Lightweight Body Designs as Enablers for Alternative Powertrain Technologies: Understanding Cost and Environmental Performance Tradeoffs

by

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ABSTRACT

The impact of today's vehicle on the global environment landscape is undeniable. In hopes for mitigating this and thereby staying ahead of regulatory constraints, the automobile industry is investing large amounts into technology research and development. A prominent element of this effort is the development of powertrain alternatives to the omnipresent internal combustion engine (ICE). While a number of these alternatives show great promise toward improved energy efficiency or reduced airborne effluent, some early prototypes lack the power density of ICEs. This deficiency implies that either performance must be compromised or the rest of the vehicle must be made lighter. Consumer purchasing behavior seems to preclude the former. Proper selection from several technology combinations requires knowledge of the customer's value function, but the first step is to quantify the decision characteristics. This thesis examines the resulting cost and environmental performance tradeoff implicit in selecting between these two complementary fuel efficiency strategies. Focus is given to reducing weight through the use of light body structures. In particular, this thesis quantifies the relationship between environmental performance and one element of cost, the cost of producing lightweight body structures.

A case based analysis is used to establish power and efficiency specifications of seven propulsion technologies, ranging from gasoline engines to hydrogen fuel cells. The body mass for six body structures, ranging from steel unibody to composite intensive vehicles, and their manufacturing and assembly cost for different production volumes are assessed through the use of detailed part lists and Technical Cost Modeling. Furthermore, the size of the powertrain required to deliver a constant vehicle performance for the selected body designs is determined. For these powertrain and body combinations the environmental performance (energy use and fuel economy) is modeled. Finally, implications of fuel price policy and increasing fuel economy standards for adoption of these alternative technologies are analyzed.

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1 Introduction

1.1. Motivation

The automobile industry has struggled for over 25 years with the idea how to reduce the “societal” impact of the vehicle. This impact manifests itself in numerous ways including dependence on petroleum fuels, more than half of which come for the US from foreign sources, and strain on the environment in the form of mostly airborne effluents. Evidence of industry efforts can be seen in the fact, that U.S. automobile fuel economy, adjusted for vehicle size, has improved markedly since the two oil price shocks of the 1970s (Stodolsky, 1995).

Within this effort, legislation has long been an influencing force on the automobile industry. Policy makers established the Clean Air Act of 1973 and its amendments, which allowed government to strictly regulate automotive exhaust emissions. In addition to the Clean Air Act, CAFE (Corporate Average Fuel Economy) requirements developed in 1976 set minimum standards of fuel efficiency for each auto-maker’s product line and penalize manufacturers not meeting this standard. Finally, individual states have passed or are considering a requirement that a certain percentage of a company’s sales be from zero or low emissions vehicles (USDOT, 1999).

In light of the existing legislation, industry is challenged to improve fuel economy or emission levels. This task can be attacked from several directions with existing and emerging technologies. There is no single best approach, but there are several changes possible in for example:

- Materials: especially those used for the vehicle structure and skin.
- Aerodynamics: reduction in aerodynamic drag, primarily from changing the shape of the vehicle.
- Tires: rolling resistance could be reduced by 20 percent or more by adopting new tire designs that combine higher pressures with new structures and materials (OTA, 1995).
- Powertrains: development of a variety of improved and alternative powertrains and powertrain/drivetrain combinations.

- Improvement of end of pipe emissions: especially with the use of improved catalytic converters.

Although this list makes clear that a range of possibilities for improvement exists, a promising one and the one, which this thesis will focus on, is the combination of new materials and designs to lightweight bodies with the adoption of alternative propulsion technologies. The body group contributes significantly (45%) to the total vehicle mass and therefore to the fuel consumption. Alternative powertrains can decrease fuel consumption and emissions through more efficient technologies and the use of for example low-carbon fuels.

In the search for these alternative technologies, companies have developed a wide range of novel vehicle propulsion systems and drivetrains, which are in varying stages of development today. Some, like stratified charge diesel, are proven technologies while others, like fuel cells, are now in the process of evolving into a credible and feasible vehicle propulsion system. Each technology approaches the problem from different angles, varying fuels, chemistries, and machines to attain the goal.

While there are unique features of each of these technologies, there is one factor which remains important for their eventual success: the cost of the technology, which must not be prohibitive. Although a cost premium will probably exist, there is an economic hurdle that must be achieved before any of these new powertrain technologies can expect to achieve market success. To understand the value of this premium, it is important to quantify the cost and the environmental gain, which will then enable a trade off decision.

Summarizing, the automaker's goal can be described as the attempt to produce a vehicle that achieves high fuel economy, without sacrificing vehicle performance and at a reasonable cost. This will be examined in this thesis in more detail. Their strategies for reducing vehicle weight and for incorporating alternative propulsion technologies are described in the next two sections.

1.2. Lightweight Strategies

An analysis of the mass distribution in a passenger car (see Figure 1) reveals that the body is the single heaviest component group, with about 45% of total vehicle mass; the powertrain and chassis follow behind, in almost equal proportions (28% and 27%). Within the body group, the body-in-white (BIW) is the single largest component, with about 28% of the total vehicle mass. Within the powertrain group, the engine is the single heaviest component, with roughly half the group weight, or about 14% of total vehicle mass, while the transmission represents approximately 5% (Stodolsky, 1995).

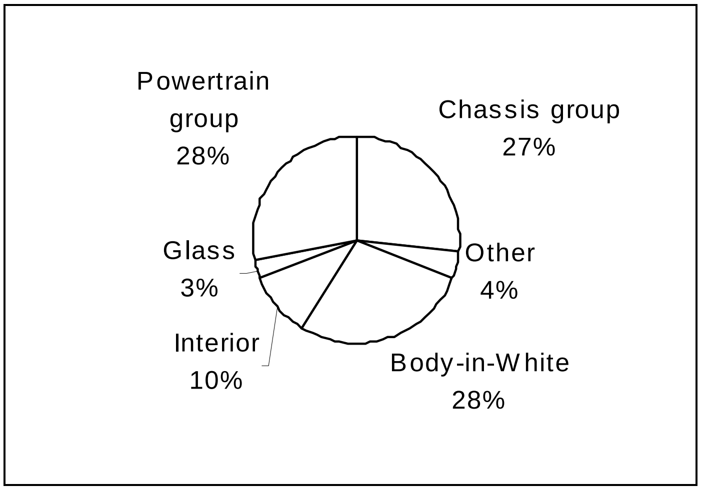


Figure 1: Passenger Car Mass Distribution (Stodolsky, 1995)

Weight reduction in the Body-in-White group has been a primary focus of efforts to improve automobile fuel economy during the past two decades as weight is a primary determinant of such critical vehicle characteristics as acceleration, handling, fuel economy, and safety performance. Between 1976 and 1982, partially in response to federal Corporate Average Fuel Economy (CAFE) regulations, automakers managed to reduce the weight of the steel portions of the average auto from 2,279 to 1,753 pounds by downsizing the fleet and shifting from body-on-frame to unibody designs (OTA, 1995).

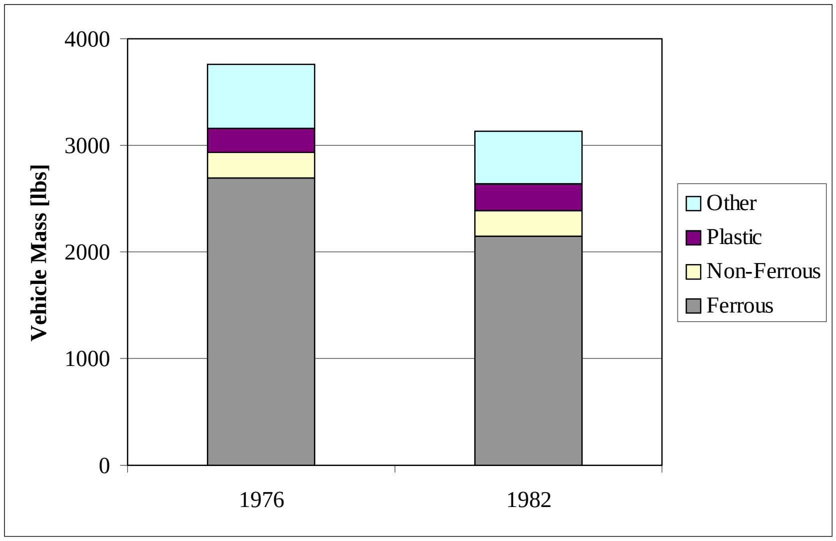


Figure 2: Passenger Car Material Content (OTA, 1995)

Furthermore, weight reductions in primary vehicle components might also enable secondary weight savings in the supporting subsystems. For example, the engine, suspension, and brake subsystems can be downsized for lighter vehicles, because their performance requirements decrease as the total weight of the vehicle drops.

The dominant material used today in manufacturing the BIW is stamped steel. It's dominance is due to its low material cost, short processing times, ease of forming and good mechanical properties. Aluminum is generally regarded as closest to competing with steel. One of the primary benefits of aluminum parts manufacture is that their processing and assembly methods are similar to those employed when using steel.

Future efforts to reduce vehicle weight will focus both on material substitution, especially those used for the vehicle structure and skin --the use of improved steel, aluminum, magnesium, plastics, and composites in place of steel--and on optimization of vehicle structures using more efficient designs (e.g. spaceframe designs). A typical 3,000 pound family sedan might lose 600 or more pounds; some analysts claim that reductions could top 50 percent (OTA, 1995).

The use of different materials and designs for the body structure will be analyzed in this thesis to understand their influence on the overall vehicle weight and their competitiveness on the basis of production costs.

1.3. Propulsion System Strategies

A variety of new propulsion technologies and powertrain/drivetrain combinations conceivably could supplant or, more likely, compete with current spark or compression ignition engine powertrains. These competitors range from two-stroke variations of current four-stroke engines that offer substantially reduced engine weight and size for the same power, to electric and hybrid-electric powertrains with power sources ranging from batteries to internal combustion engines to fuel cells.

Traditional internal combustion engines, the dominating technology used today, are handicapped by inefficiencies in the thermodynamic processes, mechanical friction associated with motion in the engine, pumping losses and increased noise and vibration. Technologies responsible for recent improvements especially in fuel economy include direct fuel injection, front-wheel drive, improved engine aspiration (multi-valves/cylinder, turbo- and supercharging) and improved catalytic converters (Stodolsky, 1995; OTA, 1995).

Although the electric drivetrain provides the advantage of eliminating driving air pollution, their major problem is the storage of energy in the battery. So far the research in battery technologies has been focussing on four types of batteries: lead alkali, alkaline, high temperature and solid electrolyte with some promising results. Nevertheless, to date production vehicles have had ranges no greater than 150 miles and take up to 8 hours to recharge. Due to these difficulties the electric vehicle is not yet fully accepted by the customer. This can be seen for example in the production volume of the GM EV1 with only about 320 vehicles manufactured in 1999 (Automotive News, 2000).

The most basic distinguishing characteristic in hybrid vehicles is the arrangement of the powertrain: there are series and parallel hybrids existing. A series hybrid drives the wheels only through the electric motor with the combustion engine generating electricity, whereas a parallel hybrid system powers the wheels directly with both the combustion engine and electric motor. As with a purely electric vehicle, hybrid vehicles have the advantage of being able to recapture part of the braking energy, an especially valuable feature for urban vehicles. Although hybrid vehicles eliminate the disadvantages of range and charging time, they do not achieve the zero driving emission level of the battery only electric vehicle. Furthermore, the complexity of manufacturing and probably maintenance of the vehicles increases with combining the two systems of electric motor and combustion engine.

Many researchers consider fuel cells to be the ultimate answer to power motor vehicles. In one package they combine the positive attributes of batteries - zero or extremely low carbon emissions - with the quick refueling capability of internal combustion engines. Fuel cells use so far gasoline, methanol or hydrogen as fuel to power the system. The main problem with using especially methanol and hydrogen fuel arises around the not existing infrastructure for the distribution of the fuel and the high cost estimated for production the fuel. Furthermore, the storage of the fuel on board requires more development.

Despite all the best efforts, many fuels and energy storage technologies do not have a similar energy density compared to gasoline fuel. The energy density of batteries for example compared to gasoline fuel can be an order of magnitude different (see Figure 3). These physical limitations of the different fuel types and storage systems can constrain vehicle performance, which is derived from energy expended on the propulsion. Therefore, to store the same amount of energy on board as for example with gasoline and have the same range for the vehicle, the weight of a less energy dense fuel and the size of the storage device would need to be higher, in some cases significantly. Today for electric vehicles, a battery which provides a range comparable to a gasoline tank is not achievable in a reasonable size and weight. An alternative approach to utilizing a less energy dense propulsion technology is to alter the design of the vehicle. Given a specified size and space to store the fuel on the vehicle, the use of fuel with a lower energy density could be accommodated by reducing the mass of the vehicle or body. In the case of the electric vehicle, the required lightweighting seems to be hardly achievable in order to maintain the range and vehicle performance. However, other alternative fuels like methanol with an energy density in the same order of magnitude as gasoline are more likely to be realized with reasonable lightweighting of the vehicle body.

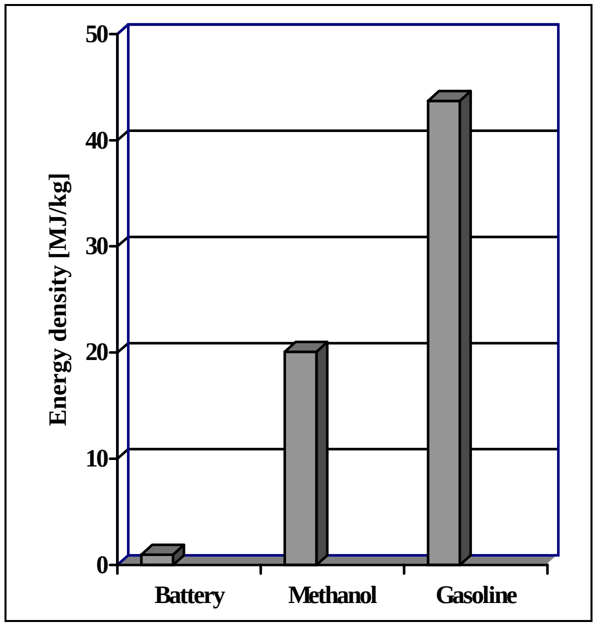


Figure 3: Energy density of fuels

Given the energy density differences of different propulsion systems lightweighting may be required to maintain vehicle performance. This interdependence between propulsion system and lightweight strategies raises a number of questions about the combined design of both.

Summarized, the overall purpose of this thesis is to understand the implications of using different lightweight strategies and propulsion technologies on vehicle performance, cost and environmental performance of the vehicles. The specific questions addressed are detailed in the next chapter.

2 Problem Statement

Today's vehicle designer have available a palette of powertrains and body designs from which to draw when creating a vehicle. Combinations of these two will provide differing levels of improved energy economy and reduced effluent intensity. In order to make such a selection the designer must tradeoff at least the characteristics of:

1. Vehicle Performance
2. Cost, and
3. Environmental performance.

Ultimately, a proper selection will require knowledge of the customer's value function, but the first step must be to quantify these characteristics for the myriad options available. This thesis attempt to take the fist steps in this direction, establishing methods and making early estimates of these characteristics for several technology combinations applied in a specific design. In particular, this thesis quantifies the relationship between environmental performance and one element of cost, the cost of producing lightweight vehicle structures.

Although the decision space does stretch across all three dimensions, fixing one of them allows for a more tractable problem and better understanding of the relationships among the remaining two. Consumer purchasing behaviors have shown that a majority will not sacrifice vehicle performance in return for improved environmental performance. The car should provide comfort, range and power similar to today's cars. As already mentioned, a good example of this low tolerance for compromised performance is the production volume of about 300 electric vehicles per year for the GM EV1. Therefore, by fixing this trade-off criterion and assuming a constant vehicle performance a real world barrier can be reflected and the relationship of manufactured cost with driving environmental performance can be better understood.

In addressing this question is important to note that both the propulsion system and the vehicle body are influencing both cost and environmental performance, and that their influence is interdependent. For example a propulsion system with lower power density requires a bigger powertrain and lightweight body design to achieve a performance target. On the other side a bigger and probably heavier powertrain needs also more support from the body frame and therefore raises also the weight of the body.

For the various powertrain technologies the overall question therefore breaks down to the questions of:

- If/When lightweighting is required?
  - What lightweight strategies are required by specific powertrains to maintain performance targets (isoperformance)?
  - How much lightweighting is required to achieve specific fuel consumption?
- What is the impact of lightweighting?
  - What are the costs?
  - What is the environmental performance?

The thesis will therefore

1. analyze and establish the power and efficiency specifications of each of the major powertrain technologies
2. catalog several body lightweight strategies assessing the resulting body mass for each in a given body size and configuration, and
3. determine the size of powertrain required to deliver consistent vehicle performance for each of the proposed powertrains.

The resulting vehicle combinations (powertrain and body) will be evaluated for their environmental performance as energy use and fuel economy. Environmental performance will be limited to driving cycle impacts.

Furthermore the thesis will develop an assessment of the magnitude of the cost hurdles attached to mass reduction of the vehicle body and closures. This cost hurdle can impede the introduction of each alternative propulsion technology into the market if it requires a lightweight body for the desired vehicle performance.

Therefore by determining the differences in cost and environmental performance of the group of powertrain and body combinations, basic information will begin to develop for the design-decision.

Finally, besides the technological and economic feasibility of building the cars, the implications of government policy can be evaluated. In general, government policies addressing transportation emissions are trying to aim for three targets: to increase fuel economy of the vehicle fleet, to increase the use of fuels that offer low carbon dioxide/mile driven and to reduce the overall travel of the vehicle. The analysis of vehicle costs and environmental performance (e.g. fuel economy) will therefore support the evaluation of increased fuel economy standards, the life cycle cost for the use phase of the vehicle or fuel price policies.

3 Methodology

This analysis is intended to provide a basis for discovering and understanding the relationship between vehicle cost and environmental performance of lightweight body and alternative powertrain combinations. As this is clearly a large and complex question, the cost aspect was limited to only the cost of production for the vehicle bodies. Both measures, cost and environmental performance, depend among others on the design specifics of the powertrains, lightweight bodies and general vehicle characteristics. These general characteristics like vehicle size, drag coefficient and front cross-sectional area, are going to be defined by selecting a specific body design. Furthermore, due to not sufficient information on design specifications of the propulsion systems, the package space in the car was assumed not to be a constraint.

For a given body design, Figure 4 diagrams each of the critical steps of the analysis.

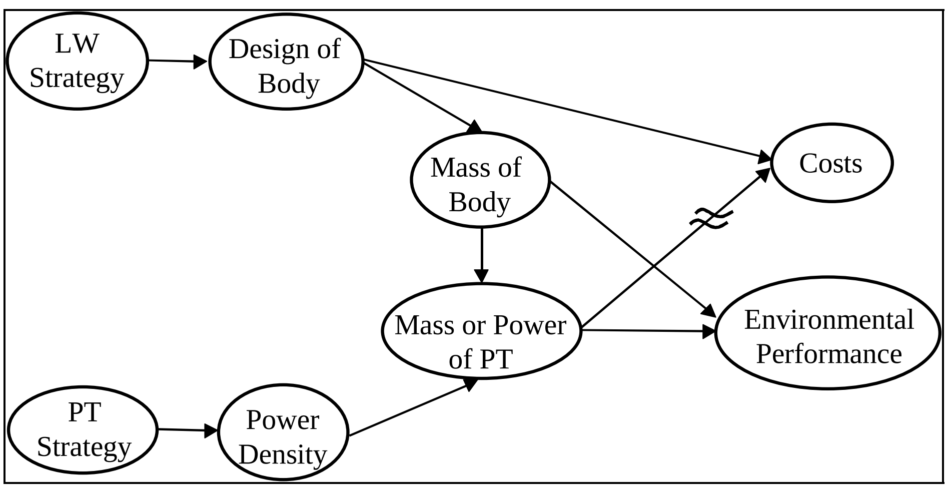


Figure 4: Overview of research approach

Using a case-based analysis, following research approach is chosen:

- Catalog lightweight body strategies and propulsion technologies:
  In order to address the question of the cost of environmental performance, first of all different lightweight strategies and propulsion technologies are going to be cataloged.

- Design and Mass of Body:
  Beginning with the lightweight strategies, the design and material of the bodies has to

be defined. This implies also the total mass of the body. In order to ensure the comparability of the results all bodies need to have the same size and therefore have an iso-body design.

- Cost:

  For further cost analysis the number of parts and some basic characteristics of each of the parts need to be collected. With an approach called Technical Cost Modeling (TCM) the cost for producing and assembling the lightweight design is going to be assessed in detail. The cost of the powertrain will be assessed very roughly in order to prove the idea and value of this analysis. Due to insufficient information on the cost of production and the limited time frame of the thesis, it was not possible to analyze this issue into detail.

- Powertrain characteristics:

  For the powertrain technologies the key characteristic is their power density. This is the ratio of the power to the mass of the powertrain. The correlation between power and mass is needed for the analysis. Unfortunately this relationship is generally not known. The necessary equations were therefore established through the use of statistical relationships derived from empirical data.

- Matching lightweight body design with propulsion systems:

  The powertrain, which will provide the necessary performance for a specific lightweight design can now be established using the defined mass of the different body designs and the correlation between the mass and the power of the powertrain. This means, matching the lightweight designs with a propulsion technology maintaining a specific vehicle performance target.

- Environmental performance:

  Finally, having the vehicle defined by the mass of body and powertrain and knowing some performance characteristics, the environmental performance of the vehicle can be modeled. The output of the modeling can be for example the energy use per kilometer or the fuel economy using specific driving cycles.

Summarizing the research approach, three basic methodologies were used: Technical Cost Modeling, Development of Statistical Relationships for the Propulsion System and

Modeling of Environmental Performance of the Vehicles. These methods are going to be described in more detail in the following chapters.

3.1 Technical Cost Model

The cost of producing the vehicle body is probably the most important trade-off characteristic for today's designers in automobile manufacturing. It is also the first part of the question of the cost of environmental performance this thesis wants to address. To assess the costs of the body, first of all the different body designs needs to be defined with the number of parts, the material used, the part size and therefore weight.

In order to analyze the economic costs associated with different lightweight strategies, a methodology developed at the Materials Systems Lab (MSL) at MIT was used. Technical Cost Modeling is a methodology that analyzes the economics of manufacturing technologies by capturing how key engineering and process characteristics relate to the total production cost of a component (e.g. body-in-white parts). Technical cost models (TCM's) improve upon traditional cost estimating techniques by relying less on rules of thumb, past experience and specific accounting practices. In addition, spreadsheet-based TCM's are much more flexible allowing the analysis of the effects of a wide range of operating conditions on the final manufacturing cost. The use of TCM's can give insights into the economics of competing material technologies and allow strategists to focus research and development efforts into a few critical areas that can have significant impact on cost performance.

The central concept of technical cost modeling is that the total cost of a manufactured part can be broken down into contributions from various elements. Once the total cost is broken down into separate components, the task of analyzing components becomes much simpler. A natural segregation of cost elements is between those costs, which are independent (variable costs) and those, which are dependent (fixed cost) on the amount of parts produced within a given time frame (typically one year).

More detail than presented here can be found on Busch (1987), Kang (1998), Kirchain (2001) and Veloso (2001).

3.1.1 Fixed and Variable Cost

Variable Cost

On a per piece basis, variable costs are those components which remain the same regardless of production volume. Variable costs are composed of the three elements:

- Material costs:

  the total material expense is the sum of all of the primary and secondary materials used in the operation. Primary materials are the raw and semi-finished material components of the fabricated part. The cost of these material depend on the final part weight, engineering scrap, weight percents of raw material and the unit cost of material. In some instances, scrap can be resold to lessen material cost; recycling of steel scrap is common practice in the steel stamping factories. Secondary materials are those used in the production process, such as cleansers and lubricant agents, which aid in the part manufacture but do not contribute to the material content of the final part. Secondary material cost is a function of the amount used and its unit cost.

- Labor cost:

  includes only those workers who are directly involved in the manufacturing process. Other personnel, such as managers and clerical staff, are not considered under the heading of labor cost. Instead, they are accounted for as part of overhead. Labor costs are determined by the number of working hours, the number of laborers required per operation and the wage paid. Wage includes not only salary but also benefits, such as health insurance and training.

- Energy cost:

  accounts for the power requirements that arise from operating equipment. Generally machines run on electricity so that energy cost is a function of the machine’s electricity usage, the amount of operating time and the unit cost of electricity. Other utility costs, such as gas and oil heating, are also captured in the energy cost calculation.

Fixed costs

Fixed costs are the costs that are necessary for the manufacturing facility. On a per piece basis, fixed cost components vary with the number of parts produced, These costs are labeled as fixed because they are typically a one time capital expenditure which is necessary to begin production (e.g. purchasing a stamping press). In the TCM's used for this thesis, there are seven fixed cost components:

1. Main Machine:

   consists of the investment cost of machine plus an additional cost of installation. The main machine refers to the primary piece of equipment in which value-adding operations are carried out. The characteristics of the part and the production volume are directly related to the cost of equipment.

2. Tooling:

   The tooling cost per set is a function of the part geometry and of the tool material. These relationships are determined through a regression analysis of industry data, relating cost to specific part characteristics. In addition, the relationships change for the various types of tool materials. Generally, more durable tool materials (such as steel) are costlier to produce relative to softer tool materials (such as epoxy). The number of tool sets required is a function of the production volume, productive tool life and the number of machines in the line.

3. Overhead:

   Accounts for those workers how are not classified as direct laborers, but are part of the production process. Indirect labor can include managerial, clerical, janitorial, security, etc.

4. Building:

   Accounts for the space requirements of the manufacturing line. Each operation requires a certain amount of floor space, which is function of the size of the machine and the number of machines required per operation.

5. Auxiliary Equipment:

   It is equipment not directly involved in the manufacturing process but necessary for production. Since the amount, cost and types of auxiliary equipment vary widely for each manufacturing facility, this cost is approximated by assuming it to be a percentage of main machine cost, which itself is a function of part characteristics and production volume.

6. Maintenance:

   Results form performing upkeep on main machines, tools and auxiliary equipment. To avoid complexities like the cost of unscheduled maintenance, the cost of maintenance is estimated by assuming a percentage of capital investment is allocated for maintenance expenses.

7. Cost of Capital:

   Whenever there are investment costs, the time value of money must be taken into account, since there are other potential uses for this money. The cost of capital can be calculated as a payment or loan or lost opportunity cost of money over this period of the loan. It is function of the expected machine life and the interest rate during this period.

3.1.2 General Inputs

The separation of cost components into fixed and variable cost provides a foundation for analyzing the total manufacturing cost. The technical cost model employs user-supplied inputs and other assumptions about the operating environment in order to arrive at a calculation for fixed and variable costs.

- Component Description:

  specifies the physical characteristics of the part to be produced. The description consists of part geometry (size, shape, weight), material requirements and material characteristics.

- Process Conditions:

  For each operation in the manufacturing process, processing conditions must be specified. These include the labor requirement, engineering scrap rates, rejection rates and required production volume for each operation.

- Parameter Estimation Data:

  Estimations must be made for equipment capacity, equipment and tooling cost, energy usage, building space requirements and production rates. In the models, most of these production parameters are calculated using inputted equations and data from the other sets of inputs. Equations are based on engineering and scientific relationships, regression analyses and empirical data collected from industry.

- Exogenous Cost Factors:

  These are the set of economic and production inputs that describe the manufacturing environment in which the part is produced. Production inputs include wages, available working time, maintenance cost, auxiliary equipment cost, building cost, utility prices and overhead costs. Economic inputs include the cost of capital, the capital recovery period and the building recovery life.

- Dedicated/Non-dedicated Status:

  Dedicated machinery is defined as machinery, which exists only to produce a specific part. The cost of machinery is then attributed to that part. On the other hand, non-dedicated machinery can produce many different parts, so that each part "rents" the machine for a period of time and is charged accordingly. Tooling is always classified as dedicated, since the tooling is designed to manufacture only a specific part.

3.1.3 Technical Cost Model Extensions

Most applications of TCM are used with a limited number of parts, which are modeled in one or more competing individual processes to understand the economic implications of changes in process or in critical design parameters (e.g. material, production volume, factor condition) (Clark, 1997). Nevertheless, the large majority of today's products are the result of a complex combination of parts that require numerous operations in their manufacturing as well as a substantial assembly effort. As a result, there has been a growing demand for the use of TCM to estimate more complex products (Kirchain, 1999; Han, 1994; Kang, 1998).

Evaluating the cost of complex products using TCM requires the combination of a significant number of different models. For each of them, part and processing information has to be gathered and processed. Because of the high level of detail associated with TCM, combining a large number of technical cost models will require large amounts of information. This makes the estimation process extremely complex.

As the complexity of the product to be modeled increases, the problem is not only data manipulation, but also data collection. Gathering or constructing detailed design and processing data for a large number of parts is very difficult. A problem that may exist at the onset is access. As products become complex, detailed design and processing information required as input to TCM is also likely to be scattered among various persons and departments in a large organization. As a result, data may be very difficult to gather. In addition, even if it would be possible to have all the required information, inputting and analyzing such a detailed data set can become unmanageable.

However, for the overall assessment of a system in early stages of development, or to investigate the generic impact of changes in factor conditions, such a level of detail is not desirable or sometimes even possible to achieve. Therefore, it is important to find methods to approximate the estimations.

A potential approach to this problem is the extrapolative method, proposed by Han (1994) and developed by Kang (1998), to estimate the cost of the body-in-white (BIW) of an automobile. Instead of modeling approximately 150 parts existing in a BIW, a set of categories were determined and a representative part to be modeled in detail through TCM was chosen for each category. The categories were determined according to differences in part geometry, size and forming complexity. The rest of the parts in the BIW were assigned to each of the categories. Assuming that all parts were formed in a similar fashion, their cost was estimated using weight ratios and identical processing conditions to those used for the representative part in each category.

The two applications show that the extrapolative method can be extremely useful when the parts have similar processing conditions and common characteristics that can be used to establish the relative differences. The method may not be so accurate if processing technologies and conditions are very diverse. The approach for more complex cases using different processes may be still to model all the components, but to reduce the requirements in terms of the information and the modeling detail associated with each component. This is the approach of the systems cost modeling (SCM) methodology (Veloso, 2001).

The critical SCM approach to simplify traditional technical cost modeling techniques is to use four simple metrics as the basis for establishing all the cost drivers of an individual part. The metrics considered in the analysis are:

- Weight: This indicator is readily available for any component, making it a very natural choice. It is important for the material cost estimate and serves as a proxy for the volume of the component, often a major factor determining the characteristics of the required processing equipment and tooling.
- Material: Information is usually directly available for each component, even when several materials are a mixed together. Moreover, it is critical to estimate the material cost, which is often a significant portion of the total.
- Complexity: Detailed information regarding shape, thickness and other factors used to calculate equipment characteristics are substituted by a three level complexity factor, estimated by judgment. Level 1 corresponds to simple components where their size is the major factor affecting processing; higher levels of complexity imply more detail or additional features that require more complex (and therefore more expensive) equipment.
- Process: To manufacture each component, a particular process is assigned. This process is either provided or determined knowing the material and analyzing the role the component in the overall system.

These metrics are used directly to determine equipment cost, tooling cost, labor usage, cycle time and material needed for the relevant manufacturing of a component. Following the TCM logic, the costs are derived from these core estimates. Unlike TCM that uses detailed component characteristics together with engineering and statistical relationships to determine cost, SCM uses published and collected information on the ranges of costs and capabilities of equipment, tools and labor for every process and proposes functional relationships between the four simple metrics described in the previous paragraph and cost.

