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DESIGN FOR SUSTAINABILITY: PRODUCT LIFE-CYCLE ANALYSIS IN ALUMINUM AUTO BODY APPLICATIONS

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ABSTRACT OF THESIS

DESIGN FOR SUSTAINABILITY: PRODUCT LIFE-CYCLE ANALYSIS IN ALUMINUM AUTO BODY APPLICATIONS

The scope of this work is to generate quantifiable measures of sustainability elements that apply to manufactured products in terms of environmental, social and economic benefits. This thesis presents a comprehensive analysis for developing a methodology to compare the costs encountered by a vehicle over its entire life-cycle (Pre-manufacturing, Manufacturing, Use, and Post-use stages), considering two different material scenarios, aluminum versus steel, used in body-in-white (BIW) structures and exterior body panels. The potential benefits of using lighter materials in auto body applications are further evaluated through a "Sustainability Scoring" method. The proposed six major integral sustainable elements considered in this work are: product's *environmental impact, societal impact, functionality, resource utilization and economy, manufacturability and recyclability/remanufacturabilit*y. Each of these elements has corresponding sub-elements and influencing factors which are categorized as having equal importance to the product.

KEYWORDS: Automotive Life-Cycle Stages**,** Aluminum, Weight Reduction, Recyclability, Sustainability Elements.

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THESIS

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PRODUCT LIFE-CYCLE ANALYSIS IN ALUMINUM AUTO BODY APPLICATIONS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
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at the University of Kentucky

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2007

To my family

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CHAPTER 1

INTRODUCTION

1.1 Sustainability

The need to implement sustainability principle in designing new products has become, more than ever, a matter of crucial importance in today's economy. From the extraction of raw materials through to the final use and disposal, sustainable or "green" products outweigh conventional products on their environmental and social intrinsic worth [1].

It was obvious that for some years companies were mainly interested in making profits at the expense of the environment. The economic aspect was, for decades, the primary concern for all industries. Once the global climate change has become an issue of critical awareness for all of us, the manufacturers clearly understood that to survive and prosper in the future, they must have both a good economy and a healthy environment. Consequently, making its products "green", a company can at the same time, increase its profits, and dramatically reduce the use of natural resources. "Sustainability" is not a barrier to achieve profitability. Rather "sustainability" is the driving force to achieve profitability [1]. According to the Sustainable Products Corporation in Washington DC, sustainable products can be considered more profitable than conventional products as much as ten times [2]. Therefore, selection of "friendly" environmental materials, waste minimization, energy efficiency, reduced operational costs, increased lifetime span, and end-of life issues are important criteria for designers, and those aspects need to be considered starting with the early design stage, in order to make the new products "sustainable".

All these requirements create a new challenge for all companies, in which the traditional concept of growth is being challenged by innovation. The conventional business imperative, to create value by reducing only manufacturing costs, is no longer adequate. As shown in Figure 1.1, by implementing sustainability principle, the shareholder value curve takes a steeper trend, implying not only the economical benefit of making “green” products, but also the overall benefit in terms of environment and society.

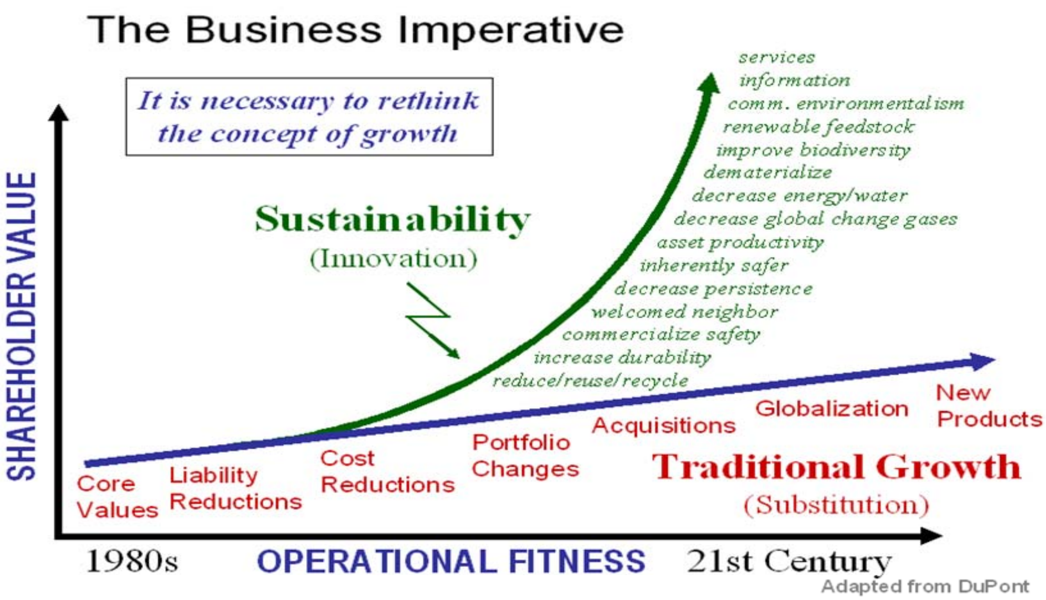

Figure 1.1: The new business imperative concept of growth [5]

