{aligned} \tag{2.12}$$

on the slope is plotted in dotted blue. The slope and the confidence interval on the slope are employed to find the expected value and the 95% confidence interval of the subsystem-specific mass influence coefficients.

As can be seen in (2.10), the mass influence coefficients are assumed to be constant, i.e. a linear relationship between the subsystem mass and GVM. Even if for some subsystems this relationship may appear non-linear, the present data are not significantly non-linear to require a different analysis procedure, nor is the accuracy of the analysis sufficiently affected to assume other than constant mass influence coefficients, as briefly discussed in Section 2.1.4.

Moreover, in order to visualize the covariance of the mass data, as analyzed in Section 2.1.4, the top two graphs group the data according to the functional parameters *cylinder number*, which correlates strongly with engine torque, and *planview area*. The upper left-hand graph shows the spread of 4, 6, and 8 cylinder engines across the subsystem mass data, while the upper right-hand graph conveys similar information about the distribution of vehicle planview area classified into three groups: $< 8\ m^2$, $< 9\ m^2$, or $< 10\ m^2$.

As expected, the observations corresponding to vehicles with 4-cylinder engines and small planview area are confined to the lower GVM and subsystem mass spectrum, while observations corresponding to vehicles with 8-cylinder engines and large planview area occupy the higher mass spectrum. The middle segment, however, which represents vehicles with 6-cylinder engines and medium planview area, seem to span a wide region, extending into the highest values of GVM.

Next, the bottom two graphs in Figure 2-2 to Figure 2-9 investigate the normality assumption of the plotted mass data. In the lower left-hand graph, the subsystem mass data are plotted in histogram-form with a normal distribution fitted to the output. This graphical representation highlights the degree of continuity in the mass data. For some subsystems, such as the Structure subsystem, which includes many subcomponents and is a significant percentage of total vehicle mass, this relationship appears mostly continuous. For other subsystems, however, such as the Suspensions, Transmission, and Exterior subsystems, this relationship resembles more closely to a series of steps between a finite number of functional capacity subsystem models and weights that are shared across many different vehicles. The step-wise nature of certain subsystem relationships does not affect the results of the mass influence coefficient analysis; nevertheless, it may cause problems when applying this analysis to a "real world" vehicle design problem. For instance, following vehicle lightweighting, this analysis may suggest a mass target for a particular vehicle subsystem that is between two discrete "steps" in the subsystem mass spectrum, which may be impossible to achieve in practice.

Lastly, the lower right-hand graph plots the residuals of the OLS regression analysis in a standard normal quantile-quantile (q-q) plot. The q-q plot is a graphical technique for determining if two data sets come from populations with a common distribution [33]. In this case, the distribution of the subsystem residuals is compared against the standard normal distribution. If the set of subsystem residuals comes from the same distribution as the normal, the points should fall approximately along the reference line (dashed red).

As can be seen in the q-q plots, the residuals of some subsystems diverge from the reference line, especially towards the lower and upper edges of the line. This is particularly true of the subsystems whose masses are highly discretized, such as the Suspensions and Transmission. In those subsystems, the divergence from normality is explained by the step-wise nature of the underlying subsystem mass data.

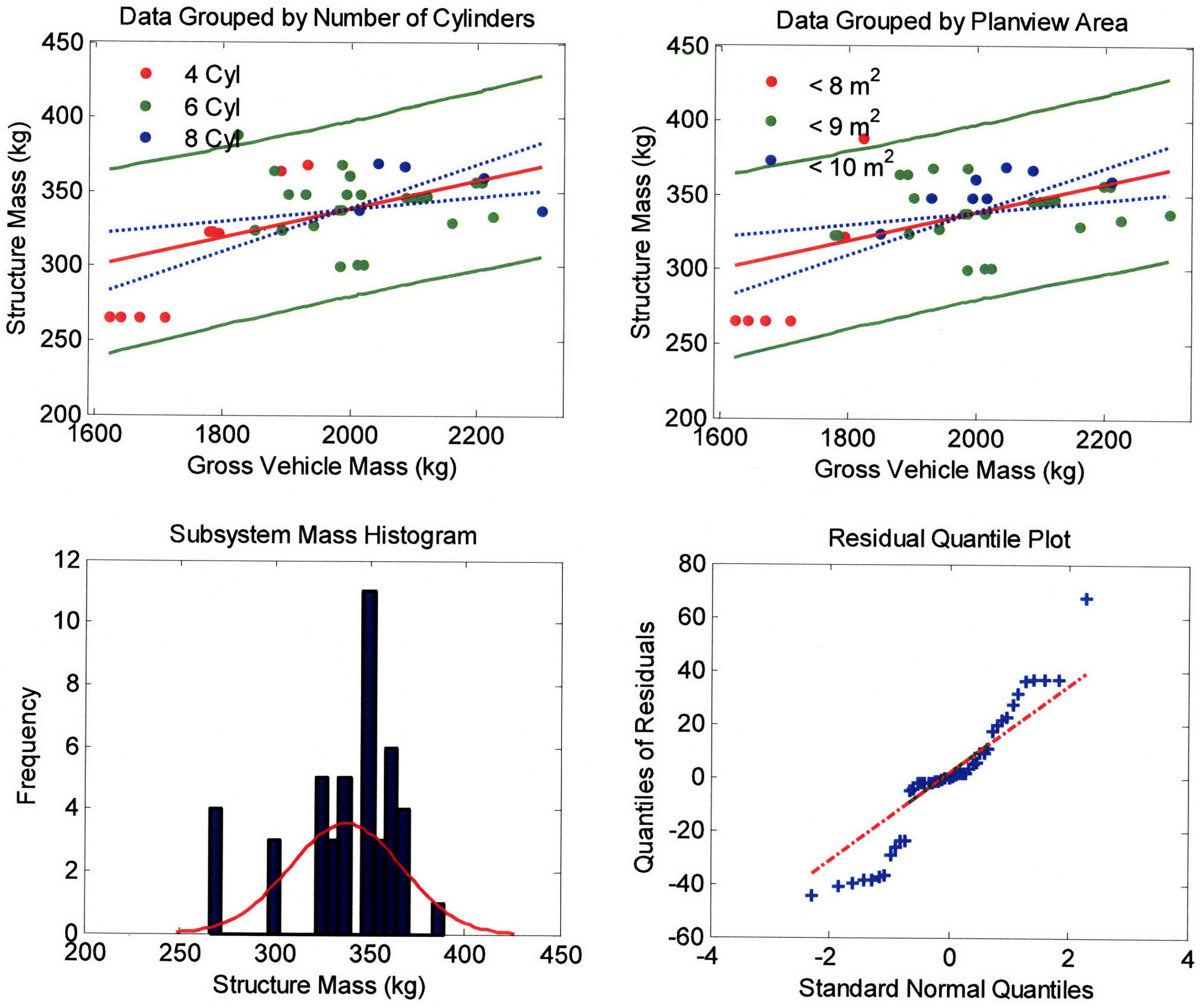


Figure 2-2: Mass influence coefficient analysis for the Structure subsystem.

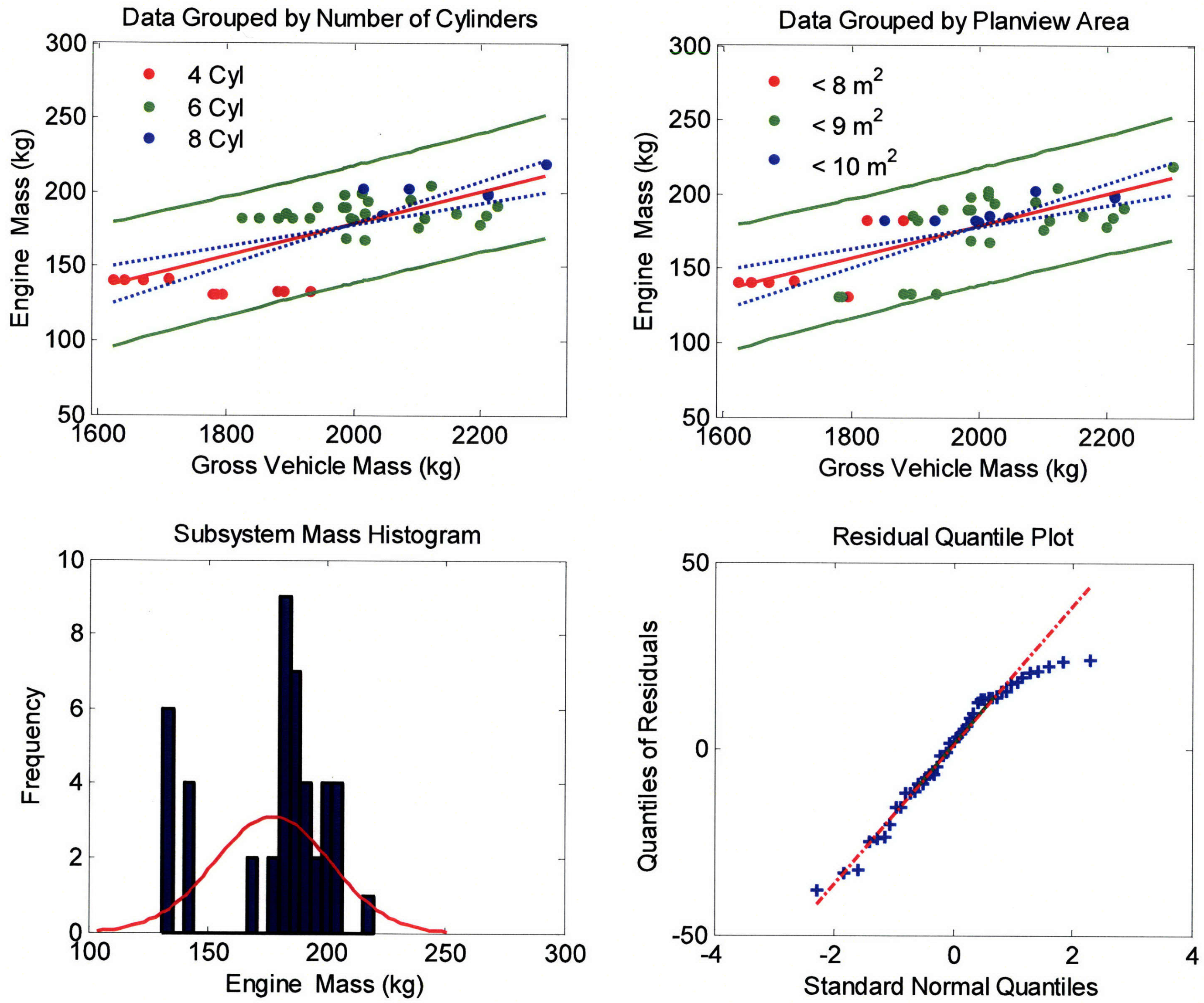


Figure 2-3: Mass influence coefficient analysis for the Engine subsystem.

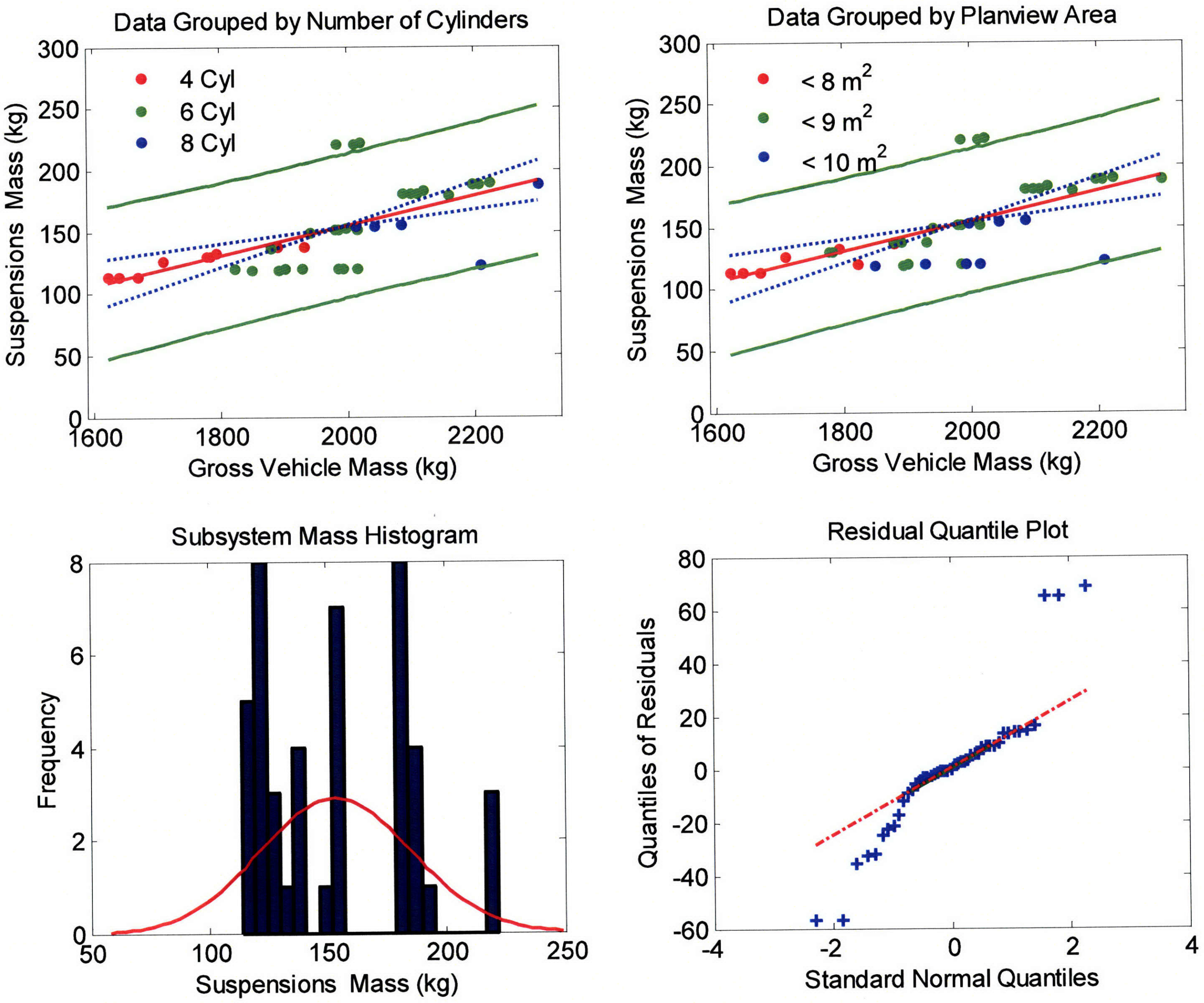


Figure 2-4: Mass influence coefficient analysis for the Suspensions subsystem.

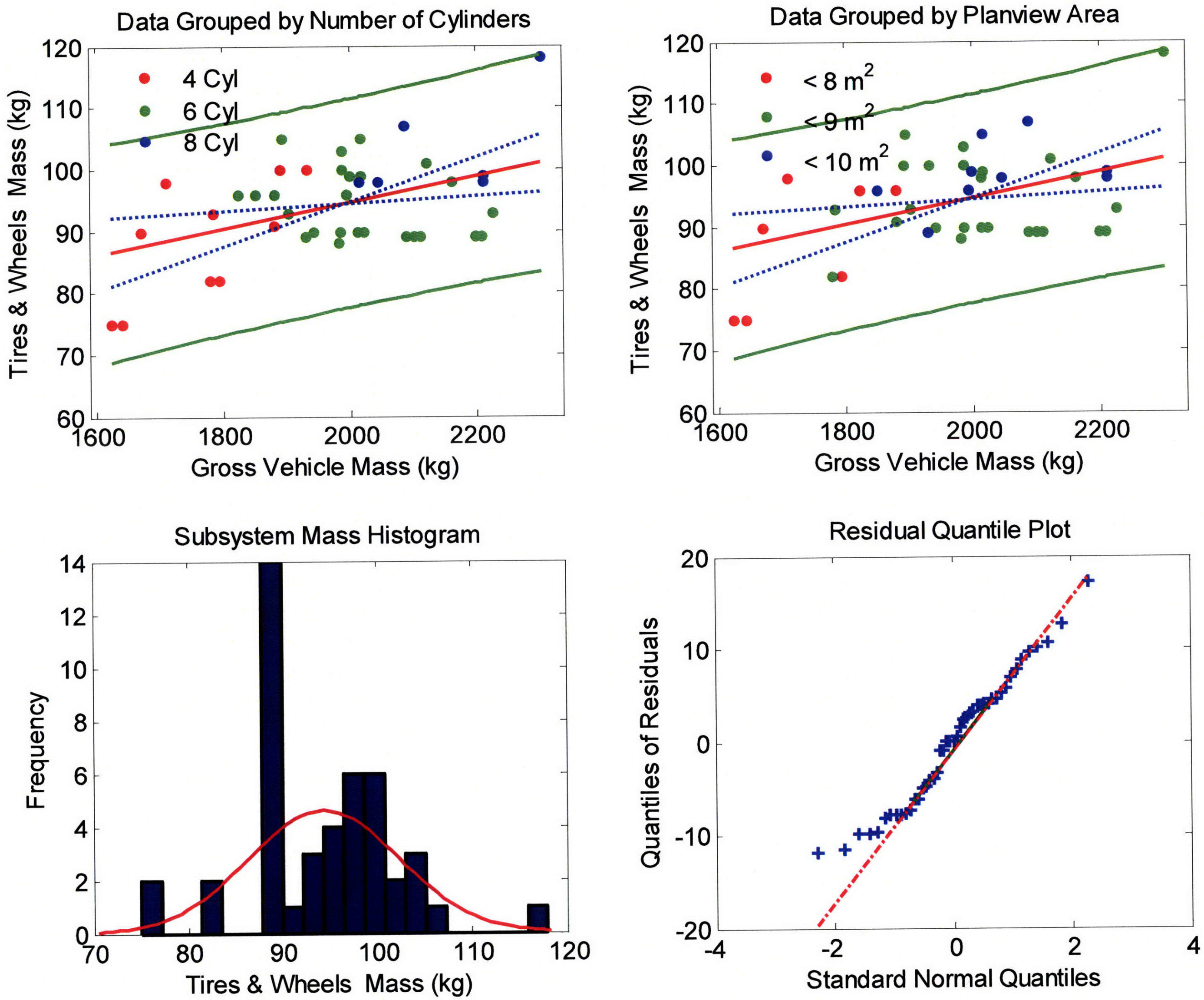


Figure 2-5: Mass influence coefficient analysis for the Tires & Wheels subsystem.

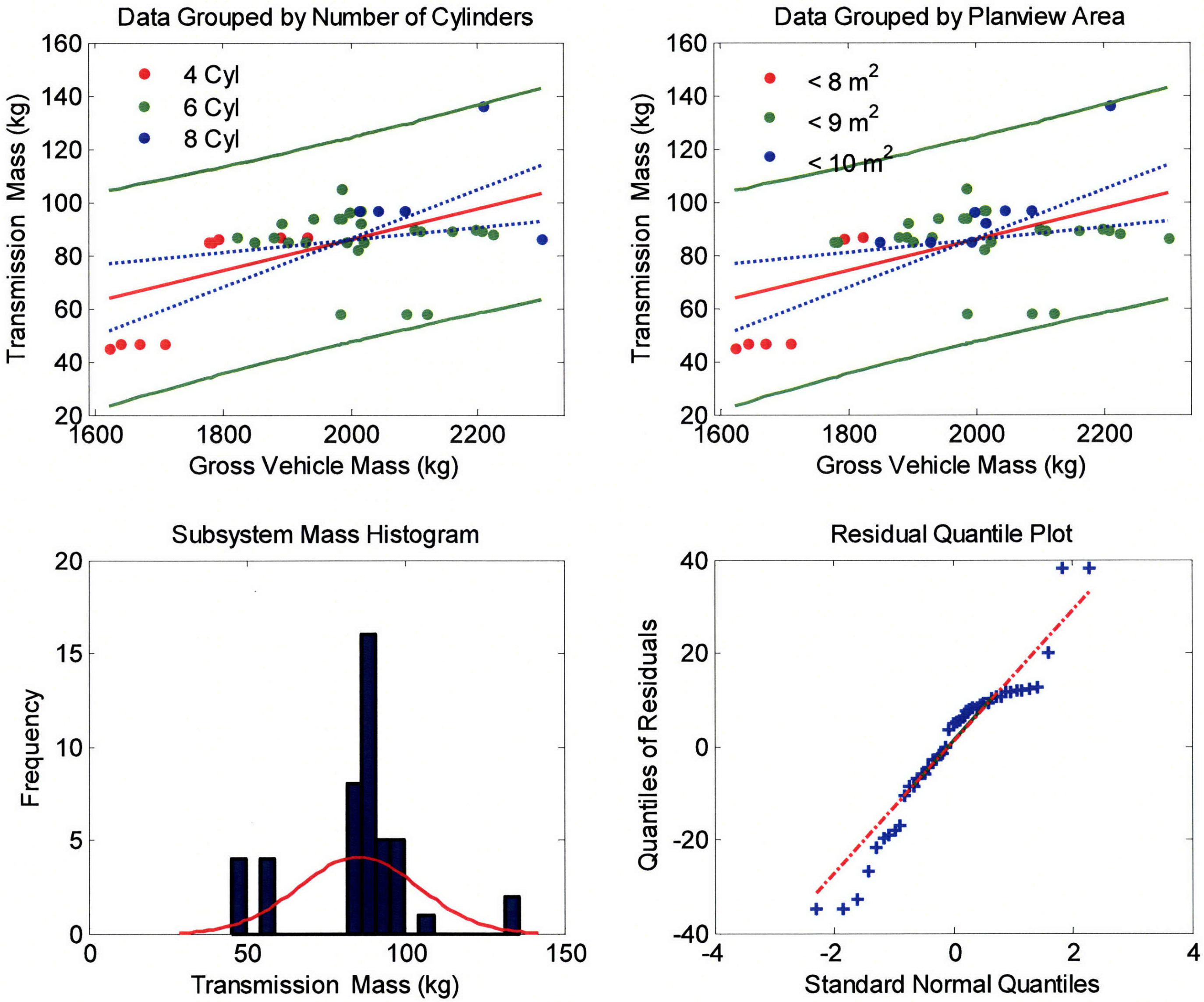


Figure 2-6: Mass influence coefficient analysis for the Transmission subsystem.