These extensions of the TCM approach though Systems Cost Modeling are important for the analysis in this thesis. Depending on the material choice and design of the bodies, the number of parts to be modeled with TCM can range between 40 and 200 parts. It is therefore advisable and accurate enough for the purpose of this thesis to use the SCM approach for the more complex body designs with high part count.

3.2 Propulsion System Characteristics

After defining the lightweight designs and the cost of production, the propulsion technologies need to be cataloged with their appropriate key characteristic.

The basic task of a powertrain is to accelerate and move the mass of the vehicle. One way to characterize this performance of the vehicle is to use the ratio of the power of the vehicle to the total vehicle mass. The power of the vehicle obviously is delivered from the powertrain, but engines must be sized appropriately to match the mass of the whole vehicle as a specific vehicle performance is desired. One salient characteristic of the powertrain is the ratio of the power to the mass of the powertrain described by the power density of the engine. Beside the required power, it is also important to know the mass of the powertrain as it contributes to the vehicle mass and probably ranges with the desired power. In today's gasoline powered vehicles for example, it can be observed that bigger and heavier cars usually use also a bigger and therefore heavier gasoline engine.

For the further analysis it is therefore important to examine and understand the relationship between power and mass of the propulsion system, if there is any existing. This fundamental relationship is so far not widely reported. A possible way to address this problem is to derive the necessary equation with empirical data and statistical analysis.

Data on the different propulsion systems produced or in development can be collected mainly through literature and company publications. The data on power, mass or power density can then be plotted and examined using regression analysis. If the two factors vary linearly, which would mean that by increasing the power of the powertrain the weight of it would increase linearly, the statistical relationship between the power and mass of the propulsion system can be developed and equations can be derived for the further analysis.

Figure 5 shows the relationship for the gasoline engine as one example. After plotting the data on power and mass of different gasoline engines a linear relationship was observed. This analytical approach can be applied to all different propulsion technologies.

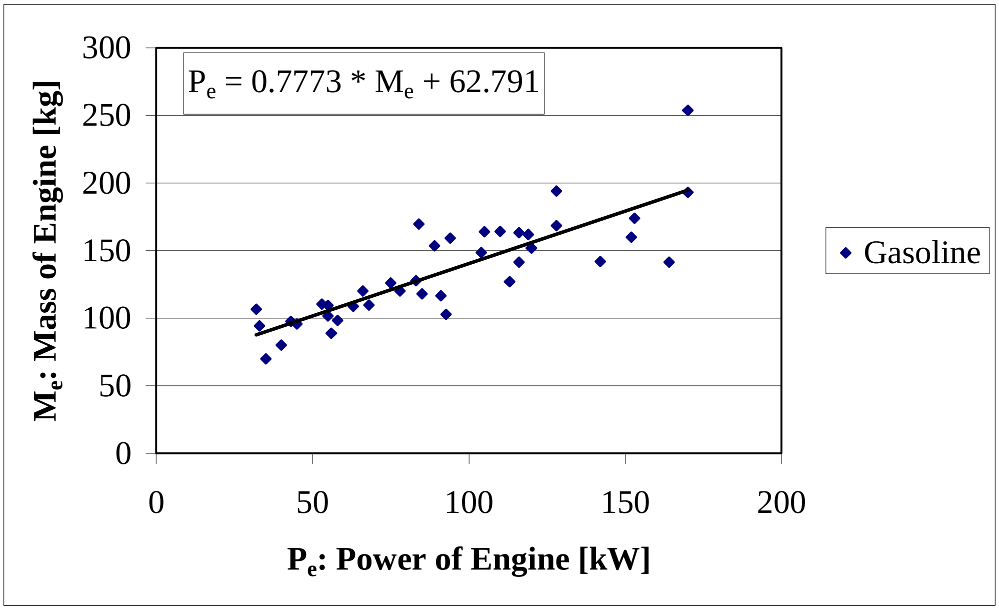


Figure 5: Power density of gasoline engines

The powertrain, which will provide the necessary vehicle performance for a specific lightweight design can now be established using the defined mass of the different body designs and the correlation between the mass and the power of the powertrain. The powertrains will be therefore matched to the lightweight designs to achieve a specific vehicle performance target.

Simplified, the total mass of the vehicle (M_v) can be defined as the sum of the mass of the body (M_b), the mass of the propulsion system (M_p) and the mass of other components (M_o):

[1] $$M_v = M_b + M_p + M_o$$

The mass distribution of the different components is known for the baseline vehicle.

The vehicle performance (a) is defined as the ratio of the power of the propulsion system (P_p) to the mass of the vehicle (M_v):

[2] $$a = P_p/M_v$$

If the power and mass of powertrain vary linearly, the power density (k) of the propulsion system can be defined as:

[3] $$k = P_p/M_p$$

Combining equation [2] and [3], the mass of the vehicle can be expressed as:

[4] $$M_v = k/a * M_p$$

The mass of the vehicle is now defined though the two equations [1] and [4]. These can now be solved simultaneous for either the mass or power of the propulsion system as a function of the mass of the body or the mass of the body as a function of the mass of the propulsion system. Using the previously established correlation on the power density for the propulsion system, the powertrain can now be fully defined. Different propulsion technologies will need a different weight of the powertrain to provide the necessary power for the vehicle performance target.

As already mentioned, the above equations are showing the basic principle for how to approach the problem. In reality, the equations are not as simple. An important concept that should be included is the effect of secondary weight savings.

Secondary weight savings are achieved when weight savings in one area permit weight reductions in other areas. For example, a lighter aluminum body and frame than a steel body enables the use of smaller, lighter springs, shocks, suspension components, smaller brakes etc. (Ford, 1999). Therefore, for every kilogram saved in the body another fraction of a kilogram can be saved in other components. There are several numbers mentioned in literature for the amount of secondary weight savings ranging up to 0.75 kg for every kilogram saved in the body.

The change in the mass of the vehicle can therefore be expressed as the sum of change in the weight of the body and the secondary weight savings factor (s) depending on the saved body mass. This is also equal to the change in the body, propulsion system and in the other components:

[5] $$\Delta M_v = \Delta M_b + s * \Delta M_b = \Delta M_b + \Delta M_p + \Delta M_o$$

The equations also need to be adjusted for the different propulsion technologies depending on their subsystems. The fuel cell for example has also a motor, battery and perhaps reformer as part of the propulsion system.

The above equations should only describe the basic idea of how the analysis was done. More detailed information on the derived equations can be found in Chapter 5.

3.3 Environmental Performance

After defining the lightweight designs and the propulsion technologies and combining them while maintaining a specific vehicle performance, the environmental performance of the vehicle needs to be assessed. This is the second trade-off characteristic of interest in this thesis.

To estimate fuel consumption to compare various vehicles with different propulsion systems, a family of Matlab Simulink simulation programs was used. Originally developed by Guzzella and Amstutz (1998) at the Eidgenössische Technische Hochschule (ETH) Zurich, these programs back-calculate the fuel consumed by the propulsion system by “driving” the vehicle through a specified cycle. Such simulations require performance models for each major propulsion system component as well as for each vehicle driving resistance. The component simulations used, which were updated and expanded by the Energy Lab at MIT, are best characterized as aggregate engineering models, which quantify component performance in sufficient detail to be reasonably accurate. Nonetheless, a substantial number of input variables must be specified for each element or component of the overall model. Additional details can be found in Au Yeung (2000) and Weiss (2000)

The simulation “drives” the vehicle through a specified driving pattern or cycle, and calculates the fuel consumed and thus the carbon dioxide emissions produced. Inputs for the calculations are the vehicle driving resistance (mass or inertia, aerodynamic drag, and tire rolling friction), and the operating characteristics or each of the major propulsion system components (e.g. engine and transmission performance and efficiency for a standard internal combustion engine).

An issue is the performance and operating characteristics of the various vehicle and powerplant combinations. Ideally each combination should provide the same (or closely comparable) acceleration, driveability, driving range, refueling ease, interior driver and passenger space, trunk storage space, and meet the applicable safety and air pollutant emissions standards.

All propulsion system and vehicle combinations are therefore adjusted to provide the same ratio of maximum power to total vehicle mass, and provide 600 km driving range, except for the special case of the pure electric vehicle, whose constraints will be discussed later. The vehicle size (including frontal area for drag estimation) is roughly constant. Driveability issues (e.g. ease of start up, driving smoothness, transient response for rapid accelerations, hill climbing, and load carrying/towing capacity) have not yet been assessed quantitatively for the technologies. These are important vehicle operating characteristics, that the various technology combinations do not necessarily provide equal value in all these different diveability and performance areas.

All of the examined vehicles are medium-size passenger cars similar to a current Toyota Camry or Ford Contour with respect to load capacity, range, performance, and auxiliary equipment. The key characteristic sought here is fuel excluding energy consumed in the fuel cycle and in vehicle manufacturing. That is, they reflect the familiar "miles per gallon" or "liters per 100 kilometers" numbers and are not well-to-wheels values. Also, air pollutants other than GHG emissions have not been considered.

These simulations require the vehicle to go through specified driving cycles. Fuel consumption during the cycle is calculated from performance models for each major component of the propulsion system and for each vehicle driving resistance.

For this study, the US Federal Test Procedure (FTP) urban and highway driving cycles were used, as shown very simplified in Figure 6 and Figure 7. These cycles are the ones used by the Environmental Protection Agency (EPA) to measure the emissions and fuel consumption of vehicles sold in the US. The results from such test are reported each year in the EPA Fuel Economy Guide, after multiplying by an empirically determined factor to take into account additional real-life driving effects. The results presented in this analysis have not been multiplied by these empirical factors. Although fuel economy is calculated and listed for US Federal urban and highway driving cycles, real-life fuel consumption is worse on the average than these driving cycles would indicate.

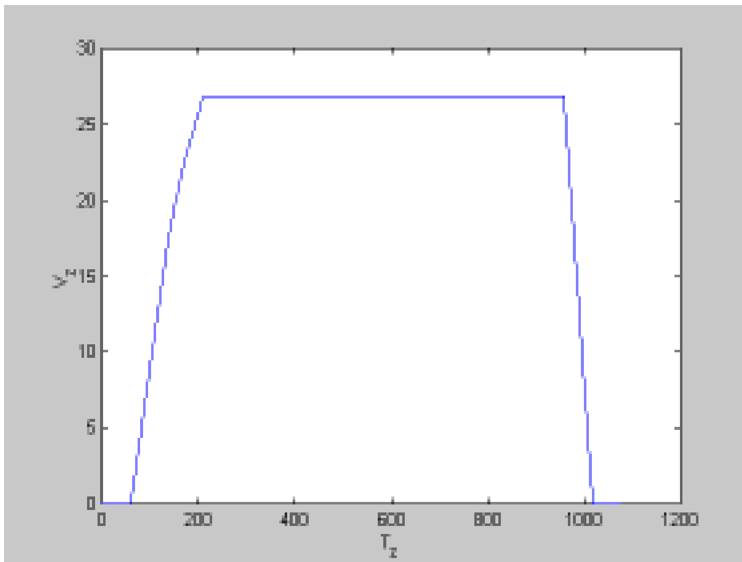


Figure 6: Highway cycle (very simplified driving cycle with one acceleration and one deceleration)

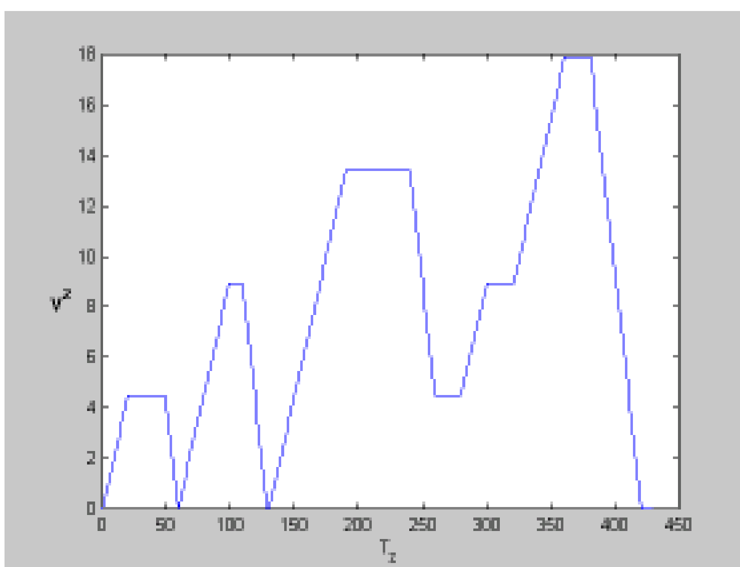


Figure 7: Urban cycle (simplified driving cycle)

The fuel consumption values predicted by the simulation for a given technology combination depend on the driving pattern or cycle used. The relative differences between fuel consumption prediction for different technology combinations, for different driving cycles, are also likely to be different. Some preliminary information suggests that the fuel consumption benefits of more advanced technology vehicles, with more realistic driving patterns than the FTP, are not as large as calculated for the FTP cycle. None the less, this combined FTP cycle (urban and highway) is the standard cycle used for vehicle fuel consumption and emissions.

The basic principle of the simulation can be explained using the example of the internal combustion engine. The basic logic flow is the same for all other propulsion technologies.

Driving Cycle ⇨ Vehicle Resistance ⇨ Transmission ⇨ Combustion Engine ⇨ Fuel Consumption

Figure 8: Calculation Logic for Internal Combustion Engines

The base vehicle with an internal combustion engine coupled to a transmission is related to the specified driving cycle as shown in Figure 8. The calculation starts with the chosen driving cycle, specified as an array of vehicle velocity versus time. From these two inputs, the vehicle acceleration is calculated. This information is used to calculate the instantaneous power needed to operate the vehicle, by adding aerodynamic drag, tire rolling resistance, and inertial force (vehicle mass times acceleration). The required total power is converted to the torque needed to drive the tires, which through the transmission is converted to the torque needed at the engine output shaft.

In addition to the power required as engine output, all the engine losses (due to engine cycle inefficiencies, engine friction, changes in rotational kinetic energy, and auxiliary component power requirements) are summed together to obtain the total rate at which fuel chemical energy is consumed. Using the lower heating value[1] (the stored usable

[1] Two fuel heating values are defined, a lower and higher, depending on whether the water in the combustion products is vapor or liquid. The energy, fuel consumption and CO_2 predictions are unaffected since the heating value cancels out.

chemical energy of a fuel), this “fuel power” is converted to the amount of fuel needed, thus generating the desired result – energy consumption per unit distance traveled.

The simulation models have been verified on a set of current production and prototype vehicles as the Toyota Camry, the Audi 100 turbo diesel, the Toyota Prius, the Ford P2000 prototype hydrogen fuel cell vehicle and the GM EV1 electric vehicle. The predicted urban and highway fuel economies were lying between ±13% of the measured values. While not all input details for these vehicles are available and some were estimated, the results show reasonable agreement with Federal Test Procedure or company published data.

The three basic methodologies presented in this chapter are used in the thesis to quantify the relationship between environmental performance and cost of producing lightweight body structures. Specifically, Technical Cost Modeling based on the mass and design of the bodies is estimating the cost of producing the body structure. The statistical analysis establishes the relationship between power and mass of the propulsion systems and allows specifying the combination of bodies and powertrains for a defined vehicle performance. Finally, the environmental performance model “drives” the defined vehicles through a driving cycle and calculates for example the energy use and fuel economy.

The chosen lightweight bodies and alternative propulsion technologies to be analyzed with these methodologies are described in detail in the following chapter with some of their characteristics, advantages and disadvantages.

4 Description of Case

To set a quantitative basis for the design trade-off decision the thesis attempts to take a first step in understanding the cost and environmental performance for a vehicle with a specific vehicle performance target. These two dimensions are quantified by using the previously presented methodologies. It is now necessary to define and catalog the specific lightweight body designs and propulsion technologies, which are going to be examined. This is carried out in a case-based approach by using actual body design and powertrain data.

A vehicle body consists basically of the body-in-white and closures. The body-in-white (BIW) is defined as the set of parts in an automobile that bear static and dynamic loads and also impart torsional stiffness. The closures include the hood, the decklid, fenders, and front and rear doors. With few exceptions, the body today is composed of a number of stamped steel parts that are welded together. Although steel has long been the dominant material, viable alternative materials technologies, in particular aluminum and polymer composites, are gaining attention in the automotive industry.

This study will therefore focus on examining six different materials or material combinations, which capture a range for weight reduction up to 55% less than the steel baseline. These are steel, "light" steel, aluminum, composite intensive vehicle (CIV), carbon reinforced composite intensive vehicle (C-CIV) and, for higher production volumes, a cost-optimized version of the composite intensive vehicle (CO-CIV) (see Table 1). Data on existing designs provided from automobile companies were used for most of the bodies. For example, information on parts for the Ford Taurus were used for the steel body design. Nevertheless, in order to ensure the comparability of the results, all bodies needed be scaled to the same size of a baseline vehicle (iso-body designs). The size of the baseline vehicle chosen is a vehicle used by the Partnership for New Generation Vehicles (PNGV). It corresponds roughly to the mid-size sedan of Toyota Camry or Ford Contour.

This class has been chosen as it represents a large segment of the cars sold in the U.S. and Europe. In the year 1999 approximately 2.5 million mid-sized cars were sold in the U.S., which corresponds roughly to 30% of sales (Automotive News, 2000).

For the propulsion technologies, five different groups could be identified as being currently widely used or in a realistic stage of development for entry to the market. These are: spark ignition internal combustion engines, compression ignition internal combustion engines, battery-powered electric vehicles, internal combustion engine hybrids (internal combustion engines and battery power plant) and fuel cell hybrids (FC and battery power plant). Every type of powertrain can be also categorized through the type of the fuel used, which are: gasoline, diesel, electricity, hydrogen and methanol fuel. The combination of propulsion technology and fuel expends the examined technologies to seven propulsion systems. These are listed together with the body designs in Table 1.

Body Designs
Steel Unibody
Light Steel Unibody
Aluminum Unibody
Composite Intensive Vehicle (CIV)
Carbon-CIV (C-CIV)
Cost optimized CIV (CO-CIV)

Propulsion Technologies
Gasoline Engine
Diesel Engine
Electric Vehicle
Gasoline Hybrid
Diesel Hybird
Hydrogen Fuel Cell
Methanol Fuel Cell

Table 1: Selected body designs and propulsion technologies

Further details on the selected body design and propulsion technologies are described in the following sections.

4.1 Body classification and materials

4.1.1 Vehicle Class

The size of the baseline vehicle chosen is a vehicle used by the Partnership for a New Generation of Vehicles (PNGV). The PNGV is a partnership between the United States Government and the U.S. Council for Automotive Research (USCAR) which represents DaimlerChrysler, Ford and General Motors. The goal of PNGV is to develop technology that can be used to create environmentally friendly vehicles that can achieve up to triple the fuel efficiency of today's vehicles with very low emissions and without sacrificing affordability, performance or safety (PNGV, 2001).

It corresponds roughly to the mid-size sedan of Toyota Camry or Ford Contour and has the overall dimensions:

Wheelbase	105.8 inch
Overall Length	188.4 inch
Overall Width	69.4 inch
Overall Height	55 inch
Curb Weight	3234 lbs.

Table 2: PNGV-sized vehicle dimensions

Focusing on materials substitution in the body, especially three material classes can meet the necessary physical characteristics (structural and load-bearing) of body parts: steel, aluminum and polymer composite materials. Because these materials are already used for many applications in the vehicle and other products, some material expertise and possibilities to expend their application in body designs is existing. The characteristics of these materials and possible body designs used for this thesis are described more detailed in the following sections.

4.1.2 Steel Body

The dominant material used in manufacturing the BIW is stamped steel. It's dominance is due to its low material cost, short cycle times, ease of forming and good mechanical properties. In addition, steel stamping and welding processes have been utilized in the car industry for decades, such that the knowledge base of processing characteristics and techniques is well documented for this technology.

Although there are many advantages of manufacturing with steel, alternative materials are poised to attack steel's market position. Studies to research the feasibility of light-weighting using steel were initiated. An example is the study sponsored by the International Iron and Steel Institute (IISI) in 1992 for the Ultralight Steel Auto Body (ULSAB). The goal of ULSAB is to reduce the weight of a steel body design (based on an average mid-size sedan), utilizing current or near term manufacturing technologies. From the results of the second stage of the study (production of prototypes) the consortium claims a 25% reduction in weight, equal or improved structural characteristics and an economically competitive design. This is achieved through the use of high strength steel, design changes and new and improved manufacturing systems (ULSAB, 1997).

4.1.3 Aluminum body

Aluminum is generally regarded as closest to competing with steel in the body design. One of the primary benefits of aluminum manufacture is that its processing and assembly methods can be similar to those employed when using steel. In addition, the design process for aluminum parts is similar to steel and therefore can draw upon the established database of design information. Aluminum's similarity to steel in the areas of manufacture and design are significant because the auto industry's multi-billion investment in steel manufacturing capabilities constrains any radical technology shift in the near term. While aluminum parts production will require some modifications to the current process, car manufacturer would not have to make the difficult choice of abandoning equipment and the familiarity of sheet based design to manufacture an aluminum body.

Despite the cost disadvantages due to high raw material costs and changes in the manufacturing, several companies have introduced aluminum intensive body designs (e.g. Ford P2000 with an aluminum unibody). Many, if not all, of the major automotive manufacturers are seriously researching aluminum. (Kelkar, 2000)

Making car bodies with extruded and mold cast aluminum requires new design and production techniques. Aluminum is clearly superior to other technically and economically feasible materials in its suitability for the manufacture of thin-walled extruded sections and castings with a level of styling freedom and high ductility. To utilize these advantages the so-called spaceframe design was developed for aluminum bodies. This body design, although very interesting and promising for this analysis, is not included due to a lack of detailed design data.

4.1.4 Polymer Composite Body

Composites have been used for many years in the automotive industry because their unique characteristics make them attractive in certain applications. Their strength and stiffness to weight ratio can be superior to those of steel used in conventional automotive applications. This allows polymer composite parts to be lighter than a comparable steel part while offering similar mechanical properties. Polymer composites have also shown to be more fatigue resistant than steel and aluminum and provide good energy absorption for crashworthiness. Furthermore, the fibers can be aligned in a specific direction so that the part will accommodate stresses in different directions. This allows physical properties to be precisely tailored according to the expected load characteristics of the application. Another benefit is the inherent design flexibility. This potentially allows the consolidation of multiple steel pieces into a single composite part. Reducing the total number of parts results in lower tooling and assembly costs (Kang, 1998). On the other side, disadvantages lie mainly in long cycle times and higher material costs.

4.2 *Propulsion Technologies*

4.2.1 Spark Ignition Engines

During the 1980s, most automotive engine manufacturers improved engine technology to increase thermodynamic efficiency, to reduce pumping loss and to decrease mechanical friction and accessory drive losses. These improvements have resulted in fuel economy benefits of as much as 10 percent in most vehicles and can be described as (OTA, 1995):

1. Increasing thermodynamic efficiency: spark timing, faster combustion, increased compression ratios.
2. Reducing mechanical friction: Rolling contacts and lighter valvetrain, fewer rings, lighter pistons, coatings, improved oil pump, lubricants.
3. Reducing pumping loss: Intake manifold design, multiple valves, lean burn, variable valve timing.

Direct Injection Stratified Charge (DISC) Engines are considered as the highest level of technology refinement for SI engines today. These engines are almost completely unthrottled, and will require variable valve timing to reach their maximum potential fuel efficiency, but still have problems associated with meeting future hydrocarbon (HC) and NO_X standards. Nevertheless, the use of a DISC engine coupled with available friction reduction technologies promise to yield a 17 to 25 percent fuel consumption reduction. These reductions can be achieved with no tradeoff in performance although cost and complexity will increase. New zeolite catalysts being developed have shown the ability to reduce NO_X in lean exhaust, providing some hydrocarbon is present. This and other post combustion technologies may help the efficient DISC engine to meet the environmental standards.

4.2.2 Diesel Engines

Diesel engines differ from SI engines in their method of combustion initiation; instead of igniting the mixture of fuel and air with a spark, diesels rely on compression alone. Diesel engines enjoyed a brief burst of popularity during the early 1980s, following the second oil price shock of 1980. Since the oil price collapse of 1986, diesels have practically disappeared from the U.S. market. In Europe, however, diesels have recently enjoyed a rebirth and new diesel car registrations are now above 25%, with some countries in a strong upward trend, for example to 48% in France in 1995 (Newsome, 1998).

The major advantage of the diesel engine over the gasoline engine is its high fuel efficiency. Diesels are more fuel-efficient than gasoline engines for two reasons. First, the diesel cycle uses high compression ratios to ignite the fuel spontaneously upon contact with hot compressed air, which leads to high engine efficiency. Second, diesels do not experience the pumping losses characteristic of SI engines because they do not throttle their intake air; the efficiency benefit under light load conditions over a gasoline engine is impressive.

On the negative side, diesel engines have much higher internal mechanical fiction because of their high cylinder pressures, and they must expend additional energy to drive their high-pressure fuel injection pumps. The high compression ratio and combustion process also lead to higher engine weight relative to a similar displacement gasoline engine, as well as reduced specific output and increased noise and vibration.

The recent development in Direct Injection (DI) systems avoids the heat and flow losses from the pre-chamber by injecting the fuel directly into the combustion chamber. Turbocharging has also been found to be particularly effective in combination with diesel engines. As a result, the specific power of diesel engines with turbocharging now exceeds the specific power output of naturally aspirated, two-valve per cylinder gasoline engines and approaches that of four-valve per cylinder gasoline engines. Turbocharging is quite costly, however, and turbocharged engines still have some low-speed driveability deficiencies.

4.2.3 Electric Drivetrain

The appeal of using electricity to power automobiles is that it would eliminate vehicular air pollution (although there would still be pollution at the power source), and that electricity can be reversibly translated to shaft power with precise control and high efficiency. The main problem with this use is that electricity cannot be easily stored on a vehicle. California's mandate for the introduction of zero emission vehicles in 1998 has resulted in a major research effort to overcome this storage problem. The only commercially available systems for storage today, however, are the lead acid and nickel-cadmium battery, and both have limited capabilities in range and charging time.

In general batteries can be divided into four thematic groups: lead acid, alkaline, high temperature, and solid electrolyte (OTA, 1995):

Lead acid batteries have been in existence for decades, and more advanced traction batteries with improved specific power and energy, as well as durability, are under development.

The three most successful candidates in the alkaline category are nickel-cadmium, nickel-iron and nickel-metal hydride. Nickel-cadmium (Ni-Cd) batteries are available commercially, but the major problem has been their relatively modest improvement in specific energy over advanced lead acid batteries relative to their high cost.

The high temperature battery category includes sodium sulfur, sodium-nickel chloride and lithium-metal disulfide batteries. All high-temperature batteries suffer from the fact that temperature must be maintained at about 300°C, which requires a sophisticated thermal management system and battery insulation and imposes severe packaging constraints.

The Lithium-Ion battery type has many supporters who consider it a leading long-term candidate for EV power. Solid electrolyte batteries are potentially extremely "EV friendly" batteries in that they are spillage proof and maintenance free. Many problems still remain to be resolved for lithium-polymer rechargeable batteries including the need for reversible positive electrode materials and stable high conductivity polymers as well as scale-up problems associated with high voltages.

Despite the extensive research on different battery technologies, to date production vehicles have had ranges no greater than 150 miles and take up to 8 hours to recharge. Due to these difficulties the electric vehicle in not yet fully accepted by the customer.

4.2.4 Gasoline or Diesel Electric Hybrid

Hybrid systems are combining internal combustion engines and storage batteries with associated inverters, controls, motors and regenerative braking taking one more step in vehicle complexity than using only one of these technologies. Starting with the most basic distinguishing characteristics, there are series and parallel hybrids. A series hybrid drives the wheels only through the electric motor with the combustion engine generating electricity, whereas a parallel hybrid system powers the wheels directly with both the combustion engine and electric motor.

There are several types of feasible hybrid configurations and different drivetrain arrangements within each configuration existing, but only two gasoline hybrids are currently in limited production in the market: the Toyota Prius with its parallel, balanced-loading, CVT hybrid configuration and the Honda Insight. Due to more detailed information on these powertrains, the parallel hybrid configuration is chosen for this analysis.

The hybrid vehicles reduced the disadvantages of range and charging time of the battery but does not reach the zero emission level of the pure electric vehicle. Furthermore, the complexity of manufacturing and maintenance of the vehicles increases with combining the two systems of electric motor and combustion engine.

4.2.5 Fuel Cell Technology

Many researchers consider fuel cells to be the ultimate answer to power motor vehicles, because they combine the positive attributes of batteries - zero or extremely low emissions - with the quick refueling capability of internal combustion engines. A fuel cell is an electrochemical device that converts the chemical energy in a fuel to electrical energy directly without first converting the chemical energy to heat energy. As a result, the thermodynamic limitations imposed by the Carnot cycle are not applicable, and fuel cells can have theoretical efficiencies of more than 90 percent. In addition, if the fuel used is hydrogen, the energy conversion process is essentially pollution free, as fuel cells can convert hydrogen and the oxygen in the air directly to electricity and water. With other fuels, such as methanol or hydrocarbons, an external reformer may be necessary to first separate the hydrogen from the fuel. The reforming process will generate small quantities of carbon monoxide and other pollutants, and substantial quantities of carbon dioxide.

The electrolyte defines the key properties, particularly operating temperature, of the fuel cell. For this reason, fuel cell technologies are named by their electrolyte:

- Polymer Electrode Membrane (PEM)
- Alkaline Fuel Cell (AFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)

The main problem for the fuel cells arises with using especially methanol and hydrogen fuel around the not existing infrastructure for the distribution of the fuel and the high cost estimated for production the fuel. Furthermore, the storage of the fuel on board requires more development. Finally, it is difficult to assess if the cost of producing the fuel cell can be lowered significantly as there is no experience with large-scale manufacturing.

Chapters 3 and 4 have established the methodologies to be used for analyzing the cost and environmental performance of vehicles and described some details of the selected body designs and propulsion technologies for this analysis. The following chapter will now expand for every step of the research approach on the detailed assumptions and required input data for each method and technology.

5 Analysis

This chapter will describe, based on the proposed methodologies and chosen cases, how the analysis was approached in detail and what assumptions were made using a case-based analysis. The approach described in Chapter 3 will be followed (see Figure 4):

- Chapter 4 has defined the selected body and powertrain technologies.
- Using existing body designs and their part lists, the assumptions made to scale the bodies to the same size and to derive their mass will be presented.
- Based on this scaled part list the necessary material processing models and input data for the technical cost modeling will be defined to estimate the cost of production for the different lightweight body designs.
- The next section will describe the approach and results of the statistical analysis to understand the relationship between power and mass of the powertrain, which is needed for the further analysis.
- The established relationship will then be used for the calculation to find the size of the powertrain, which will provide the necessary performance for specific lightweight body. The equations derived for this calculation and input data are presented in more detail.
- Finally, the input parameters and the calculation logic of the environmental performance model to assess the energy use of the selected vehicles will be explained.

5.1 Design and Scaling of Lightweight Strategies

To define the mass of the body and also perform the cost analysis using Technical Cost Modeling (TCM), detailed information on the body parts needs to be collected. For the purpose of this analysis, the data is derived mainly from real body designs and scaled to the baseline PNGV-sized body for comparison.