The desire to achieve the most output using the least input has made the new challenge even more difficult. To achieve the optimum combination of economical, environmental, and societal benefits, the conventional three aspects of sustainability have become “pillars” of equal resistance in sustaining the new products and processes (Figure 1.2). Moreover, these "three pillars" creates a new framework in which designers and manufacturers are challenged to design and manufacture products which will benefit not only the economy and the environment, but also the society as a whole, because these products are cheaper to make, can be introduced quicker to the market, and are preferred by the public [1].

By integrating environmental requirements at various stages of the product manufacture, the companies adhere to the concept of sustainable development defined by the United Nation’s Brundtland commission (WBCD, 1987), as “meeting the needs of the present without compromising the ability of future generations to meet their own needs" [3].

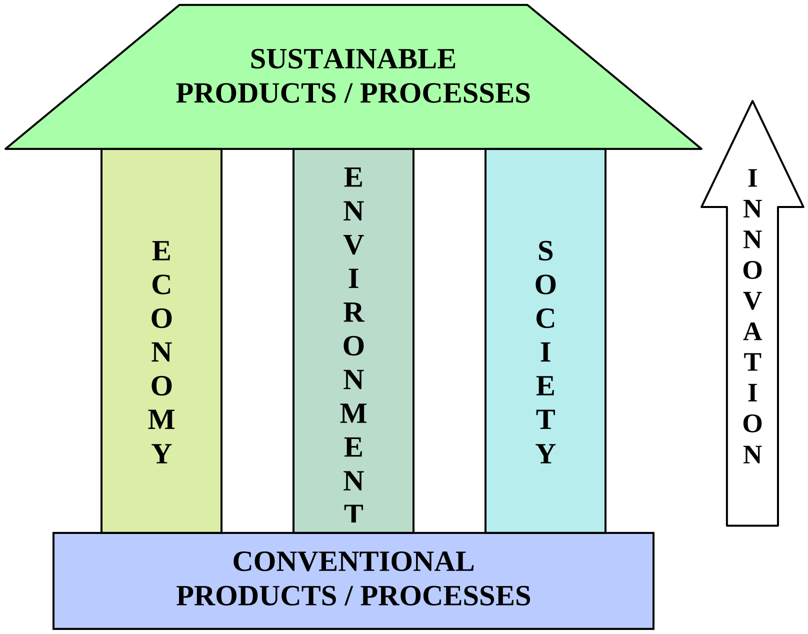

Figure 1.2: Basic elements for sustainable products and processes

1.2 Product Design for Sustainability

Since implementing sustainability principles in designing and manufacturing new products has become a priority for researchers and corporations, the need to build new models to quantify all the aspects of sustainability, has became a major issue. One such model was proposed by Jawahir and Wanigarathne at the University of Kentucky [4], showing the essential role of sustainable manufacture in overall sustainable development by illustrating how sustainable manufacture are inter-related to environment, economy and society (Figure 1.3).

According to Jawahir et al [5], the quantification of product sustainability becomes essential in understanding the" sustainability content" in a manufactured product. Even if there are many measurable methods to assess the environmental aspect of sustainability such as Life Cycle Assessment (LCA) method, in which the full environmental consequences of a product system is evaluated, there is no universally accepted method to quantify all the aspects of product sustainability [5]. The desire to assess all major aspects of sustainability, has pushed product designers to find new methods and tools to improve the existing standards and measurable factors in order to reduce the need for virgin raw materials, choose the right eco-friendly sources of energy, minimize wastes, and maximize the product end-of-life value [6].