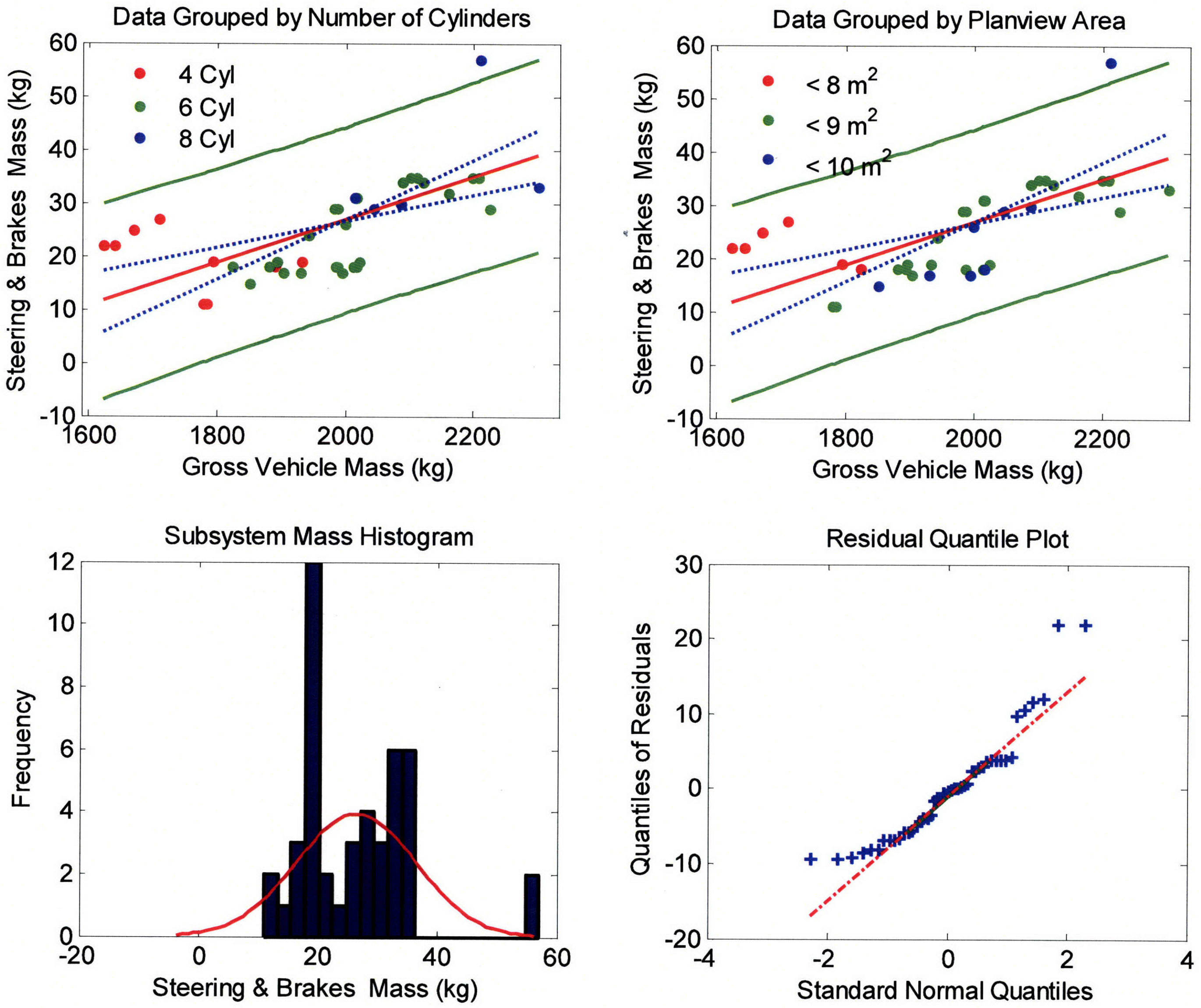


Figure 2-7: Mass influence coefficient analysis for the Steering & Brakes subsystem.

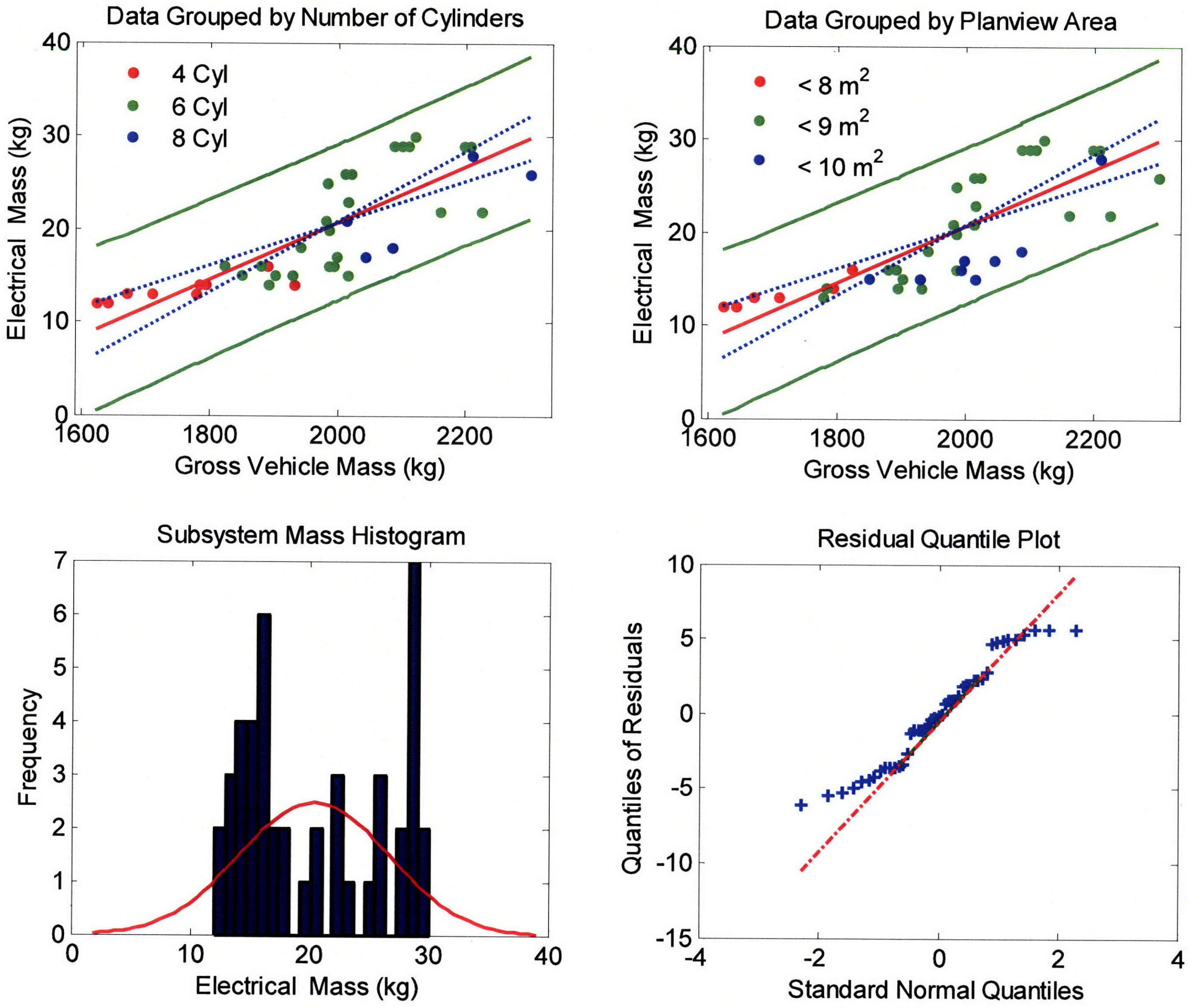


Figure 2-8: Mass influence coefficient analysis for the Electrical subsystem.

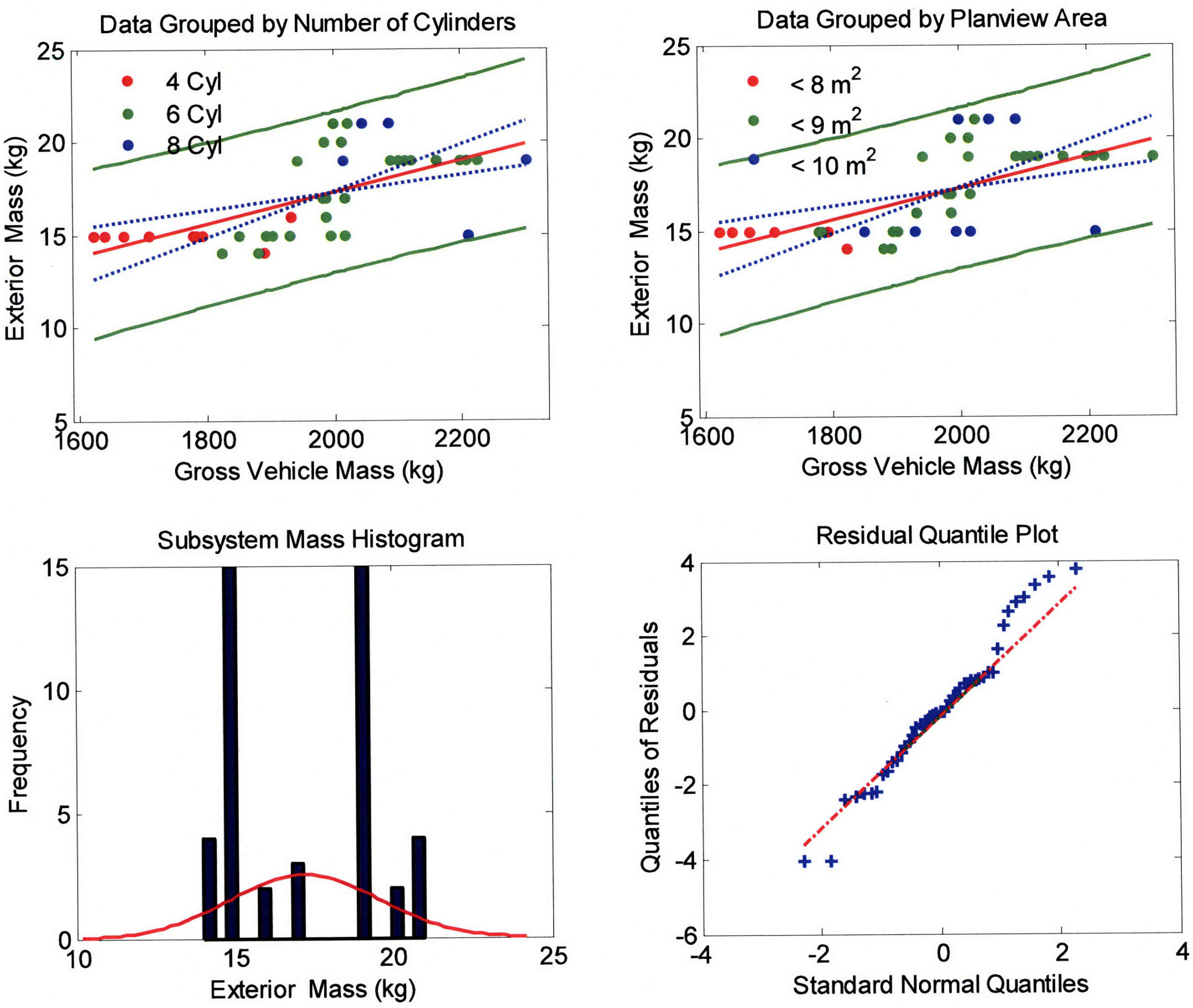


Figure 2-9: Mass influence coefficient analysis for the Exterior subsystem.

The mass influence coefficients, derived from the slopes in Figure 2-2 to Figure 2-9 are summarized in Table 2-9. As an example, it can be seen that the mass influence coefficient for the Structure subsystem is 0.124. This suggests that for ever one kilogram change in GVM there will be a 0.124 kg change in the mass of the Structure subsystem. The same concept can be applied to each mass influence coefficient. Moreover, as can be seen in Table 2-9, the Suspensions, Structure, and Engine subsystems have the largest mass influence coefficients, followed in consecutive order by the Transmission, Steering & Brakes, Electrical, Tires & Wheels, and Exterior subsystems.

The range in mass influence coefficients, from 0.140 for the Suspensions to 0.010 for the Exterior, may be explained by the design details of the subsystems, which require the mass of the Suspensions to change more in absolute terms than the mass of the Exterior for any given change in GVM.

The standard deviations and 95% confidence intervals of the mass influence coefficients will serve as inputs in the ensuing mass decompounding analysis and are summarized together with the adjusted R^2 and p-values of the regression analysis.

The R^2 values, or the coefficients of determination, represent the fraction of variation explained beyond that using only the average as an indicator variable. Although the obtained R^2 are sometimes low, they were deemed satisfactory given the cross-sectional nature of the data.

Each statistical regression model also has an associated p-value. The p-value is the probability that the null hypothesis is true. In this case, the hypothesis is that subsystem mass is affected by GVM; accordingly, the null hypothesis is that subsystem mass remains unaffected by changes in GVM. A p-value of .05, for example, indicates that there is a 5% chance of drawing the sample being tested if the null hypothesis is actually true. Since the obtained p-values are very low, the null hypothesis may be rejected with high level of confidence.

Lastly, the mass influence coefficients derived from the original dataset are also presented (Table 2-10) for comparison. It is interesting to note that the values of the mass influence coefficients do not vary significantly, but that the R^2 values improve notably after removal of the outliers. This indicates that the outliers are roughly normally distributed about the mean.

Table 2-9: Summary of the subsystem-specific mass influence coefficients after removal of the outliers, defined as lying outside of the 95% prediction interval. The table lists the mean, standard deviation, and the upper and lower bound of the 95% confidence interval for the γ-coefficients together with the adjusted R^2 and p-values of the regression.

Subsystem	γ	St Dev	Lower	Upper	Adj R^2	p-Value
Structure	0.124	0.021	0.084	0.164	0.501	0.000
Engine	0.103	0.016	0.072	0.133	0.551	0.000
Suspensions	0.140	0.014	0.112	0.168	0.735	0.000
Tires & Wheels	0.018	0.007	0.004	0.032	0.129	0.018
Transmission	0.049	0.015	0.020	0.078	0.217	0.002
Steering & Brakes	0.032	0.006	0.021	0.043	0.462	0.000
Electrical	0.031	0.004	0.024	0.038	0.665	0.000
Exterior	0.010	0.002	0.007	0.013	0.550	0.000

Table 2-10: Summary of the subsystem-specific mass influence coefficients before removal of the outliers. The table lists the mean, standard deviation, and the upper and lower bound of the 95% confidence interval for the γ-coefficients together with the adjusted R^2 and p-values of the regression.

Subsystem	γ	St Dev	Lower	Upper	Adj R^2	p-Value
Structure	0.087	0.026	0.037	0.138	0.173	0.001
Engine	0.117	0.015	0.089	0.146	0.554	0.000
Suspensions	0.125	0.025	0.075	0.174	0.315	0.000
Tires & Wheels	0.024	0.006	0.011	0.036	0.200	0.001
Transmission	0.057	0.015	0.026	0.087	0.197	0.001
Steering & Brakes	0.046	0.009	0.028	0.064	0.329	0.000
Electrical	0.026	0.005	0.017	0.035	0.376	0.000
Exterior	0.008	0.002	0.005	0.012	0.286	0.000

2.1.6 Mass Decompounding Coefficients

The final step in arriving at the subsystem-specific mass decompounding coefficients concerns the quantification of the compounding that takes place when a particular vehicle component is subjected to a material substitution, a design change, or other modification that results in an overall vehicle mass change, some examples of which are listed in Table 1-1.

If, for example, the mass of a particular subcomponent is reduced, an equivalent direct reduction in total vehicle mass will occur. Additional potential reductions in the masses of all the functional vehicle subsystems then follow from the mass influence coefficient analysis in the previous Section. This, in turn, yields further secondary mass savings in the vehicle and thus a compounding, or decompounding, of the primary mass reduction takes place [14].

The concept of mass decompounding is illustrated in Figure 2-10 for a primary mass savings of Δ and a vehicle system consisting of two functional subsystems, *a* and *b*, with mass influence coefficients γ_a and γ_b , respectively.

The first arrow in Figure 2-10 illustrates how a primary mass saving of Δ gives rise to a corresponding mass reduction of $\gamma_a \cdot \Delta$ in subsystem *a* and $\gamma_b \cdot \Delta$ in subsystem *b*. The resulting secondary savings of $\Delta(\gamma_a + \gamma_b)$ will yield additional secondary mass savings in both subsystems, as indicated by the second arrow. This iterative process continues until it converges, when the incremental secondary mass savings become negligibly small. Summing over all secondary mass savings from subsystems *a* and *b*, yields the following expression for total secondary mass saved

$$\Delta\left[(\gamma_a + \gamma_b) + (\gamma_a + \gamma_b)^2 + \ldots + (\gamma_a + \gamma_b)^n\right] \tag{2.13}$$

where *n* represents the number of iterations. Letting *n* approach infinity and using the result for the sum of an infinite geometric series [14]

$$\lim_{n \to \infty}\left\{1 + x + x^2 + \ldots + x^n\right\} = \frac{1}{1-x} \tag{2.14}$$

equation (2.13) can be simplified into the following expression

$$\Delta\left(\frac{\gamma_t}{1-\gamma_t}\right) \tag{2.15}$$

where γ_t is the sum of all the mass influence coefficients. In this two-subsystem vehicle case

$$\gamma_t = \gamma_a + \gamma_b \tag{2.16}$$

Equation (2.15) defines the total secondary mass saving in the vehicle and is shown to be a linear function of the primary mass saving, Δ. The coefficient of proportionality, $\left(\frac{\gamma_t}{1-\gamma_t}\right)$, is the mass decompounding coefficient for the entire vehicle and can be denoted as Γ_t.

Adopting a similar approach, yields the mass decompounding potential for the individual subsystems. For subsystem *a*, the total secondary mass savings is

$$\Delta\left[\gamma_a + \gamma_a\cdot(\gamma_a+\gamma_b) + \gamma_a\cdot(\gamma_a+\gamma_b)^2 + \ldots + \gamma_a\cdot(\gamma_a+\gamma_b)^n\right] \tag{2.17}$$

which, using (2.14), simplifies to

$$\Delta\left(\frac{\gamma_a}{1-\gamma_t}\right) = \Delta\cdot\Gamma_a \tag{2.18}$$

where Γ_a is the mass decompounding coefficient specific to subsystem *a*, which for the two-subsystem vehicle is related to Γ_t by

$$\Gamma_t = \Gamma_a + \Gamma_b \tag{2.19}$$

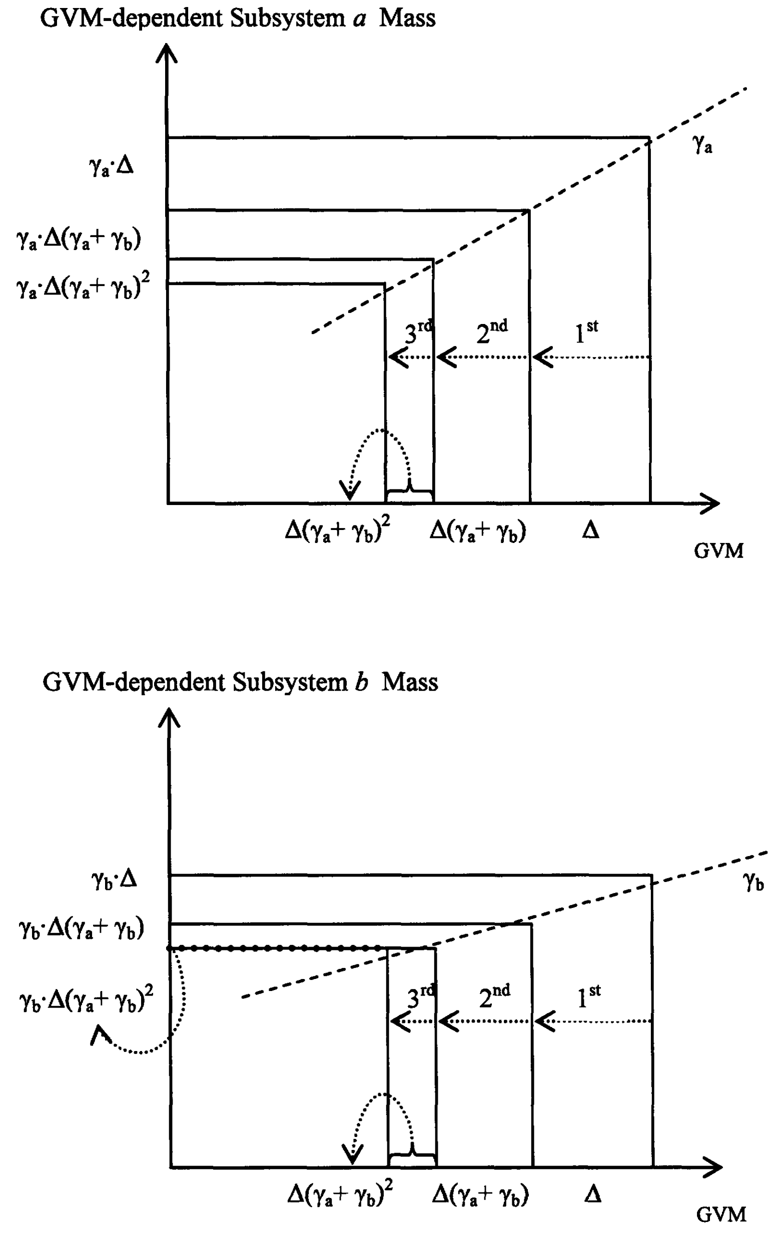


Figure 2-10: Illustration of the concept of mass decompounding for a primary lightweighting, Δ, in a vehicle consisting of two functional subsystems, *a* and *b*, with mass influence coefficients γ_a and γ_b, respectively.

This methodology will now be applied to a real case of the sedan vehicle, using the mass influence coefficients derived in Section 2.1.5. In doing so, however it is important to keep in mind that each mass influence coefficient is associated with a range of likely values, rather than one specific number. In particular, the mass influence coefficients were found to be satisfactorily modeled as following a normal distribution with a certain standard deviation about the mean, as previously summarized in Table 2-9. To account for this uncertainty, Monte Carlo simulation was employed in calculating the mass decompounding coefficients.

The Monte Carlo method is one of many methods for analyzing uncertainty propagation, where the goal is to determine how variation affects the sensitivity of the system that is being modeled. Monte Carlo simulation is categorized as a sampling method because the inputs are randomly generated from probability distributions of the underlying equations to simulate the process of sampling from an actual population [36]. Consequently, the Monte Carlo simulation requires the number of runs in the simulation to be large. For this study, 10,000 runs were used and the frequency distribution of the results for the total sedan vehicle mass decompounding coefficient is reproduced in Figure 2-11.