Part lists for several four-door sedans were existing and have been used at the Materials System Laboratory at the Massachusetts Institute of Technology in previous case studies. The bodies analyzed in this thesis are based on the design and part list of:

- Steel unibody: Ford Taurus (Han, 1994)
- Light steel unibody: Ultra Light Steel Advanced Body (ULSAB, 1997)
- Aluminum unibody: Ford P2000 (Kelkar, 2000)
- Composite Intensive Vehicles (3 variations): Composite Intensive Vehicle Project at Ford Motor Company (Kang, 1998)
- Closures: Ultra Light Steel Closures (Opbroek, 1998)

These part lists are describing the different bodies with the number of parts, the weight and dimensions of the parts and the material type used. Unfortunately not all have the same size of body. Therefore, the bodies will be scaled to the baseline vehicle. Further inputs are needed for the TCM analysis and will be described in the next chapter.

The materials used for the different designs were:

Body Design	**Material**
Steel Unibody	Mild Steel: 140 MPa
Light Steel Unibody	High Strength Steel: ranging from 210 MPa to 800 Mpa
Aluminum Unibody	5754 and 6111 Aluminum, Cast Aluminum
CIV	Sheet Molding Compound (SMC), Resin Transfer Molding (RTM) with glass fiber
Carbon-CIV	Sheet Molding Compound (SMC), Resin Transfer Molding (RTM) with carbon fiber
Cost-optimized CIV	Sheet Molding Compound (SMC), Resin Transfer Molding (RTM) with glass fiber, Mild Steel

Table 3: Material selection of body designs

In order to scale the selected bodies to the baseline, the basic data on the PNGV-sized four-door sedan need to be defined. Table 2 (see page 37) already lists the overall dimensions and the curb weight of the baseline steel body. The mass data on the steel body-in-white and closures for the baseline PNGV vehicle was derived from benchmark studies and personal conversation with industry experts (Roth, 2001).

Based on this information, the weight of the conventional steel PNGV body and closures was therefore established as:

Body-In-White	263 kg
Closures	87.2 kg
Total Body Weight	350.2 kg

Table 4: PNGV-sized four-door sedan, steel unibody baseline weight

Given the dimensions and weight of the baseline body (Table 2 and Table 4) the scaling factors for the alternative designs can be defined.

Beside the definition of the overall mass of the same sized bodies, the following use of the technical cost model requires detailed information on the individual parts, as the cost of producing the body are based on them. Therefore, comparable results require every part of the body to be scaled to the baseline body.

There is only a small difference in the size and design of the actual steel, light steel and aluminum bodies to the baseline body existing. Given the available information and the small magnitude of sizing necessary, it is assumed that the parts would scale by weight at the same rate as the whole vehicle. This is clearly a simplification, but the best available strategy. The weight of the real body designs is known through their part list and the weight reduction potential defines what the body can be expected to weight related to the baseline body. This ratio of the desired to real weight establishes the scaling factor, which can be applied to the every part on the list. It is possible to scale on weight for the metal materials mainly because the weight changes proportionally to the size of a part. A larger part weights proportionally more than a smaller one.

Previous studies at the Materials Systems Laboratory conducted from Han (1994), Kang (1998) and Kelkar (2000) examined the weight reduction potential of alternative materials. Table 5 shows their assessment of the possible weight reduction:

Body Design	Weight Reduction Potential
Steel Unibody	0%
Light Steel Unibody	25%
Aluminum Unibody	40%
CIV	35%
Carbon CIV	55%
Cost-optimized CIV	32%

Table 5: Weight reduction potential of alternative materials/designs

Using the real weight and the reduction potential the first three body designs using metals can be scaled to the baseline PNGV-sized vehicle.

In the case of the composite intensive vehicles (CIV), the existing part list is based on a minivan-style vehicle. This significant difference in the body design requires another approach than the scaling by weight used for the steel, light steel and aluminum bodies. It is now necessary to scale each part of the CIV body design to the baseline size and to derive its weight using the material properties and dimensions. Due to the consolidation of multiple steel pieces into a single composite part, the overall number of parts in the CIV design is in a reasonable range (about 40 parts) to allow this approach. Therefore using the dimensions of the PNGV-sized baseline vehicle and the existing CIV design information, the new, scaled dimensions can be established. For example, the CIV design exists of one part for the floorpan. Knowing the dimensions of the PNGV baseline body, the overall dimensions of the scaled floorpan can be derived. The specific CIV design information on the part itself (e.g. number of preforms, foam cores, cutout areas) allows to define the part more detailed and combined with the material density, the weight of the parts can be calculated. All part weights add up to the total weight of the body.

The same approach was also used for the closures. Defining the dimensions of the part and calculating their weight was appropriate.

Defining the weight and size of the body parts sets the basis for the following TCM analysis, which will be described in the next section.

5.2 Technical Cost Modeling Inputs

In order to analyze the economic costs associated with different lightweight strategies, Technical Cost Modeling (TCM) was used. This is a methodology that analyzes the economics of manufacturing technologies by capturing how key engineering and process characteristics relate to the total production cost of a component.

For the selected materials, existing models developed at the Materials Systems Laboratory could be used. These were a Steel or Aluminum Stamping Model, a Die Casting Model, a Sheet Molding Compound Model, a Resin Transfer Molding Model and an Assembly Model (Kelkar, 2000; Kang, 1998 and Jain, 1997).

Most of the general input parameters like exogenous cost factors, parameter estimation data and material cost can be used directly as described in the exiting models. Others like the component and process description, production volume and dedicated/non-dedicated equipment have to be defined (see Chapter 3.1.2).

For the steel and aluminum body designs a large number of parts need to be modeled. The use of the traditional TCM would require the combination of a significant number of models. For each of them, part and processing information has to be gathered and processed. The high level of detail associated with TCM makes the estimation process extremely complex and not always all necessary information could be gathered. The existing cost model on stamped parts was therefore changed to accommodate the idea of the Systems Cost Modeling (SCM) approach described in Chapter 3.1.3.

The necessary inputs are now reduced to the number of parts, part weight, material type, trim scrap, press type and complexity level of the part.

The number of parts, part weight and material type were already defined when the design and overall weight of the different bodies was established. Furthermore, the type of press and the complexity level to be used in the model have to be defined. Detailed information regarding shape, thickness and other factors used to calculate equipment characteristics are substituted by a three level complexity factor, estimated by judgment. Level 1 corresponds to simple components where their size is the major factor affecting processing; Level 3 corresponds to complex parts, which imply more detail or additional features requiring more complex (and therefore more expensive) equipment (Veloso, 2001).

The aluminum unibody included also two die casting parts. In this case and for the composite intensive vehicle with a lower number of parts, it was possible to use the traditional TCM approach. The part inputs required a higher level of detail. These are in general: part weight, material formulation, part length, width and depth, average/ maximum wall thickness, surface area, projected area, cutout area or perimeter.

Finally, especially some smaller parts as for example brackets or hinges are usually purchased. Average prices for these parts were estimated from industry contacts.

Besides analyzing the cost of production of the bodies, also the cost of assembly has to be assessed. The assembly model developed at the Materials Systems Laboratory is used in developing cost estimates for the assembly of three body material technologies: steel, aluminum and polymer composites. Marti and Jain, in their theses have given detailed description of the fundamentals and equations of the assembly model (Marti, 1997; Jain, 1997). The following section provides a brief summary of the more important aspects of the assembly process.

The assembly of an automotive body is accomplished by attaching various subassemblies together. A subassembly is a grouping of various parts that form a portion of the body. The subassembly groupings are chosen in order to facilitate and maximize the efficiency of the assembly process. In each subassembly step, a number of different techniques can be utilized to join parts together. These subassemblies are then joined together at the final assembly station to form the completed body.

The assembly model calculates cost using relational databases to capture the relevant information needed for each joining method. Sets of data are grouped into three tables: Assembly Methods, Groups and Group Methods.

The Assembly Methods table stores detailed information regarding each joining method and general inputs parameter used across all other tables to calculate the costs for joining. Some examples of information stored in the Assembly Methods table for each joining method would be equipment costs, number of laborers per station, material costs and process speed and for general inputs the labor wages, energy cost etc.

The Groups tables functions as an inventory of all subassemblies included in the process. It identifies each group, the number of parts included in that group and assign a unique number to the group.

Finally, the Group Methods table stores information about which joining methods are employed and their intensity of use. Specifically this includes the join length and/or number of connections for the various subassemblies to be joined. A number of different joining methods can be specified for each group.

The model calculates costs based on the amount of joining that can be conducted at each station during the time available. The station time is the amount of time the subassembly remains at the particular station before proceeding to the next station. This is calculated based on the total production time in a year (production days* shifts/day* hours/shift), downtimes and the maximum line rate that can be achieved. The station time then determines the number of stations that would be required for the specified production volume and thus the equipment costs and auxiliary machine costs.

In order to calculate costs, the assembly model selects the necessary information stored within each table as inputs for the calculation. The Group table allows the model to determine the number of parts to be joined in a particular subassembly. To join these parts, the Group Methods table contains information about the specific join methods and joins length or number of connections required for attaching that particular subassembly. Finally, the Assembly Methods table supplies the necessary cost information for the particular joining process to calculate the cost for that operation.

For the purpose of this analysis the following joining methods were used:
laser welding, metal inert gas (MIG) welding, adhesive bonding, resistance spot welding (RSW), tack-resistance spot welding, hemming, fastening and riveting. The specific information on the joining methods was different depending on the material to join.

The necessary inputs for the analysis are now to define the subassemblies and their number of parts included, the joining method, for a continuous joining process the joining length and number of segments and for a discontinuous joining process the number of connections. Then the cost for the assembly operation can be calculated.

To analyze the cost of production and assembly a large amount of detailed data is necessary. A similar analysis would have been necessary to also analyze the cost for the different propulsion systems. Unfortunately not enough design information on the powertrains as well as cost models for the different production methods were available. The time frame of this thesis did not allow for the development of these models and collection of all necessary data. Therefore, the cost of producing the propulsion technologies will be estimated roughly using literature and industry information. The results will be presented in Chapter 6.

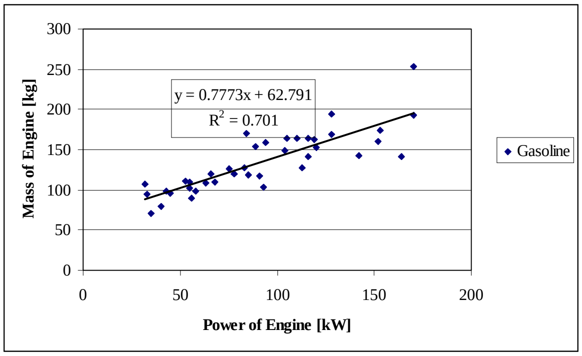
5.3 Power density of propulsion technologies

As described in Chapter 3.2, the key characteristic for the propulsion system is defined by its power density. This is the ratio of the power of the powertrain to its mass. For the further analysis it is important to understand the relationship between power and mass of the propulsion system. A possible way to analyze this problem is to derive the necessary equations with empirical data and statistical analysis.

This chapter presents the equations derived for the chosen propulsion technologies. The equations will be used for the further analysis when the lightweight body designs will be matched with the propulsion technologies.

Data on the different propulsion systems produced or in development have been collected mainly through literature and company publications. The data on power, mass or power density were plotted and examined using regression analysis.

For the gasoline and diesel internal combustion engines it was possible to collect a larger number of engine information. Figure 9 shows the correlation between the mass and power of the engines and the result of the regression analysis. Interestingly the two factors move linearly. Considering the amount of independent variables, except for the mass, influencing the dependent variable, the power of the powertrain, the R^2 of the analysis is in a reasonable range.



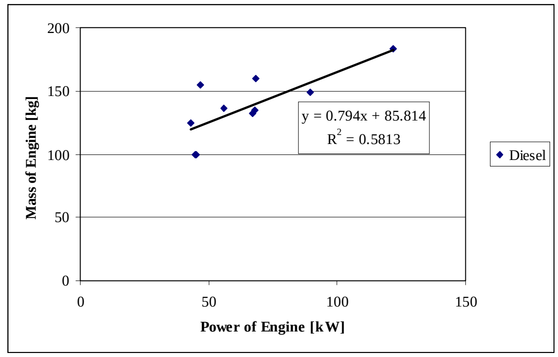


Figure 9: Mass to power correlation for gasoline and diesel engines

For the electric and gasoline or diesel hybrid powertrains only limited information was available. There are only two gasoline hybrid vehicles in the market today and also only a few electric vehicles. The results are shown in Figure 10 and Figure 11.

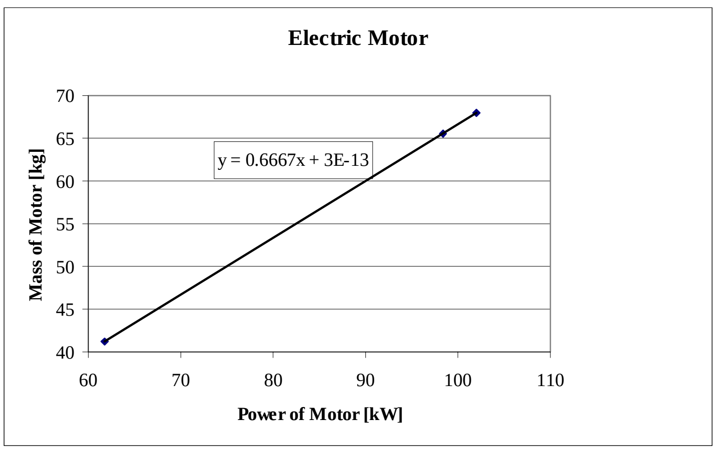


Figure 10: Mass to power correlation for electric vehicles

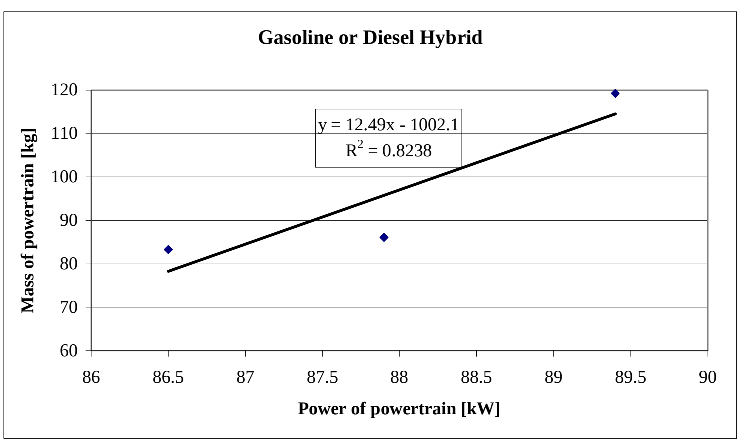


Figure 11 Mass to power correlation for gasoline or diesel hybrid engines

For the hydrogen and methanol fuel cells, again only a limited number of data sets could be used. One problem was especially that the powertrains are still in development and undergoing constant change. In the last years, more powerful fuel cells have been developed with less weight. Regression analysis of such data leads to a negative slope for the power density curves of fuel cells. By eliminating some of the older fuel cells (low power output and high weight) of the sample, this effect was reduced. But the changes in technology are still too big in recent years to show a clear correlation. Therefore, after examining the graph of power density to mass of the fuel cell, an average power density was determined and used in the further analysis for all the fuel cells.

Summarizing, the equations derived through statistical analysis of the empirical data are shown in Table 6. Their behavior is linearly, which facilitates their use in the following chapter for matching the lightweight designs with the propulsion technologies to meet the vehicle performance target.

Propulsion Technology	**Power to Mass correlation** y= mass of powertrain [kg], x= power of powertrain [kW]
Gasoline Engine	y = 0.8*x + 62.8
Diesel Engine	y = 0.8*x + 85.8
Electric Motor	y = 0.67*x
Gasoline or Diesel Hybrid	y = 12.5*x – 1002
Hydrogen Fuel Cell	y = 2.402*x
Methanol Fuel Cell	y = 3.571 *x

Table 6: Power density equations for all propulsion technologies

5.4 Matching body designs with propulsion technologies

The powertrain required to deliver consistent performance for each of the proposed propulsion technologies can now be established using the defined mass of the different body designs and the correlation between the mass and the power of the powertrain (power density, see Figure 12).

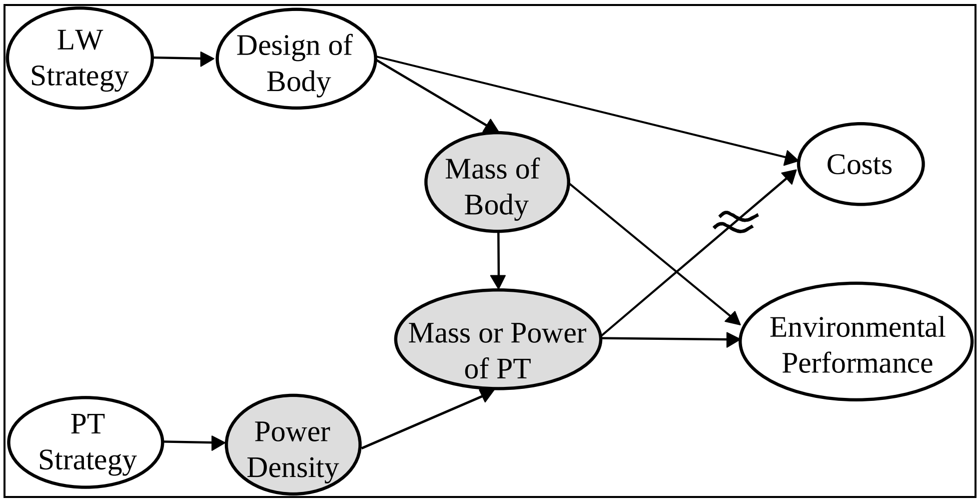


Figure 12: Research approach – determine size of powertrain for consistent performance

Consumer purchasing behaviors have shown that a majority will not sacrifice vehicle performance in return for improved environmental performance. The car should provide comfort, range and power similar to today's cars. Therefore, powertrains are picked to provide equivalent vehicle performance.

All vehicles are therefore designed to have a constant peak power to mass of vehicle ratio of 75 W/kg, which is matched to today's value. This ratio roughly, but not exactly, equalizes vehicle performances, as can be checked with acceleration calculations (Weiss, 2000). Another source suggests 95 W/kg, as the average value over a broad range of today's mid-size to luxury cars (Automotive News, 1999). As there is no consensus about the vehicle performance target, both values are going to be used for the further analysis. There is also the opinion existing that the smaller value corresponds more to European vehicles and the higher value to US vehicles. Therefore two sets of results will be presented.

The basic idea for matching the propulsion technologies with the lightweight design was described in Chapter 3.2. This section will expand on these ideas and assumptions.

The first five equations derived in Chapter 3.2 are repeated to provide the basis for the further calculations.

Simplified, the total mass of the vehicle (M_v) can be defined as the sum of the mass of the body (M_b), the mass of the propulsion system (M_p) and the mass of other components (M_o):

[1] $$M_v = M_b + M_p + M_o$$

The mass distribution of the different components is known for the baseline vehicle.

The vehicle performance (a) is defined as the ratio of the power of the propulsion system (P_p) to the mass of the vehicle (M_v):

[2] $$a = P_p/M_v$$

The power density (k) of the propulsion system can be defined as:

[3] $$k = P_p/M_p$$

Combining equation [2] and [3], the mass of the vehicle can be expressed as:

[4] $$M_v = k/a * M_p$$

The change in the mass of the vehicle when including secondary weight saving can be expressed as the sum of change in the weight of the body and the secondary weight savings factor (s) depending on the saved body mass. This is also equal to the change in the body, propulsion system and in the other components:

[5] $$\Delta M_v = \Delta M_b + s * \Delta M_b = \Delta M_b + \Delta M_p + \Delta M_o^s + \Delta M_o^c$$

Secondary weight savings do not influence all parts in the mass of other components. Therefore the term M_o was split up to M_o^s, which is expressing the changes through secondary weight savings, and a constant part M_o^c. Furthermore the "Δ" characterizes the difference between the new weight (e.g. M_b') and the baseline weight (e.g. M_b).

As ΔM_o^c is a constant, solving equation [5] for M_o^{s}' leads to:

[6] $$M_o^{s'} = s * \Delta M_b - \Delta M_p + M_o^s$$

Equation [6] can be inserted into [7], which is based on the idea presented in equation [1] and used to derive the new vehicle mass.

[7] $$M_v' = M_b' + M_p' + M_o^{s}{}' + M_o^{c}{}'$$

$$= M_b' + s * \Delta M_b + M_p + M_o$$

Again, based on the idea presented in equation [4] the new mass of the vehicle can be defined as:

[8] $$M_v' = k'/a * M_p'$$

Combining now equations [7] and [8], the mass of the body can be calculated with:

[9] $$M_b' = 1/(1+s) * [k'/a * M_p' + s * M_b - M_p - M_o]$$

Equation [9] can be solved for the required mass or power of the propulsion system to reach the vehicle performance target.

[10] $$P_p = a * (M_b' * (1+s) - s * M_b + M_p + M_o)$$

The vehicle performance (a) is defined as the ratio of the power of the propulsion system (P_p) to the mass of the vehicle (M_v). The target for vehicle performance is, as already described:

$$a_1 = 75 \text{ W/kg} \qquad \text{or} \qquad a_2 = 95 \text{ W/kg}$$

Mb' is the value of the mass of the alternative body design. This can be for example the mass of the light steel unibody, the aluminum unibody or the CIV.

The secondary weight savings (s) are estimated to be about 50% of primary weight savings (Stodolsky, 1995). Therefore "s" equals to "0.5".

The mass distribution ($M_v = M_b + M_p + M_o$) of the baseline PNGV-sized four-door sedan (steel unibody) is known through a benchmark analysis(Roth, 2001). The values are:

Mass of body (M_b)	350.2 kg
Mass of powertrain (M_p)	164 kg
Mass of other components (M_o)	953.8 kg
Mass of total vehicle	1468 kg

Table 7: Mass distribution of steel unibody baseline vehicle

Now all inputs to calculate the power of the propulsion system are defined. Using the previously established correlation of power to mass of the propulsion system, the mass of the powertrain is therefore also defined for each technology.

Equation [10] needs to be adjusted for the fuel cells, because of the interdependence of the subsystems of the fuel cell. The characteristics of the motor, battery and the reformer (if methanol is used) can be expressed in dependence of the fuel cell characteristics.

Furthermore, secondary weight savings are also effecting the powertrain. Due to the existing set of data on mass of bodies and powertrains, it is possible to derive an average value for secondary weight savings (s'), including the changes in the powertrain, with the following equation:

[11] $$\Delta M_v = (1+s) * \Delta M_b$$
$$= (1+s') * (\Delta M_b+\Delta M_p)$$

Analyzing the existing data, the value for s' is approximately 0.32
Therefore, a reduction of one kilogram in the body design leads to a reduction of 0.32 kilograms in the rest of the vehicle not including the powertrain. An example of the data used to derive s' is illustrated in Table 8.

s	**M_b'**	**M_b**	**M_p'**	**M_p**	**s'**
0.5	38.13	350.2	126.05	164	0.337
0.5	109.24	350.2	127.69	164	0.303
0.5	127.02	350.2	118.06	164	0.244
0.5	162.58	350.2	153.45	164	0.420
….	….	….	….	….	….
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….	….	….	….	….	….
0.5	64.80	350.2	120.00	164	0.300
0.5	295.91	350.2	148.57	164	0.167
0.5	509.24	350.2	193.94	164	0.263
0.5	166.13	350	149.00	164	0.387
				Average	0.317
				Stdv.	0.131

Table 8: Excerpt of s' calculation

Including the interdependence of the subsystems of the fuel cell, the mass of the fuel cell (M_{fc}) can now be calculated directly with:

[12] $M_{fc} = A/B$

[13] $A = (1+s')*M_b'-s'*M_b'-s'*M_p+M_o$

[14] $B = C/a-(1+s')*(1+C/k_m+D+E)+D+E$

[15] $C = 1.2*k_{fc}$ $D = k_{bat}/P_{spec}$ $E = k_{fc}/k_{ref}$

The factor 'k' defines the power and mass ratio of the powertrain (see Equation [3]). The abbreviation 'fc' stands for fuel cell, 'bat' for the battery, 'm' for the motor, 'ref' for the reformer and P_{spec} for the specific power of the battery. Due to the problematic of constant change in the development of fuel cells mentioned earlier in this chapter, an average power density for the different subsystems was used.

These calculations allow one to select the power and mass of the optimal powertrain for the different lightweight body designs and the vehicle performance targets. The underlying assumption is that every calculated powertrain is available. In the real world, the powertrains used in the vehicles are designed in discrete steps. Every company has several different sized powertrains from which they select. They do not have the resources to optimize powertrains for each vehicle. Therefore, cars are often either slightly over- or under-powered compared to the performance target. This analysis assumes freedom in selecting hypothetical powertrains, which match the performance target exactly.

The vehicle is now completely defined with the mass of the body, mass and power of the powertrain, and the mass of the other components including secondary weight savings for the different powertrains and body designs. These data can now be used to model the environmental performance of the different vehicles.

5.5 Environmental Performance Inputs

To estimate fuel consumption to compare various vehicles with different propulsion systems, a family of Matlab Simulink simulation programs was used. Originally developed by Guzzella and Amstutz (1998) at the Eidgenössische Technische Hochschule (ETH) Zurich, these programs back-calculate the fuel consumed by the propulsion system by driving the vehicle through the US Federal Test Procedure (FTP) urban and highway driving cycles. Urban and highway cycle results as well as combined cycle (55% urban and 45% highway) results will be reported (Weiss, 2000).

Such simulations require performance models for each propulsion system component as well as for each vehicle driving resistance. The component simulations used are best characterized as aggregate engineering models which quantify component performance in sufficient detail to be reasonable accurate but avoid excessive detail. Nonetheless, a substantial number of input variables must be specified for each element or component of the overall model. Additional details can be found in Weiss (2000) and AuYeung (2000).

The output of the model is the energy used (MJ/km), which can be converted to the energy consumption per unit distance traveled (L/100km) using the lower heating value of the fuel (except for the electric vehicle). Furthermore, the cycle carbon emissions can be calculated. As only the driving cycle is modeled, the energy use of the different fuels can also be converted to a gasoline equivalent fuel economy.

The vehicle and powerplant simulations used for this analysis are summarized in Table 9. Existing vehicles, if used to develop the component simulations, are mentioned in the last column titled "Base Vehicles".

Family	**Transmission**	**Power Unit**	**Fuel**	**Base Vehicles**
Mechanical	Automatic	Spark Ignition ICE	Gasoline	Toyota Camry, 2.2L, I-4
		Compression Ignition ICE	Diesel	Audi 100, turbodiesel
Dual	Continuously Variable	ICE with Batteries and Electric Motor	Gasoline, Diesel	Toyota Prius
Electrical	Single Ratio	Fuel Cell	Gasoline, Methanol	Ford P2000
		Battery	Electricity	GM EV1

Table 9: Powertrain and fuel combinations modeled

Based on the previous calculations for the mass of the body, powertrain and other components, the mass of the vehicle is defined. The battery and fuel mass are separated in this model for ease of reference. The fuel mass is two-thirds of the amount of fuel needed to achieve approximately a range of 600 km in the combined cycle. An occupant and cargo mass is added to the total raw vehicle mass. It is the standard FTP test procedure occupant and cargo mass of 300 lbs. This estimated average load for a vehicle is held constant for all vehicles. Therefore the total operating vehicle mass is the summation of the mass of the body mass, the propulsion mass, the battery mass, the fuel mass, and the occupant and cargo mass. Other key simulation variables for the vehicle and transmission, with their assumptions and description are listed below:

- Aerodynamic drag coefficient (C_d): is a dimensionless number describing the drag induced by a body traveling in a fluid at a known relative velocity. For this study the vehicle has an estimated C_d of 0.33
- Cross Sectional Area (A_x): is the largest area in a plane perpendicular to the direction of vehicle motion. A_x estimated to be 2.0 m^2
- Rolling Resistance Coefficient (C_{rr}): is a dimensionless number used to characterize the energy dissipated due to friction between the road and the tires. C_{rr} is estimated to be 0.009
- Transmission Efficiency (η_{trans}): Transmissions are modeled with a constant efficiency during all modes of operation, although in practice the efficiency varies among gears. Idling in neutral or in drive is taken into account, but shifting losses are not. For a 4-speed automatic a 70% efficiency urban and 80% efficiency highway was used, while gasoline or diesel hybrids use continuously variable transmission at 88% efficiency.
- Auxiliary Load (P_{aux}): is assumed to be constant at 400W during all times of vehicle operation.

The next step is to define the input characteristics for the selected propulsion technologies and their calculation flow in the simulation.

For the gasoline and diesel engines the basic principle was already explained in Chapter 3.2. The logic diagram is repeated here for completeness in Figure 13.

Driving Cycle ⇨ Vehicle Resistance ⇨ Transmission ⇨ Combustion Engine ⇨ Fuel Consumption

Figure 13: Calculation Logic for Internal Combustion Engines

The performance characteristics of gasoline and diesel internal combustion engines are well documented. For the simulation, a typical maximum torque curve was constructed for a 1.6 L gasoline engine and a 1.7 L turbocharged direct-injection diesel engine. These torque-rpm curves can be scaled over a range of engine displacements, and define the performance of actual engines today. Knowing the necessary performance P_{max} for the engine, the necessary engine displacement can be therefore calculated for the simulation.

Combustion engine efficiency maps were modeled using a constant indicated energy conversion efficiency (fraction of fuel chemical energy transferred to the engine's pistons as work) and a constant friction mean effective pressure (total engine friction divided by displaced cylinder volume). This simple method is correct in aggregate but does not take into account the effect of increasing engine speed on engine friction. However, over the normal engine speed range, this assumption is adequate for predicting engine brake efficiency.

The electric vehicle with batteries driving an electric motor is modeled in a similar manner, as shown in Figure 14. In many ways, this electric vehicle is simpler, having a single gear transmission, and easier to predict motor and battery characteristics.

Driving Cycle ⇨ Vehicle Resistance ⇨ Electric Motor ⇨ Battery Status

Figure 14: Calculation Logic for Battery Electric Drivetrain

Data are available to estimate the efficiency of pure electric drive, although its history is brief and uneven. Since electric motors have been in use for many applications and have been tuned to optimize performance, a motor peak torque and power curve based on today's electric motor can be defined. For automotive purposes, the most popular choice is an AC induction electric motor.

EV batteries currently have a specific energy of about 70 Wh/kg and a specific power of about 150 W/kg. For the pure electric vehicle, both battery performance and charge density constraints (specific power and specific energy) are important. In addition to providing the power needed for peak motor power, battery energy storage capacity must be sufficient to give adequate vehicle range. However, too low a battery specific energy requires extra batteries, which add to the vehicle mass and thus require additional structural support, increased motor power, and more batteries to maintain performance, generating an undesirable compounding effect. Given this constraint, the battery pack is selected based on its power capacity, and no effort is made to augment vehicle range beyond what we estimate the available EV battery technology can provide.

With several different types of feasible hybrid configurations, and different drivetrain arrangements within each configuration, the Toyota Prius with its parallel, balanced-loading, CVT hybrid configuration was selected and modified for the simulation.

The parallel hybrid simulation combines the logic of these two models and uses both the combustion engine and the electric motor, as shown in Figure 15. The additional logic control block determines the power flow required from the engine and the battery, respectively, based on the amount of power required and the state of charge of the batteries. The objective here is to operate the engine at higher loads where it is more efficient, switch the engine off during idling and low power requirements, and use the battery and engine together at peak power levels so both components can be kept as small and light as possible.