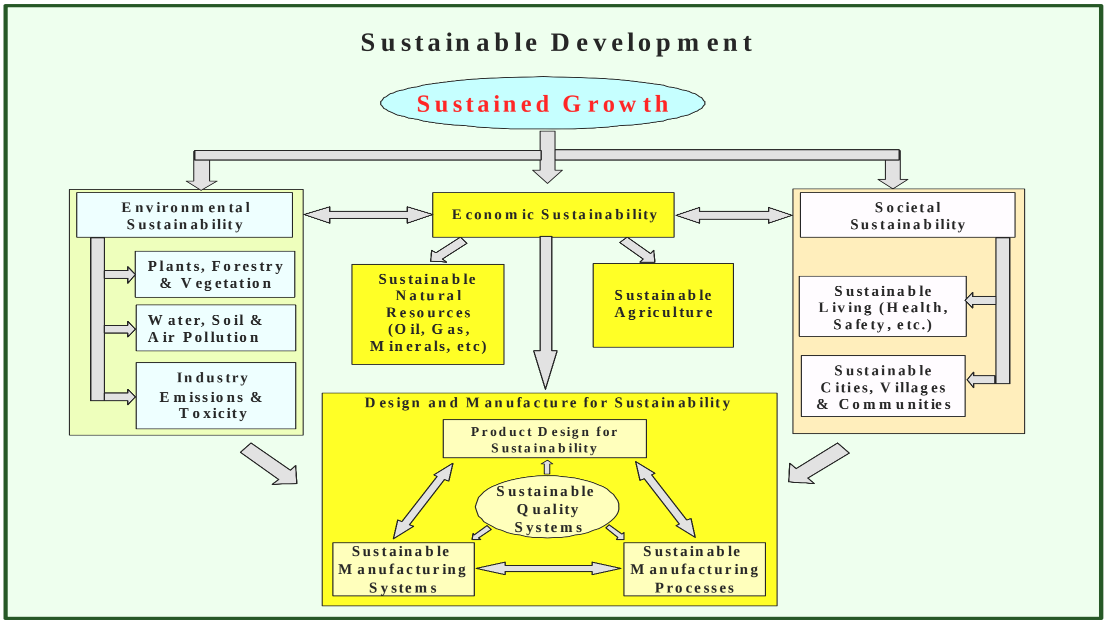

Figure 1.3: The role of sustainable manufacture in sustainable development [4]

All major efforts to improve the existing standards lead to a new concept design, called Design for Sustainability (DFS), which implies that for every step in the product design and development, new ideas have to be applied in order to achieve an optimum mix of sustainability measures in the final manufactured product. By applying sustainability principles early in the product design stage, product designers may identify the potential for multi life-cycle products or components as opposed to the traditional one life-cycle product. In other words, all manufactured products can be designed, manufactured, assembled, used and serviced/maintained/upgraded, and at the end of its life-cycle, these products can also be effectively disassembled, recycled, reused/remanufactured, and allowed to go through another cycle, or more [5].

In order to adhere to the multi life-cycle concept, it is essential that manufacturers make informed material choice decisions. Selecting the right material will become a crucial requirement in producing the new sustainable products. For instance, the two most significant requirements for materials selection and design in today's automotive industry are the use of light weight materials and the use of recycled and reused materials.

A research initiative aimed at developing a new sustainability framework is underway at the University of Kentucky, where the traditional 3R concept (Reuse, Reduce, and Recycle) has been extended to a more comprehensive and sustainable 6R concept (Recover, Reuse, Recycle, Redesign, Reduce, and Remanufacture) as shown in Figure 1.4 [5, 6]. The figure below yields two major outcomes: different design elements are associated with the life-cycle of a product, and multi-life cycles can be associated with a single product.

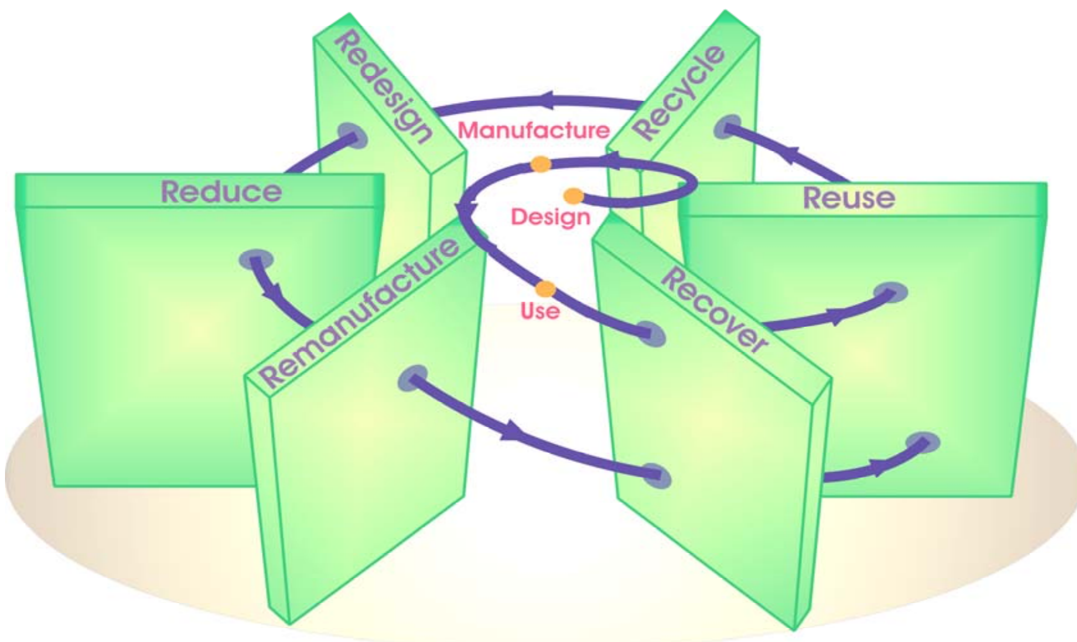

Figure 1.4: Multi life-cycle concept [5]

A more recent paper by Joshi et al [7] shows the economic benefit to manufacturers and consumers in adopting the 6R methodology at all four stages of life-cycle.