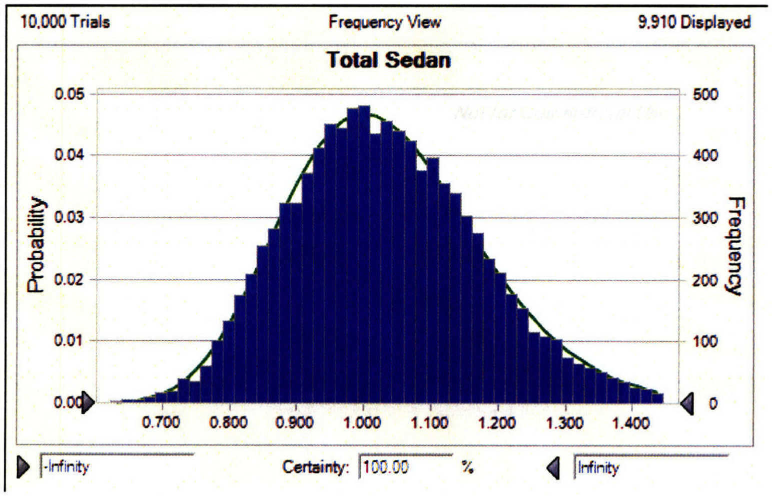


Figure 2-11: Result from Monte Carlo simulation of the total sedan vehicle mass decompounding coefficient, showing the frequency distribution and the gamma function fitted to the data.

As can be seen in Figure 2-11, the distribution of the mass decompounding coefficient is skewed with a tail extending into the higher mass decompounding coefficient range. This is because (2.18), which is employed to find the subsystem-specific mass decompounding coefficients, involves division of normally distributed variables. While the sum of normally distributed variables is expected to be normal, the quotient is not.

The observed skewness gives rise to an expected value of the mass decompounding coefficient that is higher than that which would be expected if the mass decompounding coefficient results were normally distributed. The skewness of the distribution also yields asymmetric confidence bounds on the mass decompounding coefficients. The frequency distribution results for all relevant subsystem-specific mass decompounding coefficients can be found in Appendix B. The final results from the mass decompounding analysis, including the mean, standard deviation, and the upper and lower 95% confidence bounds of the mass decompounding coefficients, are summarized in Table 2-11.

Table 2-11: Summary of the mean, standard deviation, and the upper and lower 95% confidence bounds for the subsystem-specific mass decompounding coefficients, Γ_i.

Subsystem	Mean	St Dev	Lower	Upper
Structure	0.254	0.055	0.169	0.349
Engine	0.211	0.040	0.149	0.282
Suspensions	0.286	0.041	0.222	0.357
Tires & Wheels	0.037	0.016	0.012	0.063
Transmission	0.100	0.034	0.048	0.159
Steering & Brakes	0.065	0.013	0.044	0.087
Electrical	0.063	0.009	0.048	0.078
Exterior	0.020	0.003	0.015	0.026
Interior	0	-	-	-
Info & Controls	0	-	-	-
Closures	0	-	-	-
Fuel & Exhaust	0	-	-	-
HVAC	0	-	-	-
Total	1.036	0.143	0.820	1.287

The results in Table 2-11 indicate that the Suspensions, Engine, and Structure subsystems contribute the most to the mass decompounding of the sedan class vehicle. This is because their respective mass decompounding coefficients are the largest. The results also show that on the average, for every one kilogram increase or decrease in GVM there will be a roughly 0.30 kg change in the Suspensions mass, 0.25 kg change in the Engine mass, and 0.20 kg change in the mass of the vehicle Structure. Moreover, the results demonstrate that the range of expected secondary mass savings in the Suspensions subsystem, for instance, is between 0.22 kg and 0.36 kg with 95% confidence. The mass decompounding coefficients of the non-GVM dependent subsystems, as outlined in Section 2.1.3, are zero.

The results in Table 2-11 also specify that on the average a total of 1.04 kg of secondary mass may be saved in the total sedan vehicle for every 1.00 kg of primary mass saved, provided that secondary mass savings can be gained from all vehicle subsystems. The 95% confidence interval around the expected savings is 0.80 kg to 1.30 kg of additional secondary mass for every 1.00 kg of primary mass saved in the total sedan vehicle.

Using the data in Table 2-3 and Table 2-11, Figure 2-12 outlines the expected secondary mass savings in each of the eight functional subsystems following a hypothetical lightweighting scenario of 100 kg. The hypothetical primary mass reduction is made up by 40 kg saving in the Structure, 10 kg in the Engine, and 50 kg in the Closures subsystems. The subsystem-specific secondary mass savings are found by multiplying the total mass saved by the corresponding mass decompounding coefficient.

Inputs	Subsystems	Re-design Availability	Curb Fraction	Initial Subsystem Mass (kg)	Primary Mass Saving (kg)	Secondary Mass Saving (kg)			Total Expected Mass Saving (kg)	Final Subsystem Mass (kg)
						mean	*lower*	*upper*		
Curb Mass (kg):	Structure	1	10%	175	-40	-25	-17	-35	-65	110
1800	Engine	1	11%	205	-10	-21	-15	-28	-31	174
	Suspensions	1	25%	448	0	-29	-22	-36	-29	420
No. Passengers:	Tires & Wheels	1	6%	100	0	-4	-1	-6	-4	97
5	Transmission	1	2%	44	0	-10	-5	-16	-10	34
	Steering & Brakes	1	3%	61	0	-6	-4	-9	-6	54
Cargo Volume (L):	Electrical	1	6%	109	0	-6	-5	-8	-6	103
15	Exterior	1	5%	93	0	-2	-1	-3	-2	91
	Interior	1	12%	219	0	0	0	0	0	219
GVM (kg):	Info & Controls	1	1%	11	0	0	0	0	0	11
2210	Closures	1	10%	175	-50	0	0	0	-50	125
	Fuel & Exhaust	1	6%	105	0	0	0	0	0	105
	HVAC	1	3%	55	0	0	0	0	0	55
				Total:	-100	-104	-71	-140	-204	2006

Figure 2-12: Case example examining the subsystem-specific secondary mass savings that result from a hypothetical lightweighting scenario of 50 kg, 40 kg, and 10 kg savings in the Closures, Structure, and Engine subsystems, respectively, when secondary mass savings may be gained in all functional subsystems.

2.2 Incorporating the Vehicle Development Process

The mass decompounding coefficient for the sedan vehicle, Γ_t, is a function of the constituent subsystem-specific mass decompounding coefficients. In particular, Γ_t is found by summing over the mass decompounding coefficients of each available subsystem Γ_i

$$\Gamma_t = \sum_i \Gamma_i \tag{2.20}$$

The subsystem availability refers to the feasibility of gaining the secondary mass savings in practice. Any particular subsystem will be classified as available if its design can be updated to reflect a change in GVM.

In the case of a primary reduction in GVM, perhaps through lightweighting of the vehicle closures, updating of the GVM-dependent subsystems may involve switching to lighter and lower load-capacity models of already existing subsystem models or making modifications to current designs in order to account for the overall lighter vehicle.

In a system that is as complex and interdependent as the automobile, however, subsystem design changes are not always possible. On the contrary, the designs of the vehicle subsystems become fixed at particular times during vehicle development. The exact time when and order in which the subsystem designs become locked in may vary from OEM to OEM as well as from vehicle to vehicle; however, the general concept of a master schedule that controls the numerous development and prototyping tasks involved in bringing a vehicle from concept to large scale production exists at all automakers and is often referred to as the vehicle development process. As a result, data from the vehicle development process can be employed to determine subsystem re-design availability and subsequently, the time-dependence of the vehicle mass decompounding coefficient, Γ_t.

To better understand how the vehicle development process affects the mass decompounding potential, it is useful to become familiar with some of its basics.

Hence, the first part of this Section will give an overview of the automotive development process, while the second part will outline the methodology of and results from incorporating the vehicle development timing data into the mass decompounding calculation.

2.2.1 Overview of the Vehicle Development Process

Product development has been defined as “the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product” by Eppinger and Ulrich in their book “Product Design and Development” [37]. This definition provides interesting insight into the wide variety of tasks that go into the product development process.

Further detail about the vehicle development process in particular is given in Alfred Sloan’s book “My Years with General Motors” from 1963. In this book, Sloan gives an overview of the automobile development process and defines the general phases involved [38]. In addition, Womack, Jones, and Roos offer an insightful comparison of the development process across the entire automotive industry, including comparisons of traditional mass producing firms and modern lean production firms, in their book “The Machine that Changed the World” [39]. Furthermore, Clark and Fujimoto provide an in-depth study of the product development processes across several European, North American, and Japanese automakers in their book “Product Development Performance: Strategy, Organization, and Management in the World Auto Industry” [40]. Lastly, Jain presents an interesting discussion of the automotive design and development process in his thesis “An Analysis of Automotive Body Assembly technologies and Their Implication in Lightweight vehicle Development“ [1].

The following sections have been summarized from the above, and in particular the latter of the above, sources in order to give a brief overview of the different phases involved in the vehicle development process.

Concept Generation

The automotive development process starts with the generation of a concept. The purpose of the vehicle concept is to define the essential vehicle features and functions that will serve to attract the intended customer base. The concept also outlines the intended way in which the consumers should interact with and experience the vehicle as a whole.

The vehicle concept is generated and the new vehicle targets are set based on information about future market requirements, technological advancements, and firm-wide strategic goals. First, market information – in the form of market research studies and feedback from consumers and dealers – provides important input. In particular, the market information aids in the process of identifying important consumer preferences and attractive vehicle functionalities that can be employed in the new vehicle. Second, information about technological advancements and novel processing capabilities is crucial in directing the development of the vehicle concept. Technological breakthroughs in vehicle engineering add extra design freedom and allow the concept creators to imagine new vehicle niches and personalities. For instance, the availability of advanced safety systems might allow the concept creators to visualize and generate a vehicle concept that will appeal to a certain group of consumers by demonstrating a higher than average degree of safety. In turn, the creativity, design ideas, and manufacturing needs of the concept creators help to stimulate the development of new technologies. For instance, in order to realize a vehicle design that builds upon improved environmental friendliness and high fuel efficiency, lighter vehicle body panels and structural components may be required. This may lead to the development and advancement of alternative materials and manufacturing processes, as well as to increased interest in mass decompounding. Lastly, the automaker's long-term goals and strategies also influence the development of the new vehicle concept.

Even though the various sources of information may be valued differently from automaker to automaker, the generation of a product concept is critical to the development process for any large company. The concept provides the guidelines to and defines the characteristic vehicle targets during the vehicle development process. The concept also provides the criteria against which the final product and results of the development process may be evaluated.

Product Planning

The generated vehicle concept provides inputs to the product planning stage in the vehicle development process. During product planning, the ideas defined in the vehicle concept are translated into production specifications. In order to successfully integrate the vehicle concept into a detailed product plan, meet the demands of the concept generators, and produce as accurate a reflection of the vehicle concept as possible close coordination and communication between the concept developers and the product planners are necessary.

The three main areas of activity during product planning relate to vehicle styling, component packaging, and component selection. These three tasks usually proceed simultaneously during the product planning process. The styling of the vehicle is often carried out by the design department, where the generated concept ideas are converted into sketches and drawings. The layout, or packaging, of the vehicle components is yet another important task. Although not immediately apparent, the component packaging significantly influences the overall space- and energy efficiency of the vehicle, and by extension the success of the vehicle once released to public. Next, component selection relates to the identification and selection of the major vehicle subsystems to incorporate into the vehicle. The choice of which components to include also defines the major technologies that will be employed during the large scale production of the vehicle. At this point in the vehicle development process, planners decide whether to come up with new part designs or to use existing designs, something that would impact the amount of secondary mass that may be saved in the vehicle.

The end result of the product planning phase is the generation of a set of product specifications that concretely establish the development goals of the vehicle and help to focus the efforts during the product engineering and design phases.

Product Engineering

The previously generated product plan gets implemented during product engineering. At this point in the vehicle development process, product engineers face many challenges and trade-off decisions regarding the engineering of the components and subsystems of the vehicle. Many issues remain to be resolved during product engineering, as the complexity of the vehicle makes it almost impossible for the product planners to have identified all relevant design conflicts and issues involved in the manufacturing the vehicle ahead of time.

The product engineering design and the manufacture of the vehicle are often handled by separate teams within the firm, each focusing on one of the major functional units of the vehicle, such as the engine, transmission, or structure, as briefly discussed in Section 2.1.2. This division by functional subsystem is valuable since managing the engineering of the vehicle as a whole is too intricate to be feasible in practice.

During product engineering, the engineers and technicians generate detailed design drawings that will be used for subsequent large scale production of the vehicle. The designs are evaluated through cycles of prototyping and testing to ensure that they meet the product specifications and the established structural performance criteria for the vehicle. If the prototypes fail, the necessary modifications are made and implemented and new prototypes are generated and tested. The evaluation cycle continues until the prototype performance is deemed satisfactory.

Information from the advanced engineering and corporate research departments may be obtained to aid in the product engineering phase; however, most often, the required expertise is gathered from within, i.e. from experience with current and past vehicles accomplished by the product engineers. This leads to large amounts of carryover components from one model to the next, which has become a common practice in automotive design. The use of carryover components is an important factor in reducing the overall time and cost of vehicle development. This approach may, however, limit the likelihood of novel design ideas, new materials, and new processes being introduced. By extension, as the amount for secondary mass savings is dependent on the execution of new and updated subsystem designs, this approach may also limit the potential for secondary weight savings.

Process Engineering

During process engineering, the tools, equipment, and standard operating procedures for the large-scale manufacture of the vehicle are specified, based on the detailed engineering drawings and prototypes generated in the product engineering stage.

During process engineering, engineers develop detailed plans and designs for the processes, tools, and equipment to be employed during large-scale production of the vehicle. These plans and designs are used to construct, acquire, and install, the necessary processing tools and equipment. The tools and the equipment are then tested and the output is analyzed for any errors. If the results do not meet specifications, modifications are made to the designs of the tools and equipment and the cycle is repeated until acceptable performance is achieved. Once accepted, the detailed process engineering plans and designs are implemented and installed in either a pilot production facility or at an actual plant for large scale production test-runs. When satisfactory results are obtained, the development process evolves into full scale manufacturing for commercial use.

2.2.2 Implications for Mass Decompounding

As structured above, the vehicle development process may appear as a series of linear development events. In reality, however, the automotive development process involves many parallel procedures, circular paths, and vague boundaries. Even so, the relative timing of the different development stages is generally correct. This implies that concept generation starts before product planning, which in turn supplies inputs to the product and process engineering stages.

The development stage during which mass decompounding, as part of a targeted lightweighting strategy, may be most successfully implemented is product planning. The product planning stage occurs relatively early in the vehicle development process. This is when the designs of the vehicle subsystems and associated technologies are locked in. Consequently, it is important to stress the potential for and benefit of secondary mass savings at this early stage of vehicle development. Later in the development process, it may be more challenging to optimize the vehicle design to gain benefits from mass decompounding.

Table 2-12: Times in the vehicle development process, in terms of number of weeks before start of commercial production, when the designs of the various functional subsystems become locked-in.

Subsystem	Week
Engine	-220
Transmission	-220
Structure	-190
Suspensions	-190
Steering & Brakes	-190
Electrical	-190
Info & Controls	-190
Tires & Wheels	-170
Fuel & Exhaust	-170
HVAC	-170
Interior	-130
Exterior	-90
Closures	-90

More exact information on when in the vehicle development process the designs of the different functional subsystems become locked in was gathered from discussions with experts and automotive engineers working in vehicle development. On average, the responses indicate that the decisions governing the design of the powertrain – the engine and the transmission – of the vehicle may be made as early as 220 weeks before the scheduled start of commercial production. One reason for this relatively early lock-in date is that many later decisions about the vehicle design depend on the choice of powertrain. Other decisions, governing the designs of the exterior styling and finishing of the vehicle may be made as late as 90 weeks before scheduled vehicle launch. These two design deadlines seem to mark the time window in the vehicle development process during which the designs of all subsystems become fixed. A representative vehicle development process, generated from the responses from industry, may appear as outlined in Table 2-12, with major design deadlines occurring around 190, 170, and 130 weeks before the scheduled start of commercial production.

By combining the information in Table 2-12 with Equation (2.20) it is possible to deduce the time-dependency of the mass decompounding coefficient for the sedan vehicle. The subsystem timing information indicates that all subsystems are available for re-design and the full benefit of secondary mass savings may be gained at times greater than 220 weeks before the start of commercial production. Later in the development process, as shown in Table 2-12, the design of some subsystems become fixed, which forces the respective subsystem-specific mass decompounding coefficients to zero. This effectively reduces the expected amount of secondary mass that may be saved in the vehicle as a result of any primary lightweighting. Consequently, any decision to perform vehicle lightweighting at times less than 90 weeks before the start of commercial production is not likely to yield any secondary mass benefits, since the mass decompounding coefficient is zero. The time-dependency of the expected value and of the 95% confidence interval of the mass decompounding coefficient, in number of weeks before start of commercial production, are illustrated in Figure 2-13.

Figure 2-13 visually identifies a time window that is critical for mass decompounding. This time window ends at roughly 200 weeks before start of regular production, which is when the mass decompounding potential drops from 0.5 to close to 0. As illustrated in Figure 2-13 and as discussed above, the 95% confidence interval of the mean of the mass decompounding coefficient is asymmetric and slightly skewed towards higher coefficient values.

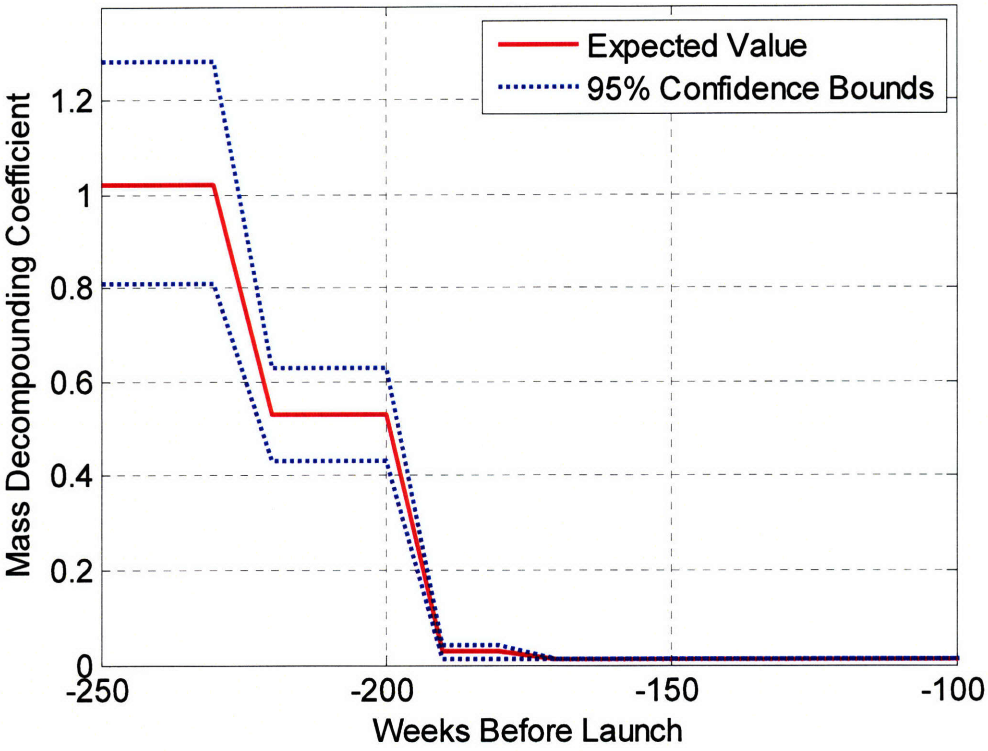


Figure 2-13: Illustration of how the mass decompounding coefficient for the total sedan vehicle varies with time in the vehicle development process. Both the expected value and the 95% confidence bounds around the mean are plotted.

2.3 Assessing Cost and Value

It is generally true that any proposition to change vehicle design needs to, at some level, demonstrate a positive value proposition. Besides, much of the design and engineering efforts expended in the planning and development phases of a new vehicle involves the assessment of profitability and potential cost savings of competing designs. Therefore, the mass decompounding analysis would not be complete without an assessment of cost and value.

Making trustworthy profitability forecasts, however, is challenging, especially since forecasts usually depend on predictions of costs, demand, and prices, which are complex functions of many variables and subject to large uncertainty [41]. Therefore, this section will not make predictions, but rather suggest a method – one of possibly many others – that could be applied in assessing the cost and value of mass decompounding and therefore serve as an input to the formation of an eventual forecast.

In brief, the proposed methodology is to employ process based cost modeling to find the expected cost of implementing a lightweighting strategy, such as a design change, material substitution, or novel processing. Next, the amount of mass savings that results from lightweighting will be converted into performance improvements, in particular into increases in fuel economy and acceleration of the vehicle, using powertrain modeling. Lastly, market modeling will be used to convert the performance improvements into expected consumer dollar value increases.

2.3.1 Process Based Cost Modeling

Process based cost modeling (PBCM) is a tool that can be used to quickly assess the cost of a certain production process at different production volumes. It was developed to provide cost estimates using engineering, technical, and economic accounting principles. PBCM analyzes the various cost drivers of a production process and uses mathematical transformations to assess the magnitude of the process-specific factors that affect total cost [42].

In essence, PBCMs consist of three seamlessly functioning models: a process model, an operations model, and a financial model. The first step in PBCM is to determine the specifics about the part to be produced and the manufacturing processes involved. The user inputs information about part dimensions, material, and processing conditions. The process model then transforms these inputs into all the production variables needed to estimate cost. These include calculations about the type of equipment (for example the press-force required during stamping), the cycle time, and other processing conditions required to make a single part or batch of parts. Next, the operations model scales this information according to the production volume and determines the total number of pieces of equipment, the total number of workers, and the total time required, etc. Finally, the financial model calculates the cost of the intermediate results produced by the process and operations models, such as the cost of the equipment, material, electricity, as well as wages. The financial model handles the appropriate allocation of costs across time, through amortization, and across products, for non-dedicated lines. Ultimately, the model generates a cost estimate based on the part and process assumptions.

The importance of PBCM, however, is not so much in calculating the cost of manufactured items as in examining how the total cost may change as a result of changes in the production process. Examples of such changes include changes to the production volume, the equipment usage, and the material selection. The scope of PBCM allows for a variety of process changes, including those relevant to automotive weight reduction, to be examined across many aspects of the production process. Table 2-13 summarizes cost, mass, and production volume results from PBCM of vehicle lightweighting using material substitution.

Table 2-13: PBCM results of material substitution vehicle lightweighting strategies, courtesy Lynette Cheah.

Vehicle Component	Substitute Material	Cost Change ($)	Mass Saving (kg)	Prod Vol (per year)	Source
Front end	High strength steel	-13	11	-	Roth 2006
Body-in-white	High strength steel	-42	60	225,000	Shaw 2002
Entire vehicle	Aluminum	661	346	200,000	Stodolsky 1995
Unibody	Aluminum	537	138	500,000	Han 1994
Body-in-white	Composite	400	127	100,000	Kang 1998
Body-in-white	Composite	930	68	250,000	Dieffenbach 1996

2.3.2 Powertrain Modeling

Simulation based analysis of vehicle performance, such as fuel consumption, acceleration, and maximum speed, is crucial to the development of new vehicles. Powertrain models allow complex new powertrain concepts and designs to be tested and optimized without the need for design validation by hardware measurement, which is only possible during the later prototype building stages of vehicle development [43]. Therefore, significant amounts of research efforts have been devoted to the development of accurate powertrain simulation programs. A few examples of such simulator programs include Simplev [44], CarSim [45], and ADVISOR [46].