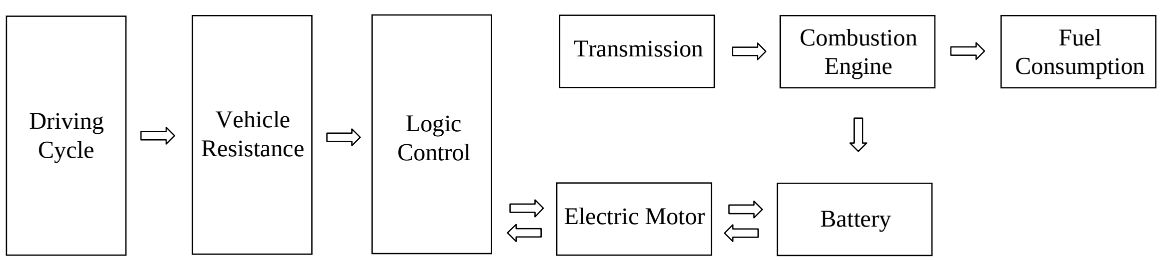

Figure 15: Calculation Logic for Internal Combustion Engines – Battery Parallel Drivetrain

For the simulation, a simplified control model is used. During low power situations, only the electric motor is in operation, thus eliminating engine idling and the less efficient and more polluting modes of operation for combustion engines. Above a preset threshold, the vehicle will be driven only by the combustion engine, except at the higher loads, such as during hard acceleration or hill climbing, when the electric motor serves as a load-leveler and provides the necessary additional power to add to the engine's maximum output.

In fuel-cell powered vehicles, the fuel cell system is combined with a battery, as a hybrid, for similar reasons: to maintain fuel cell operation in its high efficiency (part load) region as much as possible, and benefit from regenerative braking energy recovery. Its logic is shown in Figure 16. During idling and low-power operation, the batteries supply the necessary power. Over a certain threshold, the fuel cell turns on; extra power is used to recharge the batteries if they are below a set state of charge. When the power required exceeds the maximum fuel cell stack capabilities, the batteries again supplements peak loading.

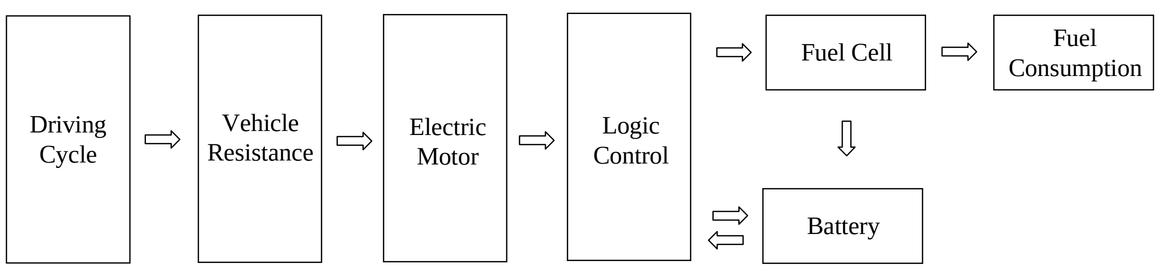

Figure 16: Calculation Logic for Fuel Cell Drivetrain

Data exist only for prototype fuel-cell systems, and many details about component performance are unavailable. Also, significant fuel-cell system technology improvements are occurring in stack size and weight for a given power, fuel storage methods, reformer performance, and cost.

In contrast to the combustion engine hybrid, the fuel-cell battery hybrid is a series hybrid, with the fuel cell generating electricity that powers the electric motor and accessories, or recharges the batteries, or does both. The power logic control operates in a similar manner to that of the combustion engine hybrid. The fuel-cell system efficiency is based on modeling by Directed Technologies (Thomas et al, 1998). First, the power versus efficiency curve is scaled to the stack size required to give the gross power output. Then, 15% of the generated power is diverted to run the needed fuel cell systems.

An additional fuel cell system loss is taken into account for reformer vehicles. Where reduced hydrogen concentration in the reformer exit fuel stream results in poorer stack performance and compromised hydrogen utilization. According to Thomas et. al. (1998), the methanol reformer generates a stream with 75% hydrogen, with a 10% reduction in fuel cell power. Because the diluted hydrogen input stream must now be an open flow, the reformer fuel cell has a hydrogen utilization rate of 85%. All numbers from Directed Technologies are taken as an average of the best and probable cases.

The results of all these analyses are presented in the following chapter. It provides the basis for assessing the cost of environmental performance by using the cost of the vehicle body and the energy use or fuel consumption of the defined vehicles.

For the lightweight body designs it will be also possible to find the non-dominated designs. These are the body designs, which are cheaper to produce and which have a better environmental performance than other body designs. They will be always chosen as the better option. Therefore some of the bodies can be ruled out depending on the production volume, as costs vary depending on it.

6 Results

The previous chapters introduced the methods, assumptions and necessary inputs to set a quantitative basis for the trade-off decision between cost and environmental performance for a mid-sized four-door sedan vehicle.

Figure 17 shows again the approach of the analysis. Beginning with the mass of the selected bodies (1), the cost of production and assembly (2) will be presented. Followed by the results of the combination of the six body designs with the seven propulsion systems to reach the two vehicle performance targets (3), the now defined vehicle will be modeled to calculate its energy use and fuel consumption (4). Finally, the two dimensions of cost and environmental performance will be compared and interpreted by for example using the notion of a dominating design. The analysis will be taken a step further by adding the rough estimated cost for the propulsion system to proof the concept.

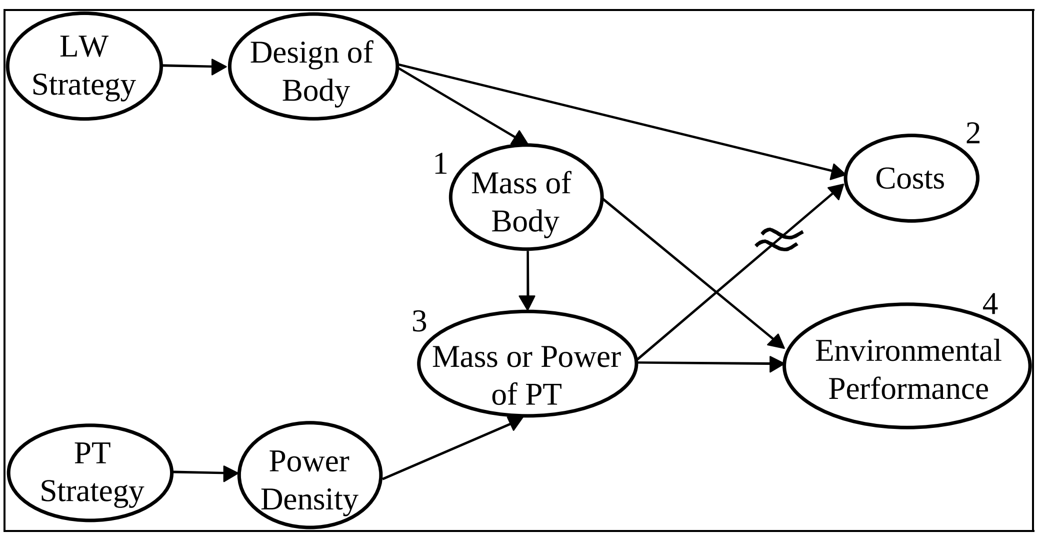

Figure 17: Research approach – presentation of results of analysis

6.1 *Mass of body designs*

The basic assumptions and calculation methods are described in Chapter 5.1. All different body designs are iso-bodies, therefore scaled to the same size based on the baseline PNGV-sized four-door steel vehicle. Table 10 and Table 11 summarize salient characteristics of the bodies:

Body Design	Mass of BIW [kg]	Mass of Closures [kg]	Total Mass of Body [kg]
Steel Unibody	263	87.2	350.2
Light Steel Unibody	189.4	68.5	257.9
Cost-optimized CIV	179.9	57.2	237.1
Composite Intensive Vehicle (CIV)	177.5	53.2	230.7
Aluminum Unibody	157.8	47.3	205.1
Carbon CIV	111.9	49.7	161.6

Table 10: Mass of lightweight body designs

Body Design	Mass of Body [kg]	Weight Reduction	Part Count BIW [#]
Steel Unibody	350.2	0%	169
Light Steel Unibody	257.9	26%	132
Cost-optimized CIV	237.1	32%	47
Composite Intensive Vehicle (CIV)	230.7	34%	40
Aluminum Unibody	205.1	41%	162
Carbon CIV	161.6	54%	40

Table 11: Weight reduction potential and part count of lightweight body designs

The number of parts reveals one measure of the complexity of the designs. The steel and aluminum are the most complex designs with approximately 150 parts only for the body-in-white. In contrast, the composite intensive vehicle (CIV) allows the consolidation of multiple steel pieces into a single composite part and reduces the number of parts to 40. Reducing the number of parts through parts consolidation should also results in lower tooling and assembly costs. The influence of material choice and part number onto the cost for manufacturing and assembly of the bodies will be presented in the next chapter.

6.2 *Cost of manufacturing and assembly of the body designs*

In order to analyze the economic costs associated with different lightweight strategies, Technical Cost Modeling (TCM) was used. Depending on the chosen body design several manufacturing and assembly methods need to be analyzed to calculate the overall cost. Table 12 summarizes the methods used for the six chosen body designs.

Body Design	**Manufacturing Method**	**Assembly Method**
Steel Unibody	Stamping	Resistance Spot Welding (RSW), Tack-RSW, MIG Welding
Light Steel Unibody	Stamping	RSW, Adhesive Bonding, MIG, Laser Welding
Cost-optimized CIV	Stamping, RTM, SMC	Adhesive Bonding, RSW
Composite Intensive Vehicle (CIV)	RTM, SMC	Adhesive Bonding
Aluminum Unibody	Stamping, Die Casting	RSW, Tack-RSW, MIG Welding
Carbon CIV	RTM, SMC	Adhesive Bonding
Closures	Stamping, RTM, SMC	Hemming, Adhesive Bonding, RSW, Riveting, Fastening

Table 12: Manufacturing and assembly methods used for TCM

The necessary input parameters to be used for TCM are described in detail in Chapter 5.2. The part lists of all body designs and input parameters can be found in Appendix 9.1. The following tables and graphs show the manufacturing, assembly and total cost for each of the body designs for different production volumes ranging from 15,000 to 200,000 bodies per year.

MANUFACTURING COST						
Production volume [parts/year]	**Steel Unibody**	**Light Steel Unibody**	**CO-CIV**	**CIV**	**Aluminum Unibody**	**Carbon-CIV**
15,000	$2,283	$1,843	$2,053	$2,332	$3,030	$2,703
20,000	$1,884	$1,565	$1,839	$2,018	$2,559	$2,370
25,000	$1,644	$1,398	$1,671	$1,890	$2,275	$2,335
30,000	$1,484	$1,288	$1,644	$1,880	$2,088	$2,330
35,000	$1,370	$1,208	$1,531	$1,752	$1,952	$2,191
60,000	$1,085	$1,010	$1,385	$1,609	$1,619	$2,011
80,000	$985	$941	$1,301	$1,543	$1,503	$1,942
100,000	$925	$899	$1,268	$1,496	$1,431	$1,902
125,000	$877	$866	$1,266	$1,495	$1,376	$1,922
200,000	$806	$816	$1,212	$1,444	$1,291	$1,859

ASSEMBLY COST						
Production volume [parts/year]	**Steel Unibody**	**Light Steel Unibody**	**CO-CIV**	**CIV**	**Aluminum Unibody**	**Carbon-CIV**
15,000	$2,503	$2,883	$2,660	$2,177	$2,214	$2,177
20,000	$1,904	$2,173	$2,010	$1,647	$1,675	$1,647
25,000	$1,552	$1,755	$1,625	$1,339	$1,374	$1,339
30,000	$1,316	$1,486	$1,364	$1,125	$1,197	$1,125
35,000	$1,175	$1,287	$1,192	$988	$1,059	$988
60,000	$829	$899	$761	$656	$809	$656
80,000	$704	$736	$620	$531	$723	$531
100,000	$645	$686	$531	$471	$666	$471
125,000	$609	$612	$485	$433	$645	$433
200,000	$601	$601	$434	$393	$652	$393

Table 13: Manufacturing and assembly cost of body designs for different production volumes

The results show a distinct advantage in cost for the composite vehicles in assembly, while the steel design has the advantage in manufacturing cost. It is expected that the steel design would incur the greatest assembly cost, since there are many more parts to assemble compared to the composite design. Although adhesive bonding as the composite joining process is more expensive per unit join than for example resistance spot welding, the lower number of parts results in lower aggregate assembly cost. Modeling the assembly process quantifies one of the more important benefits of composite use. Furthermore, the above tables show higher economies of scale for the stamped parts in manufacturing than for the composite parts.

The steel and light steel unibody designs are competitive in their parts fabrication costs. At very high production volumes the steel unibody is slightly cheaper than the light steel one. The aluminum unibody on the other hand is expensive because of higher material cost and high tooling cost. Also assembly is expensive because of the variety of joining techniques employed. Especially, the capital cost of MIG welding equipment and the cost for RSW are higher than for steel. However there are also sharp economies of scale as can be seen in the drop in costs from 15,000 to 200,000 cars per year.

Although the use of carbon fiber results in significant weight reduction, its use comes at increased manufacturing cost. There is a high material cost penalty from the use of carbon fiber.

Summing up the part fabrication and assembly cost, the total manufacturing cost of the six bodies can be examined. The following two charts show the total manufacturing costs at different production volumes (for the exact numbers see Appendix 9.2). The above mentioned trends in the use of the different body materials will be also explained in more detail.

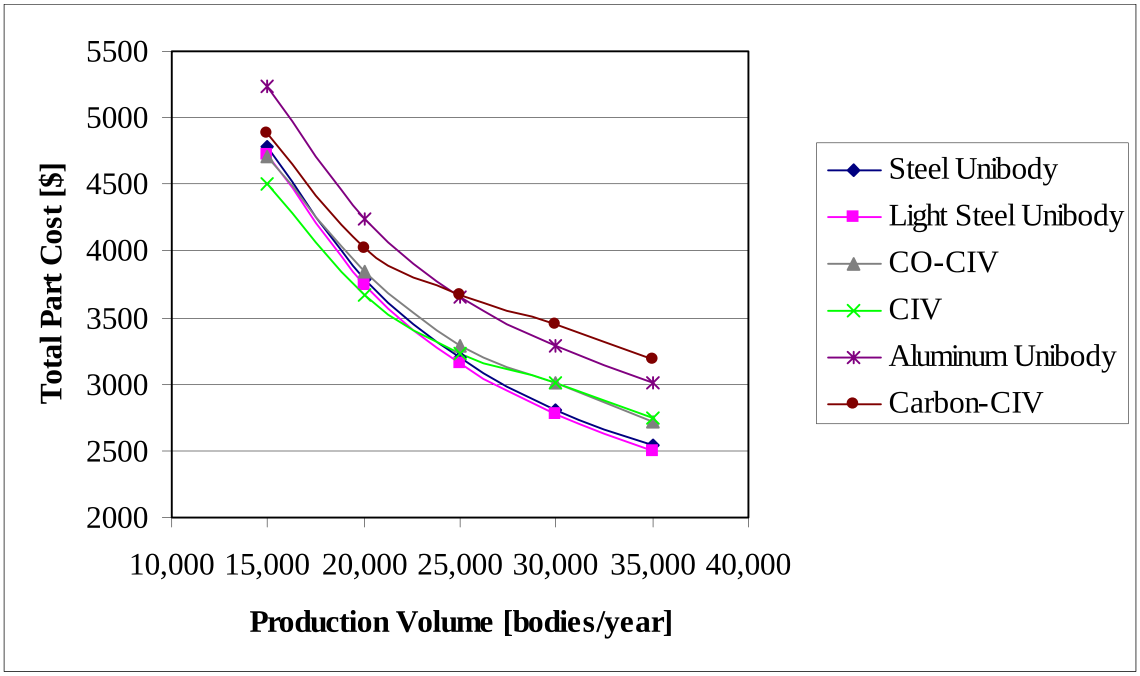

Figure 18: Total Production Cost of body designs at production volume 15,000 to 35,000

Examining the lower production volume from 15,000 to 35,000 vehicles per year, the cheapest option would be the CIV and CO-CIV with a cross over to the two steel vehicles. The aluminum unibody and the Carbon-CIV are the most expensive bodies.

The composite intensive vehicle crosses over with the steel bodies at approximately 20,000 vehicles per year. The CO-CIV due to its use of steel parts is slightly more expensive. This result can be explained by the differences between the alternative composite materials and the steel stamping process. Fundamentally, the cost drivers for the composite processes are different form those of steel because of requirements of the manufacturing processes. In order to manufacture parts from steel, much capital investment is required. The press line consists of large presses and steel tooling, which are expensive to purchase. On the other hand, composite processes incur lower capital costs for two reasons. First, composite manufacturing systems do not require presses as large as those used in steel because of the lower pressure forming process. Second, even if large presses are used, multiple presses are not required since all part-forming operations occur at one press, while a steel part requires up to five presses, depending on its complexity. In addition to the cost increase from multiple presses, each press in the press line is outfitted with a tool, further increasing the capital cost.

While the steel stamping process incurs high fixed costs, its variable cost component is low relative to the composite processes because of two reasons. First, steel material is very inexpensive and any scrap can be resold to gain additional cost savings. Second, the cycle times are short for the part-forming operations so that labor costs remain low. On the other hand, materials for composite parts are expensive. In addition, cycle times are much longer than steel stamping so that labor costs are high. However the large number of steel parts offset the labor cost advantage since more people are needed in the steel manufacturing process. Therefore at low production volumes, the composite processes can remain competitive with the steel stamping process. However, as more parts are produced annually, the contribution of fixed costs to the total cost decreases and thus the steel process becomes more cost-effective, leaving the composite parts at a disadvantage as fixed costs become less important.

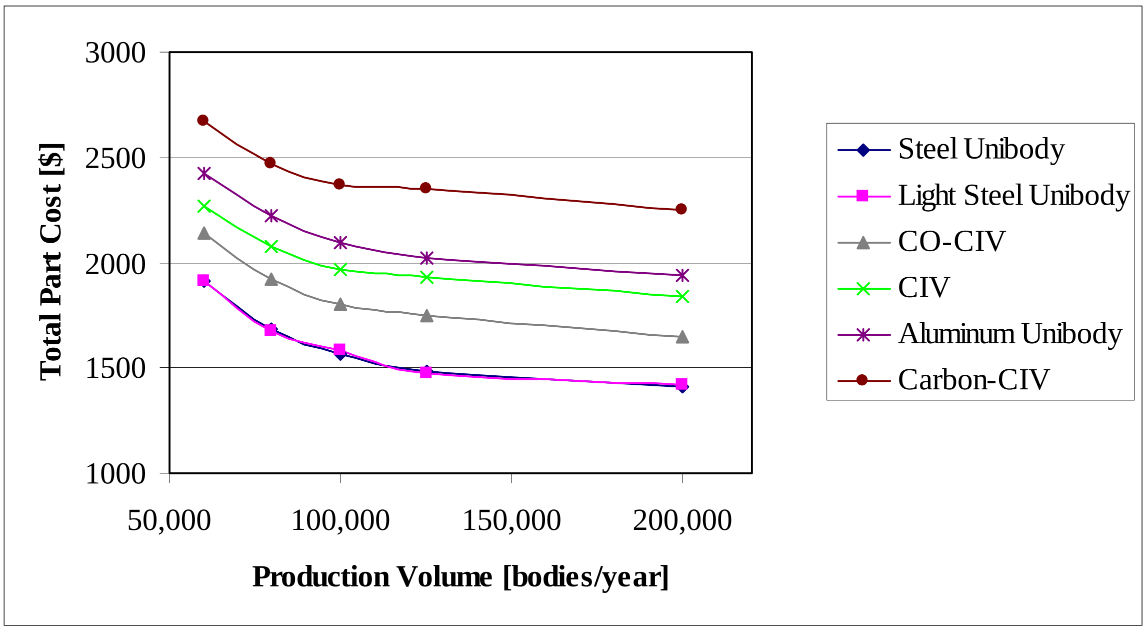

Figure 19: Total Production Costs for body designs at production volume 60,000 to 200,000

For the higher production volume between 60,000 and 200,000 bodies per year, the two steel body designs are the cheapest possibilities. They are both competitive in their total cost, although at very high production volumes the steel unibody is slightly cheaper than the light steel. The costs of the steel and aluminum bodies tend to flatten beyond the medium production volumes.

For the medium cost, first the CO-CIV (optimized for higher production volume), then the CIV and finally the aluminum unibody can be ranked with increasing total cost. One of the key factors resulting in the higher costs of the aluminum unibody design is the tooling costs of aluminum. The primary reason is that Aluminum cannot be formed in the same way as steel. Aluminum is also more sensitive to die contamination than steel. Thus special coatings have to be applied to the dies or the dies have to be frequently cleaned.

The Carbon-CIV is always the most expensive alternative mainly because of the high material cost for the carbon fiber. There are two scenarios that can be envisioned where carbon fiber would be a viable reinforcement material. One is that the price drops dramatically to more competitive position. The other scenario is that carbon fiber's superior physical properties can be utilized to achieve significant design advantages in addition to its lower material use. Nevertheless, today the composite intensive body design and aluminum unibody are, although lighter and therefore probably more environmental friendly, come at an economic premium for high production volumes.

These trends in material costs and selection for the body designs at different production volume are also observable in the following Table 14. It shows the production costs for two production volumes, 20,000 and 125,000, ranked with descending cost. The number next to the body design is a reminder of the weight ranking of the bodies. Steel as the heaviest body is represented by the number "6", Carbon-CIV as the lightest one with "1".

Body Designs		**Total Cost @ PV 20,000**
Aluminum Unibody	2	$4,234
Carbon-CIV	1	$4,017
Cost opt. CIV	4	$3,849
Steel Unibody	6	$3,788
Light Steel Unibody	5	$3,738
CIV	3	$3,666

Body Designs		**Total Cost @ PV 125,000**
Carbon-CIV	1	$2,355
Aluminum Unibody	2	$2,021
CIV	3	$1,929
Cost opt. CIV	4	$1,751
Steel Unibody	6	$1,486
Light Steel Unibody	5	$1,478

Table 14: Total body cost at production volume of 20,000 and 125,000 ranked by cost

The shaded rows in Table 14 highlight the body designs that are dominated at a given production volume. This means, that the dominating bodies are lighter and cheaper. They are preferable, because there is a correlation between the mass of the body and fuel consumption. This assumption is valid as only driving tailpipe emissions are going to be modeled in this analysis. Therefore, the body designs, which are lighter have also less fuel consumption for a given propulsion technology. These are the non-dominated solutions. On the other side, body designs, which are more expensive and have a higher fuel consumption at a given production volume are dominated. This statement is proven and discussed in more detail after modeling the environmental performance of the vehicles in Chapter 6.4.

6.3 Combined body designs and propulsion technologies

After establishing the characteristics for the body designs, the size of powertrain required to deliver consistent performance for each of the proposed powertrains has to be assessed. The equations used to calculate the necessary power and mass of the propulsion technologies have been presented in Chapter 3.2 and Chapter 5.3.

The following two tables show the results of these calculations. Two vehicle performance targets, 75 W/kg and 95 W/kg, have been modeled (see Chapter 5.4). The results for the weight for the hybrid powertrain do include the weight of the battery and the fuel cells include the weight of the motor, battery and reformer.

		@ 75 W/kg	**Mass of propulsion system**				
Body Design	**Mass of body [kg]**	**Power of powertrain [kW]**	**Gasoline engine [kg]**	**Diesel engine [kg]**	**Hybrid [kg]**	**Hydrogen Fuel Cell [kg]**	**Methanol Fuel Cell [kg]**
Steel Unibody	350.22	110.11	148.38	173.24	523.17	369.22	680.67
Light Steel Unibody	257.91	99.73	140.31	165.00	393.47	333.38	614.60
CO-CIV	237.05	97.38	138.48	163.13	364.15	325.28	599.67
CIV	230.70	96.66	137.93	162.57	355.24	322.82	595.13
Aluminum Unibody	205.10	93.78	135.69	160.28	319.25	312.87	576.80
Carbon-CIV	161.59	88.89	131.88	156.39	258.12	295.98	545.66

Table 15: Mass of body and propulsion system for a vehicle performance of 75 W/kg

		@ 95 W/kg	Mass of propulsion system				
Body Design	**Mass of body [kg]**	**Power of powertrain [kW]**	**Gasoline engine [kg]**	**Diesel engine [kg]**	**Hybrid [kg]**	**Hydrogen Fuel Cell [kg]**	**Methanol Fuel Cell [kg]**
Steel Unibody	350.22	139.47	171.20	196.56	889.91	518.39	1102.41
Light Steel Unibody	257.91	126.32	160.98	186.11	725.62	468.08	995.41
CO-CIV	237.05	123.35	158.67	183.75	688.49	456.70	971.22
CIV	230.70	122.44	157.96	183.03	677.19	453.24	963.87
Aluminum Unibody	205.10	118.79	155.13	180.13	631.61	439.29	934.18
Carbon-CIV	161.59	112.59	150.31	175.21	554.18	415.57	883.75

Table 16: Mass of body and propulsion system for a vehicle performance of 95 W/kg

The tables show clearly that the less the body weights the less power is necessary to achieve the vehicle performance target. Also, the higher vehicle performance target requires in general more power than the lower target to accelerate the mass of the vehicle.

Regarding the mass of the propulsion technologies, it is observable that the diesel engine is heavier than the gasoline engine. The high compression ratio and combustion process of the diesel engine leads to higher engine weight relative to a similar displacement gasoline engine (see Chapter 4.2.2).

Furthermore, the methanol fuel cell has a higher weight than the hydrogen fuel cell. This is due to an additional fuel cell system loss for methanol. Reduced hydrogen concentration in the reformer exit fuel stream results in poor stack performance and compromised hydrogen utilization (see Chapter 5.5). Therefore to achieve a similar performance as the hydrogen fuel cell, the methanol fuel cells needs more stacks, which adds also more weight to the system.

The hybrid vehicles on the other side seem to be more sensitive to the vehicle weight. The slope of the change in weight of the propulsion system is steeper than for the other technologies, which is probably due to the combination of two propulsion systems. It is difficult to find a balance between the size of the internal combustion engine and the motor. It depends mostly on the desired driving properties. Arguments for more engine or more motor power must be carefully weighed. A larger engine means smaller battery/motor mass and better highway operation, when the internal combustion engine is more efficient; a larger motor means more effective regenerative braking energy capture and better dual-mode operation, when the electric motor is preferred in a city setting.

Finally, the battery-electric car had to be taken out of the analysis. The specific energy and specific power of the battery required to produce an acceptable electric vehicle are not currently attainable (namely a specific energy of 150 Wh/kg and a specific power of 300 W/kg) (US ABC, 2000; Weiss, 2000). Furthermore, the electric vehicle design is not fully comparable to other systems because it has a range of less than 2/3 of the range of the other vehicles assessed. However, that range may be acceptable to many customers changing the design to match the range and other capabilities of other technologies would result in large increases in weight and cost of an already-costly vehicle, and would decrease interior space. Therefore the electric vehicle is not going to be included in the rest of the analysis.

In the next step, the environmental performance of the now defined vehicles is going to be modeled.

6.4 Results of environmental performance model

The previous chapters have defined the mass and performance characteristics of the different vehicles. The resulting vehicle combinations will be evaluated for their environmental performance using a family of Matlab Simulink simulation programs originally developed by Guzzella and Amstutz (1998) at the Eidgenössische Technische Hochschule (ETH) Zurich. Environmental performance will be limited only to driving cycle impacts (see Chapter 3.3 and Chapter 5.5).

The simulations are run by choosing the propulsion technology, inserting the vehicle and powertrain characteristics, coupling it to the transmission and model the US Federal Test Procedure (FTP) urban and highway driving cycles.

The outputs of the model are the fuel energy use, fuel consumption, range and, if need be, the battery status for both driving cycles respectively. The tank-to-wheel efficiency and in the cases where both a battery and fuel is used, the combined energy use can be calculated.

The following tables show the detailed result for the gasoline engine as an example achieving the vehicle performance target of 75 W/kg. Table 17 lists the vehicle and powertrain characteristics to be inputted to the simulation file. The smaller the weight of the body, the lighter the engine and due to secondary weight savings also the other vehicle components can be designed. There is also a correlation between the power of the gasoline engine and the engine displacement, which was used to calculate its value.

Gasoline Engine for vehicle performance of 75W/kg					
Body Design	**Mass of body [kg]**	**Mass of Engine [kg]**	**Mass of other components [kg]**	**Power of powertrain [kW]**	**Engine Displacement [m^3]**
Steel Unibody	350.22	148.38	969.53	110.11	0.0025044
Light Steel Unibody	257.91	140.31	931.45	99.73	0.0022682
CO-CIV	237.05	138.48	922.84	97.38	0.0022148
CIV	230.70	137.93	920.22	96.66	0.0021986
Aluminum Unibody	205.10	135.69	909.66	93.78	0.0021331
Carbon-CIV	161.59	131.88	891.71	88.89	0.0020217

Table 17: Vehicle and gasoline engine characteristics

The next Table 18 demonstrates the results for the urban and highway driving cycle for gasoline engines. Again, the lighter vehicles show less energy use, fuel consumption and a larger driving range than the heavier steel bodies. Furthermore, in the results for the urban driving cycle a higher energy use, fuel consumption and a bigger driving range is observable. This can be accounted to the fact, that the urban driving cycle has more accelerations and decelerations than the highway cycle, which require more energy.

URBAN Driving Cycle for vehicle performance of 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	3.249	0	3.249	10.09	23.31	538	13.77%
Light Steel Unibody	2.994	0	2.994	9.295	25.31	583.9	13.86%
CO-CIV	2.935	0	2.935	9.112	25.81	595.6	13.89%
CIV	2.917	0	2.917	9.056	25.97	599.3	13.90%
Aluminum Unibody	2.849	0	2.849	8.847	26.59	613.5	13.92%
Carbon-CIV	2.731	0	2.731	8.478	27.74	640.1	13.96%

HIGHWAY Driving Cycle for vehicle performance of 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	2.176	0	2.176	6.756	34.82	803.4	17.71%
Light Steel Unibody	2.036	0	2.036	6.321	37.21	858.6	18.06%
CO-CIV	2.004	0	2.004	6.222	37.80	872.3	18.15%
CIV	1.994	0	1.994	6.129	38.38	876.5	18.17%
Aluminum Unibody	1.957	0	1.957	6.077	38.71	893.2	18.27%
Carbon-CIV	1.894	0	1.894	5.88	40.00	923.1	18.44%

Table 18: Urban and highway driving cycle results for energy use, fuel consumption and range of gasoline engines

The results for the urban and highway driving cycle can be combined into an overall equivalent energy use, by using 55% of the urban and 45% of the highway driving cycle value. The energy use can be converted into the gasoline equivalent consumption or economy and for the fuels containing carbon, also the cycle carbon emissions in grams of carbon per kilometer can be calculated. The following table shows the results of these calculations again for the gasoline engine as an example for the vehicle performance target of 75 W/kg.

COMBINED Driving Cycle for vehicle performance of 75 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	2.766	8.589	27.39	54.12
Light Steel Unibody	2.563	7.958	29.56	50.14
CO-CIV	2.516	7.812	30.11	49.23
CIV	2.502	7.767	30.28	48.95
Aluminum Unibody	2.448	7.600	30.95	47.89
Carbon-CIV	2.354	7.310	32.18	46.06

Table 19: Combined driving cycle equivalent energy use, gasoline equivalent fuel consumption and cycle carbon emissions for gasoline engines @ 75W/kg

The same trend as mentioned before can be also observed here. The lighter the vehicle body, the less energy is used and therefore also the fuel consumption and carbon emission are lower than with the heavier bodies. The detailed results for all examined propulsion technologies for a vehicle performance of 75 and 95 W/kg are shown in Appendix 9.4 and Appendix 9.5.