With regard to manufacturing, it also needs to be transformed from traditional manufacturing to sustainable manufacturing. As shown in Figure 1.5 additional phases must be added besides the traditional product life-cycle phases and innovation in management must complete the necessary requirements needed for a product to be ecologically competitive [8].

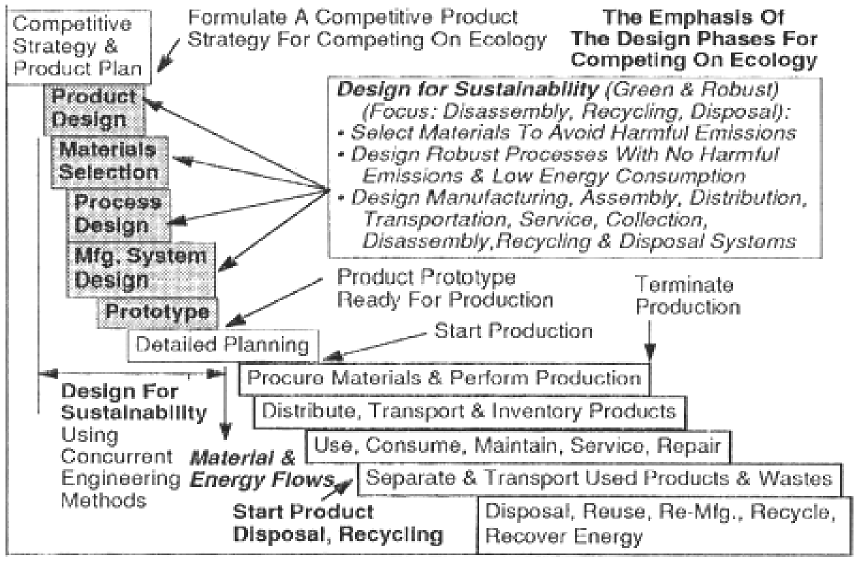

Figure 1.5: Product life-cycle phases for competing on ecology [8]

To successfully implement sustainable products, it is also essential to educate our society and customers to preserve the product’s value during the use stage and to assure that the product will enter the recovery stream at the end of its useful life [5].

1.3 Automotive Life-Cycle Stages

The product life-cycle stages include activities associated with material acquisition and primary material processing, manufacturing, use, and post-use activities. Since automotive applications make the object of this study, the automobile life-cycle stages are further referred to.

The life-cycle for an automobile begins with material production or pre-manufacturing stage, which includes resource extraction and primary material processing activities. Being by far, the dirtiest stage of the life-cycle, activities such as mining of minerals, their transportation from virgin ore sites to the first refining processes, and fabrication of raw materials (e.g., sheet, extrusions and castings) are highly energy-intensive. Apart from being highly energy intensive, these activities are also not environmentally-friendly operations resulting in a variety of environmental and societal burdens.

The manufacturing stage for automotive applications involves producing and assembling the parts into sub-assemblies and assemblies. Forming and stamping machinery, which transform the raw material into automotive parts and the assembly of parts into sub-assemblies by joining or fastening operations, require energy to power and operate the equipment. Since, solid and liquid wastes associated with this stage, such as the amount of material removed as a result of forming, trimming and machining operations, and the different compounds used to cool down the work material, are the subjects of continued research, being approximately entirely recycled and reused, the only major environmental burden associated with this stage is the gaseous effluents resulted from the use of electricity.

The use and service stage dominates overall environmental impacts of the vehicle across its life-cycle. Petroleum refining and combustion are considered primary sources of environment effluents. Beside the combustion of gasoline which results in tailpipe emissions, the usage and services phase also include: components for running an automobile such as oils, fluids, additives or lubricants and replacement parts such as tires, hoses, lights, belts, batteries, and filters. All these components and replacement parts, most of the time, end-up being dumped in landfill.

At the end of its useful life, an automobile typically enters the recycling infrastructure, which consists of automotive parts and scrap dismantlers, automotive parts remanufactures, automobile shredders, and automotive materials recyclers [9]. Approximately 95 percent of the cars and trucks are currently returned to dismantling and shredding facilities [9]. The dismantlers remove reusable parts and some recyclable materials from the vehicles for resale, remanufacturing or recycling, before sending what is left – the “hulks” – to the shredders. The shredders rip the hulk into small pieces and recover much of the metal for recycling. What is left, known as the automotive shredder residue (ASR or fluff), is a low density material consisting of textiles, rubber, wood, plastics and dirt that is usually sent to the landfill [10].