These programs work based on a network of component models that each describe separate parts of the vehicle [47]. In order to model vehicle performance, the component models require vehicle and powertrain-specific inputs. Therefore, these simulator programs make use of extensive databases of vehicle characteristics such as mass, engine and component maps, duty cycles, and transmission data to predict performance parameters like tractability, acceleration, and fuel economy. Secondly, a simulated driving trajectory, or duty cycle, is also needed as an input to model the powertrain. The duty cycle is used to calculate the road-loads and acceleration requirements of the vehicle, which in turn are needed to estimate the energy losses in each component model. Finally, the model outputs vehicle-specific performance metrics, based on the total energy requirements of the vehicle [48].

The powertrain model and the powertrain model results presented in this study were provided by one of the major automakers. The employed proprietary powertrain model has previously been shown to produce results that are consistent to within 1% of actual values. The provided powertrain results were generated using a composite duty cycle with 55% urban and 45% highway simulated driving. A reduction in total vehicle mass, in discrete increments from 0 to 200 kg, was provided to the model as an input and the resulting changes in fuel economy and acceleration performance were recorded as outputs. The expected mass-driven performance changes were recorded for typical powertrains belonging to compact, midsize, and large sedans.

The raw data provided from the automaker was converted into percent-space and manipulated to form the relationships needed for the present study. The resulting relationships for fuel economy and acceleration are presented in Figure 2-14 and Figure 2-15, respectively. Figure 2-14 shows percent fuel economy increasing almost linearly with percent mass saved. It is interesting to note that the results for the compact, midsize, and large sedan fall close to the 5%-10% line, in agreement with results found in previous studies [6]. Figure 2-15 illustrates the expected percentage improvement in acceleration for a given percentage mass saving for the compact, midsize, and large sedan powertrains. The results for acceleration improvement cluster around the 10%-10% line, indicating an expected 10% improvement in acceleration for a 10% mass saving; however, the slopes are not constant, but appear to level off at a certain maximum acceleration improvement for each powertrain.

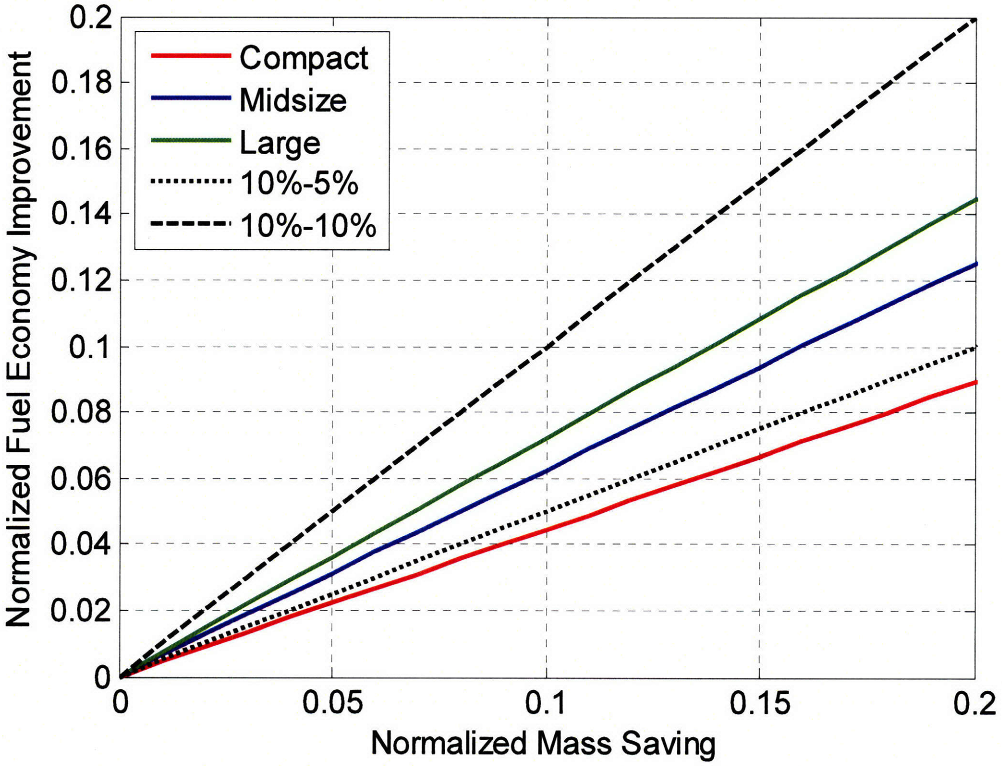


Figure 2-14: Percentage fuel economy improvement resulting from percentage mass saving for compact, midsize, and large sedans.

found in previous studies [6]. Figure 2-15 illustrates the expected percentage improvement in acceleration for a given percentage mass saving for the compact, midsize, and large sedan powertrains. The results for acceleration improvement cluster around the 10%-10% line, indicating an expected 10% improvement in acceleration for a 10% mass saving; however, the slopes are not constant, but appear to level off at a certain maximum acceleration improvement for each powertrain.

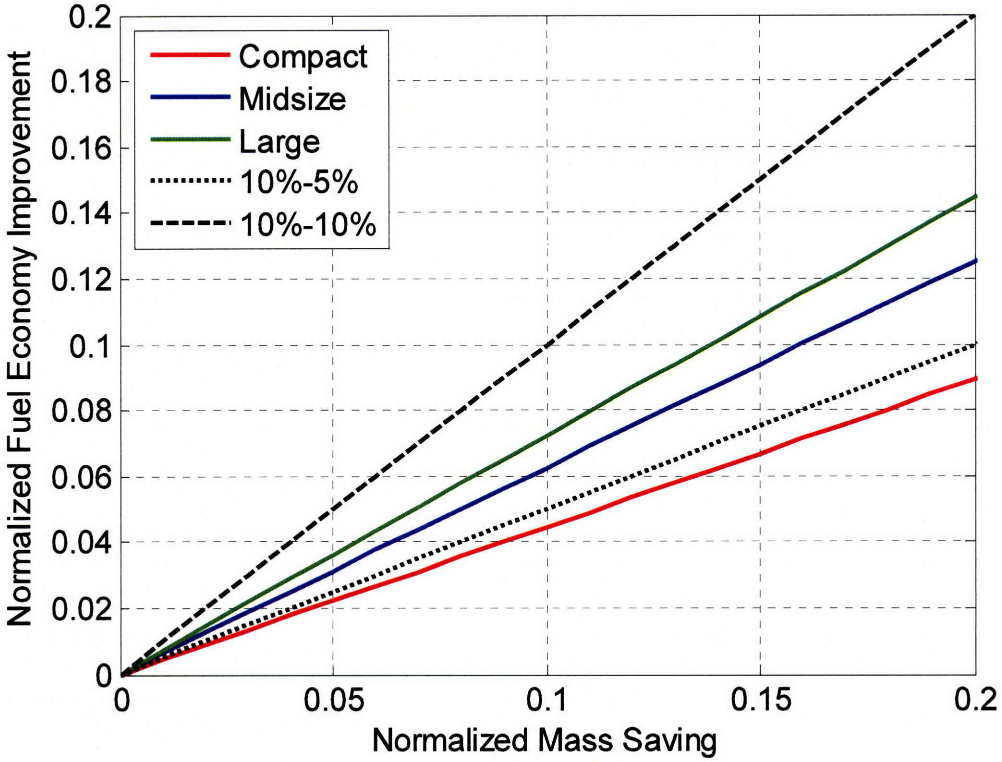


Figure 2-14: Percentage fuel economy improvement resulting from percentage mass saving for compact, midsize, and large sedans.

consumer's reaction will be to an attribute change and how that reaction will affect the profitability of the product.

Several product decision support tools exist today that could provide the automotive engineer with guidance during the cost and value assessment of novel design changes and provide support in the decision-making process about those designs. For example, multidimensional scaling [50] and conjoint analysis [51] are important consumer survey tools that are currently used by market researchers to gain an understanding of the utility of product attributes. However, these tools have received little interest by engineers who instead seem to prefer tools such as Taguchi's robust design methodology [52], value engineering methods [53], and quality function deployment [54] in making product trade-off decisions changes.

For the purposes of this research, the incremental consumer value arising from changes in fuel economy and acceleration performance were of particular interest. These value-responses were effectively modeled using the Automotive Market Insight Simulator (AMIS).

AMIS is a decision support system designed to mimic consumer options and choices in the automotive retail market. The simulator enables users to simulate likely market share for a very large number of existing or proposed vehicle scenarios. Thus, the impact of competitive products, features, and pricing scenarios on market preferences can be measured. The foundation of the simulator is a mathematical choice model that is created from consumer response data collected from consumers, using choice-based experiments in which consumer trade-off vehicle features and vehicle prices and select the preferred vehicles [55].

In order to generate the desired market modeling results, the vehicles of interest were selected first. In particular, the analysis was performed for one compact, one midsize, and one large vehicle, to match the choice of vehicles in Section 2.3.2. Next, fuel economy, acceleration, and vehicle market price were selected as variable vehicle attributes. Increments of market price reductions, fuel economy improvements, and acceleration improvements were provided to the model as inputs and the resulting changes in total market share were recorded as outputs. The shared variable 'market share' was eliminated by identifying the amount of price reduction whose corresponding market share increase exactly offset the market share increase caused by improvements in fuel economy or acceleration. Consequently, data showing how consumer value increases with fuel economy and acceleration improvements were obtained, as shown in Figure 2-16 and Figure 2-17, respectively.

Figure 2-16 indicates that consumer's willingness to pay increases almost linearly with fuel economy improvement for the compact, midsize, and large sedan vehicle consumer. The large sedan vehicle consumers appear to be willing to pay more in absolute terms for a given normalized fuel economy improvement compared to the midsize and compact. In percentage terms, however, where the added value is normalized to initial vehicle price, the midsize and compact vehicle owners appear to be willing to pay more for a given normalized fuel economy improvement.

In Figure 2-17, the consumer's willingness to pay for acceleration performance is seen to increase steeply for the first 0.2 to 0.3 units of normalized acceleration improvement. Beyond that, however, the perceived value added for acceleration improvement can be seen to level off. This behavior may be explained by the belief that consumers perceive acceleration performance to be "good enough" beyond a certain 0-60 mph acceleration time and are less willing to pay extra for improved performance beyond that.

Additionally, for any given normalized acceleration improvement, the modeled compact sedan consumer is willing to pay more in both absolute and percentage terms compared to the midsize and large sedan consumers. This may be because of relative preference for performance over fuel economy in the smaller car, which already achieves relatively high fuel economy but may have poor initial acceleration. Conversely, consumers who purchase midsize and large sedan vehicles, whose initial fuel economy may be poor, appear to be more likely to pay extra for improved fuel economy than for improved acceleration.

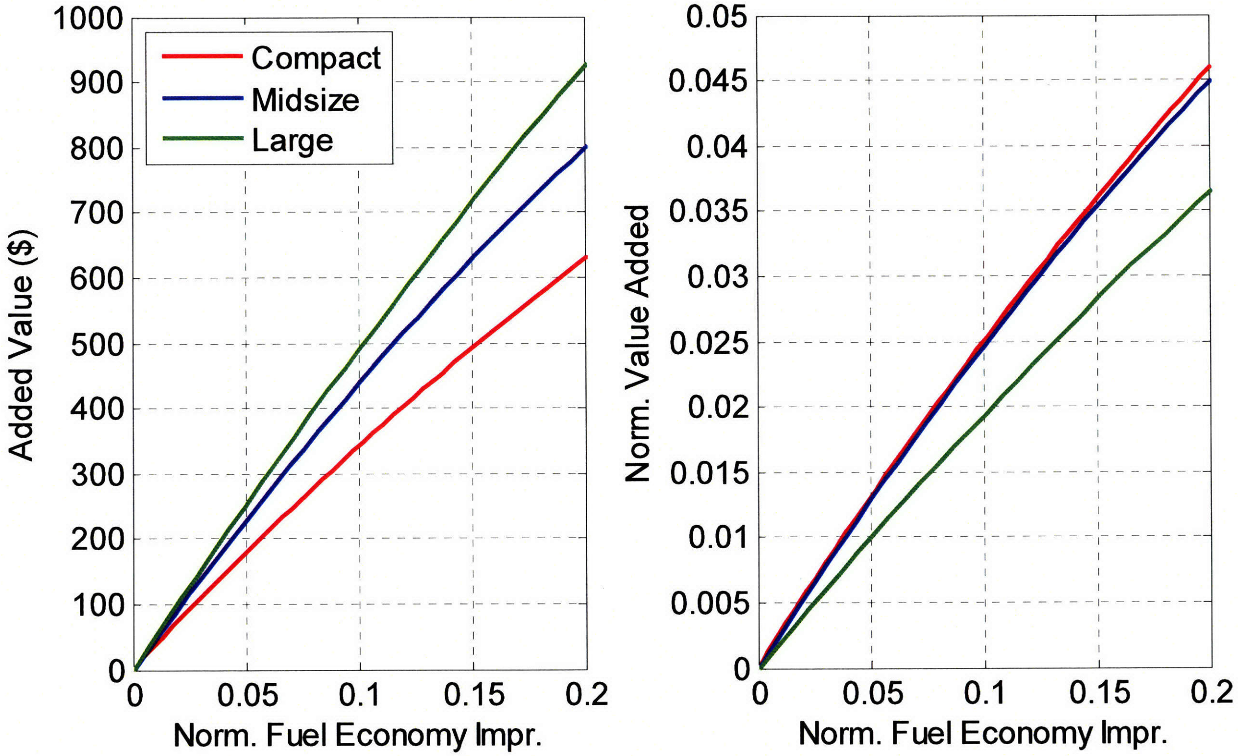


Figure 2-16: Absolute value added (left) and value added normalized to vehicle price (right) for normalized fuel economy improvement as perceived by consumers for a typical compact, midsize, and large sedan vehicle.

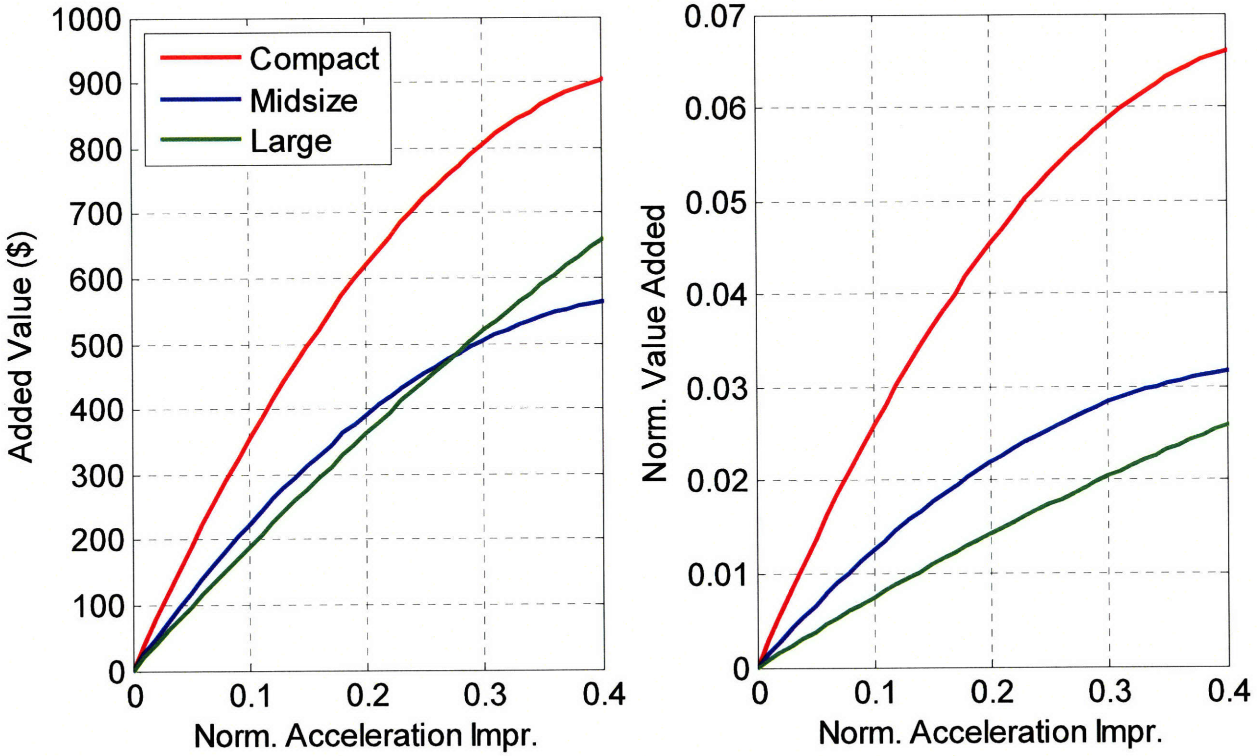


Figure 2-17: Absolute value added (left) and value added normalized to vehicle price (right) for normalized acceleration improvement as perceived by consumers for a typical compact, midsize, and large sedan vehicle.

Chapter 3

Model Overview and Case Study

Chapter 2 outlined the method to obtain Equations (2.2), (2.3), and (2.4), which govern the application of the mass decompounding, the timing, and the valuing analyses in the study, respectively. The results, together with a discussion about the findings, were also presented in Chapter 2. This Chapter will combine the results into an independent model that can be used to assess the net value of lightweighting, taking secondary mass savings into account.

3.1 Overview

The model substitutes (2.2) into (2.3), and (2.3) into (2.4), in order to obtain the compounded value of lightweighting

$$\begin{aligned} \Delta\text{value}_{\text{FE}} &= f\left(\Delta\text{mass}_{\text{primary}}, \text{time, subsystem, powertrain, vehicle type, vehicle class}\right) \\ \Delta\text{value}_{\text{ACC}} &= f\left(\Delta\text{mass}_{\text{primary}}, \text{time, subsystem, powertrain, vehicle type, vehicle class}\right) \end{aligned} \tag{3.1}$$

The value found in (3.1) is then compared against the cost found in (2.5) to obtain a measure of the net benefit of lightweighting.

In more detail, $\Delta\text{mass}_{\text{primary}}$ is first used to calculate the secondary mass savings at a particular *time* in the vehicle development process for the available *subsystems* in the vehicle. Next, the total mass savings, found by adding the primary and the secondary mass savings, is used as an input to find the resulting fuel economy and acceleration improvements for a particular *powertrain* combination. Last, the consumer values of the fuel economy and acceleration improvements are calculated by selecting the desired *vehicle type*. This analysis is confined to sedans, but the work could be extended to include other vehicle categories, in which case the *vehicle category* parameter would select the appropriate set of mass decompounding coefficients.

An overview of how the model works can be found in Figure 3-1. The figure summarizes the main results from Chapter 2 in graphical format and emphasizes their interconnectivity visually. For example, consider a decision to implement a light-weighting strategy, which will save 7.5% primary mass, taken at 200 weeks before the start of commercial production. The lower left-hand graph in the figure indicates that an additional 3.5% to 5.0% secondary mass may be saved with 95% confidence. This is demonstrated by the arrows. The lower middle and right-hand graphs display how the total mass saving may be translated into fuel economy or acceleration improvements for a certain powertrain combination. By following the arrows to the top two graphs, the improvement in vehicle performance is translated into value for a particular vehicle type.

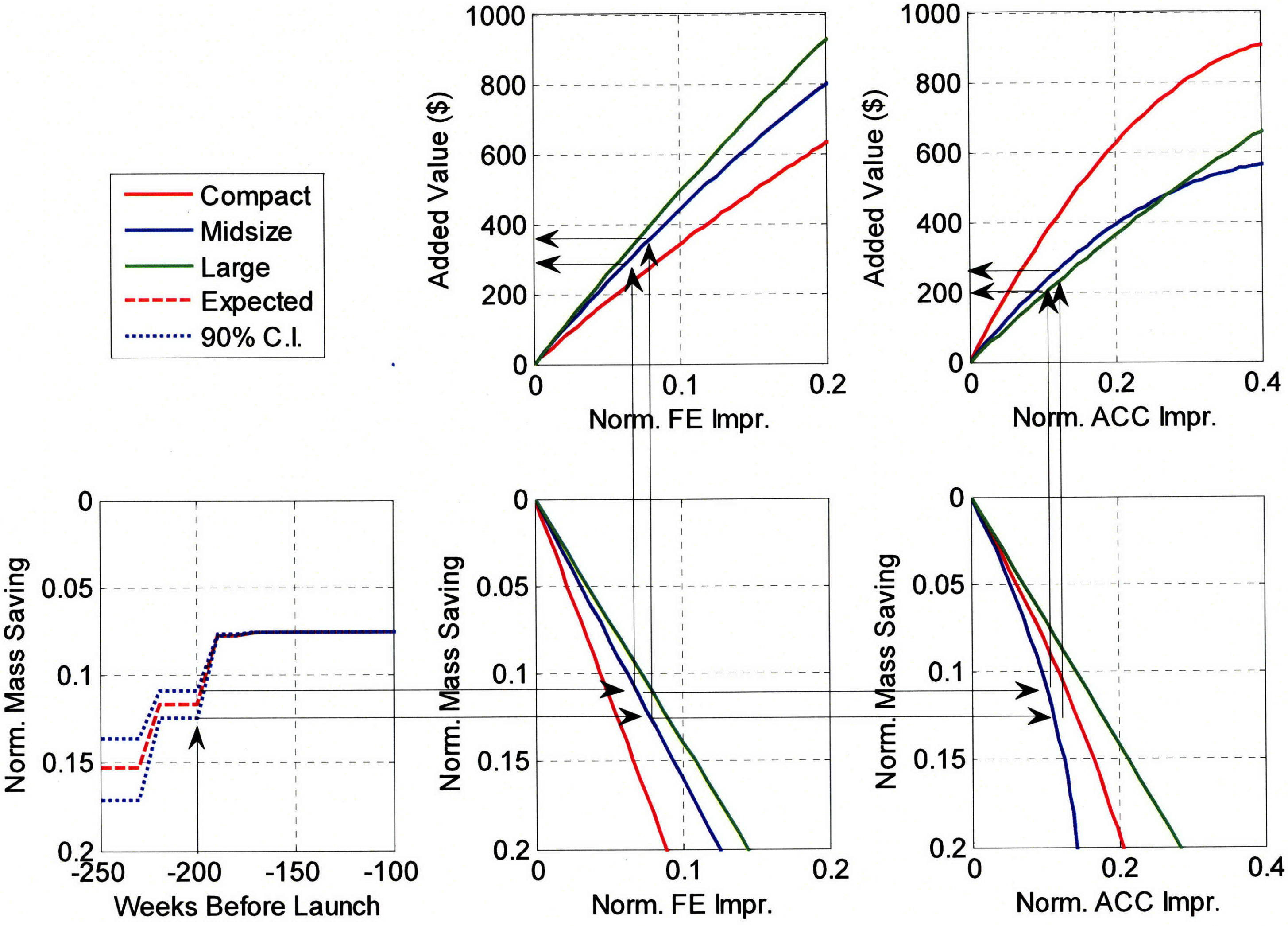


Figure 3-1: Overview of the key relationships and features in the combined model. The arrows indicate how the model calculates the value of a decision to save 7.5% primary mass, taken at 200 weeks before vehicle launch, in the midsize sedan.