It is now important to compare the results of all the different propulsion technologies. There are three tables following (Table 20, Table 21 and Table 22), which show the results for the vehicle performance of 75 W/kg for all propulsion technologies and body designs. First the equivalent energy use is presented, followed by the gas equivalent fuel economy and the cycle carbon emissions. The results for the vehicle performance of 95 W/kg can be found in Appendix 9.5 and follow the same trends as the 75 W/kg results.

In all three tables similar trends can be observed. Diesel engines are more efficient in energy use and fuel consumption than gasoline engines because the diesel cycle uses high compression ratios to ignite the fuel and they do not experience the pumping loss characteristics. The same is valid for the gasoline and diesel hybrid vehicles. Due to poorer stack performance and compromised hydrogen utilization, the methanol fuel cell is less efficient than the hydrogen fuel cell. The best technology in regard of its energy use is the hydrogen fuel cell, followed by the diesel and gasoline hybrid engine, then the methanol fuel cell and finally the diesel and gasoline engine.

		Equivalent Energy Use [MJ/km] @ 75W/kg					
Body Design	**Mass of body [kg]**	**Gasoline Engine**	**Diesel Engine**	**Gasoline Hybrid**	**Diesel Hybrid**	**Hydrogen Fuel Cell**	**Methanol Fuel Cell**
Steel Unibody	350.22	2.766	2.023	1.119	0.908	0.837	1.428
Light Steel Unibody	257.91	2.563	1.885	1.080	0.878	0.788	1.354
CO-CIV	237.05	2.516	1.852	1.071	0.871	0.778	1.337
CIV	230.70	2.502	1.841	1.068	0.869	0.774	1.332
Aluminum Unibody	205.10	2.448	1.805	1.058	0.862	0.761	1.313
Carbon-CIV	161.59	2.354	1.733	1.041	0.849	0.739	1.281

Table 20: Combined driving cycle equivalent energy use @ 75W/kg vehicle performance for all propulsion technologies and vehicle designs

		Gasoline Equivalent Fuel Economy [mpg] @ 75W/kg					
Body Design	**Mass of body [kg]**	**Gasoline Engine**	**Diesel Engine**	**Gasoline Hybrid**	**Diesel Hybrid**	**Hydrogen Fuel Cell**	**Methanol Fuel Cell**
Steel Unibody	350.22	27.387	37.443	67.701	83.473	90.538	53.062
Light Steel Unibody	257.91	29.558	40.185	70.163	86.306	96.098	55.963
CO-CIV	237.05	30.109	40.905	70.718	86.943	97.423	56.669
CIV	230.70	30.282	41.143	70.924	87.184	97.837	56.874
Aluminum Unibody	205.10	30.951	41.974	71.600	87.834	99.522	57.690
Carbon-CIV	161.59	32.177	43.713	72.762	89.211	102.541	59.154

Table 21: Combined driving cycle gasoline equivalent fuel economy @ 75W/kg vehicle performance

		Cycle Carbon Emission [g C/km] @ 75W/kg					
Body Design	**Mass of body [kg]**	**Gasoline Engine**	**Diesel Engine**	**Gasoline Hybrid**	**Diesel Hybrid**	**Hydrogen Fuel Cell**	**Methanol Fuel Cell**
Steel Unibody	350.22	54.120	42.211	21.893	18.934	0	26.636
Light Steel Unibody	257.91	50.144	39.330	21.125	18.313	0	25.255
CO-CIV	237.05	49.227	38.639	20.959	18.179	0	24.941
CIV	230.70	48.945	38.415	20.898	18.128	0	24.850
Aluminum Unibody	205.10	47.888	37.654	20.701	17.994	0	24.499
Carbon-CIV	161.59	46.063	36.156	20.370	17.717	0	23.892

Table 22: Combined driving cycle carbon emission @ 75W/kg vehicle performance

Examining the fuel economy of the different body and powertrain combinations, the range in fuel economy due to the vehicle body is small compared to the variation due to the propulsion technology. The difference between the gasoline equivalent fuel consumption of a gasoline-powered vehicle and one with a hydrogen fuel cell ranges from 27.4mpg for a steel design to 102.5mpg for a Carbon-CIV design. By contrast, the change in fuel economy in the gasoline engine because of a lighter body design is at most 5 mpg. In order to improve fuel economy significantly, alternative propulsion technologies like fuel cells need to be introduced to the market. That is also a reason for the high investment in this technology lately from most automobile manufactures. Although the methanol fuel has a smaller fuel economy than the hydrogen fuel cell, it can help introduce the new technology easier into the market because of better infrastructure and storage possibilities of the fuel.

The cycle carbon emissions are calculated from the energy use and not from the gas equivalent energy use. For example hydrogen fuel has no carbon content. Therefore, the cycle carbon emissions of the hydrogen fuel cell are zero. On the other side, the carbon content of diesel fuel (87wt%) is higher than that of gasoline fuel (85.5wt%), but including the higher fuel economy of the diesel engines the carbon emissions are in total lower. The same relationship can be noticed also with the gasoline and diesel hybrid. Nevertheless, their carbon emissions are due to the smaller energy use or fuel consumption better than of the pure internal combustion engines. Finally, the fuel cell operated with methanol (37.5wt% carbon content) is in the middle range of the carbon emission.

The interpretation of these results shows that the propulsion technology has the largest influence and importance on the fuel economy of the vehicle. For a given propulsion technology it is better from an environmental standpoint to use a lighter vehicle body for the improved fuel economy. Nevertheless, the environmental performance is not the only dimension of the trade-off decision for the designer. How this decision space changes when including the cost of production for the different body designs is presented in the following chapter.

6.5 Cost of body production and environmental performance

The previous analysis set the basis to understand the effects of different materials on body design, production and manufacturing and the effects of the propulsion system characteristics on the vehicle performance. Furthermore, the environmental performance of different vehicles (body and powertrain combinations) was modeled to understand the influence of vehicle weight and propulsion technology on fuel economy.

To understand and answer the question of the cost of environmental performance these two dimensions have to be combined. Figure 20 shows the fuel economy for the gasoline engine and the cost of production for the different bodies at a low production volume of 20,000 bodies/year. This graph confirms the idea of non-dominated designs mentioned in Chapter 6.2. The lighter bodies have a higher driving fuel economy. Therefore the bodies, which are lighter and cheaper to produce, will be preferable. In the case of a low production volume, either the CIV or the Carbon-CIV is cheaper to produce while providing a higher fuel economy than each of the other body designs. The two points can be connected by a step function to show the viable options. The cost and therefore the ranking of the dominating designs changes depending on the production volume of the bodies.

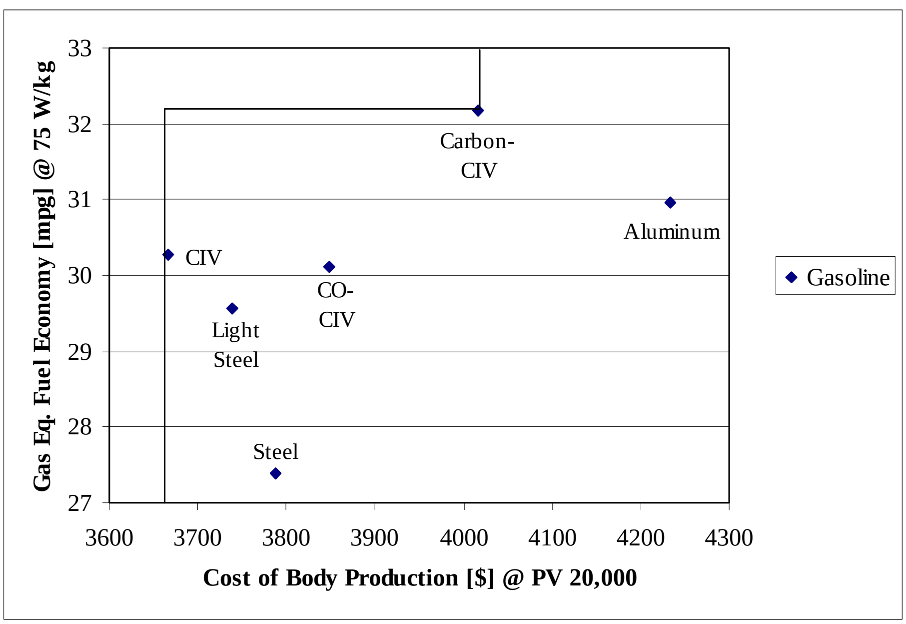

Figure 20: Gasoline equivalent fuel economy and cost of body production at production volume of 20,000 and a vehicle performance of 75 W/kg for gasoline engines

If the curves of the other propulsion technologies would overlap for a specific fuel economy, one could comment on the environmental value of the more efficient powertrain. If for a given fuel economy two different propulsion technologies and body combinations would exist, the cost difference of the two bodies could be spent on the alternative powertrain of the body with lower cost and still be viable economically. In fact, the results show that there is no overlap in the level of fuel economy of the different propulsion technologies. The effect of the body or vehicle weight on the fuel economy is small compared to the effect of alternative powertrains (see Chapter 6.4). This is illustrated in Figure 21. The fuel economy and cost of body production at a production volume of 20,000 parts/year for a vehicle performance of 75 W/kg for gasoline and diesel engines is demonstrated. There is no overlap of the curves. The change in fuel economy is between distinct boundaries.

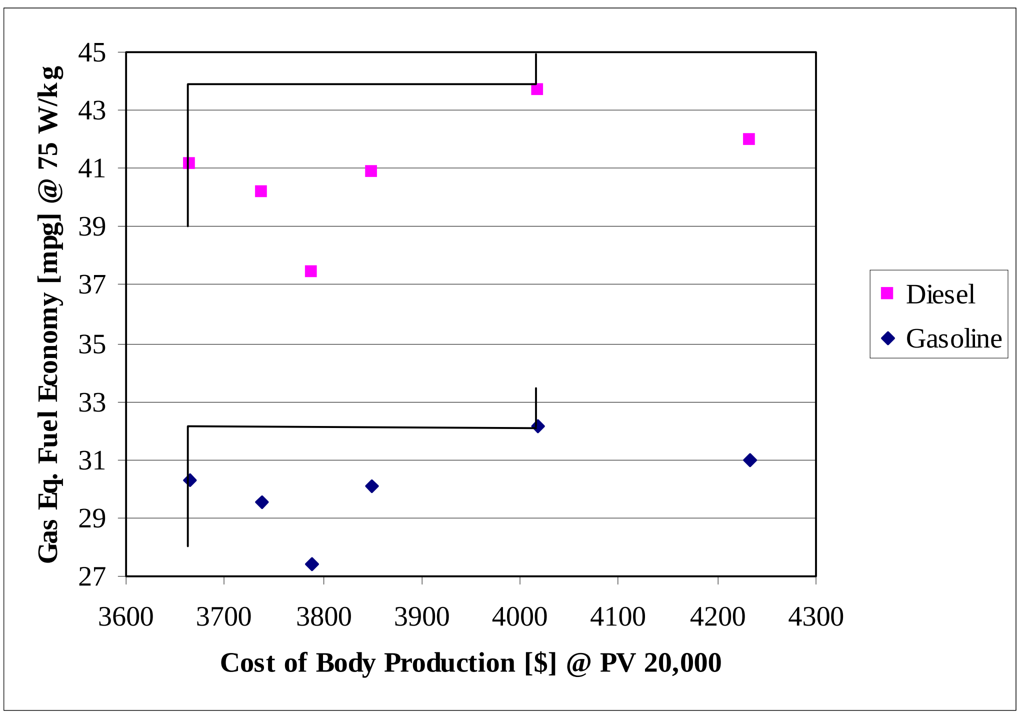

Figure 21: Gasoline equivalent fuel economy and cost of body production at production volume of 20,000 and a vehicle performance of 75 W/kg for gasoline and diesel engines

Given all of the above information it is possible to compare the fuel economy and cost of bodies for all propulsion technologies. Figure 22 shows these two dimensions again for a low production volume of 20,000 parts/year and an overall vehicle performance of

75 W/kg. The results for a vehicle performance of 95 W/kg are located in the Appendix. As the effect of lightweighting is significantly smaller on the fuel economy than the effect of the propulsion technology, it is at this point sufficient to discuss the analysis with one body production volume. A detailed discussion of the different body designs and trends at different production volumes has been presented in Chapter 6.2.

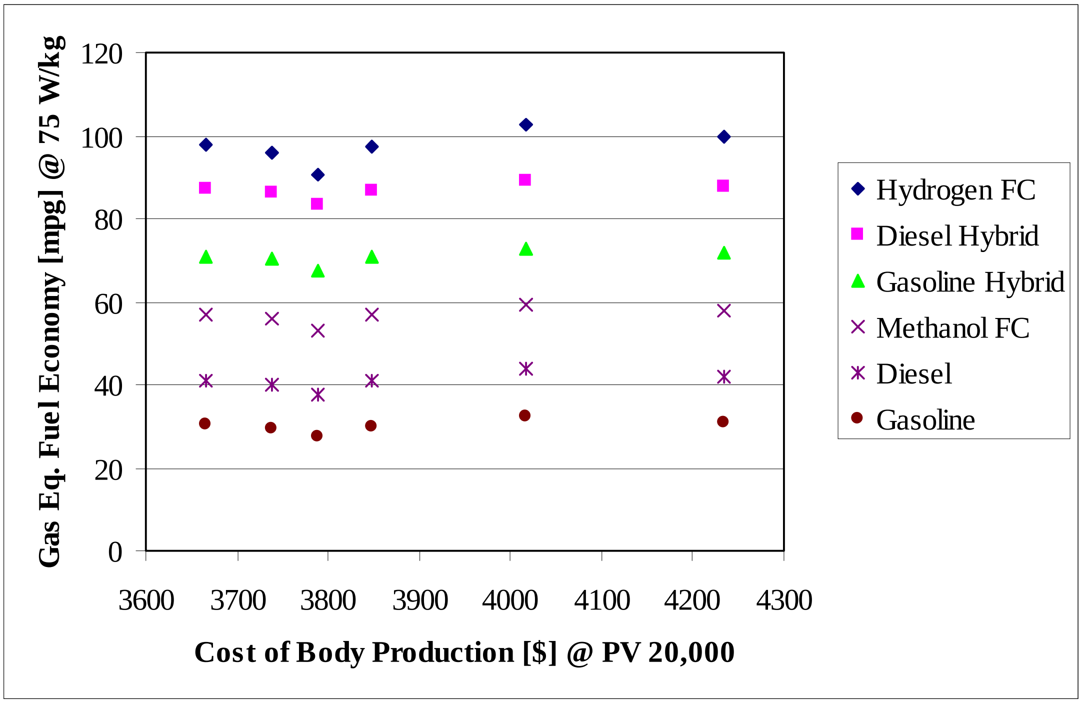

Figure 22 Gasoline equivalent fuel economy and cost of body production at production volume of 20,000 and a vehicle performance of 75 W/kg for all propulsion technologies

Two trends can be demonstrated with Figure 22. First, the depth of the step function connecting the dominating designs is different for the propulsion technologies. Lightweight body designs therefore have a different effect on the fuel economy depending on the powertrain technology. For example, the range in fuel economy for different bodies for gasoline engines is smaller than for the hydrogen fuel cell. The second and more important observation is that if only the cost of body production would be taken into account, one propulsion technology would always dominate. The hydrogen fuel cell has the best fuel economy of all powertrains and would be selected if no other decision trade-offs had to be made.

This analysis takes the fist step in analyzing and quantifying the cost of environmental performance. If the decision is based on the cost of the body production, it will depend mainly on the desired production volume and the value of the fuel economy. To decide for a specific propulsion technology, this analysis is so far not providing enough information. It is necessary to also include the cost for producing the powertrain itself. Nevertheless, this analysis has established one important part for the decision-making process. To prove the validity and value of the method, the cost of the propulsion system were roughly estimated. In the time frame of this analysis and due to a lack of modeling tools and design information, it was not possible to assess the cost in more detail using for example technical cost modeling techniques. Table 23 presents the estimates used for the production cost of the different propulsion technologies. These were generated simply through literature review and judgement.

Propulsion System	**Gasoline Engine**	**Diesel Engine**	**Gasoline Hybrid**	**Diesel Hybrid**	**Hydrogen Fuel Cell**	**Methanol Fuel Cell**
Cost of Powertrain	$1000	$1500	$2500	$3000	$5500	$6000

Table 23: Estimation of propulsion system production cost

The cost for the gasoline engine is the lowest of all powertrains. This is a mass manufactured product for many years and the process is optimized. The diesel engines are more expensive because of their larger mass and therefore material cost and a more expensive exhaust system. Furthermore, hybrid vehicles have a cost penalty because they are using two different propulsion systems. The powertrain is more complex and the cost for both technologies add up. The fuel cell is still in the development phase and it is difficult to assess the cost of manufacture. There is no mass production existing and the technology and subsystems are constantly changing. Although there is some uncertainty in the data existing, the estimates seem to be in a reasonable range (Weiss, 2000; personal communication). The cost difference between the hydrogen and methanol fuel cell can be attributed to the additional cost for the reformer and higher cost of the exhaust system for the methanol fuel cell, which overcomes the higher cost for the storage system of the hydrogen fuel cell.

By adding the estimated cost of the powertrain to the cost of the body designs, a technology frontier is created (Figure 23).

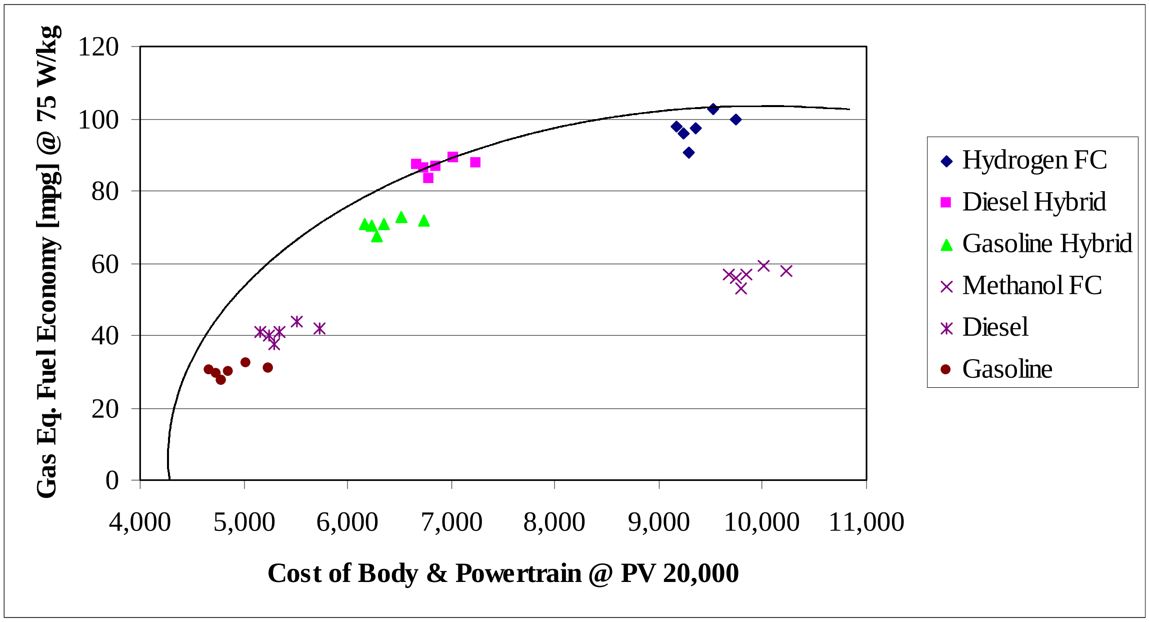

Figure 23: Gasoline equivalent fuel economy and cost of vehicle production (body PV 20,000 and propulsion system cost estimation) for a vehicle performance of 75 W/kg

The individual data points of each propulsion system are shifted to the right depending on value of the powertrain cost. In general, the alternative propulsion technologies, which have high fuel economies are the most expensive and to the right in the above graph. The established technologies are less costly and lie to the left.

This addition to the analysis provides several vehicle combinations with different fuel economies as viable alternatives for the automobile manufacturer. Their ultimate choice will depend on the level of cost they are willing to incur on the production of the vehicle and the relative importance they place on fuel economy versus cost. In order to select an option, it is necessary to have the value function of the user of this analysis. A user can be for example the automobile manufacturer or government agencies. Depending on their specific value function the user might choose a different option. The automobile manufacturer might use this analysis together with their value function to decide the direction of future business and the technology to invest in. Government agencies can assess the impact of government policies. They may influence the automobile manufacturer to choose and invest in more expensive but environmental friendlier technology by setting higher fuel economy regulation standards. Furthermore, they may influence the consumer by educating him on the effects of for example greenhouse gases, as the consumer's value function might be currently too steep to include fuel cell as a viable option in their selection process. Nevertheless, this thesis is not attempting to analyze the different value functions of the stakeholders and present their selections on the vehicle combinations.

Figure 23 still allows some interpretations, which are summarized below:

- Today's mass produced propulsion technologies are gasoline and diesel engines. From an environmental standpoint, examining only energy use or fuel economy, the diesel engines seem to be a better option than the gasoline engines (not including any health effects of particulates and other issues). The higher fuel economy of diesel engines is valued especially in Europe (30% of the vehicles in France are diesel powered). Because of high fuel prices in Europe, customers are more interested in fuel economy than in the United States. This perception might change in the US too, probably mostly because of rising fuel prices. In order to improve fuel economy of the internal combustion engines, it is necessary to reduce vehicle weight. Up to a 20% increase in fuel economy body can be achieved with lighter bodies compared to a gasoline engine with a steel body.

- Hybrid vehicles are the alternative technology, which seems to be ready for the market today. The cost penalty for the powertrain seems to be not too high and there is also experience with the technology and manufacturing existing. Sales numbers for the Toyota Prius, the first hybrid vehicle produced at a higher production volume, increased significantly last year (5500 vehicles sold in 2000), which might represent a raising interest of the customers in this type of vehicle. Furthermore, they achieve high fuel economies, in the case of the diesel hybrids even close to the fuel economy of hydrogen fuel cells.

- The methanol fuel cell is today not close to the technology frontier. Industry has recognized its disadvantages. Especially in Europe there are many research activities to replace the reformer by a direct system. Therefore, the weight of the fuel cell could be reduced, resulting in a higher fuel economy and also reduced cost. This would bring the methanol fuel cell closer to the technology frontier to be considered an viable option.

- Diesel hybrid powertrains and fuel cells with steel bodies are very close in their fuel economy. The investment into a fuel cell with a steel body would be high compared to the cost and level of fuel economy of the diesel hybrid. In this case an alternative lightweight body design would be more reasonable and valuable. This can be seen in the investment and intensive search in industry to use alternative materials for the body design of fuel cells. Composite vehicles can be an option for lower production volumes as shown in this analysis.
- Finally, the hydrogen fuel cell appears very promising from an environmental standpoint: it has a high fuel economy and no carbon emissions in the driving cycle. Nevertheless, the costs for the vehicle are the highest of all alternatives in this study and should be reduced. Acknowledging this, industry has to invest heavily in developing fuel cells to reduce their costs.

Although adding the cost for producing the propulsion technologies allows for a broader interpretation of possible vehicle concepts, it is important to keep in mind that these costs are speculative in this analysis. Returning to the cost of producing the body structures, which are examined in detail, it should be restated that the body choice at a given production volume can be based on the non-dominating body solutions. These bodies are lighter and cheaper. They are preferable, because there is a correlation between the mass of the body and fuel consumption as only driving tailpipe emissions have been modeled and because a lighter body allows also the use of a lighter propulsion system for a specific vehicle performance. Therefore, lighter body designs have a lower fuel consumption for a given propulsion technology. For the low production volume of 20,000 bodies per year, the CIV and Carbon-CIV are the non-dominated solutions. For the high production volume of 125,000 bodies per year the ranking of the bodies has changed. Now the dominated solution is the steel unibody. In both cases of a low and high production volume the lightweight body designs should be preferred over today's used steel unibody if only the cost of producing the body are taken into account.

Nevertheless, which body and propulsion technology should be chosen at the end clearly depends on the value function of the stakeholders. Which stakeholders are involved and where governmental policy can influence the technology decision through legislation is analyzed in the next chapter.

7 Stakeholder Impacts

The push for a propulsion technology or lightweight body can be initiated by and can influence several interest groups. The stakeholders of concern include four major groups, whose buy-in is required for successful development, introduction and penetration of a new technology. These are:

1. Vehicle purchasers
2. Government
3. Vehicle manufacturers
4. Fuel manufacturers and distributors

A complete assessment should consider the impact of each technology, as its cost and energy use assessed in this analysis will affect different stakeholders in different ways. At the basic level, changes in technology to improve fuel economy will happen when any or all of the following occurs (Plotkin, 2000; Weiss, 2000):

1. Vehicle purchasers value fuel economy more than they do today and value less those features that compete with fuel economy – acceleration, performance, vehicle size and weight, efficiency-robbing features as four-wheel drive, and so forth. Furthermore, eliminating problems with availability and refueling convenience of new fuels (especially in early introduction) and secure technology reliability and serviceability are important.
2. Government creates and implements international and national policy actions on greenhouse gas emissions, almost certainly including stricter fuel economy mandates. It mitigates economic impacts related to new fuel infrastructure investments and environmental stewardship. Finally, a government can impact the competitiveness of vehicle and fuel manufacturer in global markets by pushing for technologies with significant less environmental impact than required in other countries, if these technologies impose higher cost to the manufacturer.
3. The cost and availability of efficiency technology improves through research and product development, allowing vehicle manufacturers to improve fuel economy with

less technical and financial risk, and less need to trade fuel economy against competing consumer values. Also relationships to new suppliers need to be built up and established. Finally, future fuel economy and recycling issues driven by government requirements might challenge them.

4. Fuel manufacturers and distributors will have to invest significantly in offshore facilities, infrastructure, fuel station storage, transfer facilities and increased safety if alternative fuels are going to be established in the market. Therefore, these fuels will be facing a robust competitor in the petroleum industry, where prices are substantially higher than production costs today creating room for aggressive price competition. This may inhibit or delay major private investments in alternative fuel infrastructures. Major new infrastructure costs are sufficiently high that responsible investment requires the new infrastructure meet even longer term goals to avoid poor choices and wasted capital.

This thesis was focused so far mainly on issues concerning vehicle manufacturers by analyzing their costs for producing a vehicle with specific vehicle performance and its fuel economy. Nevertheless, changes in technology can affect all stakeholders and be especially driven by the government. Regulations can push and influence a technology and all of the stakeholders. The next sections therefore describe briefly existing regulation on fuel economy and emissions followed by an outlook at government policies, which could address these issues further. Analysis of some of these proposed policies and their implications can be supported by using the quantitative basis of fuel economy and body or vehicle cost provided by this thesis.

7.1 Existing Emissions and Fuel Economy Regulations

Today's most widely used propulsion technology in automobiles is the gasoline-fueled internal combustion engine. During the combustion process, where gasoline fuel is burned, a number of gases are emitted to the environment. A group of them can be characterized as greenhouse gases (GHG), which include for example CO and CO_2. Especially these two gases are, because of the emitted volumes, an important factor considering global warming trends. With the use of carbon based fuels these consequences are inevitable. Therefore, lowering the fuel consumption would at least support the reduction of GHG emissions in general. One option today may be to switch to non-carbon fuels like hydrogen.

The transportation sector is the second largest producer of greenhouse gas emissions in the United States. In 1990, the transportation sector was responsible for 32% of carbon emissions (Davis, 1998). Light-duty vehicles – automobiles and light trucks- account for more than half of the sector's emissions. This makes the light-duty fleet an appealing target for carbon emissions reductions. Further, the current light-duty fleet is essentially fully dependent on petroleum for its energy supply, so that reductions in greenhouse gases will yield similar reductions in U.S. oil use, an attractive proposition to those concerned about U.S. dependence on petroleum imports (Plotkin, 2000).

The government has undertaken several attempts to regulate emissions and fuel economy levels. Several laws, regulations and programs are existing, but for the purpose of this analysis only some of them are going to be briefly presented here: The Clear Air Act, The California's Low Emission Vehicle Program and The Corporate Average Fuel Economy Standards.

The Clean Air Act was amended and signed into law on November 15, 1990. This was the most recent of three significant developments in environmental legislation in years, along with the Clean Air Act of 1970 and the 1977 Clean Air Act Amendments.

The 1990 Amendments contain 7 separate titles covering different regulatory programs. The basic framework of the Clean Air Act (CAA) remains basically constant, but the 1990 Amendments do significantly alter and add to the regulatory requirements to act to reduce three major threats: acid rain, urban air pollution, and toxic air emissions. Specifically Title 2 of the Amendments established tighter pollution standards for emissions from automobiles and trucks. These standards will reduce tailpipe emissions of hydrocarbons, carbon monoxide, nitrogen oxides and particulate matter on a phased-in basis (e.g. 42 USC §7521). Also fuel quality will be controlled.

An interesting way of how states could handle the Clear Air Act goals can be illustrated with the Low Emission Vehicle (LEV) Program in California. LEV standards were necessary for California to meet the federally mandated clean air goals outlined in the

1994 State Implementation Plan (SIP). The SIP is the states "road map" to attain federal clean air standards by 2010 and includes among its measures strategies to further reduce air pollution from automobiles and other mobile sources. The LEV I regulations included for example standards for Zero Emission Vehicles, and requirements that specified that 10% of 2003 and subsequent model vehicles need to be certified as ZEVs. (CARB, 2001).

One of many ways to reduce most tailpipe emissions is to reduce the fuel consumption of automobiles. Fuel economy standards represent perhaps the most contentious way to achieve this. Corporate Average Fuel Economy (CAFE) standards imposed by the federal government in 1975 worked well and were responsible for a large part of the doubling of fuel economy the new car fleet achieved by the middle 1980s.

The CAFE standards specify fuel economies for all new cars and light trucks sold in the United States. Compliance with the standards is measured by calculating a sales-weighted harmonic mean of the fuel economies of a given manufacturer's product line, with domestically produced and imported vehicles measured separately. The policy increased average new-car fuel economy from about 15 to 27.5 miles per gallon (mpg) by 1985, reducing green house gas emissions accordingly. Today the standard remains 27.5 mpg for cars. Unfortunately, the standard does not address vehicle travel, which has doubled since 1975 (Ayres, 1999).

7.2 Policy options

There are many ways to affect GHG emissions existing. So far, government policies have focused on a small range of regulatory possibilities. To improve fuel economy and GHG emissions further, policy should aim in general at decreasing the intensity of fuel use or to decrease the impact of a unit of use. This can be broken down into three targets:

- Fix the car: increase the fuel economy of the vehicle fleet by targeting new vehicles and/or existing vehicles.

- Fix the driver: reduce the overall travel of the vehicle through increasing the variable cost of driving, decreasing the cost of substitutes like public transportation, and introducing transportation control measures to encourage efficient driving behavior.
- Fix the fuel: increase the fuel price to reflect the real total costs, and increase the use of fuels that offer low carbon emissions per mile of travel.

These three targets are interrelated and effective policies must include all three. Figure 24 shows these targets and suggests several policies, which can support each goal.