The material flow along with the major life-cycle stages for automotive industry is schematically illustrated in Figure 1.6. Three closed-loop systems can be identified, which show the basic options for automotive manufacturers, once sustainability principles have been implemented in vehicle's design. The first closed-loop system, in which certain parts from end-of-life vehicles can be re-used, is considered to be the most economical option.

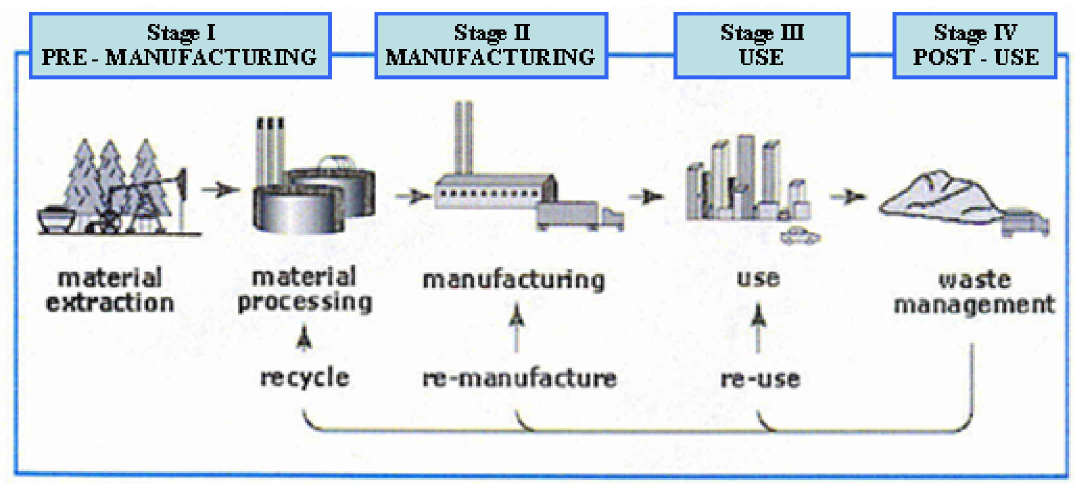

Figure 1.6: Automotive life-cycle stages (Adapted from [11])

1.4 Scope of Current Work

Automotive product design continues to evolve, and it has been well-accepted that light-weight materials can save fuel consumption, improve vehicle performance and increase safety. Understanding manufacturing costs alone is no longer adequate for manufactured products and processes. The growing emphases on the total cost and environmental impact have in recent times placed the total life-cycle cost issue to the forefront as a major driving factor. In addition, the drive to decrease the cost of metals used in the automotive manufacture through greater recycling is continually encouraged and publicized. Therefore, this work is aimed at comparing the life-cycle costs and the potential for environmental improvement in manufacturing selected automotive components. The traditional use of steel is compared against the applications of aluminum alloys by considering the total costs in four major life-cycle stages: pre-manufacturing (materials processing), manufacturing, use and post-use. Also, the likely environmental impact of using aluminum versus steel will be discussed along with the societal benefits of sustainable manufacture. The potential benefits of using lighter materials in autobody structures are evaluated through a “sustainability” scoring method.

CHAPTER 2

LITERATURE REVIEW

2.1 Summary of Previous Work

Since physical properties, costs, and producibility are important criteria which make a material suitable for the automotive application, researchers have long been focusing on understanding the full range of benefits and drawbacks, for a new generation of materials likely to have the potential for replacing the current heavy materials used in auto vehicles construction.

As the gas price is continuously rising, the main concern for automobile manufacturers today has become the attempt to improve the vehicle's fuel consumption. A lot of research has already been done to achieve this goal, including the change from rear-wheel drive to front-wheel drive, improved engine design for improved fuel economy, improved aerodynamics, tires and lower rolling resistance, transmission technologies, fuel injection and increased use of lighter materials [12]. Many of these measures have already been implemented in the production of vehicles, however, reducing the vehicle's weight by using lighter materials for body and chassis components seems to be one area that promises important improvements in fuel economy for the future cars [12].

Stodolsky et al identified at least three ways to decrease the weight of a vehicle in order to improve its fuel consumption: reduce its size, optimize its design to minimize weight, and replace the heavy materials currently used in its construction with lighter mass equivalents. Since safety and performance are important features for the American customers who have shown interest for bigger cars, the first two options are not of real interest for automakers. Thus, they have been forced to investigate new alternative materials to reduce vehicle weight without sacrificing vehicle utility [12].

In the early to mid-nineties, Kurihara Yuri [13 - 15] provided, in a series of three articles, a thorough analysis, of the future of the automotive industry and aluminum's role in automobile weight reduction technology. This study concluded that apart from the cost barrier to produce virgin material, aluminum generally satisfies the necessary conditions to be the new material of choice for automotive industry. Once the electrolytic method of producing aluminum will be altered and aluminum can be produced at much lower prices, the demand for the metal would rapidly emerge in the automotive industry.