3.1.1 Model Inputs

$\Delta\text{mass}_{\text{primary}}$	The primary mass savings expected for a given lightweighting strategy.
$\Delta\text{cost}_{\text{primary}}$	The change in production cost associated with the implementing the lightweighting strategy associated with $\Delta\text{mass}_{\text{primary}}$. This cost may be estimated using any cost estimation technique, such as PBCM, or may already be known.
time	The time in the vehicle development process when primary lightweighting is implemented. The current model specifies a time window of 250 to 0 weeks before the start of commercial production (vehicle launch).
subsystem	Allows the user to select which subsystems should be included in the mass decompounding calculation. For instance, it is possible that some subsystems are unavailable for redesign, for various design reasons, independent of the vehicle development timing.
powertrain	The variable that selects which combination of engine and transmission that should be employed to evaluate the mass-driven performance improvements of the vehicle. The current model includes model results of typical powertrains for the compact, midsize, and large sedans.
vehicle category	Represents a certain larger grouping of automobiles, such as sedan, SUV, or pickup. The *vehicle category* determines which set of mass decompounding coefficients the model should use to es-

	timate the secondary mass savings. In this study, the mass decompounding coefficients for the sedan vehicle category have been found.
vehicle type	Allows the user to specify which relationship the model should use to calculate value. In this model, value-responses for typical examples of compact, midsize, and large sedan vehicle types have been modeled.
fuel economy	The initial fuel economy of the vehicle under investigation.
acceleration	The initial acceleration of the vehicle under investigation.
GVM	The initial gross vehicle mass of the vehicle under investigation.

3.1.2 Model Outputs

For the inputs specified above, the model calculates the output values and presents the data in graphical format. In particular, the following parameters and their variation with time in the vehicle development process are calculated:

1. The compounded – both primary and secondary – mass saving and the metric $\Delta\$/\Delta\mathrm{kg}$, based on $\Delta\mathrm{cost}_{\mathrm{primary}}$.

2. The resulting fuel economy improvement in *mpg* and the metric $\Delta\$/\Delta\mathrm{mpg}$, based on $\Delta\mathrm{cost}_{\mathrm{primary}}$.

3. The resulting acceleration improvement in *sec* and the metric $\Delta\$/\Delta\mathrm{sec}$, based on $\Delta\mathrm{cost}_{\mathrm{primary}}$.

4. The additional consumer value derived from lightweighting when the compounded mass saving is applied towards improving fuel economy.

5. The additional consumer value derived from lightweighting when the compounded mass saving is applied towards improving acceleration.

3.2 Case Study

To illustrate how the model works, a hypothetical lightweighting case study has been prepared for representative examples of compact, midsize, and large sedans. The lightweighting scenario that will be evaluated is loosely modeled after the process based cost modeling results established by Kang, 1998. Kang shows that by using composite materials in the body-in-white it may be possible to save 127 kg of vehicle weight at a cost premium of \$400. These outputs will be employed to generate the inputs for the case study; however, in order to compare the mass savings across different vehicle types, a relative mass saving of 7.5% will be used instead of the absolute saving of 127 kg. The complete list of model inputs for the case study can be found in Table 3-1.

Table 3-1: Input variables for the case study of representative compact, midsize, and large sedans.

Input Variables	Compact	Midsize	Large
$\Delta mass_{primary}$ (kg)	120	139	150
$\Delta cost_{primary}$ (\$)	400	400	400
Time	-	-	-
Subsystem	all	all	all
Powertrain	"compact"	"midsize"	"large"
Vehicle Type	"compact"	"midsize"	"large"
Vehicle Category	"sedan"	"sedan"	"sedan"
Initial Fuel Economy (mpg)	29	24	22
Initial Acceleration (sec)	10	11	9
Initial Gross Vehicle Mass (kg)	1600	1850	2000

The first result, Figure 3-2, shows how the mean and the 95% confidence interval of the total mass saving varies with time in the vehicle development process. As all subsystems are available for redesign, the total saving at 250 weeks before the start of regular production corresponds to a primary saving of 7.5% and a secondary saving of 1.04 times the primary. The multiplier corresponds to the mass decompounding coefficient for the entire sedan vehicle (Table 2-11).

The cost to lightweight was found by dividing the cost of the primary lightweighting by the total mass saved. Consequently, it is assumed that the secondary mass savings may be obtained at no extra cost. This is a simplistic view, but further elaboration on this topic is left for a future study. At 250 weeks before vehicle launch, the cost to lightweight is $1.76/kg compared to $3.57/kg, at 150 weeks before vehicle launch for the midsize sedan.

If the combined mass saving is applied towards improving the fuel economy of the vehicle, the expected time-varying improvement in miles per gallon is as shown in Figure 3-3. The cost to improve fuel economy varies from $175/mpg at 250 weeks before vehicle launch to $355/mpg at week 150 before launch for the midsize sedan.

Conversely, if the total mass saving is applied towards improving the acceleration of the vehicle, the expected time-dependent acceleration performance is displayed in Figure 3-4. For the midsize sedan, the cost to improve acceleration varies from $288/sec to $475/sec over the course of the vehicle development process.

Figure 3-5 and Figure 3-6 show the time-variation in expected value, when all the mass saving is applied towards fuel economy improvement and acceleration improvement, respectively. The Figures also show at what point in the vehicle development process the primary cost, $400 (green dashed), exceeds the value derived from lightweighting. If the value is greater than the costs, there will be a net benefit to lightweighting.

The final results (Table 3-2) indicate that the net value for the compact sedan is positive if lightweighting is implemented at 200 weeks or more before start of regular production, and all the mass saving is applied towards improving the acceleration performance of the vehicle. For the midsize and large sedans, the net value remains positive until 220 and 200 weeks, respectively, before start of commercial production, when the mass saving is applied towards improving fuel economy.

The output of the analysis helps the user to select an optimal lightweighting strategy by comparing the net value for different vehicle types at different times in the vehicle development process.

Table 3-2: Derived cross-over point in number of weeks before start of commercial production and suggested focus attribute for a net positive value resulting from a 7.5% primary mass reduction in representative compact, midsize, and large sedan vehicles at a cost premium of $400.

Vehicle Type	Focus Attribute	Cross-over Point (Week)
Compact	Acceleration	-200
Midsize	Fuel Economy	-220
Large	Fuel Economy	-200

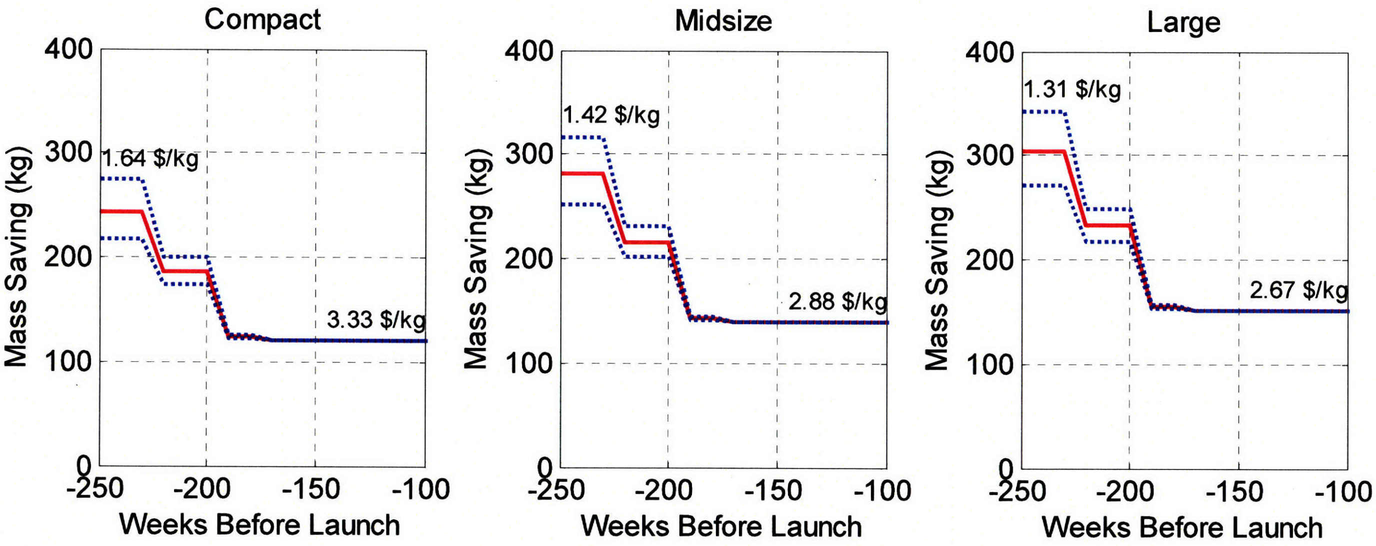


Figure 3-2: Variation with time in the vehicle development process of the mean and the 95% confidence interval of the compounded mass savings for representative compact, midsize, and large sedans.

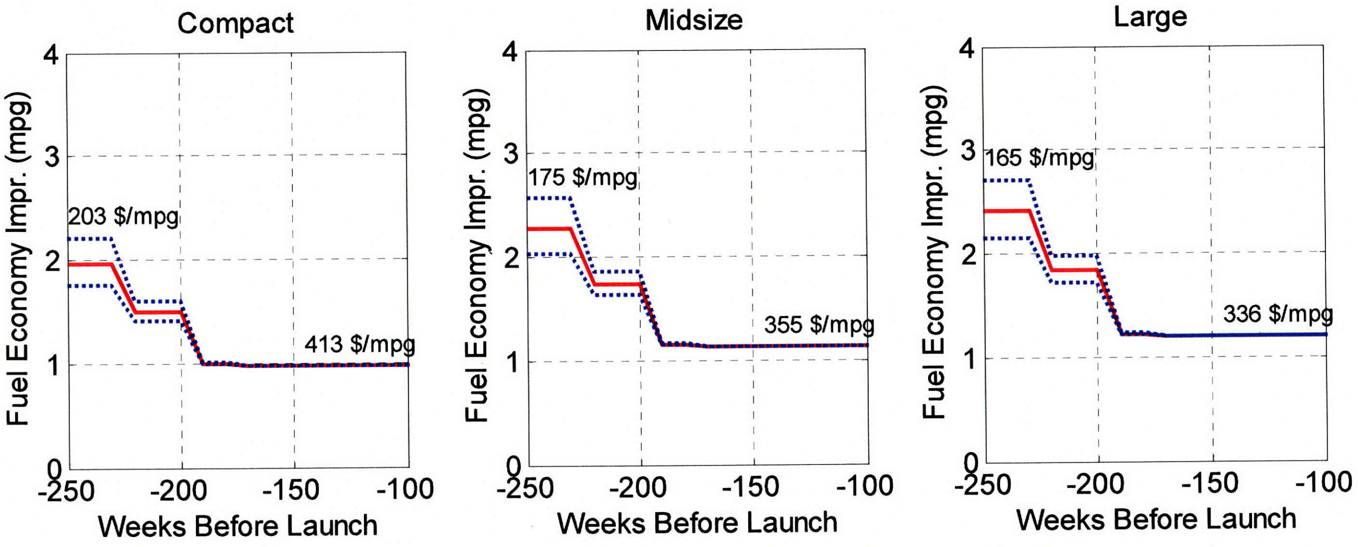


Figure 3-3: Variation with time in the vehicle development process of the mean and the 95% confidence interval of the fuel economy improvement for representative compact, midsize, and large sedans. The model assumes that all mass savings is applied towards improving fuel economy.

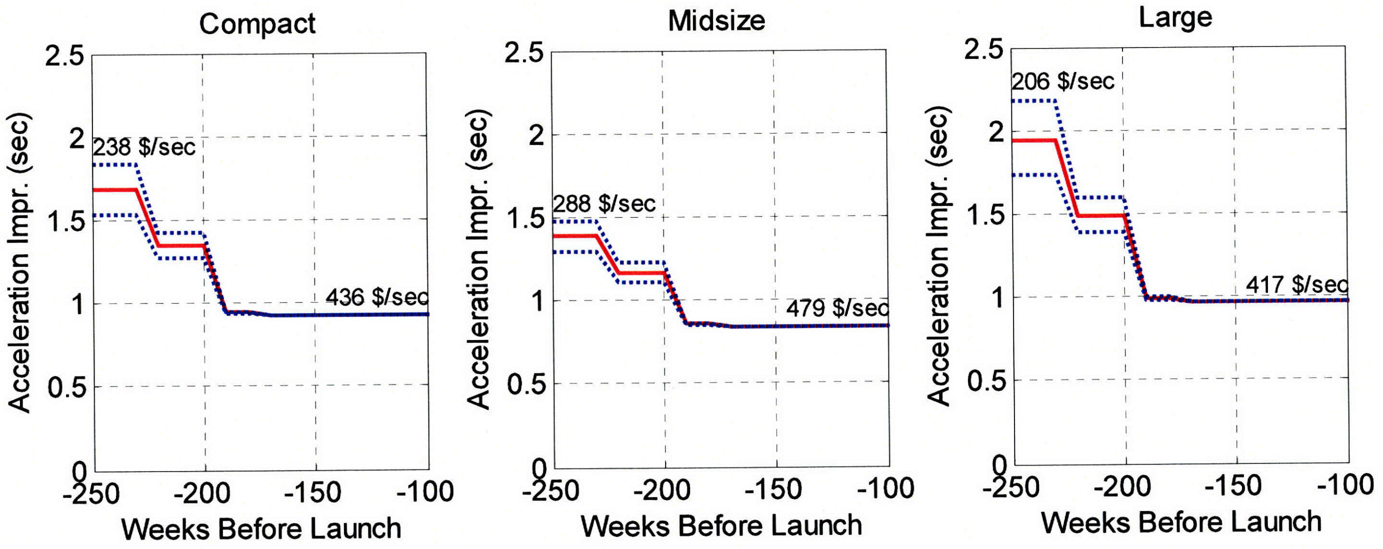


Figure 3-4: Variation with time in the vehicle development process of the mean and the 95% confidence interval of the acceleration improvement for representative compact, midsize, and large sedans. The model assumes that all mass savings is applied towards improving acceleration.

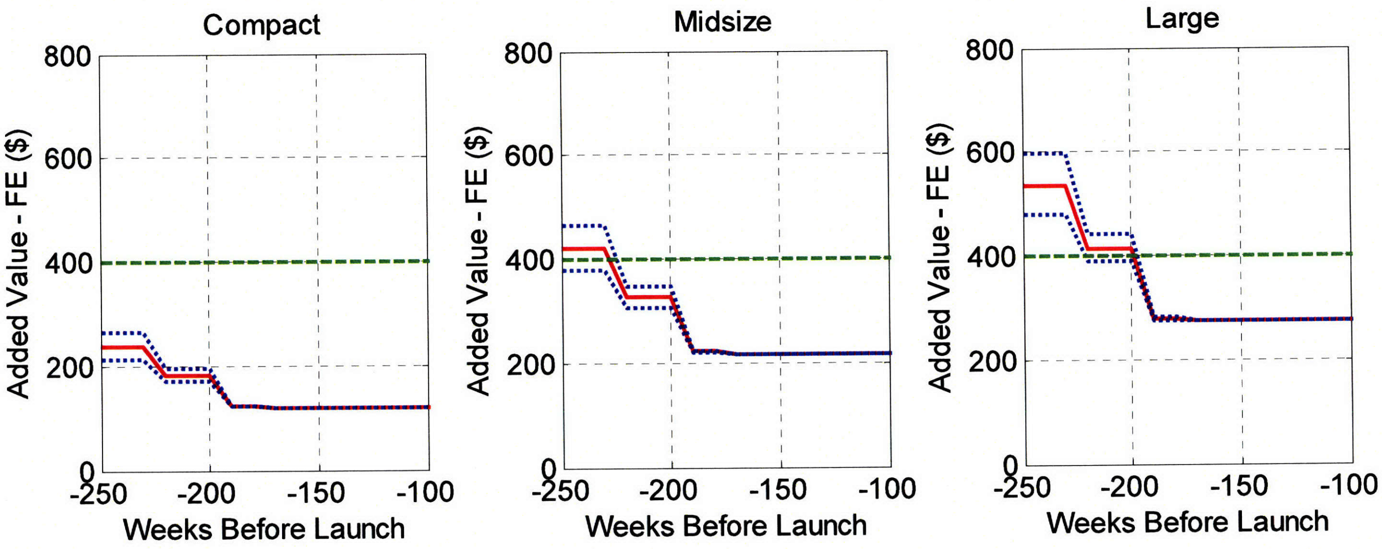


Figure 3-5: Variation with time in the vehicle development process of the mean and the 95% confidence interval of the compounded value for fuel economy improvement in representative compact, midsize, and large sedans. The model assumes that all mass savings is applied towards improving fuel economy.

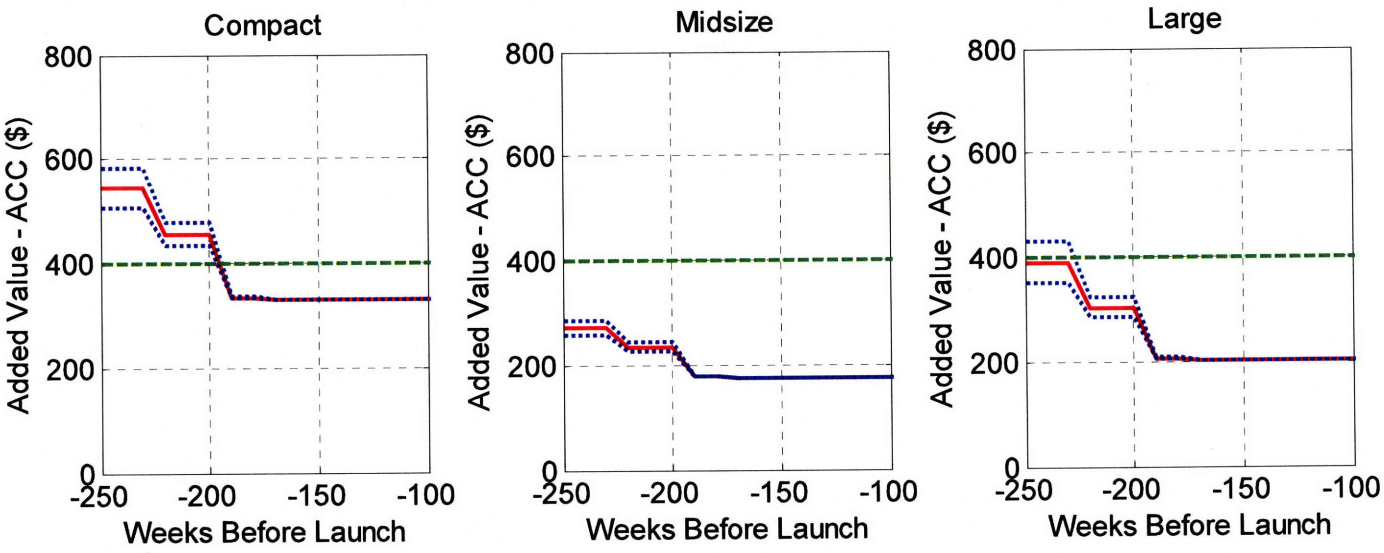


Figure 3-6: Variation with time in the vehicle development process of the mean and the 95% confidence interval of the compounded value for acceleration improvement in representative compact, midsize, and large sedans. The model assumes that all mass savings is applied towards improving acceleration.

Chapter 4

Sensitivity Analysis

This Chapter will analyze the sensitivity of the results to changes in the underlying model methodology. Three scenarios will be analyzed: first the effect of changing the outlier detection process, second the effect of changing the classification of subsystem GVM-dependency, and third the effect of changing the subsystem design deadlines in the vehicle development process.

The sensitivity of the end result to changes in the powertrain and market model results may be evaluated by assessing the range in outputs obtained for the case study of the compact, midsize, and large sedan vehicles.

4.1 Outlier Detection Process

One of the underlying assumptions of linear regression analysis is that the distribution of the errors is approximately normal with a mean of zero. A normal distribution has the property that about 68% of the values will fall within +/- 1 standard deviation from the mean, 95% will fall within +/- 2 standard deviations, and 99% will fall within +/- 3 standard deviations of the mean. This implies that for a normally distributed set of data one would expect an observation to occur outside of the 95% and 99% prediction intervals once every 20 and once every 500 observations, respectively.

How likely an observation is to occur may prompt its classification as an outlier. When outliers are found, it is important to investigate (1) whether they are mere coincidences due to either data entry errors or the result of unlikely conditions that are not expected to recur, or if they represent a real effect that should be included in the model; and (2) how much they affect the final regression coefficients of the model.

Outliers have the potential to cause large problems in models fitted to small data sets, similar to the one analyzed in this study. Bad outliers in small data set can skew the results and affect the residuals, which are the basis for estimating regression parameters and calculating error statistics and confidence intervals.

To analyze the effect of outliers in the present analysis of the mass decompounding coefficients, three outlier-detection schemes were tested, where an outlier was defined in one of three ways:

1. Any observation occurring outside of the 99% prediction interval
2. Any observation occurring outside of the 95% prediction interval
3. Any observation occurring outside of the 90% prediction interval

Scheme number two corresponds to the base case, which was employed in the analysis in Chapter 2.

As can be seen in Figure 4-1, the effect of the different outlier-detection schemes on the resulting mass decompounding coefficients appears to be minor. In comparing scheme 1, where outliers are defined as occurring outside of the 99% prediction interval, to the base case a slight difference in mass decompounding coefficients can be detected. In particular, the coefficients derived under scheme 1 are shown to be smaller than those obtained in the base case analysis. This may be explained by the occurrence of non-normally distributed observations representing vehicles with larger than average GVM and smaller than average subsystem mass, or vice, as these observations would have the largest effect on making the subsystem mass versus GVM slopes shallower and, by extension, decreasing the mass decompounding coefficients. Moreover, as discussed previously, the R^2 values of the OLS regression models were found to improve significantly after the removal of the outliers occurring outside of the 95% prediction intervals.

When comparing the coefficients resulting from scheme 3 with the base case, on the other hand, the difference is seen to be negligible. The absence of variation indicates that the error is approximately normally distributed about the mean and that no additional enhancement of the model is gained by narrowing the prediction intervals to include only 90% instead of 95% of the expected observations. Consequently, it may be concluded that the mass decompounding analysis is relatively robust to the removal of outliers, once the outliers occurring outside of the 95% prediction interval have been identified and removed.