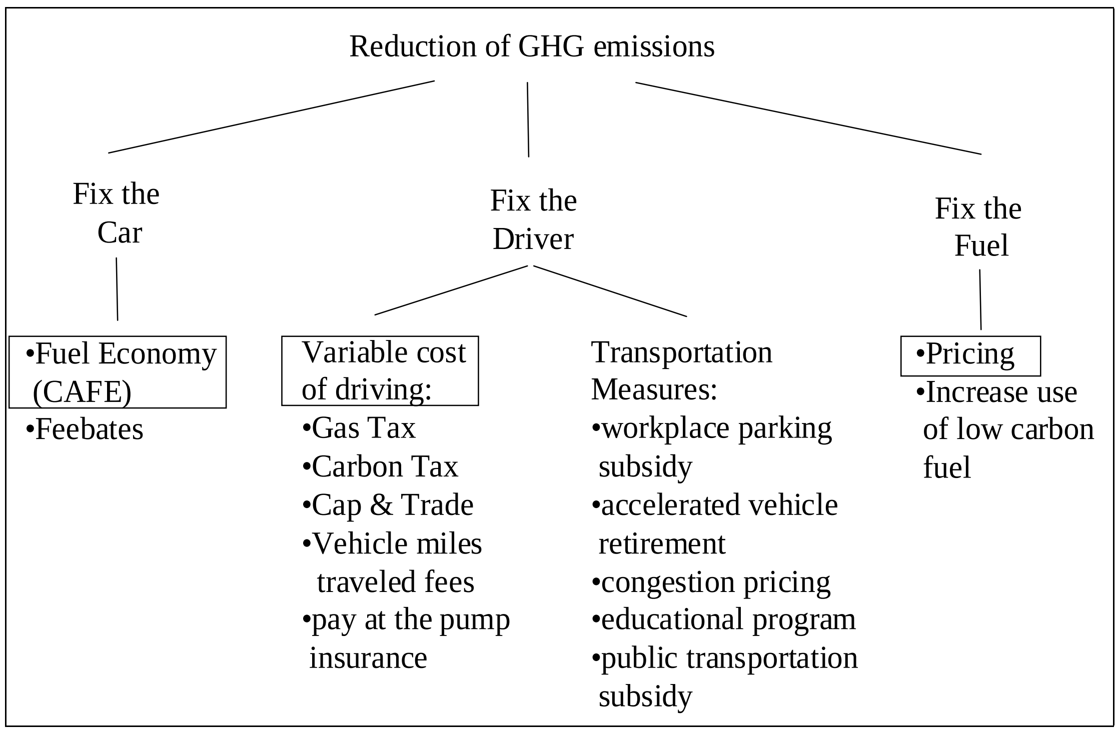

Figure 24: Targets and proposed policies

These policies can range from increasing CAFE standards to introducing gas and/or carbon taxes or even implementing educational programs, to promote the use of low-carbon fuels. This is only an outlook of some possible policies. Many of these proposals have received extensive analysis and debate. There are many further ideas on this topic existing.

In general, the key part of government policy today has been the idea of technology forcing. By setting for example high fuel economy standards the automobile manufacturer might need to invest heavily in a specific alternative technology to meet the target. Nevertheless, this approach raises the basic problem that if the implications of the standards are not evaluated carefully, it might steer into a domain where the technology is unfeasible in regard to consumer values, economical burden to the consumer and producer, and technological achievability. To contribute to the discussion and evaluation of standards and regulation, this thesis can set a quantitative basis for two previously mentioned polices:

1. Increasing CAFE standards: assessing the cost to the automobile manufacturer if he has to meet stricter fuel economy regulation and therefore has to shift to lightweight technologies or to alternative propulsion technologies.

2. Fuel cost of vehicle use: assessing the cost of using vehicles with a specific fuel economy and different fuel types. By estimating these costs, two things can be evaluated:

   a) based on today's fuel prices, what would the customer be willing to pay for a vehicle with higher fuel economy based on the cost of using it.

   b) how much the price of different fuels can change before they are no longer competitive. This change can happen for example through increasing the variable cost of driving with taxes.

These issues are also highlighted in Figure 24 and explained in more detail subsequently.

7.3 Changing CAFE Standards

The CAFE standards specify fuel economies for all new cars and light trucks sold in the United States. Compliance with the standards is measured by calculating a sales-weighted harmonic mean of the fuel economies of a given manufacturer's product line, with domestically produced and imported vehicles measured separately. Today the standard remains 27.5 mpg for passenger cars and 20.7 for light trucks. CAFE standards are influencing the automaker's research and development investment decisions. They can force an automobile manufacturer to develop technologies to increase fuel efficiency, but only in response to customer demand.

Nevertheless, since the advent of the original CAFE standards the U.S. industry has complained bitterly about the severe market distortions that have accompanied the standards. Among the worst of these have been price distortions, whereby companies sold smaller, more efficient cars at a loss to balance the sales of less efficient larger cars and maintain adequate levels of fleet fuel economy, and the shifting of cars between “import” and “export” fleets – with movement of jobs from U.S. to overseas, or vice versa – to allow the more efficient import fleets to “donate” their most efficient models or to “absorb” the least efficient U.S. models. These market distortions are not a necessary product of fuel economy standards but are instead the product of the specific form of the standard. Changes of the standards could include for example:

- Making no distinction between imports and domestic fleets
- Allowing trading of fuel economy “credits” among companies versus internally today
- Combining autos and light trucks into one fleet

Choosing an appropriate target level for a new CAFE standard is difficult. Achieving improvements to fuel economy is likely to demand the acceptance of both technological risk and the market risk associated with forcing automakers to choose high fuel economy over other competing automotive values (e.g. vehicle prize, size, acceleration).

The thesis provides a quantitative analysis on the cost of producing different vehicle bodies, an estimate of the cost of the propulsion system and the fuel economy of the vehicles. This can be used now to assess the cost of the body and powertrain production for the automobile manufacturer if the fuel economy is going to be increased.

As a baseline, a vehicle with a steel body and a gasoline internal combustion engine was used. This vehicle achieves an overall fuel economy of 27.4 mpg (see Table 21), which is very close to the CAFE standard. By using cost and environmental data, the increase in vehicle cost can be assessed which corresponds to a specific increase in fuel economy (Figure 25).

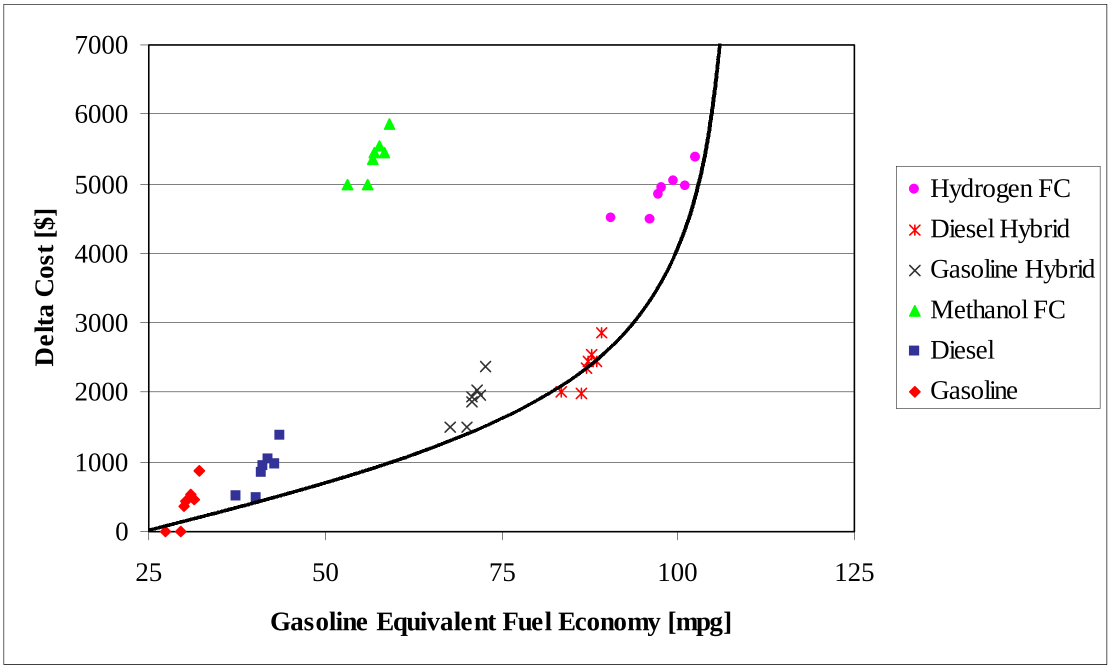

Figure 25: Vehicle cost (@ PV 125,000) with increase of gasoline equivalent fuel economy (Baseline of delta cost: steel unibody gasoline powered vehicle)

Increasing the gasoline equivalent fuel economy by 5 mpg will still be achievable with gasoline engines and lightweight bodies for an additional cost of $870 to the baseline vehicle for the manufacturer. However, an increase of more than 60 mpg to 90 mpg in fuel economy results in an exponential increase in cost.

Diesel engines with lightweight bodies can increase fuel economy up to 20 mpg for an increase in cost of $1500. Beginning at this cost range, the gasoline hybrids can achieve fuel economies of about 75mpg, which is close to doubling today's vehicle fuel economy. A diesel hybrid can even provide an increase in fuel economy of about 60 mpg to 90mpg for an increase in body and powertrain costs of around $3000. Finally, the hydrogen fuel cell has the highest fuel economy of more than 100mpg. Unfortunately the additional cost to the baseline gasoline powered vehicle is about $5500. Although this fuel economy is impressive, its cost is undeniably steep. However, considering issues other than fuel savings (e.g. reduced emissions) may ultimately motivate the switch.

In order to evaluate whether the additional costs for alternative propulsion technologies and lightweight bodies would ever be accepted, it is necessary to know how much the consumer is willing to pay for the improved environmental vehicle performance. One way to analyze this is to examine the cost for driving the vehicle (fuel costs). If the customer can pay less during the use phase due to a higher fuel economy, they might be willing to invest this amount up-front in a more expensive vehicle. This is going to be addressed in the next section.

7.4 Cost of powering the vehicle to the consumer

Results shown earlier describe the energy use of a vehicle going trough a specific driving cycle (see Chapter 6.4). This data can be used to calculate the lifetime cost of powering a vehicle and will reveal the fuel cost savings or penalties, which derive from using a lightweight body design or an alternative powertrain. In cases, where more efficient technology provides fuel cost savings, the customer might be willing to invest these savings into the more expensive vehicle technologies. Furthermore, pricing policies by using for example gasoline taxes to increase the competitiveness for alternative fuels can be analyzed.

The results of the Mathlab Simulink environmental performance model estimating the energy use of the different vehicles are presented in Table 20 of Chapter 6.4. The energy use is expressed in MJ/km. To calculate the lifetime energy use in MJ of the vehicles the following assumptions were made:

- Driving distance: 20,000 km per year
- Lifetime of the vehicle: 13 years

Knowing the energy content of the fuels and the fuel density allows for converting the energy use into the amount of fuel needed in liters. Table 24 demonstrates these values for the examined fuels:

		Gasoline	**Diesel**	**Methanol**	**Hydrogen**
Lower Heating Value	**MJ/kg**	43.7	41.7	20.1	120.2
Fuel Density	**kg/L**	0.737	0.856	0.792	0.070

Table 24: Lower heating value and fuel density of different fuels

For further analysis it is necessary to know the fuel prices. Published fuel prices at the end of the year 2000 are presented in Table 25.

		Gasoline	Diesel	Methanol	Hydrogen
Fuel Price (2000)	**$/L**	0.374	0.406	0.263	
Fuel Price (2000)	**$/kg**				3.084

Table 25: Fuel Prices at the end of year 2000 (DOE, 2001a and 2001b)

With this information it is possible to calculate the cost to the consumer of powering a vehicle over its lifetime. As the fuel expenditures occur over a period of 13 years and the results need to be compared to the additional cost of producing a vehicle today, the fuel costs were discounted to a present value using a discount rate of 10%. As a first analysis, the costs of a gasoline-powered vehicle with different lightweight bodies will be examined. The results are summarized in Table 26.

Gasoline Engine	Steel Unibody	Light Steel Unibody	CO-CIV	CIV	Aluminum Unibody	Carbon-CIV
Energy Use [MJ/km] @ 75W/kg	2.77	2.56	2.52	2.50	2.45	2.35
Fuel cost/ lifetime [$]	8350	7740	7600	7550	7390	7110
Discounted value [$]	4720	4380	4300	4270	4180	4020

Table 26: Fuel cost of a vehicle with a gasoline engine and different lightweight bodies

Based on the current gasoline prices, the use of a lightweight body can provide a cost saving in the use phase (discounted value) as much as $700 compared to the steel unibody. The consumer might be willing to invest these savings against the higher up-front cost of these lightweight designs. For the case of the a gasoline-powered vehicle, the cost savings through fuel economy and additional cost of production, at a high production volume of 125,000 bodies per year, are compared to the steel unibody as a baseline in following table.

Gasoline Engine	Steel Unibody	Light Steel Unibody	CO-CIV	CIV	Aluminum Unibody	Carbon-CIV
Fuel Savings	0	$347	$427	$452	$544	$703
Additional Body Prod. Cost	0	($8)	$265	$443	$535	$869

Table 27: Comparison of fuel cost savings to additional cost for lightweight bodies at high production volume (125,000 bodies/year)

As the steel unibody is dominated from the light steel unibody at a high production volume, the light steel design has lower cost in the production of the body and also fuel savings due to the lower weight of the vehicle. This should be already today's design solution when considering fuel economy and production cost. For the other body designs, only the CO-CIV shows good market potential. The savings from the use phase are about $150 higher than the additional cost of body production, which would be a good selling argument to the consumer. The CIV and aluminum unibody designs are nearly equal from a cost perspective in their fuel savings and additional production costs. Although they do not provide overall cost savings for the consumer, their environmental performance is better than the baseline steel vehicle. Only the Carbon-CIV would not be a design option as its fuel cost savings are less than what the consumer would have to pay additionally for its production.

This analysis can be extended to all other powertrain and body combinations. For simplicity, only the steel unibody design is used to evaluate all propulsion technologies. This baseline should serve to prove the value of this analysis. The results are presented in Table 28.

Steel Unibody	Gasoline Engine	Diesel Engine	Gasoline Hybrid	Diesel Hybrid	Hydrogen Fuel Cell	Methanol Fuel Cell
Energy Use [MJ/km] @ 75W/kg	2.77	2.02	1.12	0.91	0.84	1.43
Fuel cost/ lifetime [$]	8350	5980	3380	2680	5580	6130
Discounted value [$]	4720	3270	1850	1470	3050	3350

Table 28: Fuel cost of a vehicle with steel unibody and different propulsion technologies

Due to their low fuel economy, vehicle's utilizing gasoline engines have the highest discounted fuel cost of all alternatives. It is therefore cheaper to use every other propulsion technology because of their significant differences in fuel economy than gasoline, despite sometimes higher unit fuel prices.

The consumer might be willing to spend these savings in fuel cost for the additional cost of alternative powertrains. How these compare is demonstrated in Table 29.

Steel Unibody	Gasoline Engine	Diesel Engine	Gasoline Hybrid	Diesel Hybrid	Hydrogen Fuel Cell	Methanol Fuel Cell
Fuel Savings	0	$1,454	$2,877	$3,257	$1,674	$1,372
Estimated Additional Powertrain Cost	0	$500	$1,500	$2,000	$4,500	$5,000

Table 29: Comparison of fuel cost savings to additional cost for alternative powertrains

The first row shows the saving in fuel cost compared to the cost of powering a gasoline engine. In the second row, the estimated additional costs of producing a vehicle with an alternative powertrain compared to a vehicle with a gasoline engine are listed. For this analysis, all of the modeled vehicles are based on a steel unibody design.

In all cases of a diesel, gasoline hybrid and diesel hybrid powered car, the amount the customer can save during the driving phase of the vehicle outweighs the additional cost of the propulsion technologies. If the customer is therefore interested in paying the least amount to buy and operate a vehicle, he/she should choose the gasoline hybrid for the powertrain. This combination creates the highest monetary value for the customer, if only the cost of producing and operating the vehicle are taken into account. There are also additional costs existing like maintaining and repairing the vehicle, which are not included here.

For the hydrogen and methanol fuel cell the cost of the powertrain are three to four times higher than the savings achieved through the lower fuel use. If only the costs to the consumer are considered, it will be difficult to introduce these vehicles into the market today. In this case, either the cost of the powertrain needs to be reduced or fuel pricing policy must change. It is important to keep in mind that these calculations are based on today's fuel prices and estimates for propulsion system costs, which might change. Furthermore, reasons other than strictly monetary ones may influence this technology decision. The value function of the stakeholders needs to be examined in detail.

Although it is possible to use this analysis to evaluate the economical feasibility of lightweight body designs and also alternative propulsion technologies for the customer, it is important to restate that the cost of the powertrains are speculative in this work. The focus has been on the cost of producing the lightweight bodies, which are assessed in detail. Therefore, the use of the quantitative analysis to evaluate lightweight body choices at different production volumes as shown in Table 27 is more reliable.

However, consumers experience difficulty in making rational choices about trading off the costs and benefits of different levels of energy efficiency when making vehicle purchases. One cause is the substantial uncertainty with future fuel prices, which can also change the previous assessment of fuel cost savings. For example, current real oil prices are near historic lows, but energy analysts widely acknowledge that disturbances to oil markets could cause future prices to escalate rapidly to multiples of today's prices. There is also growing controversy about the potential of oil resource shortages, coupled with higher prices. Furthermore, proposed polices like carbon or gasoline tax can increase the fuel price significantly. These issues should encourage the consideration of fuel prices.

The previous analysis of the driving costs of a vehicle can be used to evaluate the implications the evaluation of changing fuel prices. For example, it can be used to analyze how much the gasoline price has to vary for the fuel cell to become a competitive alternative, i.e. the price at which fuel savings offset the additional initial cost of the powertrain. In this case:

1) the cost of gasoline needs to increase from \$0.374/L to \$2.02/L to offset the additional \$4500 for a hydrogen fuel cell powertrain, or
2) the cost of hydrogen needs to be reduced significantly: here hydrogen has to be available basically for free to be competitive.

Although the cost for gasoline fuel can be increased by using taxes or through market mechanisms, the degree required seems at this point unrealistic. Industry has recognized this problem and is trying to reduce the cost of the fuel cell powertrain though design and manufacturing changes and further development.

This thesis provides a good basis to assess the relationship between environmental performance and the cost of producing lightweight body structures. It can also be used for example to analyze the some economical implications of increased fuel economy standards, the customer's willingness to pay for a vehicle with higher fuel economy based on the cost of using it and changes in the technology selection due to changes in fuel prices. A range of possibilities exists for expanding the use of this analysis for further assessment of policies or for vehicle design choices. Nevertheless, proper selection from several technology combinations requires knowledge of the customer's value function, which was beyond the scope of this thesis.

8 Conclusions and Future Work

8.1 Conclusions

The impact of today's vehicle on the global environment landscape is undeniable. In hopes for mitigating this and thereby staying ahead of regulatory constraints, the automobile industry is investing large amounts into technology research and development. A prominent element of this effort is the development of powertrain alternatives to the omnipresent internal combustion engine (ICE). While a number of these alternatives show great promise toward improved energy efficiency or reduced airborne effluent, some early prototypes lack the power density of ICEs. This deficiency implies that either performance must be compromised or the rest of the vehicle must be made lighter. Consumer purchasing behavior seems to preclude the former. Proper selection from several technology combinations requires knowledge of the customer's value function, which was beyond the scope of this thesis. However, the first necessary step was to quantify and to examine the resulting cost and environmental performance tradeoff implicit in selecting between these two complementary fuel efficiency strategies. Focus was given to reducing weight through the use of light body structures. In particular, this thesis quantified the relationship between environmental performance and one element of cost, the cost of producing lightweight body structures.

This study focused on six vehicle body architectures using different material combinations for the lightweight bodies and seven propulsion technologies listed below.

Body Designs:

- Steel Unibody
- Light Steel Unibody
- Aluminum Unibody
- Composite Intensive Vehicle (CIV)
- Carbon-CIV (C-CIV)
- Cost optimized CIV (CO-CIV) (for high production volumes)

Propulsion Technologies:

- Gasoline Engine
- Diesel Engine
- Electric Vehicle
- Gasoline Hybrid
- Diesel Hybird
- Hydrogen Fuel Cell
- Methanol Fuel Cell

A case-based approach was chosen for the analysis. Detailed part lists on existing lightweight body designs were used to scale the bodies to a baseline mid-sized four-door sedan and to derive the overall mass of the bodies. The baseline steel unibody design had a mass of 350.2 kg with the other lightweight bodies ranging up to 55% in weight reduction to the baseline. Technical Cost Modeling was used to estimate the cost for manufacturing and assembly of the bodies.

The analysis indicated that body manufacturing costs varied substantially with changes in the production volume, and more importantly, the ordering of different designs by cost changed at different volumes. For example designs, which were highly dependent on sheet metal stamping had a large cost penalty at low volumes but were very economical at high volumes. At a given production volume, the number of viable body designs was reduced by eliminating the “dominated” designs, those designs for which other bodies were both less costly and had less mass. These are preferable, because there is a correlation between the mass of the body and fuel consumption. This assumption is valid as only driving tailpipe emissions have been modeled. Therefore, the body designs, which are lighter also have less fuel consumption for a given propulsion technology. For the low production volume of 20,000 bodies per year, the CIV and Carbon-CIV are the non-dominated solutions. For the high production volume of 125,000 bodies per year all body designs are feasible except the steel unibody, which is both heavier and more expensive than the light steel unibody design. In both, the case of a low and high production volume, lightweight body designs should be preferred over today’s used steel unibody if only the costs of producing the body are taken into account.

For the set of propulsion technologies the power and efficiency specifications have been established. A statistical analysis was used to develop the relationship between the power and mass of the powertrain. It is represented as linear over the range of propulsion technologies examined.

After establishing the characteristics for the body designs and the propulsion technologies, the size of powertrain required to deliver consistent vehicle performance of 75 and 95 W/kg for each of the proposed powertrains was assessed. The mass of the propulsion system is a function of the mass of the body including the effect of secondary weight savings and the vehicle performance target. The derived equations were used to calculate the necessary power of the propulsion technologies to achieve the vehicle performance target. The less the body weights the less power is necessary to achieve the target. Also, a higher vehicle performance requires in general more power than the lower target to accelerate the mass of the vehicle. The necessary weight of the individual propulsion systems was derived from the required power using the previously established relationship between mass and power of each powertrain. All of the propulsion systems examined in this study can provide the desired vehicle performance with reasonable power and weight of the powertrain except for the electric vehicle. The battery-electric car had to be taken out of the analysis. The specific energy and specific power of the battery required to produce an acceptable electric vehicle are not currently attainable with the existing technology.

All combinations of feasible body designs and powertrain systems were evaluated for their environmental performance. The model back-calculated the fuel consumed by the propulsion system by using the US Federal Test Procedure. Examining the results of fuel economy of the different body and powertrain combinations, the range in fuel economy due to the vehicle body is small compared to the variation due to the propulsion technology. The difference between the gasoline equivalent fuel consumption of a gasoline powered vehicle and one with a hydrogen fuel cell ranges from 27.4mpg for a steel design to 102.5mpg for a Carbon-CIV design. By contrast, the change in fuel economy in the gasoline engine because of a lighter body design is at most 5 mpg. In order to improve fuel economy significantly, alternative propulsion technologies like fuel cells need to be introduced to the market. These results showed that the propulsion technology has the largest influence and importance on the fuel economy of the vehicle. However, lightweighting is not without its benefits. For a given propulsion technology it is better from an environmental standpoint to use a lighter vehicle body for the improved fuel economy.

Nevertheless, the environmental performance is not the only dimension of this analysis. If the decision must include a consideration of the cost of the body, it will depend mainly on the desired production volume and the value of the fuel economy. However, it is insufficient to consider only the cost of body production. It is necessary to also include the cost for producing the powertrain itself.

To demonstrate the validity and value of the method, the costs of the propulsion system were roughly estimated through literature review and judgment. By adding the estimated cost of the powertrain to the cost of the body, a technology frontier was created (Figure 26).

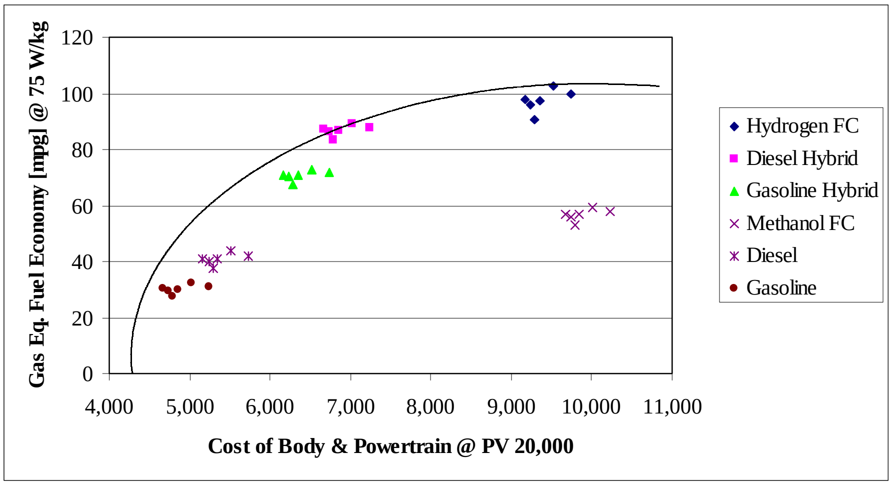

Figure 26: Gasoline equivalent fuel economy and cost of vehicle production (body PV 20,000;vehicle performance: 75 W/kg)

In general, the alternative propulsion technologies, which have high fuel economies are the most expensive and to the right in the above graph. The established technologies are less costly and lie to the left. The costs resulting from the use of an alternative propulsion technology are larger than the costs added through the use of lightweight body structures. Nevertheless, several vehicle combinations with different fuel economies provide viable alternatives for the automobile manufacturer. Their ultimate choice will depend on the level of cost they are willing to incur on the production of the vehicle and the relative importance they place on fuel economy versus cost. In order to select an option, it is necessary to have the value function of the user of this analysis.

The push for a propulsion technology or lightweight body can be initiated by and can influence several interest groups. The stakeholders include four major groups: the vehicle purchasers, government, vehicle manufacturers, and fuel manufacturers and distributors. The government has long been an influencing force on the automobile industry. Policy makers established for example the Clean Air Act of 1973 and CAFE (Corporate Average Fuel Economy) requirements developed in 1976,which set minimum standards of fuel efficiency for each auto-maker's product line and penalize manufacturers not meeting this standard. Nevertheless, the existing government policies do not affect all stakeholders and do not capture the whole range of regulatory possibilities. To improve fuel economy and GHG emissions, policy should aim in general at decreasing the intensity of fuel use or to decrease the impact of a unit of use. There are many proposals for additional policies existing. This thesis supported the evaluation of some of them.

Increased fuel economy standards are influencing or forcing the choice and development of technology. The thesis provided the basis to assess the cost for the vehicle manufacturer if the standards would be increased. For example, increasing the gasoline equivalent fuel economy by 5 mpg from today's value (27.5mpg) will still be achievable with gasoline engines and lightweight bodies for an additional cost of $870 to the baseline steel vehicle for the manufacturer. However, an increase of more than 60 mpg to 90 mpg in fuel economy results in an exponential increase in cost. In order to evaluate whether the additional costs for alternative propulsion technologies and lightweight bodies would ever be accepted, it was necessary to know how much the consumer is willing to pay for the improved environmental vehicle performance.

Therefore, the cost for driving the vehicle (fuel costs) over its lifetime was assessed. If the customer can pay less during the use phase due to a higher fuel economy, they might be willing to invest this amount up-front in a more expensive vehicle. In the case of a diesel, gasoline hybrid and diesel hybrid powered car the money the customer will save during the driving phase of the vehicle outweigh the additional cost of the propulsion technologies. For the hydrogen and methanol fuel cell the cost of the powertrain are three to four times higher than the savings achieved through the lower energy use.

These calculations were based on today's fuel prices and estimates for propulsion system costs, which might be subject to change. Nevertheless, the previous analysis of the driving costs of a vehicle can support the evaluation of changing fuel prices. For example, it can be used to analyze how much the gasoline price has to vary until the fuel cell becomes a competitive alternative, i.e. the price at which fuel savings offset the additional initial cost of the powertrain. This can happen for example through tax policies on gasoline fuel.

The final decision on which propulsion system and lightweight body to choose depends on the value function of the stakeholders and the regulatory environment. This thesis provides a quantitative basis to evaluate the options and support the decision-making process. It can be expended to many directions and different options.

8.2 Future Work

The thesis raises a number of additional questions that are not addressed in the work presented here. Some areas for future research are listed below.

- Propulsion system costs need to be assessed in more detail by building for example the necessary technical cost models and collecting design and part data of the powertrains.
- Collect more data on existing propulsion systems to improve the statistical analysis of the relationship between power and mass characteristics.
- Assess the package space availability in the body design and fit of the powertrain.
- Expand on the evaluated body designs (e.g. aluminum spaceframe body) and propulsion technologies (e.g. CNG propulsion system).
- Conduct additional analysis on different vehicle classes as for example on a C-Class vehicle (small cars), which are popular in Europe. Furthermore, due to the performance of alternative propulsion technologies a smaller and therefore lighter vehicle produced at low production volume might be more appropriate.
- Conduct interviews with different stakeholders for a multi-attribute utility analysis to establish their value functions and to choose a body or powertrain technology.
- Expand the analysis to the life cycle of the vehicle (life-cycle assessment).
- Analyze the effects of specific policy recommendations on the stakeholders taking into account their value functions.

Any of the proposed areas provide an avenue of research that can be pursued.