The selection of new materials for automobiles is driven by a series of techno-economic issues. According to Arnold [16], when part of the body-in-white is replaced with a different material, there are so many changes in the design and manufacturing processes that the expense and risk of using new materials may outweigh the benefits. However, according to the same source, the best strategy for offsetting the risk and costs against the benefits of new technology is to apply it where the current technology remains an acceptable alternative.

Han and Clark [17] developed a methodology for comparing lifetime costs and benefits associated with the use of alternative materials in automotive applications by focusing on steel and primary (virgin) aluminum in the unibody body-in-white (BIW) design. The BIW structure and included body panels are considered an assembly in which aluminum could potentially replace the traditional steel. The study concluded that aluminum's cost advantages in the use and post-use stages, due to primary weight savings and the higher metal scrap value, do not completely offset the cost disadvantages incurred by materials during production and processing stages. However, the study recognizes that reducing the weight of the body-in-white can have significant effect upon its lifetime monetary cost, as the gas price increases and vehicle lives are extended. Moreover, this study fails to identify both the economical and the environmental benefits of using recycled metallic materials in the body structure, since there is an obvious and growing post-use management concern.

Dieffenbach and Mascarin [18] analyzed the comparative life-cycle costs of mid-size four-door sedans for different automotive body designs and exterior closure panels - made from steel, aluminum and plastics. This study identifies fuel consumption as having the primary impact on the post-manufacturing portion of the life-cycle. Repair costs do not differ significantly from one material to another, and post-use costs are minimal compared to fuel consumption. Concerning the vehicle's design, the study concludes that steel unibody is the choice for design for high production volumes. Once aluminum spaceframe design's technology evolves, it has the potential to replace steel unibody at medium and low production volumes. The aluminum unibody becomes the choice of design if spaceframe technology fails to expand and additional importance is placed on weight savings and fuel economy. Regarding exterior panels, steel dominates at medium to high volumes, with continued challenges from plastic at lower volumes. Aluminum sheets compete only when weight savings are important.

Mariano et al [19] investigated the cost sensitivity of three body-in-white designs: a steel unibody, an aluminum unibody and an aluminum spaceframe assembly function of the key parameters affecting the body-in-white manufacturing costs and the vehicle-life costs. The steel unibody costs much less to manufacture than the aluminum unibody at all production volumes. For small production volumes (i.e., less than 40,000 vehicles per year), the spaceframe design has lower manufacturing costs than the steel unibody and lower manufacturing costs than the aluminum unibody at volumes less than 150,000 vehicles per year. Considering vehicle-life costs, the steel unibody has the highest cost for all production volumes. The aluminum unibody has the lowest cost for all production volumes greater than 90,000 vehicles per year, and spaceframe design the lowest cost at lower production volumes.

In order to understand how manufacturing costs influence the material and design changes, it is shown that the unibody designs are more sensitive to material-price variations than the spaceframe design. All three designs show high sensitivity to body-in-white piece count and production volume, but none of the body-in-white manufacturing costs are sensitive to scrap price, tooling costs, or percentage of scrap from stamping.

Regarding assembly, manufacturing cost is sensitive to the body-in-white assembly rate but not as sensitive to the number of joints per part. As long as vehicle-life costs are concerned, both aluminum unibody and spaceframe have lower costs than the steel unibody. Among the parameters that significantly affect the vehicle-life costs, variations in fuel price and body-in-white weight have the most significant impact. Secondary weight savings have less effect. At the end of the vehicle's useful life, closed-loop recycling, where each material is returned to its original use, reduces directly the initial material price, affecting significantly the body-in-white manufacturing cost. Open-loop recycling, where materials are returned as general scrap, has low impact on vehicle-life cost.

Kelkar et al [20] compared and analyzed the manufacturing costs (fabrication and assembly) of aluminum and steel auto bodies in two classes (small, fuel-efficient designs and mid-size designs) considering current primary aluminum price and using current aluminum fabrication technology. This study identified two keys obstacles for aluminum to become a substitute for steel: higher material cost and higher tooling costs for aluminum panels and stated that it is unclear which aluminum design (spaceframe design or unibody design) is economically better suited for mass production. It is believed that, in order to produce an aluminum car with the same overall manufacturing costs as steel, the price of aluminum must decrease to about $ 1 per pound ($2.2 per kg.). However, aluminum has the potential to become the primary material used in the auto body structures once the new legislation forces automakers to improve fuel economy and to consider easy to recycle materials.

Apart from the monetary cost dimension, previous research also focused on evaluating environmental or health dimension for the entire life-cycle of the body-in-white applications.