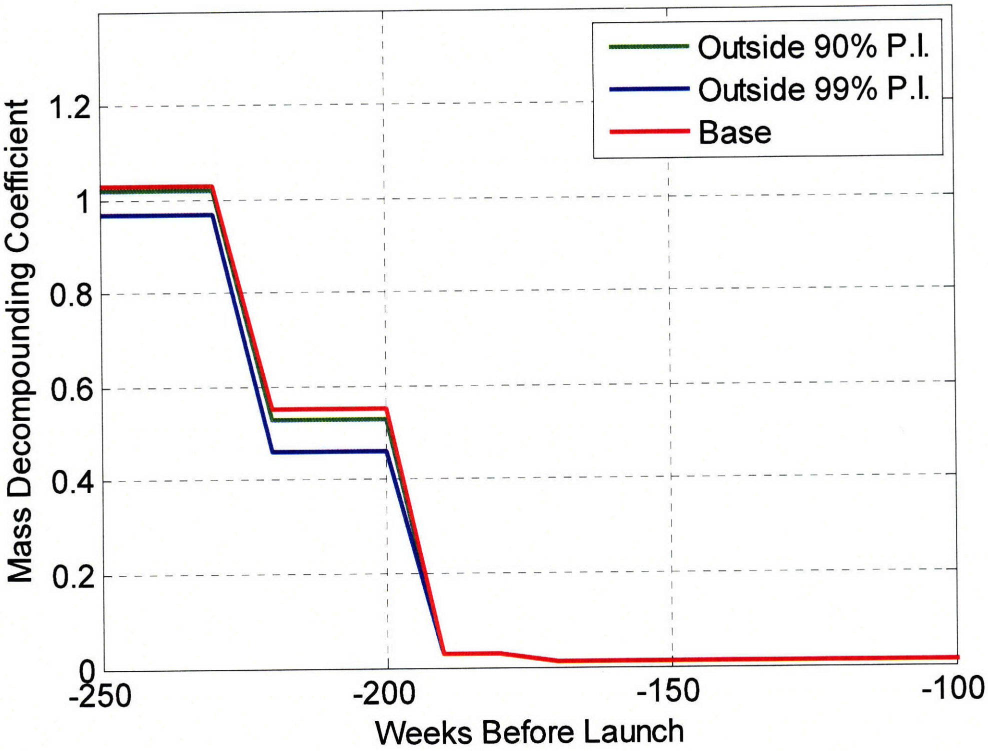


Figure 4-1: The effect of changing the outlier-detection process on the final mass decompounding coefficients, here investigated for outliers defined as occurring outside of the 90%, 95% (base case), and 99% prediction intervals.

4.2 GVM-Dependency Classification

Another important assumption that was made in regard to the mass decompounding coefficient analysis was that only certain subcomponents in each subsystem contribute to mass decompounding. The classification rules employed in this study, which will be referred to as the base case, were obtained from industry experts. Should such information not be available, however, another way to determine the subsystem-specific GVM-dependency might be to evaluate each subcomponent's correlation with GVM.

This approach was adopted in assessing the sensitivity of the final mass decompounding coefficients on the GVM-dependency selection process. In particular, the base case was compared against two scenarios where the subcomponents were classified as GVM-dependent if their correlation with GVM was greater than (1) 0.3 and (2) 0.6.

As can be seen in Figure 4-2, the mass decompounding coefficients are highly dependent on the number of subcomponents that are classified as GVM-dependent. Specifically, the resulting mass decompounding coefficients are seen to increase as the decision variable – the correlation coefficient – is decreased and the number of GVM-dependent subcomponents is increased. For instance, when the cut-off correlation is 0.3 most of the subcomponents are considered GVM-dependent and thus subject to mass decompounding, resulting in larger mass decompounding coefficients. Conversely, when the cut-off correlation is 0.6, fewer subcomponents are classified as GVM-dependent and the derived mass decompounding coefficients are smaller.

For the mass decompounding coefficients to be affected, there needs to be a change in regression slope of the subsystem mass versus GVM. Consequently, the process by which the number of GVM-dependent subsystems is increased appears to disproportionately increase the subsystem masses of observations associated with larger GVM. This would cause the slope of subsystem mass versus GVM to steepen and by extension the mass decompounding coefficients to increase. In summary, it is concluded that the mass decompounding coefficients are highly sensitive to the GVM-dependency classification scheme and that care should be taken in selecting the GVM-dependent subcomponents.

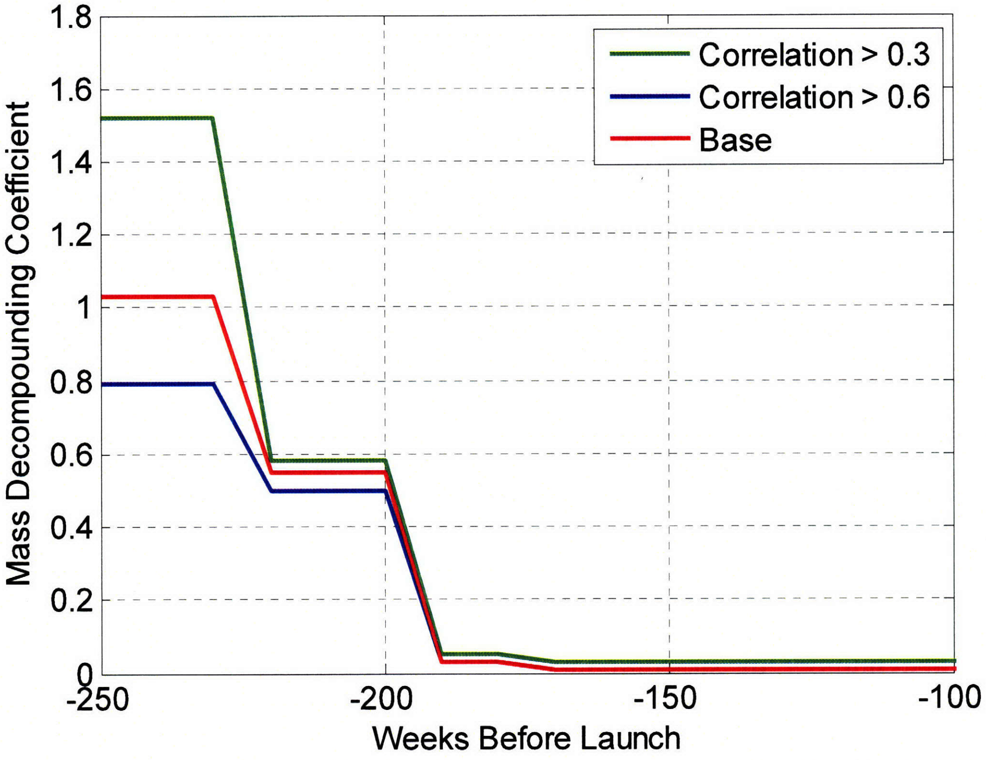


Figure 4-2: The effect of different GVM-dependency selection metrics on the final mass decompounding coefficients. Here the base case is compared against scenarios where subcomponents are classified as GVM-dependent based on their correlation with GVM.

4.3 Subsystem Timing

A third parameter, whose effect on the mass decompounding results it was decided to investigate, is the subsystem timing. The subsystem timing affects how quickly and at what point in the vehicle development process the total vehicle mass decompounding coefficient drops to zero. For the present analysis, the mass decompounding coefficients were obtained using subsystem timing data from industry experts. This scenario will be referred to as the base case. This data was judged highly dependable; however, it was hypothesized that some design flexibility might remain even after the given design deadlines, as defined in Table 2-12. The underlying reasoning is that in a system that is as interdependent as an automobile some minor modifications may still occur during later stages of vehicle development. Therefore, it was conjectured that the majority of the design details be fixed by the prescribed date, but that some smaller amount be fixed in the weeks immediately following the initial design deadline. In particular, two cases were selected for demonstration purposes and compared against the base case. The first case involves a hypothetical scenario where 60% of a subsystem's mass is fixed in the first week, 40% in the following week, and 10% in each of the second and third week following the initial design deadline. The second case involves a hypothetical scenario where 40% of a subsystem's mass is fixed in the first week, 20% in the following week, 20% in the second week, and 10% in each of the third and fourth week following the initial design deadline. The effect of the different timing scenarios on the time-dependency of the mass decompounding coefficient is displayed in Figure 4-3.

As can be seen in the Figure, the added flexibility increases the number of discrete values that the mass decompounding coefficient assumes during the course of the vehicle development process. As a result, the time-dependent mass decompounding coefficient curve appears smoother and the coefficient remains larger until later in the vehicle development process. In the base case, the significant time interval for secondary weight savings was identified as 200 or more weeks before the start of commercial production. With increased design flexibility, some considerable amount of secondary mass may also be saved in week 190 and 180 before vehicle launch, especially for the case where only 40% of the subsystem mass is locked-in during the first week.

In general, the subsystem timing deadlines may vary from automaker to automaker as well as from one vehicle program to the next, and the percentage of the subsystem-specific design that becomes locked in, and thus unavailable for mass decompounding, at different times in the vehicle development process is indeed subject to variation. As seen in this analysis, changes in the subsystem timing results in different mass decompounding time-dependencies. Even so, there appears to be a certain time window during which the potential for secondary weight savings is the greatest. This time window appears to end at around 200 to 180 weeks before the start of commercial production.

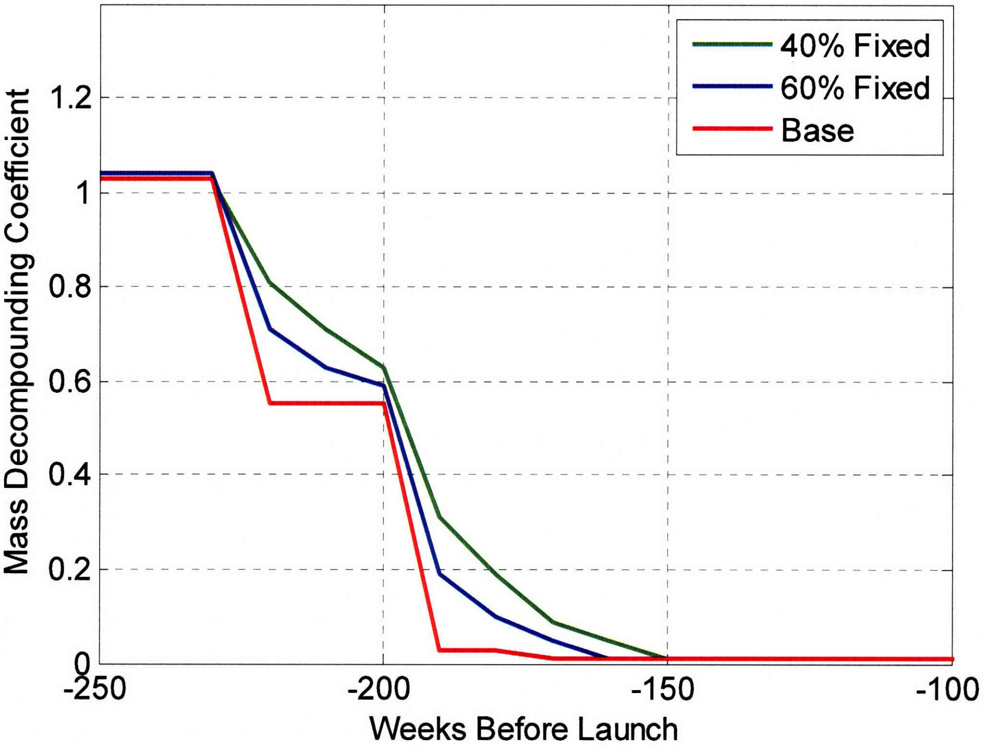


Figure 4-3: The effect of subsystem timing on the final mass decompounding coefficients. Here the base case is compared against two scenarios where (in green) 40% of the subsystem design details are fixed in week 1 with additional 20%, 20%, 10%, and 10% fixed in the following weeks; and where (in blue) 60% of the design is fixed in week 1 with additional 40%, 20%, 10%, and 10% of the subsystem design details are fixed in the weeks immediately following the initial design deadline.

Chapter 5

Conclusion

A methodology was presented to easily estimate and assess the value of the secondary mass savings in the sedan vehicle at different times in the vehicle development process. Regression analysis of detailed mass data from 52 2007 to 2008 model sedans was employed to calculate the subsystem-specific mass decompounding coefficients for thirteen functional subsystems of the sedan vehicle. The mass decompounding coefficients were found using a refined statistical treatment that particularly addressed concerns about outlier data, GVM-dependent subsystem mass classification, and confidence bounds. The most significant contributions to secondary weight savings were found to be obtained from the Suspensions, Structure, and Engine subsystems, whose mass decompounding coefficients were found to be 0.29, 0.25, and 0.21, respectively.

The mass compounding coefficients were analyzed in light of the vehicle development timing in order to incorporate the subsystem-specific redesign availability. Consequently, a time-varying mass decompounding coefficient was established that can be used to find the expected total, primary and secondary, mass saving resulting from primary lightweighting at different times in the vehicle development timing. The critical time for mass decompounding was identified to occur around 200 weeks or more before the start of commercial production

Next, the resulting primary and secondary mass saving was analyzed in terms of the expected mass-driven performance improvements and performance-driven value increases. In particular, fuel economy and acceleration were targeted as performance metrics. The analysis was carried out for typical compact, midsize, and large sedan vehicles. For the compact sedan, acceleration was identified as the target attribute that would yield the greatest value added during vehicle lightweighting and correspondingly fuel economy was established as the target attribute in midsize and large sedans.

5.1 Implications for Industry

The study shows that the potential benefits from vehicle lightweighting are greater than what may be immediately apparent. When secondary mass savings are considered, an additional amount of mass roughly equal to the primary lightweighting may be saved in the sedan vehicle. The additional mass saving contributes to increased benefits such as improved fuel economy and acceleration performance of the vehicle. The compounded weight saving may also positively impact other vehicle attributes, such as the level of CO_2 emissions. Furthermore, additional value may be gained from reduced materials handling and transportation costs during manufacture of the lighter vehicle.

The mass decompounding coefficient was found to decrease during the course of the vehicle development process, as the designs of the vehicle subsystems become fixed. The importance of lightweighting early, before the designs of the subsystems with the largest mass decompounding coefficients become locked in, should therefore be emphasized.

Last, increased awareness of and design optimization for secondary mass savings on the subsystem level may help to turn the economic argument in favor of lightweighting, provided that a systems approach to subsystem design and vehicle lightweighting is adopted. For instance, it is essential to consider the combined, rather than individual, effect of mass decompounding, timing, and valuing when assessing the benefits of vehicle lightweighting.

5.2 Future Work

A number of areas of future work have been identified relating to the mass decompounding, timing, and valuing analyses of this study:

1. The model could be extended to include not only sedans, but also other vehicle categories, such as SUV, pickup, and cross-over. These other vehicle categories are believed to be associated with different mass decompounding coefficients, different subsystem timing-relationships, different powertrain performance improvements, and different value functions. The presented analytical approach can still be applied; however, new data for the analysis would be needed.

2. The model could also be extended within the sedan vehicle category to include powertrain and market value results not only for compact, midsize, and large sedans, but also for typical budget, luxury, sport, etc type sedans. The powertrain modeling could furthermore be extended to include different drivetrains, such as hybrid.

3. The statistical methodology may be improved either through successful data segmentation of larger data sets or by the inclusion of additional factors in the regression model. Other fits beyond linear, such as power or log may also be investigated to assess and improve the predictive relationships between subsystem mass and GVM.

4. In the current implementation of the model, cost is treated as an input and a constant primary cost of lightweighting ($400) was employed in the case study. A future analysis could explore and quantify the additional costs or

benefits associated with obtaining the secondary mass savings. In particular, costs derived from optimizing subsystem design to gain the secondary mass savings and costs associated with changes in the engineering, the processing, and the material of the optimized subsystem design could be investigated. This analysis could also include an assessment of the potential cost benefits associated with reduced material usage during large scale manufacturing.

5. The consumer value equations employed in the present study assume that the total mass saving is applied towards improving either fuel economy or acceleration. In a future study, the effect of multi-attribute variation could be assessed in order to find the optimum combination of attribute improvement that yield the highest consumer value. For instance, different fractions of the total mass saving could be allocated towards improving fuel economy and acceleration, respectively.

6. In addition to fuel economy and acceleration, other mass-driven value metrics could be investigated. In particular, CO_2 emissions and noise-vibration-harshness may be interesting such examples. Reduced total vehicle mass results in improved fuel economy, which in turn leads to reduced CO_2 emissions. It is further believed that total vehicle weight has an impact on the noise and vibrations of the overall vehicle. Consequently, the changes in these mass-driven value metrics may be analyzed using vehicle design modeling and market trend modeling.

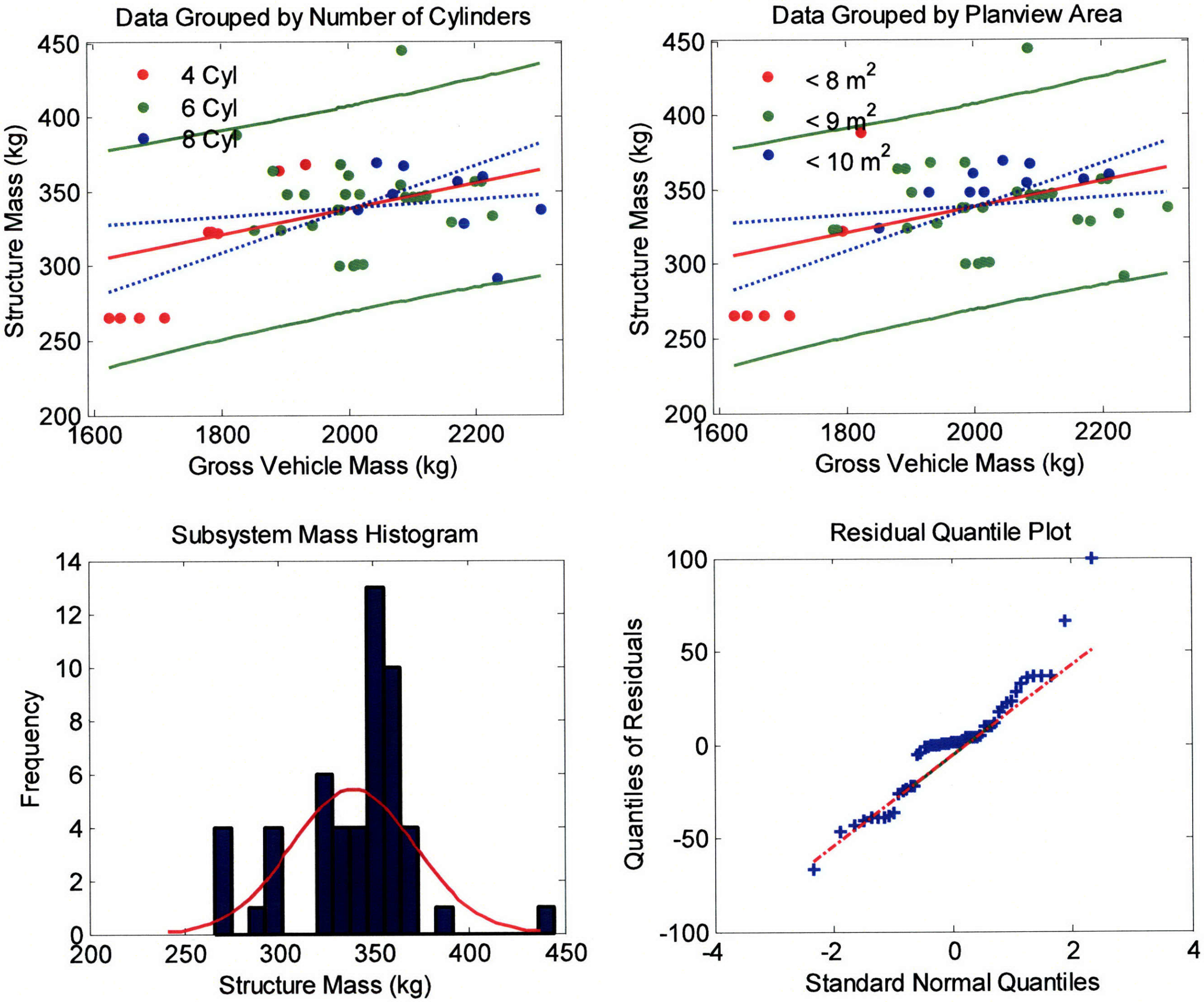
7. The powertrain and the market value modeling results are believed to be sensitive to time. In particular, the market data is believed to be time-sensitive because the AMIS model calculates prices and vehicle attributes based on current information about vehicles, competitor vehicles, and consumer preferences. As new vehicles constantly emerge in the market, as vehicle attributes and performance change, and as fuel economy is becoming increasingly important in

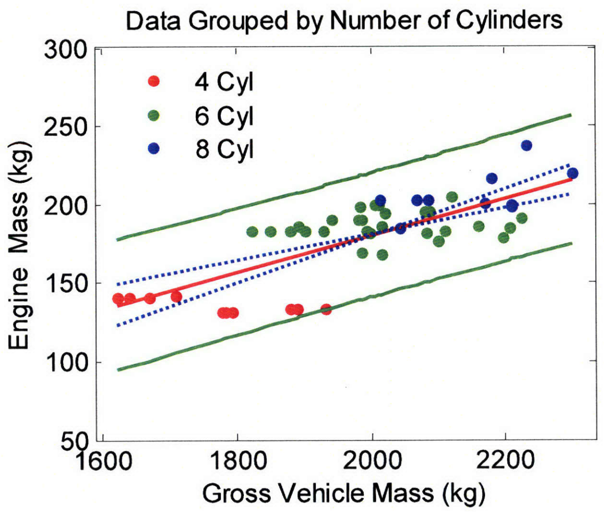
the minds of consumers, the accuracy of the AMIS results is believed to decrease over time. Also the powertrain modeling results may exhibit a certain time dependency. In particular, it is believed that the amount of fuel economy or acceleration improvement that can be expected from a reduction in GVM may change over time as the powertrains become more efficient and different drivetrains appear in the market. In summary, this observations leads to the suggestion that the powertrain and market model data be updated on a continual basis.