9 Appendix

9.1 TCM part lists

Part List - Car Design: Steel Unibody

Part Name	Number Required	Part Weight	Trim Scrap	Material Specification	Press Technology	Complexity Level
	#	*kg*	*%*			*#*
Roof	1	11.52	45%	140 MPa Steel	Transfer	1
Quarter Panel Inner RH	1	4.52	45%	140 MPa Steel	Tandem	3
Quarter Panel Inner LH	1	4.52	45%	140 MPa Steel	Tandem	3
Quarter Panel Outer RH	1	5.89	45%	140 MPa Steel	Tandem	3
Quarter Panel Outer LH	1	5.89	45%	140 MPa Steel	Tandem	3
Floor Panel	1	16.64	45%	140 MPa Steel	Tandem	3
Apron front fender lower R&L	1	1.82	45%	140 MPa Steel	Transfer	2
Reinf front fender apron horn mtg	1	0.02	45%	140 MPa Steel	Progressive	1
Support radiator	1	2.78	45%	140 MPa Steel	Transfer	2
Bracket air cond cond mounting bracket	2	0.10	45%	140 MPa Steel	Progressive	1
Bracket air cond cond mounting lower	2	0.12	45%	140 MPa Steel	Progressive	1
Pan front floor	1	8.97	45%	140 MPa Steel	Tandem	3
Reinf rad supt upr	1	1.28	45%	140 MPa Steel	Transfer	2
Reinf rad supt at hood latch	1	0.09	45%	140 MPa Steel	Progressive	1
Member front cross at dash	1	5.90	45%	140 MPa Steel	Tandem	3
Panel cowl top inner	1	4.74	45%	140 MPa Steel	Transfer	2
Panel cowl top outer	1	3.38	45%	140 MPa Steel	Transfer	2
Panel w/wiper mounting	1	1.92	45%	140 MPa Steel	Transfer	1
Reinf cowl top panel side r.h.	2	0.32	45%	140 MPa Steel	Progressive	1
Extension dash panel	1	1.20	45%	140 MPa Steel	Transfer	2
Reinf w/wiper motor mounting	1	0.13	45%	140 MPa Steel	Progressive	1
Bracket w/wiper arm stop	1	0.09	45%	140 MPa Steel	Progressive	1
Bracket cowl top vent screen	1	0.06	45%	140 MPa Steel	Progressive	1
Reinf assy cowl top outer	1	1.64	45%	140 MPa Steel	Transfer	1
Bracket hoodlift on body l.h.	2	0.12	45%	140 MPa Steel	Progressive	1
Ext frt body pillar l.h.	1	0.25	45%	140 MPa Steel	Progressive	1
Reinf front floor pan seat track	2	0.55	45%	140 MPa Steel	Transfer	1
PNL dash	1	7.23	45%	140 MPa Steel	Tandem	3
Reinf dash PNL at brk mstr cyl	1	0.80	45%	140 MPa Steel	Progressive	2
Strainer package tray to floor center	1	0.35	45%	140 MPa Steel	Progressive	1
Panel lower back	1	3.86	45%	140 MPa Steel	Tandem	3
Reinf lower back panel	1	0.88	45%	140 MPa Steel	Progressive	2
Plate lugg compt door lock stkr anchor	1	0.04	45%	140 MPa Steel	Progressive	1
Bracket lugg compt door lock striker	1	0.36	45%	140 MPa Steel	Progressive	2
Bracket asy rad support lower r.h.	2	0.14	45%	140 MPa Steel	Progressive	1
Bracket asy front for to frt fnd apr	2	0.15	45%	140 MPa Steel	Progressive	1
Reinf frt crs mbr at dash R&L	1	1.91	45%	140 MPa Steel	Transfer	1
Member front side outer rear R&L	1	4.61	45%	140 MPa Steel	Transfer	1
Reinf front side outer rear member R&L	1	2.80	45%	140 MPa Steel	Transfer	1
Plate front suspension housing reinf	2	0.15	45%	140 MPa Steel	Progressive	1
Member front floor cross rear #1	1	2.44	45%	140 MPa Steel	Transfer	2
Supt prkg brk cbl	1	0.08	45%	140 MPa Steel	Progressive	1
Member front floor cross rear	1	2.05	45%	140 MPa Steel	Transfer	2
Reinf asy frt floor pan seat track inr	2	0.04	45%	140 MPa Steel	Progressive	1

Member front floor side inner R&L	1	4.70	45%	140 MPa Steel	Transfer	1
Extension floor side inner member R&L	1	3.67	45%	140 MPa Steel	Transfer	1
Reinf front door hinge lower on bdy	2	0.38	45%	140 MPa Steel	Progressive	1
Plate door upper hinge anchor on bdy	4	0.03	45%	140 MPa Steel	Progressive	1
Reinf front door hinge upper on bdy	2	0.42	45%	140 MPa Steel	Progressive	1
Pillar front body lower R&L	1	2.14	45%	140 MPa Steel	Transfer	2
Panel cowl side R&L	1	2.39	45%	140 MPa Steel	Transfer	2
Reinf center body pillar R&L	1	1.73	45%	140 MPa Steel	Transfer	2
Plate front door lock strider anchor	2	0.03	45%	140 MPa Steel	Progressive	1
Pillar center body inner R&L	1	3.21	45%	140 MPa Steel	Transfer	2
Reinf asy frt st shldr strp gid	2	0.25	45%	140 MPa Steel	Progressive	1
Reinf rear seat belt anc	2	0.03	45%	140 MPa Steel	Progressive	1
Moulding roof drip side	2	0.30	45%	140 MPa Steel	Progressive	1
Frame door opening RH	1	7.18	45%	140 MPa Steel	Tandem	3
Frame door opening LH	1	7.18	45%	140 MPa Steel	Tandem	3
Pillar front body upper R&L	1	3.42	45%	140 MPa Steel	Transfer	2
Rain roof side inner R&L	1	2.99	45%	140 MPa Steel	Transfer	1
Support package tray side	2	0.62	45%	140 MPa Steel	Transfer	2
Bracket asy rear seat shoulder strap	2	0.17	45%	140 MPa Steel	Progressive	1
Support asy muffler o/let pipe rear	1	0.15	45%	140 MPa Steel	Progressive	1
Housing asy rear bumper isolator R&L	1	1.59	45%	140 MPa Steel	Transfer	1
Bracket spare wheel mounting	1	0.04	45%	140 MPa Steel	Progressive	1
Bracket fuel tank support front R&L	1	1.32	45%	140 MPa Steel	Transfer	1
Retainer rear seat cushion	2	0.09	45%	140 MPa Steel	Progressive	1
Reinf asy seat belt anc to floor R&L	1	1.40	45%	140 MPa Steel	Transfer	1
Bracket package tray strainer to flr	1	0.06	45%	140 MPa Steel	Progressive	1
Member rear floor side RH	1	4.81	45%	140 MPa Steel	Transfer	2
Member rear floor side LH	1	4.81	45%	140 MPa Steel	Transfer	2
Ext rear floor s/member rear R&L	1	2.36	45%	140 MPa Steel	Transfer	1
Reinf rr floor side member R&L	1	2.35	45%	140 MPa Steel	Transfer	2
Reinf asy rr flr side member tie dwn	2	0.10	45%	140 MPa Steel	Progressive	1
Reinf roof panel rear	1	0.59	45%	140 MPa Steel	Progressive	1
Member rear floor cross	1	4.25	45%	140 MPa Steel	Transfer	2
Washer rear susp support	4	3.10	45%	140 MPa Steel	Transfer	1
Bracket rear susp arm mount front	2	3.10	45%	140 MPa Steel	Transfer	2
Panel qtr w/house inner RH	1	3.03	45%	140 MPa Steel	Tandem	3
Panel qtr w/house inner LH	1	3.03	45%	140 MPa Steel	Tandem	3
Member rear shock ABS mounting R&L	1	2.56	45%	140 MPa Steel	Transfer	1
Reinf qtr w/house inner panel	2	0.34	45%	140 MPa Steel	Progressive	1
Reinf rad supt lower	1	1.54	45%	140 MPa Steel	Transfer	2
Reinf rad supt bmpr opng r.h.	2	0.17	45%	140 MPa Steel	Progressive	1
Housing front suspension mounting RH	1	2.29	45%	140 MPa Steel	Tandem	3
Housing front suspension mounting LH	1	2.29	45%	140 MPa Steel	Tandem	3
Reinf front suspension mounting	2	0.53	45%	140 MPa Steel	Transfer	1
Extension front fender apron	2	0.53	45%	140 MPa Steel	Transfer	2
Member front side outer front RH	1	7.51	45%	140 MPa Steel	Transfer	2
Member front side outer front LH	1	7.51	45%	140 MPa Steel	Transfer	2
Trough l/c door opening dr side	2	0.41	45%	140 MPa Steel	Progressive	2
Reinf rr dr lock striker anchor plate	2	0.08	45%	140 MPa Steel	Progressive	1
Reinf asy rear bumper mounting to qtr	2	0.38	45%	140 MPa Steel	Progressive	1
Reinf door opening front R&L	1	3.57	45%	140 MPa Steel	Transfer	2
Seal asy qtr panel to w/house	1	0.15	45%	140 MPa Steel	Progressive	1
Frame back window upper	1	0.84	45%	140 MPa Steel	Progressive	1
Panel package tray	1	4.14	45%	140 MPa Steel	Transfer	2
Reinf luggage compt door opening upper	1	2.08	45%	140 MPa Steel	Transfer	1
Reinf front body pillar at belt	2	0.43	45%	140 MPa Steel	Progressive	2
Reinf roof panel center	1	0.76	45%	140 MPa Steel	Progressive	2
Apron front fender upper R&L	1	3.64	45%	140 MPa Steel	Transfer	2
Hinge asy l/c door R&L	1	2.08	45%	140 MPa Steel	Transfer	1

Reinf front side member at frame mtg	2	0.09	45%	140 MPa Steel	Progressive	1
Reinf front side member tie down hole	2	0.19	45%	140 MPa Steel	Progressive	1
Ext frt sd mbr rr R&L	1	2.39	45%	140 MPa Steel	Transfer	1
Panel w/shield header	1	0.93	45%	140 MPa Steel	Progressive	1
Bracket rear suspension trk bar R&L	1	3.13	45%	140 MPa Steel	Transfer	1
Reinf front fender upper R&L	1	3.42	45%	140 MPa Steel	Transfer	2
Hood Outer	1	10.43	15%	140 MPa Steel	Transfer	1
Hood Inner	1	4.60	55%	140 MPa Steel	Tandem	3
4 brackets	4	0.05	15%	140 MPa Steel	Progressive	1
Decklid Outer	1	7.93	15%	140 MPa Steel	Transfer	1
Decklid Inner	1	3.62	55%	140 MPa Steel	Tandem	3
4 brackets	4	0.05	15%	140 MPa Steel	Progressive	1
Fender R&L	2	3.35	40%	140 MPa Steel	Tandem	2
Door Front Inner	2	4.74	49%	140 MPa Steel	Tandem	3
Door Front Outer R&L	2	4.35	48%	140 MPa Steel	Transfer	2
Reinforcement Panel at Hinge Front R&L	2	1.97	51%	140 MPa Steel	Transfer	1
Reinforcement Panel at Latch Front R&L	2	1.12	62%	140 MPa Steel	Progressive	1
Door Rear Inner RH	1	3.79	49%	140 MPa Steel	Tandem	3
Door Rear Inner LH	1	3.79	49%	140 MPa Steel	Tandem	3
Door Rear Outer R&L	2	3.48	48%	140 MPa Steel	Transfer	2
Reinforcement Panel at Hinge Rear R&L	2	1.58	51%	140 MPa Steel	Transfer	1
Reinforcement Panel at Latch Rear R&L	2	0.90	62%	140 MPa Steel	Progressive	1
PURCHASED PARTS						
Reinforcement Panel at Waist Front Door	2	0.40				
Intrusion Beam Front Door	2	1.84				
Nut Weld M8 Square	4	0.20				
Door check	4	0.20				
Reinforcement Panel at Waist Rear Door	2	0.32				
Intrusion Beam Rear Rear Door	2	1.47				

Part List - Car Design: Light Steel Unibody

Part Name	Number Required	Part Weight	Trim Scrap	Material Specification	Press Technology	Complexity Level
	#	*kg*	*%*	*MPA Steel*		*#*
Reinf Radiator Support Upper	1	1.57	66%	350	Tandem	2
Reinf Front Rail Extension	1	0.95	59%	350	Tandem	1
Rail Front Extension	1	4.04	43%	350	Tandem	2
Bracket Roof Rail Mount Lower	1	0.29	64%	350	Tandem	1
Panel Dash	1	5.66	46%	210	Transfer	3
Member Dash Front	1	2.21	41%	600	Tandem	2
Panel Cowl Lower	1	1.23	50%	210	Tandem	1
Panel Cowl Upper	1	1.33	67%	210	Tandem	1
Member Front Floor Support	2	0.63	37%	800	Tandem	1
Reinf Floor Front Seat Rear Outer	2	0.06	72%	280	Progressive	1
Pan Front Floor	1	14.22	28%	210	Tandem	3
Member Rear Suspension	1	1.30	36%	350	Tandem	1
Member Panel Back	1	1.27	54%	210	Tandem	1
Panel Back	1	2.43	55%	140	Transfer	1
Panel A-Pillar Inner Lower	1	2.66	58%	350	Transfer	2
Panel B-Pillar Inner	1	6.96	58%	350	Transfer	2
Reinf B-Pillar Lower	2	0.40	49%	350	Tandem	1
Panel Wheelhouse Inner	1	3.74	48%	210	Transfer	2
Panel A-Pillar Inner Upper	1	2.76	33%	350	Transfer	2
Panel Package Tray Upper	1	1.82	56%	210	Tandem	2
Panel Package Tray Lower	1	1.45	65%	210	Tandem	2
Support Package Tray RH	1	0.16	49%	280	Progressive	1
Panel Front Header	1	0.79	62%	280	Tandem	1
Panel Rear Header	1	0.75	60%	140	Tandem	1
Member Kick Up	1	1.36	48%	800	Tandem	2
Reinf Radiator Rail Closeout	1	1.11	61%	350	Tandem	2
Panel Gutter Deck Lid	1	0.85	62%	140	Tandem	2
Support Panel Rear Header	1	0.19	41%	140	Progressive	1
Rail Fender Support Inner	1	5.25	45%	420	Transfer	1
Rail Fender Support Outer	1	2.52	60%	350	Transfer	1
Reinf Front Rail	1	1.62	43%	350	Tandem	1
Plate Rear Spring Upper	2	0.26	19%	350	Progressive	1
Reinf Panel Dash Brake Booster	1	0.44	64%	350	Progressive	1
Bracket Rear Shock Absorber Mount	1	0.65	51%	350	Progressive	1
Reinf Floor Front Seat Rear Center	1	0.24	52%	350	Progressive	1
Reinf Rear Seat Inner Belt Mount	2	0.12	50%	350	Progressive	1
Bracket Member Pass Through Lower	2	0.03	50%	350	Progressive	1
Bracket Member Pass Through Up Fr & R	1	0.27	50%	350	Progressive	1
Reinf Panel Dash Upper	1	0.10	27%	350	Progressive	1
Pan Rear Floor	1	4.12	62%	210	Transfer	1
Reinf Hinge Decklid	2	0.11	42%	350	Progressive	1
Reinf A-Pillar	1	0.45	48%	350	Progressive	1
Closeout Fender Support Rail	1	0.22	48%	350	Progressive	1
Reinf Rail Dash	1	0.60	44%	350	Tandem	1
Assy Reinf Cowl Lower	1	0.12	37%	350	Progressive	1
Bracket Trailing Arm Mount Inner	1	0.65	43%	350	Progressive	1
Reinf Seat Belt Retractor Rear	2	0.03	72%	350	Progressive	1
Panel Roof	1	8.43	18%	210	Tandem	1
Hood Outer	1	8.94	15%	210	Transfer	1
Hood Inner	1	4.60	55%	140	Tandem	3
4 brackets	4	0.05	15%	140	Progressive	1

Decklid Outer	1	6.80	15%	210	Transfer	1
Decklid Inner	1	3.62	55%	140	Tandem	3
4 brackets	4	0.05	15%	140	Progressive	1
Fender R&L	2	2.87	40%	210	Tandem	2
Door Front Inner	2	2.17	49%	210	Tandem	3
Door Front Outer R&L	2	1.93	48%	210	Transfer	2
Frame Front Door R&L	2	1.53	20%	210	Tandem	1
Reinforcement Panel at Hinge Front R&L	2	1.86	51%	210	Transfer	1
Reinforcement Panel at Latch Front R&L	2	1.06	62%	210	Progressive	1
Door Rear Inner RH	1	1.73	49%	210	Tandem	3
Door Rear Inner LH	1	1.73	49%	210	Tandem	3
Door Rear Outer R&L	2	1.55	48%	210	Transfer	2
Frame Rear Door R&L	2	1.22	20%	210	Tandem	1
Reinforcement Panel at Hinge Rear R&L	2	1.49	51%	210	Transfer	1
Reinforcement Panel at Latch Rear R&L	2	0.84	62%	210	Progressive	1

TUBULAR PARTS						
Rail Front Outer RH/LH	1	5.87	54%	TB8	Tandem	2
Rail Front Inner RH/LH	1	10.65	45%	TB10	Tandem	2
Panel Rocker Inner	1	12.73	53%	TB42	Transfer	3
Rail Rear Inner	1	10.18	50%	TB46	Transfer	3
Rail Rear Outer	1	4.94	50%	TB48	Transfer	3
Panel Body Side Outer RH	1	15.32	64%	TB60	Tandem	3
Panel Body Side Outer LH	1	15.19	65%	TB60	Tandem	3
Panel Wheelhouse Outer	1	4.18	63%	TB70	Transfer	3
Panel Skirt	1	6.72	20%	TB96	Transfer	3
PURCHASED PARTS						
Rail Side Roof RH	1	4.56		Tube		
Rail Side Roof LH	1	4.72		Tube		
Member Pass Through	2	0.32		140		
Brace Radiator	2	0.12		350		
Hinges/Small Brackets	58	0.00		280/140		
Weld Studs	100	0.00				
Panel Dash Insert (laminate)	1	0.85		Sandwich		
Panel Spare Tire Tub (laminate)	1	2.05		Sandwich		
Reinforcement Panel at Waist Front Door	2	0.30				
Intrusion Beam Front Door	2	1.38				
Nut Weld M8 Square	4	0.20				
Door check	4	0.20				
Reinforcement Panel at Waist Rear Door	2	0.24				
Intrusion Beam Rear Rear Door	2	1.10				

Part List - Car Design: Aluminum Unibody

Part Name	Number Required	Part Weight	Trim Scrap	Material Specification	Press Technology	Complexity Level
	#	*kg*	*%*			#
Front Structure-Rad support	1	1.21	17%	5754 Aluminum	Transfer	2
	1	0.63	18%	5754 Aluminum	Progressive	1
	1	0.48	16%	5754 Aluminum	Progressive	1
	1	0.20	15%	5754 Aluminum	Progressive	1
	1	1.07	19%	5754 Aluminum	Transfer	2
	1	1.31	15%	5754 Aluminum	Transfer	2
Front Structure-Front End Structure	1	3.01	18%	5754 Aluminum	Tandem	3
	1	2.90	13%	5754 Aluminum	Transfer	2
	1	0.19	15%	5754 Aluminum	Progressive	1
	1	0.31	15%	5754 Aluminum	Progressive	1
	1	0.66	20%	5754 Aluminum	Progressive	2
	1	0.39	15%	5754 Aluminum	Progressive	2
	1	0.02	15%	5754 Aluminum	Progressive	1
	1	0.04	15%	140 MPa Steel	Progressive	1
	1	0.29	15%	5754 Aluminum	Progressive	1
	1	0.05	15%	140 MPa Steel	Progressive	1
	1	0.02	15%	5754 Aluminum	Progressive	1
	1	0.03	15%	5754 Aluminum	Progressive	1
	1	4.95	50%	5754 Aluminum	Transfer	2
	1	2.41	60%	5754 Aluminum	Transfer	2
	1	1.40	60%	5754 Aluminum	Transfer	2
	1	0.26	15%	5754 Aluminum	Progressive	1
	1	0.18	15%	140 MPa Steel	Progressive	1
	1	0.11	15%	5754 Aluminum	Progressive	1
	1	0.12	15%	5754 Aluminum	Progressive	1
	1	0.04	15%	5754 Aluminum	Progressive	1
	1	0.12	15%	5754 Aluminum	Progressive	1
	1	0.30	15%	5754 Aluminum	Progressive	1
	1	0.72	15%	140 MPa Steel	Progressive	1
	1	0.53	15%	140 MPa Steel	Progressive	1
	1	0.83	46%	5754 Aluminum	Progressive	2
	1	0.56	63%	5754 Aluminum	Progressive	2
	1	0.40	15%	5754 Aluminum	Progressive	1
	1	3.36	60%	5754 Aluminum	Transfer	2
Dash and Cowl-Dash	1	0.12	15%	5754 Aluminum	Progressive	1
	1	2.28	18%	5754 Aluminum	Tandem	3
	1	0.86	13%	5754 Aluminum	Tandem	3
	1	0.11	15%	5754 Aluminum	Progressive	1
	1	0.04	15%	5754 Aluminum	Progressive	1
Dash and Cowl-Cowl	1	1.36	5%	5754 Aluminum	Tandem	3
	1	0.75	31%	5754 Aluminum	Progressive	1
	1	0.80	26%	5754 Aluminum	Progressive	1
	1	0.08	15%	5754 Aluminum	Progressive	1
	1	0.02	15%	5754 Aluminum	Progressive	1
	1	0.02	15%	5754 Aluminum	Progressive	1
	1	0.04	15%	5754 Aluminum	Progressive	1
	1	0.02	15%	5754 Aluminum	Progressive	1
	1	0.02	15%	5754 Aluminum	Progressive	1
	1	0.22	15%	140 MPa Steel	Progressive	1
	1	0.01	15%	5754 Aluminum	Progressive	1
	1	1.02	60%	5754 Aluminum	Progressive	1
	1	0.05	15%	5754 Aluminum	Progressive	1

	1	0.06	15%	5754 Aluminum	Progressive	1
	1	0.26	15%	5754 Aluminum	Progressive	1
	1	0.27	15%	5754 Aluminum	Progressive	2
Underbody-Front floor	1	9.23	7%	5754 Aluminum	Tandem	3
	1	2.87	59%	5754 Aluminum	Transfer	1
	1	0.18	15%	5754 Aluminum	Progressive	2
	1	0.38	15%	5754 Aluminum	Progressive	2
	1	0.06	15%	140 MPa Steel	Progressive	1
	1	1.36	50%	5754 Aluminum	Transfer	1
	1	0.53	15%	140 MPa Steel	Progressive	1
	1	0.91	58%	5754 Aluminum	Progressive	1
	1	0.34	15%	5754 Aluminum	Progressive	1
	1	0.33	15%	5754 Aluminum	Progressive	1
	1	0.06	15%	5754 Aluminum	Progressive	1
	1	0.10	15%	5754 Aluminum	Progressive	1
	1	1.59	62%	5754 Aluminum	Transfer	1
	1	0.10	15%	5754 Aluminum	Progressive	1
	1	0.16	15%	5754 Aluminum	Progressive	1
	1	1.01	15%	140 MPa Steel	Progressive	1
	1	0.14	15%	140 MPa Steel	Progressive	1
	1	0.46	15%	5754 Aluminum	Progressive	1
Rear Floor	1	2.87	18%	5754 Aluminum	Tandem	3
	1	1.28	14%	5754 Aluminum	Transfer	2
	1	0.47	15%	5754 Aluminum	Progressive	1
	1	1.37	5%	5754 Aluminum	Transfer	2
	1	0.15	15%	140 MPa Steel	Progressive	1
	1	0.03	15%	5754 Aluminum	Progressive	1
	1	0.38	15%	5754 Aluminum	Progressive	1
	1	0.17	15%	140 MPa Steel	Progressive	1
	1	0.17	15%	5754 Aluminum	Progressive	1
	1	3.28	18%	5754 Aluminum	Transfer	2
	1	0.28	15%	5754 Aluminum	Progressive	1
	1	0.22	15%	140 MPa Steel	Progressive	1
	1	4.62	49%	5754 Aluminum	Transfer	2
	1	4.32	49%	5754 Aluminum	Transfer	2
	1	0.48	15%	5754 Aluminum	Progressive	1
	1	0.30	15%	140 MPa Steel	Progressive	1
	1	0.16	15%	5754 Aluminum	Progressive	1
	1	0.13	15%	140 MPa Steel	Progressive	1
	1	0.43	15%	140 MPa Steel	Progressive	1
	1	0.50	15%	140 MPa Steel	Progressive	1
	1	0.61	15%	140 MPa Steel	Progressive	1
	1	0.08	15%	6061 Aluminum	Progressive	1
	1	0.03	15%	140 MPa Steel	Progressive	1
	1	0.67	19%	5754 Aluminum	Progressive	1
	1	0.61	25%	5754 Aluminum	Progressive	1
	1	0.22	15%	6061 Aluminum	Progressive	1
	1	2.00	22%	5754 Aluminum	Tandem	3
Bodyside -Inner	1	1.52	59%	5754 Aluminum	Transfer	2
	1	4.10	47%	6111 Aluminum	Transfer	2
	1	3.27	53%	6111 Aluminum	Transfer	1
	1	5.97	69%	5754 Aluminum	Tandem	3
	1	5.92	70%	5754 Aluminum	Tandem	3
	1	1.22	21%	5754 Aluminum	Tandem	3
	1	1.03	33%	5754 Aluminum	Tandem	3
	1	0.27	15%	140 MPa Steel	Progressive	1
	1	0.17	15%	140 MPa Steel	Progressive	1
	1	8.93	79%	5754 Aluminum	Tandem	3
	1	2.64	52%	6111 Aluminum	Tandem	3

	1	3.78	45%	5754 Aluminum	Transfer	2
	1	0.12	15%	5754 Aluminum	Progressive	1
	1	0.24	15%	5754 Aluminum	Progressive	1
	1	3.94	46%	5754 Aluminum	Transfer	2
	1	0.89	50%	5754 Aluminum	Progressive	1
	1	0.13	15%	5754 Aluminum	Progressive	1
	1	0.08	15%	5754 Aluminum	Progressive	1
	1	0.16	15%	5754 Aluminum	Progressive	1
	1	0.44	15%	140 MPa Steel	Progressive	1
	1	0.02	15%	5754 Aluminum	Progressive	1
	1	0.74	15%	140 MPa Steel	Progressive	1
	1	0.39	15%	5754 Aluminum	Progressive	1
	1	2.21	59%	5754 Aluminum	Transfer	1
	1	2.18	60%	5754 Aluminum	Transfer	1
	1	0.72	22%	5754 Aluminum	Progressive	1
	1	0.38	15%	5754 Aluminum	Progressive	1
	1	0.13	15%	5754 Aluminum	Progressive	1
	1	0.48	15%	5754 Aluminum	Progressive	1
	1	0.91	15%	140 MPa Steel	Progressive	1
	1	0.08	15%	5754 Aluminum	Progressive	1
	1	0.29	15%	5754 Aluminum	Progressive	1
	1	0.02	15%	5754 Aluminum	Progressive	1
	1	0.13	15%	5754 Aluminum	Progressive	1
	1	0.16	15%	6111 Aluminum	Progressive	1
Roof	1	3.80	17%	6111 Aluminum	Transfer	1
	1	0.57	26%	5754 Aluminum	Progressive	2
	1	0.62	26%	5754 Aluminum	Progressive	1
	1	0.25	15%	5754 Aluminum	Progressive	1
	1	0.06	15%	5754 Aluminum	Progressive	1
Package Tray	1	1.90	25%	5754 Aluminum	Transfer	2
	1	0.92	27%	5754 Aluminum	Progressive	2
	1	0.92	27%	5754 Aluminum	Progressive	1
	1	1.21	21%	5754 Aluminum	Transfer	2
	1	0.41	15%	5754 Aluminum	Progressive	1
	1	0.05	15%	5754 Aluminum	Progressive	1
	1	0.79	20%	5754 Aluminum	Progressive	1
	1	0.03	15%	5754 Aluminum	Progressive	1
Lower Back Panel and Decklid opening	1	1.18	23%	5754 Aluminum	Transfer	2
	1	0.89	13%	5754 Aluminum	Tandem	3
	1	0.18	15%	5754 Aluminum	Progressive	1
	1	1.01	45%	5754 Aluminum	Progressive	1
	1	0.34	15%	5754 Aluminum	Progressive	1
Hood Outer	1	4.83	15%	6111 Aluminum	Transfer	1
Hood Inner	1	5.37	55%	6111 Aluminum	Tandem	3
4 brackets	4	0.05	15%	140 MPa Steel	Progressive	1
Decklid Outer	1	3.68	15%	6111 Aluminum	Transfer	1
Decklid Inner	1	4.09	55%	6111 Aluminum	Tandem	3
4 brackets	4	0.05	15%	140 MPa Steel	Progressive	1
Fender R&L	2	1.55	40%	5754 Aluminum	Tandem	2
Door Front Inner	2	2.28	49%	5754 Aluminum	Tandem	3
Door Front Outer R&L	2	1.99	48%	5754 Aluminum	Transfer	2
Reinforcement Panel at Hinge Front R&I	2	0.71	51%	5754 Aluminum	Transfer	1
Reinforcement Panel at Latch Front R&I	2	0.40	62%	5754 Aluminum	Progressive	1
Door Rear Inner RH	1	1.82	49%	5754 Aluminum	Tandem	3
Door Rear Inner LH	1	1.82	49%	5754 Aluminum	Tandem	3
Door Rear Outer R&L	2	1.59	48%	5754 Aluminum	Transfer	2
Reinforcement Panel at Hinge Rear R&L	2	0.57	51%	5754 Aluminum	Transfer	1
Reinforcement Panel at Latch Rear R&L	2	0.32	62%	5754 Aluminum	Progressive	1

DIE CASTING MODEL						
Dash-Casting	1	3.91	33%	6001 Casting	Die Casting	2
	1	1.96	15%	6001 Casting	Die Casting	1
PURCHASED PARTS						
Reinforcement Panel at Waist Front Doo	2	0.48				
Intrusion Beam Front Door	2	2.21				
Nut Weld M8 Square	4	0.20				
Door check	4	0.20				
Reinforcement Panel at Waist Rear Door	2	0.39				
Intrusion Beam Rear Rear Door	2	1.77				

Part List - Car Design: Composite Intensive Vehicle (CIV)

Part Name	Number Required	Part Weight	Max. Length	Max. Width	Part Thickness	Material Specification	Foam Cores	Preforms
	#	*kg*	*m*	*m*	*m*		*#*	*#*
Roof - Inner	1	6.74	1.15	1.70	0.0020	RTM	0	1
Roof - Outer	1	13.36	1.20	1.80	0.0025	SMC	-	-
Floorpan	1	37.19	3.60	1.70	0.0100	RTM	4	5
Cross Member	1	6.79	1.70	0.50	0.0200	RTM	1	1
Inserts	32	0.80				Steel	-	-
Bodyside	2	30.54	3.10	1.30	0.0250	RTM	1	2
Front End	2	13.37	1.20	0.60	0.0350	RTM	2	2
Hood - Outer	1	8.15	1.15	1.65	0.0020	SMC	-	-
Hood - Inner	1	4.69	1.15	1.65	0.0015	RTM	0	1
Brackets	4	0.05				Steel	-	-
Decklid - Outer	1	6.20	0.88	1.65	0.0020	SMC	-	-
Decklid - Inner	1	3.56	0.88	1.65	0.0015	RTM	0	1
Brackets	4	0.05				Steel	-	-
Door Front Inner	2	1.59	1.07	0.60	0.0015	RTM	0	1
Door FrontOuter	2	2.76	1.07	0.60	0.0020	SMC	-	-
Door Front Frame RH	2	1.67	3.90	0.04	0.0035	SMC	-	-
Door Front Frame LH	2	1.67	3.90	0.04	0.0035	SMC	-	-
Door Rear Inner	2	1.26	0.85	0.60	0.0015	RTM	0	1
Door Rear Outer	2	2.19	0.85	0.60	0.0020	SMC	-	-
Door Rear Frame RH	2	1.58	3.67	0.04	0.0035	SMC	-	-
Door Rear Frame LH	2	1.58	3.67	0.04	0.0035	SMC	-	-
PURCHASED PARTS								
Nut Weld M8 Square	4	0.20						
Door check	4	0.20						

Material Composition of RTM parts:

RTM Component	Roof	Floorpan	Cross Member	Bodyside	Front End	Density
	wt%	*wt%*	*wt%*	*wt%*	*wt%*	kg/m^3
Resin	40.0%	39.5%	40.0%	39.5%	39.5%	1000
Filler	14.5%	0.0%	0.0%	0.0%	0.0%	2700
Fiber	45.0%	45.0%	34.5%	40.0%	40.0%	2500
Catalyst	0.5%	0.5%	0.5%	0.5%	0.5%	1200
Foam	0.0%	15.0%	25.0%	20.0%	20.0%	96.15

Part List - Car Design: Carbon Composite Intensive Vehicle (C-CIV)