Han [21] extended the previous cost analysis for aluminum and steel BIWs and included the lifetime environmental impact of these two structures. It is shown that producing

virgin steel generates much less environmental damages in terms of power consumption, gaseous, solid and liquid residues as compared to producing primary aluminum.
Since the manufacturing and assembly processes differ only slightly, the environmental burdens are quite similar for both materials. The use stage of the BIW life generates the most environmental problems in terms of gaseous emissions. Petroleum refining and combustion are assumed to be the two primary sources of effluents. Having a fuel consumption improvement, the study concludes that aluminum BIW generates less atmospheric emission than steel BIW during the total operational stage. For post-use stage environmental burdens for recycling aluminum BIW structure are lower compared to recycling steel BIW. Whether aluminum generates sufficient environmental and health benefits to offset its cost disadvantage is difficult to predict since these benefits must be weighed against the monetary cost.

Das [22] compared the energy usage and carbon dioxide emission for body-in-white applications made from conventional steel, aluminum and ultra light steel auto body (ULSAB) at both the vehicle and fleet levels. The study yield a major conclusion: the benefits of using aluminum in automotive components are significantly reduced when compared to the ULSAB counterpart than when compared to the traditional steel. Regarding the energy usage, the benefits of the lower energy used during the use stage, are voided by the higher manufacturing energy of aluminum, leaving the energy saved during the recycling stage the main contributor to the total life-cycle benefits of aluminum. In terms of carbon dioxide emissions, steel and ULSAB advantages in the early life-cycle years, due to their relatively low energy use and emissions during the manufacturing stage, diminish each year because of better fuel efficiency of aluminum BIW. From both the energy and carbon dioxide emissions perspective, it would take about four years and ten years, respectively, for aluminum vehicles to achieve life-cycle equivalence with steel and the ULSAB. At fleet level, the benefits of aluminum are delayed, because vehicle replacement occurs over several years rather than all at once.

Important research in lightweight materials is also being pursued by major U.S., Japanese, and European automakers. Audi A8 and Jaguar XJ are two examples of the most known all aluminum vehicles. Ford is also an active partner in different development programs on new generation of vehicles. The Ford-Reynolds Contour and the Audi-Alcoa are the most known projects to develop and manufacture new commercially available body designs such as spaceframe design [19].

2.2 Sustainable Aluminum

Aluminum is no question a sustainable material, being the third most common element found in the earth's crust, after oxygen and silicon [23]. At the current primary aluminum production level, known bauxite reserves will last for hundreds of years [24, 25]. At the end of their useful life, products made from aluminum can be recycled without any loss of quality to produce new products [26]. For instance, it is assumed, that more than 70 percent of the aluminum used in today's vehicles is sourced from recycled metal [26, 27], and data from the Audi Company claims that 34 kg of the 38 kg car chassis is used for the second time [28]. The increasing use of recycled metal saves both energy and natural resources needed for primary production. The recycling of aluminum requires only 5% of the energy to produce secondary metal as compared to primary metal and generates only 5% of the green house gas emissions associated with primary production [29-31].

This property of aluminum to be recycled again and again means that the world's increasing stock of aluminum acts like an "energy resource bank" over time, delivering more and more practical use and value from the energy embodied in the metal at the time of its manufacture. In 2002 was estimated that over 200,000,000 tones of aluminum was being in use and eventually will be available as scrap [25].

Apart from being environmentally friendly, aluminum possesses other characteristics which make it an interesting candidate to replace steel in automotive body structures such as: three times lower density, a high corrosion resistance, and a high degree of utilization reaching 85 – 95% [28].

According to The Aluminum Association's Auto & Light Truck Group (ALTG), aluminum is the green choice for automotive materials. It is proven to safely lighten vehicles for better fuel economy and reduced green house emissions [32]. It is assumed, as a general rule, that a 10 percent weight reduction in the vehicle's mass can increase the vehicle's fuel economy up to 8 percent or as much as 2.5 extra miles per gallon. [33, 34].

Despite, the fact that the use of aluminum in the structure of automobiles was slowed down by two factors: the cost of aluminum alloys and the difficulties in manufacturing car bodies under the conditions of large-scale production [28], there is no doubt that over the years the amount of aluminum used by automotive applications continued to grow steadily. Aluminum use has risen from 183 pounds per vehicle in 1991 to more than 319 pounds in 2006 as shown in Figure 2.1, and has become the second most used material in light vehicles after steel [32, 35].