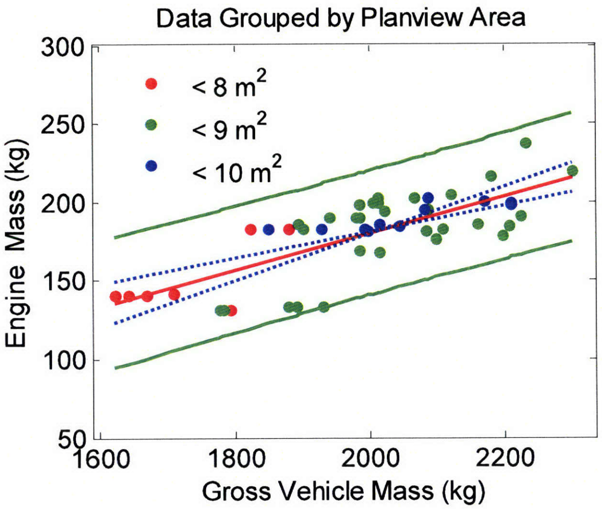
8. Last, a future analysis would be to validate the model results against real-life scenarios of primary and secondary mass savings. First, the mass decompounding analysis could be compared to the amount of secondary mass that can be saved in a real vehicle as a result of primary mass reduction. Second, the timing data could be validated by obtaining information, real-time, during the development process of a new vehicle. Third, the market model results may be validated through surveys among consumers and at dealerships to investigate how much customers are in fact willing to pay for improvements in different vehicle attributes. As previously mentioned, the powertrain model results had been found to be accurate to within 1% of actual values.

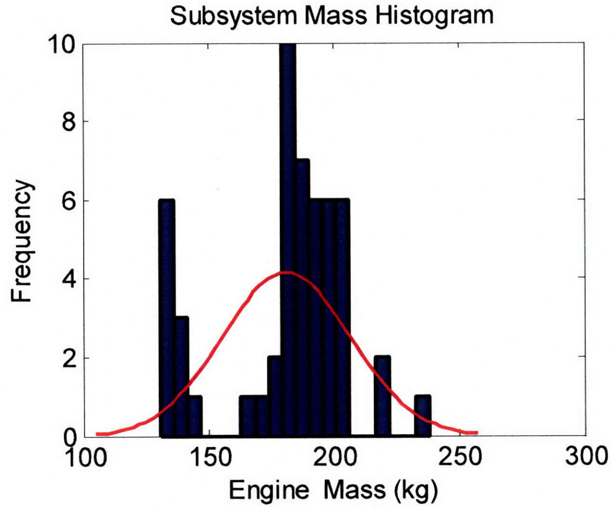
Appendix A

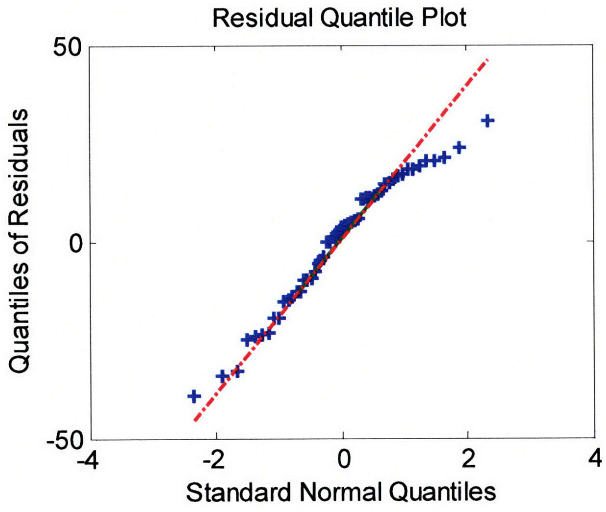
Mass Influence Coefficient Analysis of Original Dataset

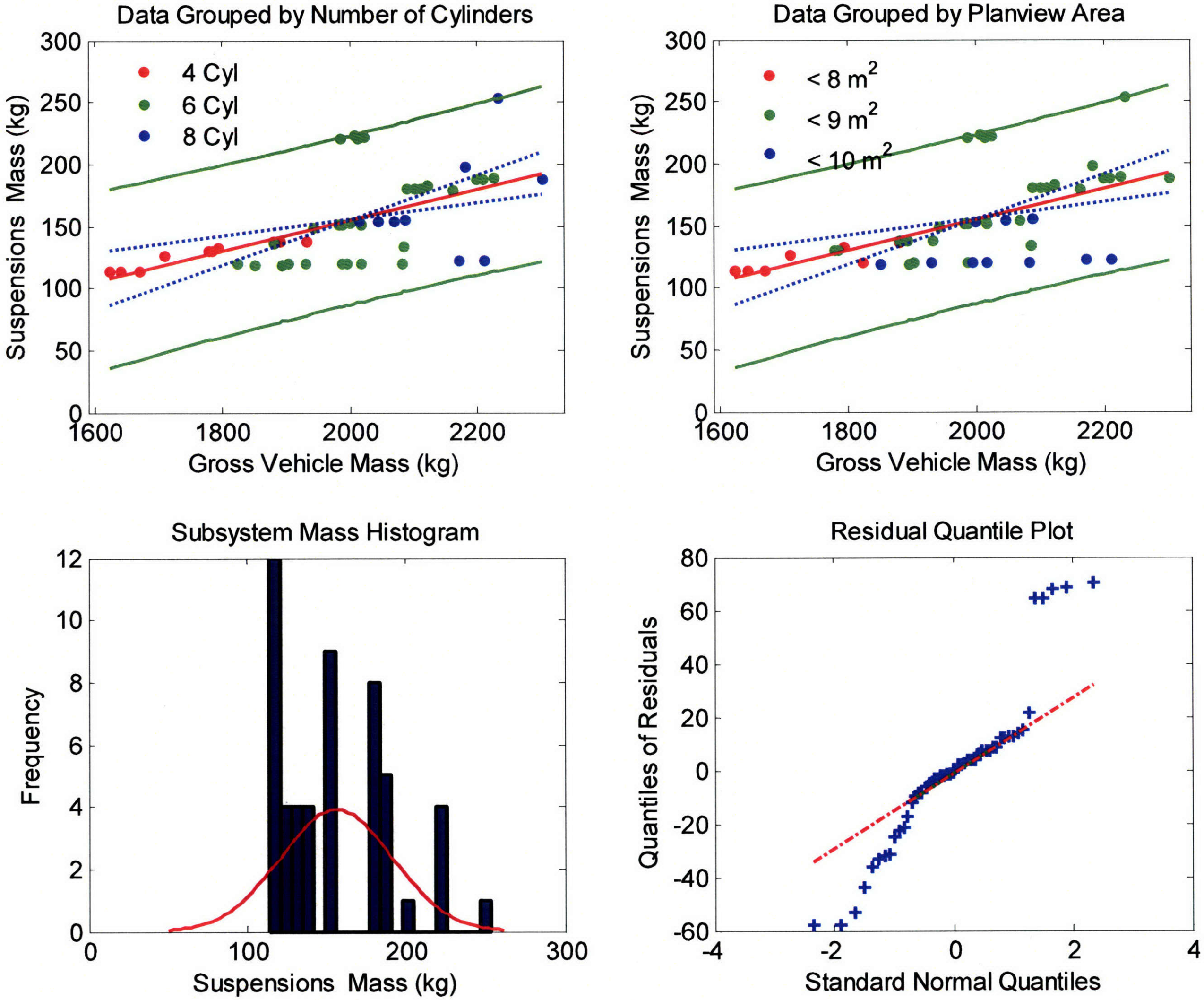

Data Grouped by Number of Cylinders
4 Cyl
6 Cyl
8 Cyl
Structure Mass (kg)
450
400
350
300
250
200
1600
1800
2000
2200
Gross Vehicle Mass (kg)
Data Grouped by Planview Area
< 8 m^2
< 9 m^2
< 10 m^2
Structure Mass (kg)
450
400
350
300
250
200
1600
1800
2000
2200
Gross Vehicle Mass (kg)
Subsystem Mass Histogram
Frequency
14
12
10
8
6
4
2
0
200
250
300
350
400
450
Structure Mass (kg)
Residual Quantile Plot
Quantiles of Residuals
100
50
0
-50
-100
-4
-2
0
2
4
Standard Normal Quantiles

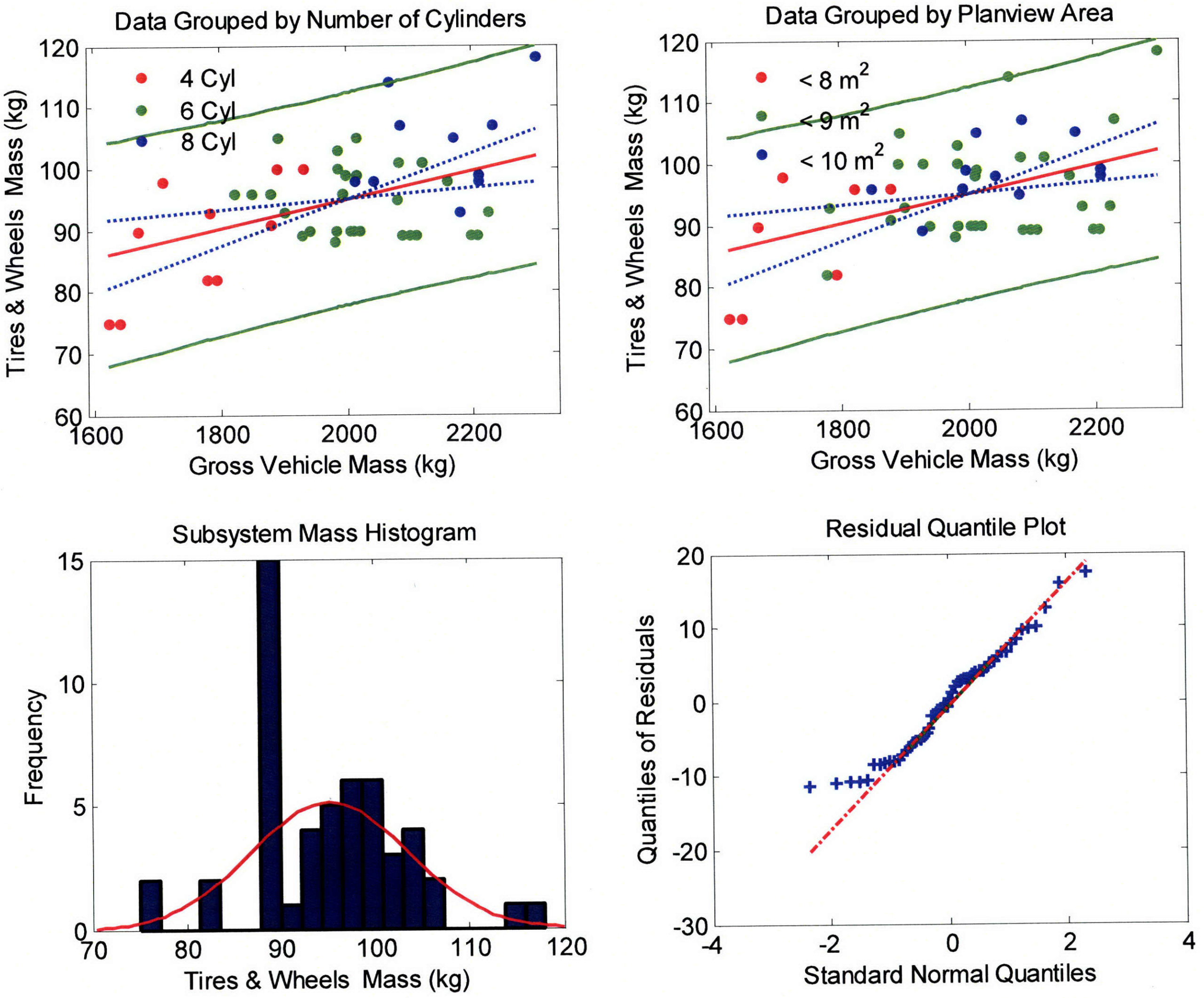

Data Grouped by Number of Cylinders
4 Cyl
6 Cyl
8 Cyl
Engine Mass (kg)
300
250
200
150
100
50
1600
1800
2000
2200
Gross Vehicle Mass (kg)


Data Grouped by Planview Area
$< 8\ m^2$
$< 9\ m^2$
$< 10\ m^2$
Engine Mass (kg)
300
250
200
150
100
50
1600
1800
2000
2200
Gross Vehicle Mass (kg)


Subsystem Mass Histogram
Frequency
10
8
6
4
2
0
100
150
200
250
300
Engine Mass (kg)


Residual Quantile Plot
Quantiles of Residuals
50
0
-50
-4
-2
0
2
4
Standard Normal Quantiles

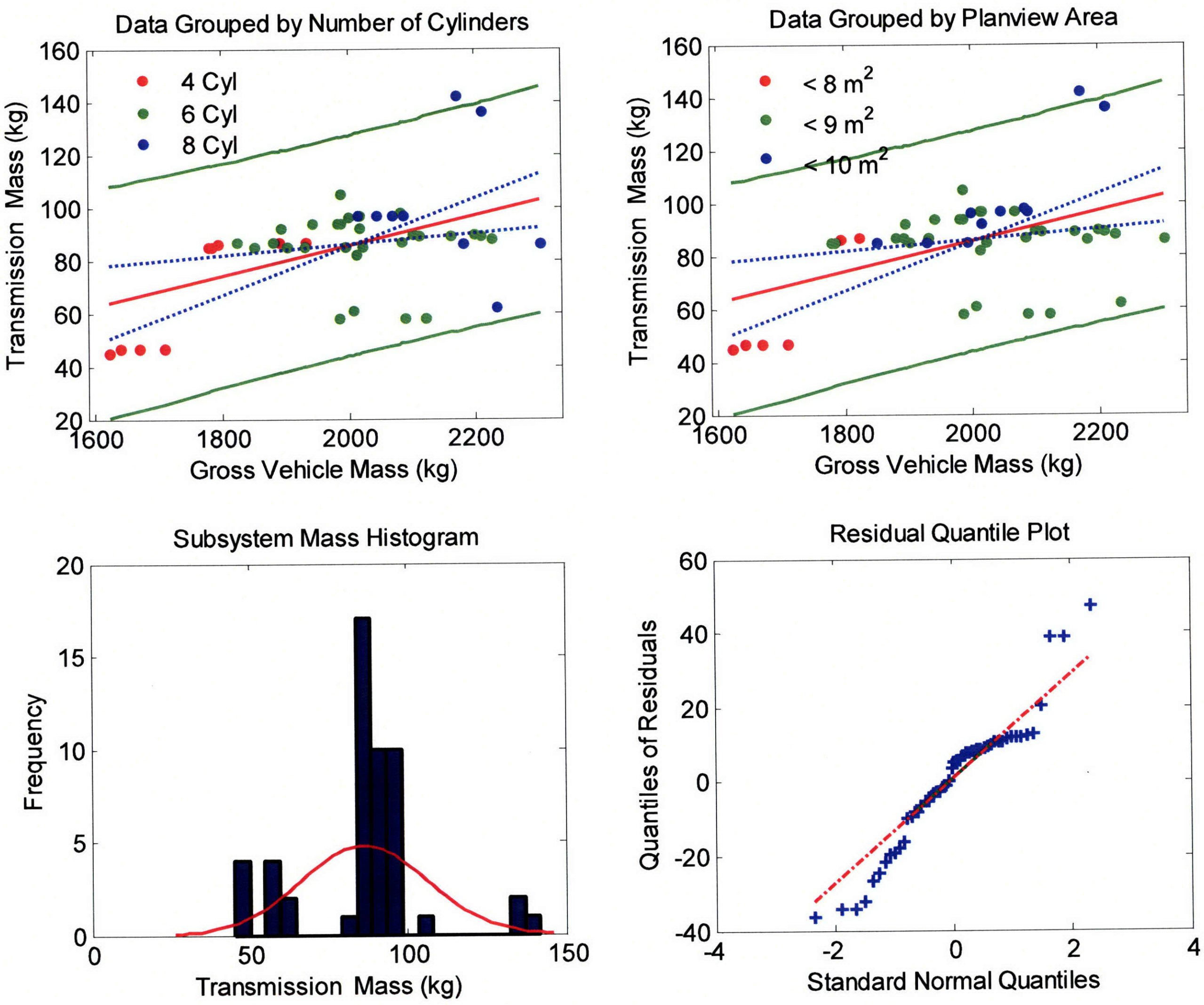

Data Grouped by Number of Cylinders
Suspensions Mass (kg)
Gross Vehicle Mass (kg)
4 Cyl
6 Cyl
8 Cyl
0
50
100
150
200
250
300
1600
1800
2000
2200
Data Grouped by Planview Area
Suspensions Mass (kg)
Gross Vehicle Mass (kg)
< 8 m²
< 9 m²
< 10 m²
0
50
100
150
200
250
300
1600
1800
2000
2200
Subsystem Mass Histogram
Frequency
Suspensions Mass (kg)
0
2
4
6
8
10
12
0
100
200
300
Residual Quantile Plot
Quantiles of Residuals
Standard Normal Quantiles
-60
-40
-20
0
20
40
60
80
-4
-2
0
2
4