Part Name	Number Required	Part Weight	Max. Length	Max. Width	Part Thickness	Material Specification	Foam Cores	Preforms
	#	kg	m	m	m		#	#
Roof - Inner	1	5.24	1.15	1.70	0.0018	C-RTM	0	1
Roof - Outer	1	13.36	1.20	1.80	0.0025	SMC	-	-
Floorpan	1	20.54	3.60	1.70	0.0080	C-RTM	4	5
Cross Member	1	4.41	1.70	0.50	0.0180	C-RTM	1	1
Inserts	32	0.80				Steel	-	-
Bodyside	2	19.80	3.10	1.30	0.0230	C-RTM	1	2
Front End	2	8.88	1.20	0.60	0.0330	C-RTM	2	2
Hood - Outer	1	8.15	1.15	1.65	0.0020	SMC	-	-
Hood - Inner	1	3.51	1.15	1.65	0.0013	C-RTM	0	1
Brackets	4	0.05				Steel	-	-
Decklid - Outer	1	6.20	0.88	1.65	0.0020	SMC	-	-
Decklid - Inner	1	2.67	0.88	1.65	0.0013	C-RTM	0	1
Brackets	4	0.05				Steel	-	-
Door Front Inner	2	1.19	1.07	0.60	0.0013	C-RTM	0	1
Door FrontOuter	2	2.76	1.07	0.60	0.0020	SMC	-	-
Door Front Frame RH	2	1.67	3.90	0.04	0.0035	SMC	-	-
Door Front Frame LH	2	1.67	3.90	0.04	0.0035	SMC	-	-
Door Rear Inner	2	0.94	0.85	0.60	0.0013	C-RTM	0	1
Door Rear Outer	2	2.19	0.85	0.60	0.0020	SMC	-	-
Door Rear Frame RH	2	1.58	3.67	0.04	0.0035	SMC	-	-
Door Rear Frame LH	2	1.58	3.67	0.04	0.0035	SMC	-	-
PURCHASED PARTS								
Nut Weld M8 Square	4	0.20						
Door check	4	0.20						

Material Composition of Carbon RTM parts:

RTM Component	Roof	Floorpan	Cross Member	Bodyside	Front End	Density
	wt%	wt%	wt%	wt%	wt%	kg/m^3
Resin	46.6%	42.5%	39.6%	40.8%	40.8%	1000
Filler	16.9%	0.0%	0.0%	0.0%	0.0%	2700
Fiber	35.9%	33.1%	23.4%	28.2%	28.2%	1750
Foam Core	0.0%	23.9%	36.6%	30.5%	30.5%	96.15
Catalyst	0.6%	0.5%	0.5%	0.5%	0.5%	1200

Part List - Car Design: Cost Optimized Composite Intensive Vehicle (CO-CIV)

Part Name	**Number Required**	**Part Weight**	**Max. Length**	**Max. Width**	**Part Thickness**	**Material Specification**	**Foam Cores**	**Preforms**
	#	*kg*	*m*	*m*	*m*		*#*	*#*
Floorpan	1	37.19	3.60	1.70	0.0100	RTM	4	5
Cross Member	1	6.79	1.70	0.50	0.0200	RTM	1	1
Bodyside	4	16.48	1.55	1.30	0.0050	SMC	-	-
Front End	2	13.37	1.20	0.60	0.0350	RTM	2	2
Door Front Inner	2	1.59	1.07	0.60	0.0015	RTM	0	1
Door FrontOuter	2	2.76	1.07	0.60	0.0020	SMC	-	-
Door Front Frame RH	2	1.67	3.90	0.04	0.0035	SMC	-	-
Door Front Frame LH	2	1.67	3.90	0.04	0.0035	SMC	-	-
Door Rear Inner	2	1.26	0.85	0.60	0.0015	RTM	0	1
Door Rear Outer	2	2.19	0.85	0.60	0.0020	SMC	-	-
Door Rear Frame RH	2	1.58	3.67	0.04	0.0035	SMC	-	-
Door Rear Frame LH	2	1.58	3.67	0.04	0.0035	SMC	-	-
PURCHASED PARTS								
Nut Weld M8 Square	4	0.20						
Door check	4	0.20						

Part Name	**Number Required**	**Part Weight**	**Trim Scrap**	**Material Specification**	**Press Technology**	**Complexity Level**
	#	*kg*	*%*			*#*
Roof	1	11.52	45%	140 MPa Steel	Transfer	1
Rain roof side inner R&L	2	1.50	45%	140 MPa Steel	Transfer	1
Reinf roof panel rear	1	0.59	45%	140 MPa Steel	Progressive	1
Frame back window upper	1	0.84	45%	140 MPa Steel	Progressive	1
Reinf roof panel center	1	0.76	45%	140 MPa Steel	Progressive	2
Panel w/shield header	1	0.93	45%	140 MPa Steel	Progressive	1
Inserts	32	0.80	45%	140 MPa Steel	Progressive	1
Hood Outer	1	10.43	15%	140 MPa Steel	Transfer	1
Hood Inner	1	4.60	55%	140 MPa Steel	Tandem	3
Brackets	4	0.05	15%	140 MPa Steel	Progressive	1
Decklid Outer	1	7.93	15%	140 MPa Steel	Transfer	1
Decklid Inner	1	3.62	55%	140 MPa Steel	Tandem	3
Brackets	4	0.05	15%	140 MPa Steel	Progressive	1

9.2 Total production cost of lightweight bodies

TOTAL COST						
Production volume [parts/year]	**Steel Unibody**	**Light Steel Unibody**	**CO-CIV**	**CIV**	**Aluminum Unibody**	**Carbon-CIV**
15,000	$4,786	$4,726	$4,713	$4,508	$5,244	$4,880
20,000	$3,788	$3,738	$3,849	$3,666	$4,234	$4,017
25,000	$3,196	$3,153	$3,296	$3,229	$3,649	$3,674
30,000	$2,800	$2,774	$3,008	$3,005	$3,286	$3,455
35,000	$2,545	$2,495	$2,722	$2,740	$3,011	$3,179
60,000	$1,914	$1,909	$2,145	$2,265	$2,428	$2,667
80,000	$1,689	$1,677	$1,921	$2,073	$2,226	$2,472
100,000	$1,571	$1,585	$1,799	$1,966	$2,097	$2,373
125,000	$1,486	$1,478	$1,751	$1,929	$2,021	$2,355
200,000	$1,407	$1,417	$1,646	$1,837	$1,943	$2,252

9.3 *Mass of body and propulsion systems for 75 and 95 W/kg vehicle performance*

		@ 75 W/kg	Mass of propulsion system				
Body Design	**Mass of body [kg]**	**Power of powertrain [kW]**	**Gasoline engine [kg]**	**Diesel engine [kg]**	**Hybrid [kg]**	**Hydrogen Fuel Cell [kg]**	**Methanol Fuel Cell [kg]**
Steel Unibody	350.22	110.11	148.38	173.24	523.17	369.22	680.67
Light Steel Unibody	257.91	99.73	140.31	165.00	393.47	333.38	614.60
CO-CIV	237.05	97.38	138.48	163.13	364.15	325.28	599.67
CIV	230.70	96.66	137.93	162.57	355.24	322.82	595.13
Aluminum Unibody	205.10	93.78	135.69	160.28	319.25	312.87	576.80
Carbon-CIV	161.59	88.89	131.88	156.39	258.12	295.98	545.66

		@ 95 W/kg	Mass of propulsion system				
Body Design	**Mass of body [kg]**	**Power of powertrain [kW]**	**Gasoline engine [kg]**	**Diesel engine [kg]**	**Hybrid [kg]**	**Hydrogen Fuel Cell [kg]**	**Methanol Fuel Cell [kg]**
Steel Unibody	350.22	139.47	171.20	196.56	889.91	518.39	1102.41
Light Steel Unibody	257.91	126.32	160.98	186.11	725.62	468.08	995.41
CO-CIV	237.05	123.35	158.67	183.75	688.49	456.70	971.22
CIV	230.70	122.44	157.96	183.03	677.19	453.24	963.87
Aluminum Unibody	205.10	118.79	155.13	180.13	631.61	439.29	934.18
Carbon-CIV	161.59	112.59	150.31	175.21	554.18	415.57	883.75

9.4 Environmental performance for 75 W/kg vehicle performance

GASOLINE: URBAN Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	3.249	0	3.249	10.09	23.31	538	13.77%
Light Steel Unibody	2.994	0	2.994	9.295	25.31	583.9	13.86%
CO-CIV	2.935	0	2.935	9.112	25.81	595.6	13.89%
CIV	2.917	0	2.917	9.056	25.97	599.3	13.90%
Aluminum Unibody	2.849	0	2.849	8.847	26.59	613.5	13.92%
Carbon-CIV	2.731	0	2.731	8.478	27.74	640.1	13.96%

GASOLINE: HIGHWAY Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	2.176	0	2.176	6.756	34.82	803.4	17.71%
Light Steel Unibody	2.036	0	2.036	6.321	37.21	858.6	18.06%
CO-CIV	2.004	0	2.004	6.222	37.80	872.3	18.15%
CIV	1.994	0	1.994	6.129	38.38	876.5	18.17%
Aluminum Unibody	1.957	0	1.957	6.077	38.71	893.2	18.27%
Carbon-CIV	1.894	0	1.894	5.88	40.00	923.1	18.44%

GASOLINE: COMBINED Driving Cycle @ 75 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	2.766	8.589	27.39	54.12
Light Steel Unibody	2.563	7.958	29.56	50.14
CO-CIV	2.516	7.812	30.11	49.23
CIV	2.502	7.767	30.28	48.95
Aluminum Unibody	2.448	7.600	30.95	47.89
Carbon-CIV	2.354	7.310	32.18	46.06

DIESEL: URBAN Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	2.322	0	2.322	6.505	36.16	538.8	20.67%
Light Steel Unibody	2.152	0	2.152	6.028	39.02	581.4	20.80%
CO-CIV	2.113	0	2.113	5.921	39.73	591.9	20.84%
CIV	2.1	0	2.1	5.884	39.98	595.6	20.86%
Aluminum Unibody	2.055	0	2.055	5.758	40.85	608.7	20.89%
Carbon-CIV	1.967	0	1.967	5.51	42.69	636.1	21.05%

DIESEL: HIGHWAY Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	1.658	0	1.658	4.644	50.65	754.7	24.32%
Light Steel Unibody	1.559	0	1.559	4.366	53.87	802.6	24.73%
CO-CIV	1.533	0	1.533	4.296	54.75	816	24.89%
CIV	1.525	0	1.525	4.273	55.05	820.1	24.94%
Aluminum Unibody	1.499	0	1.499	4.2	56.00	834.5	25.04%
Carbon-CIV	1.447	0	1.447	4.053	58.03	864.7	25.37%

DIESEL: COMBINED Driving Cycle @ 75 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	2.023	6.282	37.44	42.21
Light Steel Unibody	1.885	5.853	40.19	39.33
CO-CIV	1.852	5.750	40.90	38.64
CIV	1.841	5.717	41.14	38.41
Aluminum Unibody	1.805	5.604	41.97	37.65
Carbon-CIV	1.733	5.381	43.71	36.16

GASOLINE HYBRID: URBAN Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	1.257	-0.0168	1.183	3.673	64.04	539.6	33.18%
Light Steel Unibody	1.160	-0.0050	1.138	3.533	66.58	584.9	31.83%
CO-CIV	1.138	-0.0024	1.128	3.501	67.18	596	31.52%
CIV	1.133	-0.0021	1.124	3.489	67.42	598.6	31.44%
Aluminum Unibody	1.110	0.0002	1.111	3.449	68.21	611.1	31.05%
Carbon-CIV	1.069	0.0041	1.087	3.375	69.70	634.8	30.43%

GASOLINE HYBRID: HIGHWAY Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	0.989	0.012	1.041	3.231	72.79	685.7	26.47%
Light Steel Unibody	0.943	0.015	1.009	3.132	75.11	719.1	25.84%
CO-CIV	0.935	0.015	1.002	3.112	75.58	725.9	25.67%
CIV	0.932	0.016	1.000	3.106	75.73	728.1	25.61%
Aluminum Unibody	0.916	0.018	0.994	3.085	76.23	740.9	25.37%
Carbon-CIV	0.882	0.023	0.985	3.059	76.89	768.8	24.88%

GASOLINE HYBRID: COMBINED Driving Cycle @ 75 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	1.119	3.474	67.70	21.89
Light Steel Unibody	1.080	3.352	70.16	21.12
CO-CIV	1.071	3.326	70.72	20.96
CIV	1.068	3.316	70.92	20.90
Aluminum Unibody	1.058	3.285	71.60	20.70
Carbon-CIV	1.041	3.233	72.76	20.37

DIESEL HYBRID: URBAN Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	1.019	-0.0167	0.956	2.677	87.85	532	41.00%
Light Steel Unibody	0.940	-0.0047	0.922	2.583	91.06	576.9	39.22%
CO-CIV	0.923	-0.0023	0.914	2.562	91.83	587.3	38.79%
CIV	0.919	-0.0020	0.911	2.553	92.14	590	38.70%
Aluminum Unibody	0.900	0.0004	0.901	2.525	93.15	602.5	38.20%
Carbon-CIV	0.867	0.0044	0.883	2.475	95.05	625.6	37.36%

DIESEL HYBRID: HIGHWAY Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	0.804	0.012	0.849	2.378	98.93	674.4	32.43%
Light Steel Unibody	0.767	0.015	0.824	2.307	101.94	706.6	31.60%
CO-CIV	0.760	0.015	0.819	2.294	102.55	713.3	31.38%
CIV	0.758	0.016	0.817	2.289	102.75	715.4	31.32%
Aluminum Unibody	0.738	0.020	0.815	2.283	103.02	734.5	30.90%
Carbon-CIV	0.717	0.024	0.807	2.262	103.99	756.2	30.32%

DIESEL HYBRID: COMBINED Driving Cycle @ 75 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	0.908	2.818	83.47	18.93
Light Steel Unibody	0.878	2.725	86.31	18.31
CO-CIV	0.871	2.705	86.94	18.18
CIV	0.869	2.698	87.18	18.13
Aluminum Unibody	0.862	2.678	87.83	17.99
Carbon-CIV	0.849	2.637	89.21	17.72

HYDROGEN FC: URBAN Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	1.06	-0.0873	0.921			396.3	48.81%
Light Steel Unibody	0.96	-0.0629	0.864			436.1	47.87%
CO-CIV	0.94	-0.0560	0.851			447.3	47.65%
CIV	0.93	-0.0542	0.847			450.5	47.58%
Aluminum Unibody	0.91	-0.0466	0.831			464.4	47.28%
Carbon-CIV	0.86	-0.0365	0.804			487.7	46.77%

HYDROGEN FC: HIGHWAY Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	0.758	-0.0156	0.733			556.4	41.69%
Light Steel Unibody	0.711	-0.0096	0.696			591.4	41.33%
CO-CIV	0.701	-0.0081	0.688			600.2	41.21%
CIV	0.698	-0.0078	0.685			602.8	41.19%
Aluminum Unibody	0.685	-0.0060	0.676			614.1	41.05%
Carbon-CIV	0.663	-0.0028	0.659			634.2	40.81%

HYDROGEN FC: COMBINED Driving Cycle @ 75 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	0.837	2.598	90.54	0
Light Steel Unibody	0.788	2.448	96.10	0
CO-CIV	0.778	2.414	97.42	0
CIV	0.774	2.404	97.84	0
Aluminum Unibody	0.761	2.363	99.52	0
Carbon-CIV	0.739	2.294	102.54	0

METHANOL FC: URBAN Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	1.965	-0.1135	1.568	9.848	23.88	368.3	32.98%
Light Steel Unibody	1.795	-0.0889	1.484	9.321	25.23	403.2	32.01%
CO-CIV	1.755	-0.0829	1.465	9.201	25.56	412.3	31.78%
CIV	1.744	-0.0816	1.459	9.162	25.67	414.8	31.72%
Aluminum Unibody	1.693	-0.0727	1.438	9.036	26.03	427.5	31.35%
Carbon-CIV	1.608	-0.0592	1.401	8.799	26.73	449.9	30.79%

METHANOL FC: HIGHWAY Driving Cycle @ 75 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	1.333	-0.0219	1.256	7.893	29.80	542.8	27.02%
Light Steel Unibody	1.252	-0.0164	1.195	7.504	31.35	578	26.65%
CO-CIV	1.236	-0.0159	1.180	7.416	31.72	585.2	26.57%
CIV	1.232	-0.0156	1.177	7.396	31.80	587.5	26.52%
Aluminum Unibody	1.211	-0.0146	1.160	7.286	32.28	597.5	26.42%
Carbon-CIV	1.170	-0.0103	1.134	7.122	33.03	618.6	26.14%

METHANOL FC: COMBINED Driving Cycle @ 75 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	1.428	4.433	53.06	26.64
Light Steel Unibody	1.354	4.203	55.96	25.26
CO-CIV	1.337	4.151	56.67	24.94
CIV	1.332	4.136	56.87	24.85
Aluminum Unibody	1.313	4.077	57.69	24.50
Carbon-CIV	1.281	3.976	59.15	23.89

9.5 Environmental performance for 95 W/kg vehicle performance

GASOLINE: URBAN Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	3.653	0	3.653	11.34	20.74	478.6	12.24%
Light Steel Unibody	3.361	0	3.361	10.44	22.53	520.1	12.35%
CO-CIV	3.293	0	3.293	10.22	23.02	530.9	12.38%
CIV	3.272	0	3.272	10.16	23.15	534.2	12.39%
Aluminum Unibody	3.196	0	3.196	9.923	23.70	546.9	12.41%
Carbon-CIV	3.061	0	3.061	9.503	24.75	571.1	12.46%

GASOLINE: HIGHWAY Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	2.407	0	2.407	7.472	31.48	726.3	16.01%
Light Steel Unibody	2.245	0	2.245	6.07	38.75	778.7	16.37%
CO-CIV	2.207	0	2.207	6.854	34.32	791.9	16.48%
CIV	2.196	0	2.196	6.82	34.49	795.9	16.50%
Aluminum Unibody	2.154	0	2.154	6.687	35.17	811.6	16.60%
Carbon-CIV	2.081	0	2.081	6.46	36.41	840.2	16.79%

GASOLINE: COMBINED Driving Cycle @ 95 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	3.092	9.601	24.50	60.50
Light Steel Unibody	2.859	8.876	26.50	55.93
CO-CIV	2.804	8.707	27.01	54.87
CIV	2.788	8.656	27.17	54.54
Aluminum Unibody	2.727	8.467	27.78	53.36
Carbon-CIV	2.620	8.135	28.91	51.26

DIESEL: URBAN Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	2.634	0	2.634	7.379	31.88	475	18.22%
Light Steel Unibody	2.438	0	2.438	6.83	34.44	513.2	18.36%
CO-CIV	2.394	0	2.394	6.706	35.08	522.6	18.39%
CIV	2.379	0	2.379	6.665	35.29	525.8	18.42%
Aluminum Unibody	2.327	0	2.327	6.52	36.08	537.5	18.44%
Carbon-CIV	2.224	0	2.224	6.231	37.75	562.4	18.62%

DIESEL: HIGHWAY Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	1.842	0	1.842	5.159	45.59	679.3	21.89%
Light Steel Unibody	1.727	0	1.727	4.839	48.61	724.3	22.32%
CO-CIV	1.697	0	1.697	4.755	49.47	737.1	22.48%
CIV	1.688	0	1.688	4.73	49.73	740.9	22.53%
Aluminum Unibody	1.658	0	1.658	4.646	50.63	754.4	22.64%
Carbon-CIV	1.597	0	1.597	4.474	52.57	783.4	22.99%

DIESEL: COMBINED Driving Cycle @ 95 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	2.278	7.072	33.26	47.52
Light Steel Unibody	2.118	6.576	35.77	44.19
CO-CIV	2.080	6.459	36.41	43.40
CIV	2.068	6.421	36.63	43.15
Aluminum Unibody	2.026	6.290	37.39	42.27
Carbon-CIV	1.942	6.029	39.01	40.51

GASOLINE HYBID: URBAN Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	1.179	-0.0071	1.148	3.563	66.01	575.4	32.10%
Light Steel Unibody	1.089	0.0026	1.101	3.417	68.84	623.2	30.73%
CO-CIV	1.070	0.0040	1.088	3.377	69.65	633.8	30.47%
CIV	1.065	0.0046	1.085	3.370	69.80	637.1	30.34%
Aluminum Unibody	1.041	0.0067	1.071	3.324	70.77	651.5	29.98%
Carbon-CIV	0.987	0.0153	1.055	3.275	71.82	687.1	29.08%

GASOLINE HYBRID: HIGHWAY Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	0.953	0.014	1.015	3.152	74.63	712	25.98%
Light Steel Unibody	0.893	0.022	0.992	3.080	76.38	759.3	25.08%
CO-CIV	0.883	0.023	0.986	3.061	76.84	768	24.90%
CIV	0.878	0.024	0.985	3.059	76.88	772.3	24.81%
Aluminum Unibody	0.867	0.025	0.978	3.036	77.48	782.6	24.57%
Carbon-CIV	0.835	0.031	0.969	3.008	78.18	812.8	24.09%

GASOLINE HYBRID: COMBINED Driving Cycle @ 95 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	1.088	3.378	69.63	21.29
Light Steel Unibody	1.052	3.265	72.04	20.57
CO-CIV	1.042	3.235	72.71	20.38
CIV	1.040	3.230	72.82	20.35
Aluminum Unibody	1.029	3.194	73.64	20.13
Carbon-CIV	1.016	3.155	74.55	19.88

DIESEL HYBRID: URBAN Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	0.956	-0.0069	0.930	2.605	90.31	567.2	39.56%
Light Steel Unibody	0.883	0.0026	0.893	2.501	94.04	614.1	37.80%
CO-CIV	0.868	0.0041	0.884	2.475	95.02	624.5	37.43%
CIV	0.884	0.0047	0.901	2.525	93.14	627.7	36.45%
Aluminum Unibody	0.844	0.0072	0.871	2.440	96.39	642.5	36.76%
Carbon-CIV	0.799	0.0161	0.861	2.411	97.57	678.2	35.56%

DIESEL HYBRID: HIGHWAY Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	0.775	0.014	0.829	2.321	101.32	699.8	31.79%
Light Steel Unibody	0.727	0.022	0.812	2.274	103.42	746.1	30.61%
CO-CIV	0.719	0.023	0.807	2.261	104.01	754.5	30.38%
CIV	0.715	0.024	0.807	2.261	104.02	758.8	30.24%
Aluminum Unibody	0.705	0.025	0.801	2.245	104.79	768.7	29.95%
Carbon-CIV	0.679	0.031	0.796	2.229	105.54	798.9	29.30%

DIESEL HYBRID: COMBINED Driving Cycle @ 95 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	0.884	2.746	85.67	18.45
Light Steel Unibody	0.856	2.659	88.46	17.87
CO-CIV	0.849	2.637	89.20	17.72
CIV	0.859	2.667	88.19	17.92
Aluminum Unibody	0.840	2.607	90.23	17.52
Carbon-CIV	0.831	2.581	91.13	17.34

HYDROGEN FC: URBAN Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	1.169	-0.122	0.974			360	50.24%
Light Steel Unibody	1.056	-0.096	0.903			398.6	49.32%
CO-CIV	1.028	-0.088	0.887			409.3	49.10%
CIV	1.017	-0.085	0.881			413.5	49.05%
Aluminum Unibody	0.986	-0.077	0.862			426.8	48.73%
Carbon-CIV	0.929	-0.062	0.829			452.9	48.20%

HYDROGEN FC: HIGHWAY Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	0.809	-0.0233	0.771			520.3	42.22%
Light Steel Unibody	0.753	-0.0166	0.726			559.1	41.80%
CO-CIV	0.742	-0.0160	0.716			567.2	41.68%
CIV	0.738	-0.0158	0.713			569.7	41.65%
Aluminum Unibody	0.725	-0.0147	0.701			580.6	41.49%
Carbon-CIV	0.698	-0.0109	0.680			602.9	41.24%

HYDROGEN FC: COMBINED Driving Cycle @ 95 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	0.883	2.741	85.82	0
Light Steel Unibody	0.823	2.556	92.01	0
CO-CIV	0.810	2.515	93.53	0
CIV	0.806	2.502	94.02	0
Aluminum Unibody	0.790	2.452	95.92	0
Carbon-CIV	0.762	2.366	99.39	0

METHANOL FC: URBAN Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	2.397	-0.1923	1.724	10.829	21.72	301.9	35.63%
Light Steel Unibody	2.184	-0.1612	1.620	10.175	23.12	331.3	34.75%
CO-CIV	2.129	-0.1513	1.599	10.047	23.41	339.8	34.47%
CIV	2.109	-0.1468	1.595	10.021	23.47	343.1	34.34%
Aluminum Unibody	2.051	-0.1387	1.566	9.834	23.92	352.7	34.08%
Carbon-CIV	1.939	-0.1188	1.523	9.568	24.58	373.1	33.44%

METHANOL FC: HIGHWAY Driving Cycle @ 95 W/kg							
Body Design	**Fuel Energy Use [MJ/km]**	**Battery Status [MJ/km]**	**Combined Energy Use [MJ/km]**	**Combined Fuel Consumption [L/100km]**	**Combined Fuel Economy [mpg]**	**Range (fuel only) [km]**	**Tank-to-Wheel Efficiency [%]**
Steel Unibody	1.553	-0.0435	1.401	8.798	26.73	466.1	27.74%
Light Steel Unibody	1.441	-0.0339	1.322	8.307	28.32	502	28.94%
CO-CIV	1.416	-0.0318	1.305	8.196	28.70	510.8	27.35%
CIV	1.409	-0.0311	1.300	8.167	28.80	513.6	27.31%
Aluminum Unibody	1.378	-0.0285	1.278	8.031	29.29	525	27.21%
Carbon-CIV	1.328	-0.0245	1.242	7.803	30.14	544.7	27.03%

METHANOL FC: COMBINED Driving Cycle @ 95 W/kg				
Body Design	**Equivalent Energy Use [MJ/km]**	**Gasoline Eq. Consumption [L/100km]**	**Gasoline Eq. Economy [mpg]**	**Cycle Carbon Emission [g C /km]**
Steel Unibody	1.578	4.901	47.99	29.45
Light Steel Unibody	1.486	4.614	50.98	27.72
CO-CIV	1.467	4.554	51.64	27.37
CIV	1.462	4.541	51.80	27.28
Aluminum Unibody	1.436	4.460	52.74	26.80
Carbon-CIV	1.397	4.337	54.24	26.06

References

1. Automotive News (1999). “Market Data Book 1999.” May 1999
2. Automotive News (2000). “Market Data Book 2000.” May 2000
3. AuYeung, F. (2000). “Future light-duty vehicles: Predicting their fuel consumption and assessing their potential.” MS thesis, Cambridge, MIT, June 2000
4. Ayres, G. (1999). “Consumer Incentives to Reduce Greenhouse Gas Emissions from Personal Automobiles.” Society of Automotive Engineers, Paper 1999-01-1307, 1999
5. Busch, J.V. (1987). “Technical Cost Modeling of Plastic Fabrication Processes.” Materials Science and Engineering. Cambridge, MIT, 1987
6. CARB (2001). “The California Low-Emission Vehicle Regulations for Passenger Cars, Light-Duty Trucks and Medium-Duty Vehicles.” California Air Resource Board, http://www.arb.ca.gov/msprog/levprog/levprog.htm
7. Clark, J.P., R. Roth et al. Eds. (1997). “Techno-Economic Issues in Materials Selection.” Materials Selection and Design. Materials Park, OH, ASM International
8. Davis, S.C. (1998). “Transportation Energy Data Book: Edition 18.” ORNL-6941, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 1998
9. DOE (2001a). Energy Information Administration. http://www.eia.doe.gov
10. DOE (2001b). H2 Information Network http://www.eren.doe.gov/hydrogen/faqs.html#cost
11. Ford Motor Company (1999). Press release http://www.ford.ca/english/LearnAbout/NewsReleases/pr19990219.asp
12. Guzzella, L. and A. Amstutz (1998). “Quasi-Stationaeren-Simulationen.” Matlab programs and text, Benutzteranleitung, Laboratorium fuer Motorsysteme, Institut fuer Energietechnik, ETH Zurich, 1998
13. Han, H.N. (1994). “The Competitive Position of Alternative Automotive Materials.” Materials Science and Engineering. Cambridge, MIT, 1994
14. Hoegh, H. (2000). “An Economic Analysis of Aluminum Sheet Production and Prospects of Aluminum for the Automotive Unibody.” Materials Science and Engineering. Cambridge, MIT, 2000
15. Jain, A. (1997). “An Analysis of Automotive Body Assembly Technologies and Their Implications in Lightweight Vehicle Development.” Materials Science and Engineering/Technology and Policy Program. Cambridge,MIT, 1997
16. Kang, P.J. (1998). “A technical and economic analysis of structural composite use in automotive body-in-white applications.” Technology and Policy Program. Cambridge, MIT 1998
17. Kelkar, A. (2000). “Analysis of Aluminum in Auto Body Designs and its Strategic Implications for the Aluminum Industry.” Technology and Policy Program. Cambridge, MIT, 2000

18. Kirchain, R.E. (1999). "Modeling Methods for Complex Manufacturing Systems: Studying the Effects of Material Substitution on the Automobile Recycling Infrastructure." Materials Science and Engineering, Cambridge, MIT, 1999

19. Kirchain, R.E. and F.R. Field III (2001). "Process Based Cost Modeling: Understanding the Economics of Technical Decisions." The Encyclopedia of Material Science & Engineering, Elsevier Science Publications, 2001

20. Newsome and Galliard (1998). "The optimum balance between automobile gas-oil and gasoline to minimize environmental impact." F98 P005, FISITA World Automotive Congress, Paris, 27 September - 1 October 1998

21. Opbroek, E. and U. Weissert (1998). "Ultra Light Steel Auto Closures: Progress Report." Society of Automotive Engineers, Paper 982308, 1998

22. OTA, Office of Technology Assessment (1995). "Advanced Automotive Technology: Visions of a Super-Efficient Family Car." September 1995, OTA-ETI-638, GPO stock #052-003-01440-8

23. Plotkin, S. (2000). "Technologies and Policies for Controlling Greenhouse Gas Emissions from the U.S. Automobile and Light Truck Fleet." Argonne National Laboratory, Center for Transportation Research. January 2000

24. PNGV (2001). Partnership for a New Generation of Vehicles, http://www.uscar.org/pngv

25. Politis, D. (1995). "An Economic and Environmental Evaluation of Aluminum Designs for Automotive Structures." Aeronautics and Astronautics. Cambridge, MIT

26. Roth, Richard (2001). Personal conversation

27. Stodolsky, F., A. Vyas, et al. (1995). "Life-Cycle Energy Savings Potential from Aluminum-Intensive Vehicles." Conference Paper, 1995 Total Life Cycle Conference & Exposition. October 16-19, 1995. Vienna, Austria

28. Thomas, C.E., B.D. James, et al. (1998). "Societal Impacts of Fuel Options for Fuel Cell Vehicles." SAE Paper No. 982496. Presented at Society of Automotive Engineers International Fall Fuel and Lubricants Meeting and Exposition, San Francisco, California, October 19-22, 1998

29. ULSAB (1997). Data distributed by the ULSAB organization

30. US ABC (2000). "United States Advanced Battery Consortium, Battery Criteria: Commercialization." http://www.uscar.org, May 2000

31. USDOT, U.S. Department of Transportation (1999). "Twenty-Fourth Annual Report to Congress." http://www.nhtsa.dot.gov/cars/problems/studies/fuelecon/

32. Veloso, F. (2001). "Local Content Requirements and Industrial Development: Economic Analysis and Cost Modeling of the Automotive Supply Chain." Technology and Policy Program. Cambridge, MIT 2001

33. Weiss, M. A., J.B. Heywood et al. (2000). "On the Road in 2020: A life-cycle analysis of new automobile technologies." Energy Laboratory Report #MIT EL 00-003, Energy Laboratory, MIT, October 2000