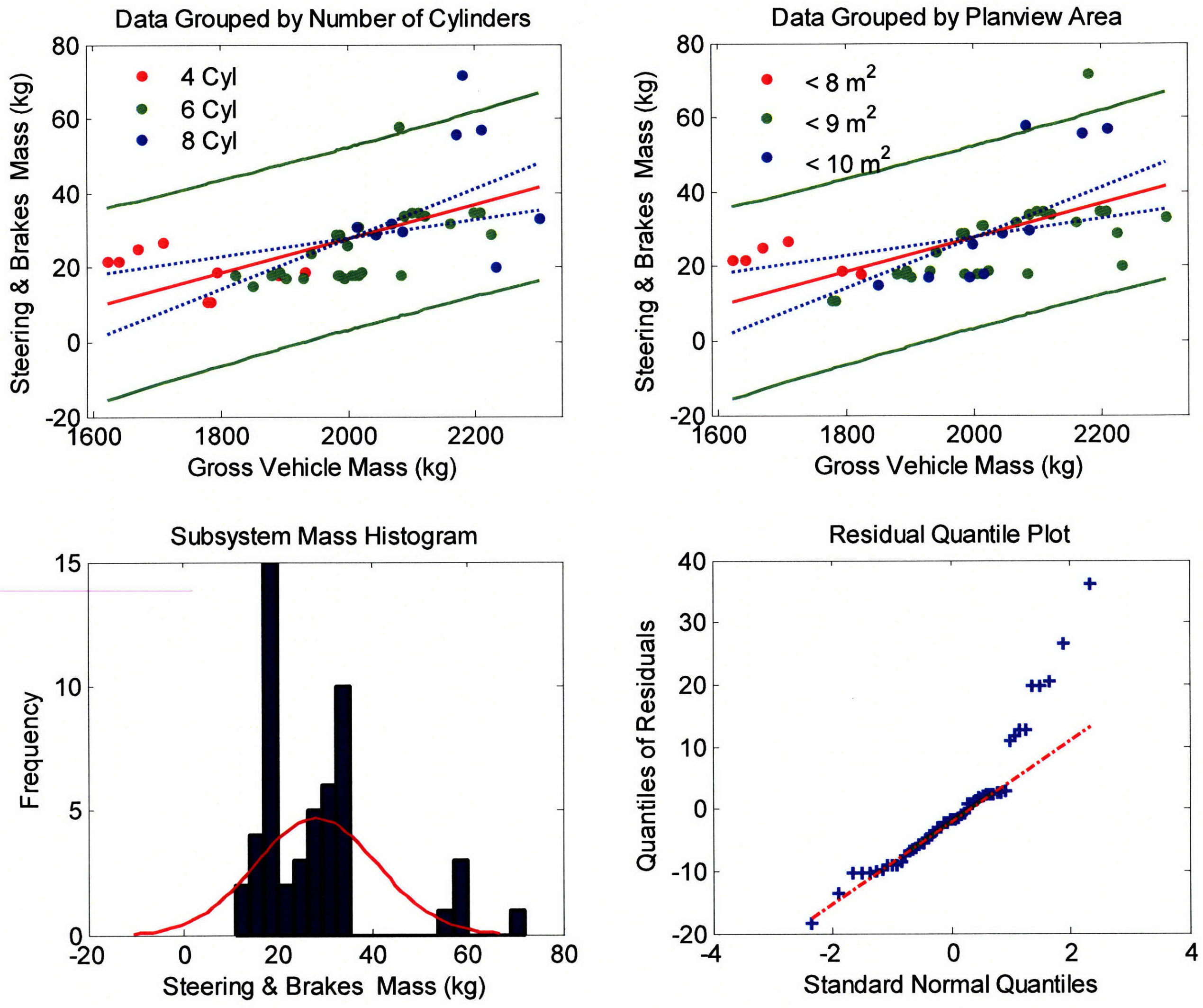

Data Grouped by Number of Cylinders

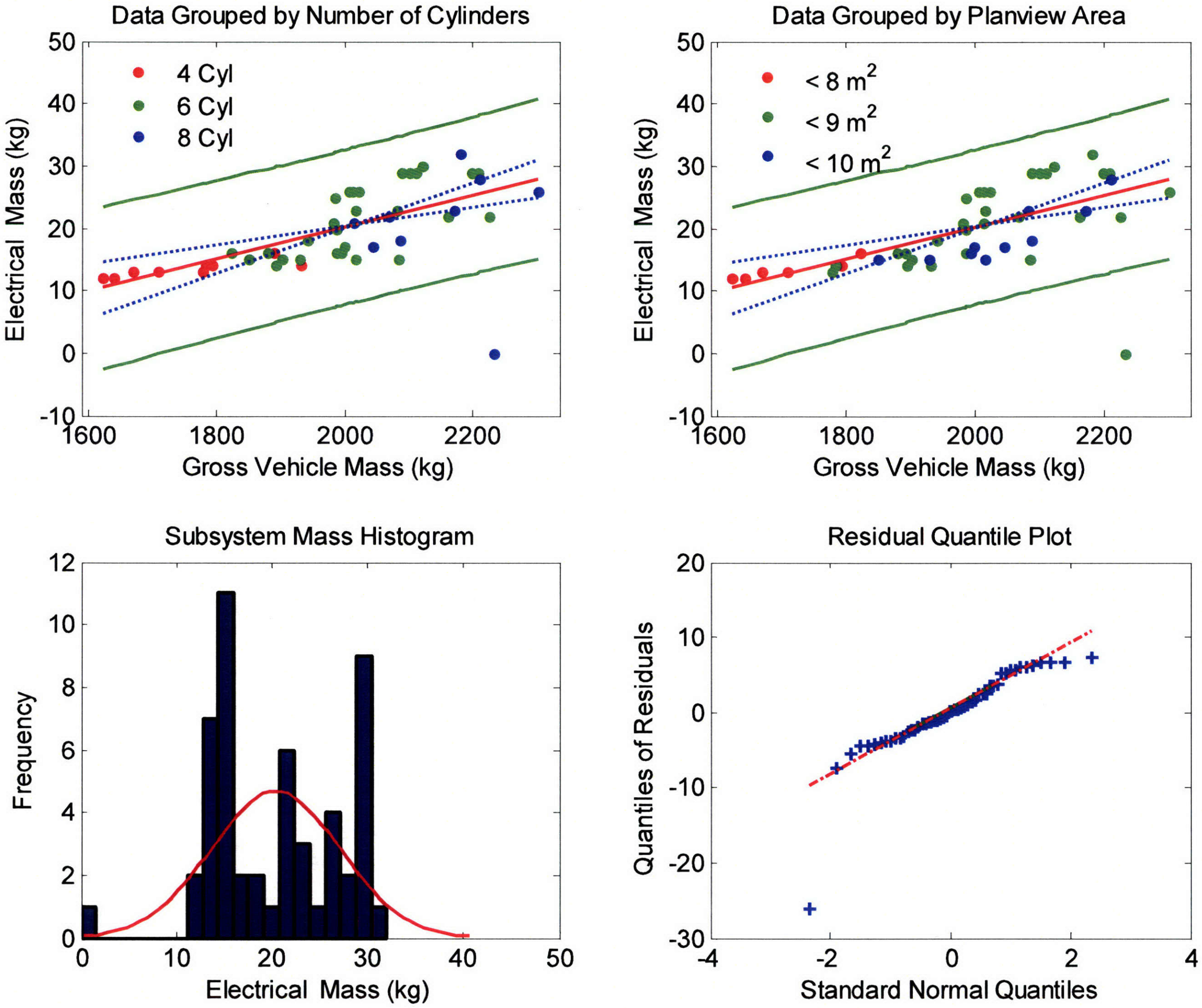
Data Grouped by Planview Area

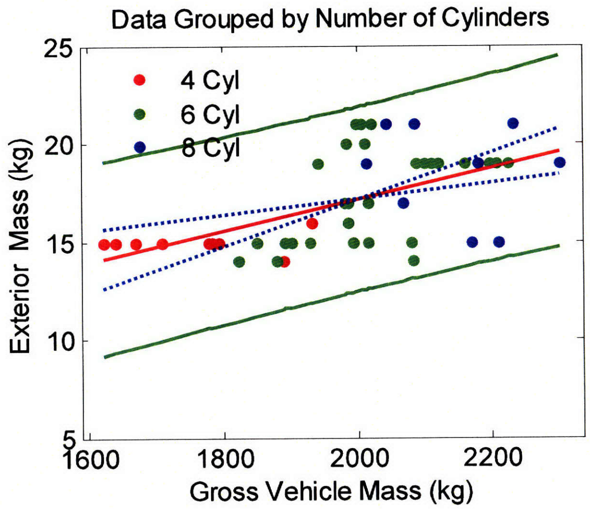
Subsystem Mass Histogram

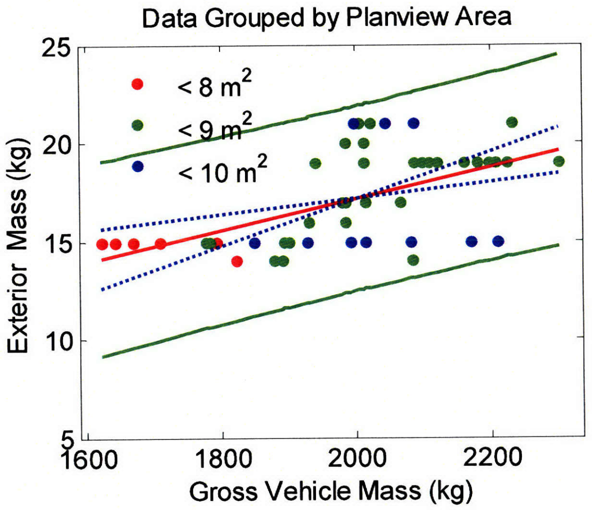
Residual Quantile Plot

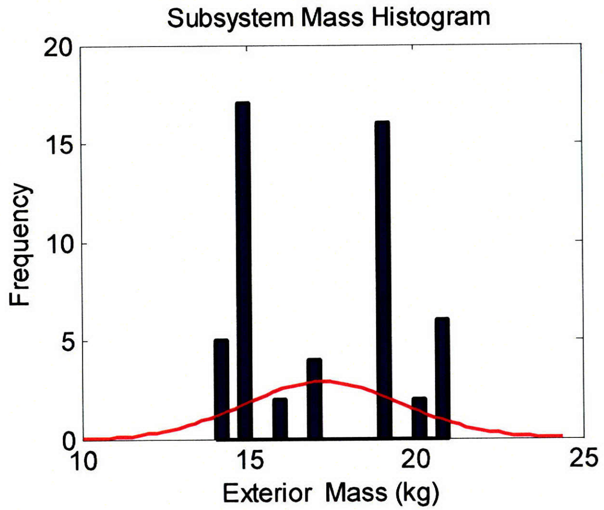

Data Grouped by Number of Cylinders
4 Cyl
6 Cyl
8 Cyl
Transmission Mass (kg)
Gross Vehicle Mass (kg)
160
140
120
100
80
60
40
20
1600
1800
2000
2200
Data Grouped by Planview Area
< 8 m²
< 9 m²
< 10 m²
Transmission Mass (kg)
Gross Vehicle Mass (kg)
Subsystem Mass Histogram
Frequency
Transmission Mass (kg)
0
5
10
15
20
50
100
150
Residual Quantile Plot
Quantiles of Residuals
Standard Normal Quantiles
60
40
20
0
-20
-40
-4
-2
2
4

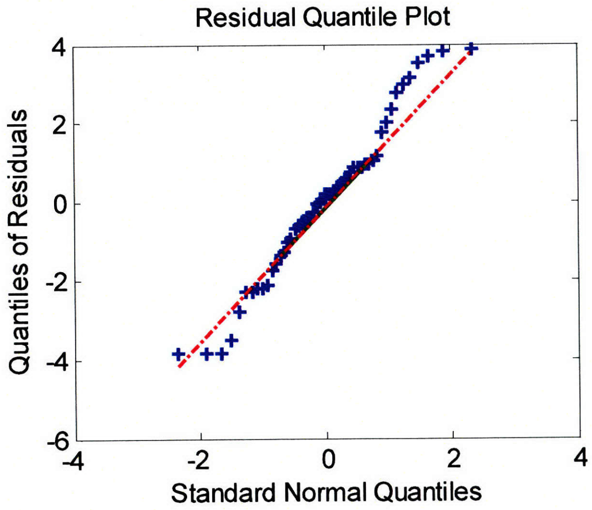

Data Grouped by Number of Cylinders
4 Cyl
6 Cyl
8 Cyl
Steering & Brakes Mass (kg)
Gross Vehicle Mass (kg)
80
60
40
20
0
-20
1600
1800
2000
2200
Data Grouped by Planview Area
< 8 m^2
< 9 m^2
< 10 m^2
Steering & Brakes Mass (kg)
Gross Vehicle Mass (kg)
Subsystem Mass Histogram
Frequency
15
10
5
0
-20
0
20
40
60
80
Steering & Brakes Mass (kg)
Residual Quantile Plot
Quantiles of Residuals
40
30
20
10
0
-10
-20
-4
-2
0
2
4
Standard Normal Quantiles


Data Grouped by Number of Cylinders
Electrical Mass (kg)
Gross Vehicle Mass (kg)
4 Cyl
6 Cyl
8 Cyl
50
40
30
20
10
0
-10
1600
1800
2000
2200
Data Grouped by Planview Area
Electrical Mass (kg)
Gross Vehicle Mass (kg)
< 8 m^2
< 9 m^2
< 10 m^2
50
40
30
20
10
0
-10
1600
1800
2000
2200
Subsystem Mass Histogram
Frequency
Electrical Mass (kg)
12
10
8
6
4
2
0
0
10
20
30
40
50
Residual Quantile Plot
Quantiles of Residuals
Standard Normal Quantiles
20
10
0
-10
-20
-30
-4
-2
0
2
4


Data Grouped by Number of Cylinders
● 4 Cyl
● 6 Cyl
● 8 Cyl
Exterior Mass (kg)
Gross Vehicle Mass (kg)
25
20
15
10
5
1600
1800
2000
2200

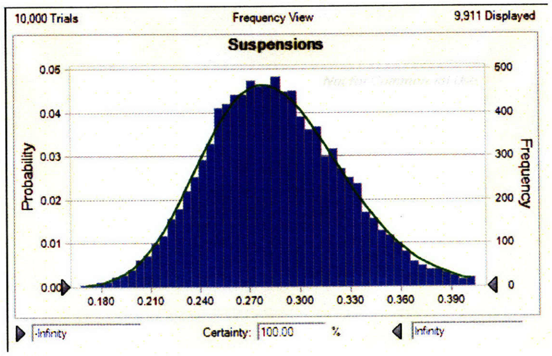

Data Grouped by Planview Area
● < 8 m^2
● < 9 m^2
● < 10 m^2
Exterior Mass (kg)
Gross Vehicle Mass (kg)
25
20
15
10
5
1600
1800
2000
2200

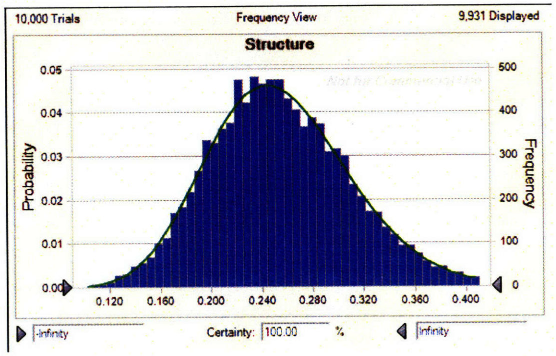

Subsystem Mass Histogram
Frequency
Exterior Mass (kg)
20
15
10
5
0
10
15
20
25

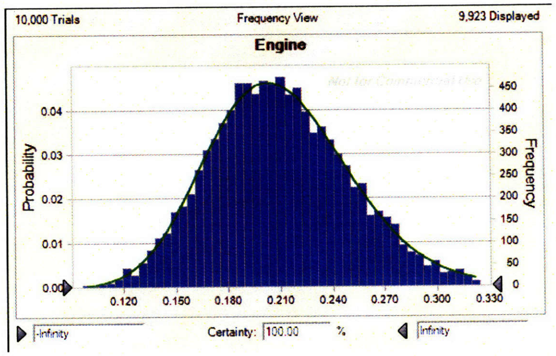

Residual Quantile Plot
Quantiles of Residuals
Standard Normal Quantiles
4
2
0
-2
-4
-6
-4
-2
0
2
4

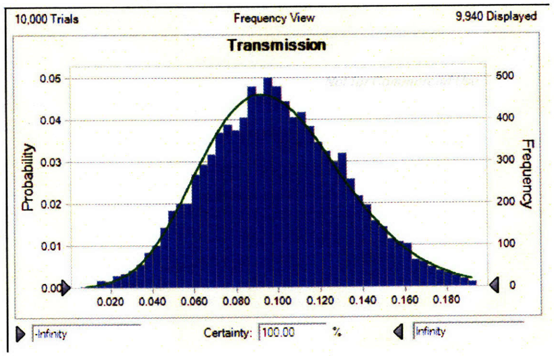
Appendix B

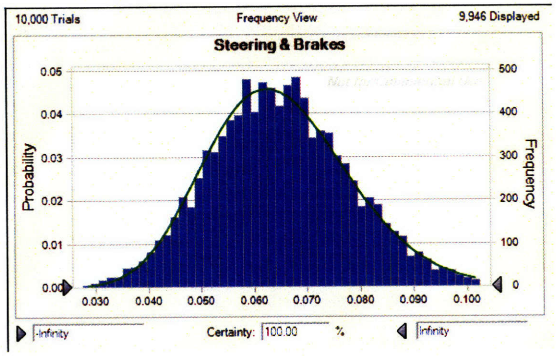
Mass Decompounding Coefficient Monte Carlo Analysis

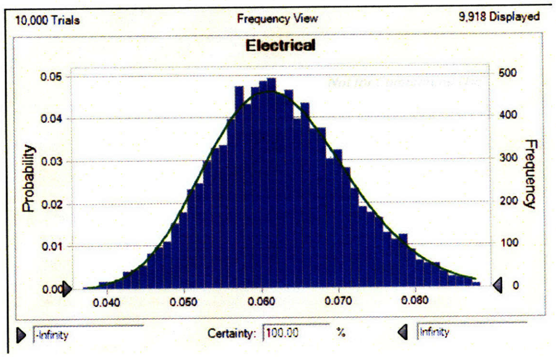

10,000 Trials
Frequency View
9,911 Displayed
Suspensions
Probability
Frequency
0.05
0.04
0.03
0.02
0.01
0.00
500
400
300
200
100
0
0.180
0.210
0.240
0.270
0.300
0.330
0.360
0.390
-Infinity
Certainty: 100.00 %
Infinity

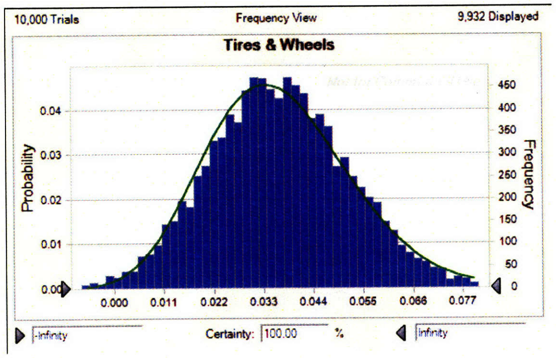

10,000 Trials
Frequency View
9,931 Displayed
Structure
Probability
Frequency
0.05
0.04
0.03
0.02
0.01
0.00
500
400
300
200
100
0
0.120
0.160
0.200
0.240
0.280
0.320
0.360
0.400
-Infinity
Certainty: 100.00 %
Infinity

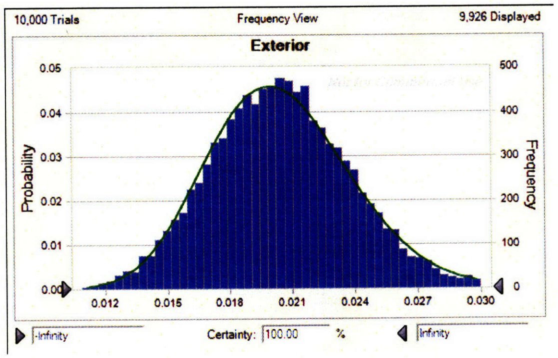

10,000 Trials
Frequency View
9,923 Displayed
Engine
Probability
Frequency
0.04
0.03
0.02
0.01
0.00
450
400
350
300
250
200
150
100
50
0
0.120
0.150
0.180
0.210
0.240
0.270
0.300
0.330
-Infinity
Certainty: 100.00 %
Infinity


10,000 Trials
Frequency View
9,940 Displayed
Transmission
Probability
Frequency
0.05
0.04
0.03
0.02
0.01
0.00
500
400
300
200
100
0
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
-Infinity
Certainty: 100.00 %
Infinity


10,000 Trials
Frequency View
9,946 Displayed
Steering & Brakes
Probability
Frequency
0.05
0.04
0.03
0.02
0.01
0.00
500
400
300
200
100
0
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.100
-Infinity
Certainty: 100.00 %
Infinity


10,000 Trials
Frequency View
9,918 Displayed
Electrical
Probability
Frequency
0.05
0.04
0.03
0.02
0.01
0.00
500
400
300
200
100
0
0.040
0.050
0.060
0.070
0.080
-Infinity
Certainty: 100.00 %
Infinity


10,000 Trials
Frequency View
9,932 Displayed
Tires & Wheels
Probability
Frequency
0.04
0.03
0.02
0.01
0.00
450
400
350
300
250
200
150
100
50
0
0.000
0.011
0.022
0.033
0.044
0.055
0.066
0.077
-Infinity
Certainty: 100.00 %
Infinity


10,000 Trials
Frequency View
9,926 Displayed
Exterior
Probability
Frequency
0.05
0.04
0.03
0.02
0.01
0.00
500
400
300
200
100
0
0.012
0.015
0.018
0.021
0.024
0.027
0.030
-Infinity
Certainty: 100.00 %
Infinity

References

1. Jain, A., *An Analysis of Automotive Body Assembly Technologies and Their Implication in Lightweight Vehicle Development*, in *Materials Science and Engineering*. 1995, M.I.T: Cambridge, MA.
2. DiCello, J.A., et al., *High strength materials and vehicle weight reduction analysis.* SAE World Congress, 1975: p. 750221.
3. Adams, D.G., et al., *A lightweight materials development vehicle.* SAE World Congress, 1976: p. 760203.
4. Ventre, P., J.F. de Andria, and J.C. Rullier, *The development of weight reduced vehicles perceived by Renault.* SAE World Congress, 1980: p. 800829.
5. Carney, D., *Lightweight vehicle engineering.* Automotive Engineering International, 2004: p. 65-68.
6. Wohlecker, R., M. Johannaber, and M. Espig, *Determination of Weight Elasticity of Fuel Economy for ICE, Hybrid, and Fuel Cell Vehicles.* SAE International, 2007: p. 2007-01-0343.
7. Glennan, T.B., *Strategies for Managing Vehicle Mass throughout the Development Process and Vehicle Lifecylcle.* SAE International, 2007: p. 2007011721.
8. Winter, D., *Curbing curb weight.* WardsAuto, 2007.
9. *Energy policy and conservation act for the introduction of cafe standards.* Public Law, 1975: p. 94-162.

10. NHTSA. [cited; Available from: http://www.nhtsa.dot.gov/cars/rules/cafe/overview.htm.

11. Council, N.R., *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*. 2002, Washington, D.C.: National Academy Press.

12. *The Kyoto Protocol*. [cited; Available from: http://en.wikipedia.org/wiki/kyotoprotocol.

13. Rumbaugh, M.E., *Laws becoming borderless*. Automotive Engineering International, 2000.

14. Malen, D., *Preliminary vehicle mass estimation using empirical subsystem influence coefficients*. Auto/Steel Partnership, 2007.

15. Shaw, J. and R. Roth, *Achieving an affordable low emission steel vehicle; an economic assessment of the ULSAB-avc program design*. SAE World Congress, 2002.

16. Glasgow, S., D. Heatherington, and D. Evans, *Bumper system mass reduction through hybrid material and process strategy*. SAE World Congress, 2006.

17. *Tailored to Reduce Weight*. Automotive Industries, 2006: p. 24-25.

18. Gordon, J., *Will New Fuel Economy Standards Make Cars Less Safe? The auto industry says if CAFE standards rise, lives will be lost*. MSN Auto, 2007.

19. *Report of the Cost of Weight Task Force*. 1975.

20. Eberhard, P., et al., *Providing the inertia properties of vehicles and their subsystems for virtual reality and mechatronics applications*. Society of Allied Weight Engineers, 2007.

21. Morgan, J., *The systems engineering role in mass properties*. Society of Allied Weight Engineers, 2000.

22. Bertram, M., *Improving sustainability in the transport sector through weight reduction and the application of aluminum.* International Aluminum Institute, 2007.

23. Zengen, K.H., *Aluminum and energy in the E.U.* European Aluminum Association, 2006.

24. Lovins, A.B., *Supercars: Advanced hybrid vehicles.* Rocky Mountain Institute, 1995.

25. Lorenz, D., *Modeling and analysis of integrated hotforming and quenching processes.* Advanced Materials Research, 2005.

26. Das, S., *Life cycle energy impacts of automotive liftgate inner.* Resources, Conservation, and Recycling, 2005.

27. Karabin, L., *Cost: Aluminum as a cost effective technology.* Automotive Aluminum, 2006.

28. Asnafi, N., *Tubular hydroforming of automotive side members with extruded aluminum profiles.* Journal of Materials Processing Technology, 2003.

29. Hoffman, C., *The Teardown Artists.* Wired, 2007. **14.02**.

30. Hill, R.C., W.E. Griffiths, and G.G. Judge, *Undergraduate Econometrics*. 2001: John Wiley & Sons, .

31. Box, G. and N. Draper, *Response surfaces, mixtures, and ridge analyses*. 2007, Hoboken, N.J.: Wiley.

32. Wackerly, D., *Mathematical statistics with applications*. 2002, Pacific Grove, CA: Duxbury.

33. Kutner, M., *Applied linear statistical models*. 2005, Boston, MA: McGraw-Hill Irwin.

34. May, G., Spanos, C., *Fundamentals of Semiconductor Manufacturing and Process Control.* 2006, Hoboken: N.J John Wiley & Sons, Inc. (US).

35. Montgomery, D., *Introduction to Statistical Quality Control.* 5 ed. 2005, Hoboken: John Wiley & Sons, Inc.

36. Robert, C.P. and G. Casella, *Monte Carlo Statistical Methods.* 2004, New York: Springer-Verlag.

37. Eppinger and Ulrich, *Product Design and Development.* 2004, New York, NY: McGraw-Hill/Irwin.

38. Sloan, A., *My Years with General Motors.* 1990, New York, NY: Doubleday.

39. Womack, Jones, and Roos, *The Machine that Changed the World.* 1991, New York, NY: First HarperPerennial.

40. Clark and Fujimoto, *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry.* 1991, U.S.: President and Fellows of Harvard College.

41. McConville, G. and H. Cook, *Examining the Trade-Off Between Automobile Acceleration Performance and Fuel Economy.* SAE International, 1996: p. 960004.

42. Kirchain, R., *Cost Modeling of Materials and Manufacturing Processes.* Encyclopedia of Materials Science and Engineering, 2001: p. 1718 1727.

43. Zhang, Y., H. Lin, and B. Zhang, *Performance Modeling and Optimization of a Novel Multi-mode Hybrid Powertrain.* Journal of Mechanical Design, 2006. **128**: p. 79.

44. Cole, G.H., *SIMPLEV: A simple electric vehicle simulation program.* 1993, EG&G Idaho Inc.: Idaho.

45. Cuddy, M., *A comparison of modeled and measured energy use in hybrid electric vehicles.* SAE International, 1995: p. 950491.

46. Wipke, K., M. Cuddy, and S. Burch, *A user-friendly advanced powertrain simulation using a combined backward/forward approach.* National Renewable Research Laboratory, 1994.

47. Wilkins, S. and M.U. Lamperth, *An Object-Oriented Modeling Tool for Hybrid Powertrains for Vehicle Performance Simulation.* EVS19, 2002.

48. Weber, T.R., *Analysis of Unconventional Powertrains.* SAE International, 1988: p. 885023.

49. Donndelinger, J.A. and H.E. Cook, *Methods for Analyzing the Value of Automobiles.* SAE International, 1997: p. 970762.

50. Schocker, A. and V. Srinivasan, *A Consumer-Based Methodology for the Identification of New Product Ideas.* Management Science, 1974. **20**: p. 921-937.

51. Green, P.E. and Y. Ward, *New Way to Measure Consumers' Judgments.* Harvard Business Review, 1975: p. 107-117.

52. Fowler, T.C., *Value Analysis in Design*. 1990, New York: Van Nostrand Reinhold.

53. Akio, Y., *Quality Function Deployment*. 1990, Cambridge, MA: Productivity Press.

54. Cook, H.E. and R.P. Kolli, *Using Value Benchmarking to Plan and Price New Products and Processes.* Manufacturing Review, 1994. **7**(2): p. 134-147.

55. Smallwood, R. *Market Insight: Customer Intelligence.* 2007 [cited; Available from: http://marketinsightcorp.com/.