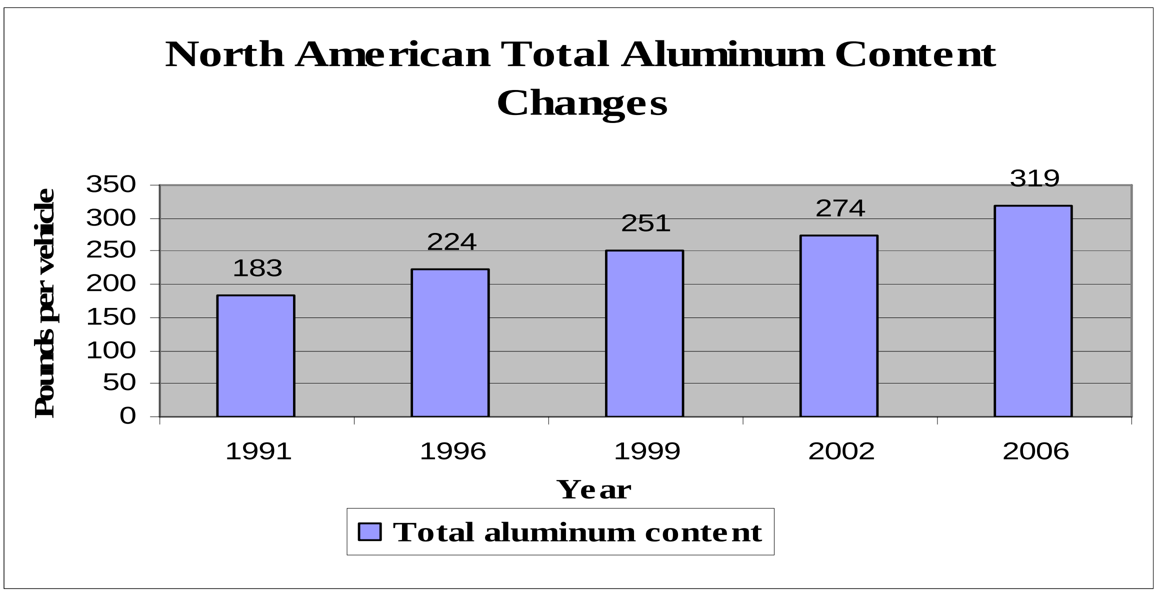

Figure 2.1: North American total aluminum content change [32, 35]

Today, the mass fraction of aluminum in a car is about 6% and aluminum components primarily replace steel components in the engine compartment, transmission housing, and wheels, making cast aluminum the major form of aluminum used in vehicles in North America [28, 36]. It is estimated that castings make up for more than 75 % of the total aluminum used in a car [36], and the current distribution of aluminum use by product form in automotive applications is made up of about 74 % cast aluminum, 23 % extruded aluminum and about 4 % rolled aluminum [37].

However, the greatest gain in reducing the vehicle's weight (up to 45%) will be achieved by increasing the use of sheet and pressed semiproducts from aluminum alloys in the car bodies [28]. Sheet material could grow significantly if used as part of the body-in-white or as separate closure panels. Extrusions could also grow if new designs for the BIWs, either aluminum spaceframe designs or aluminum unibody designs, are to be considered by automakers in the future [36]. According to Gesing and Wolanski [29], weight savings achieved from replacing steel with aluminum translates into improved fuel economy and reduced greenhouse gas emissions, while offering the same or better stiffness and crashworthiness.

2.3 Regulations in the US Automotive Industry

2.3.1 Current Industry Practice

Replacing wood and canvas used in the construction of early automobiles, steel has long become the primary material used by automotive industry. Consequently, the automotive manufacturers and suppliers have invested a lot of research and capital in developing and improving the existing manufacturing technologies on iron and steel and have continued to make product innovation.

Being the major material used in the structure of automobiles for many years, mainly due to its production cost advantage, and having the existing manufacturing and design facilities under continuous research and improvement, steel has proven to have a relatively large cost saving edge as compared to aluminum and therefore, has become a preferred material in the automotive industry. In addition to cost advantage, steel industry claims the easy recyclability of the metal. Steel and iron components make up about 65 percent of the average car by weight and virtually 100 percent of the steel used can be recycled [38]. Recycling steel saves not only energy but also natural resources. The steel used in automobiles contains recycled material because steel scrap (old steel) is a necessary ingredient in the production of new steel and about 25 percent of the steel used in car bodies is made with recycled steel [38]. In addition to being one of the most recycled materials in the world, the production of virgin steel is known to generate less carbon dioxide than analogous materials.

However, much debate and confusion created an unpublished analysis conducted by the Massachusetts Institute of Technology in 1999 which stated that it would take about 40 years for a fleet of aluminum intensive vehicles to pay back its energy production deficit [39] and a statement from the American Iron and Steel Institute (AISI) press conference which appeared in a press article "Study crushes idea for aluminum vehicle" that producing one ton of virgin aluminum generates about 10 times more carbon dioxide emissions than the production of a ton of steel [40]. Even though the results have been later reviewed, the automotive industry continued to show preference for using steel, as the cost issue of producing aluminum continued to be the main obstacle.

Moreover, once aluminum has become a real threat, the American Iron and Steel Institute (AISI) have also intensified the research for finding new ways to optimize the use of steel in auto body structures. One solution to the environmental challenge facing automakers today proposed by steel industry is the Ultra Light Steel Auto Body (ULSAB), which is claimed to be 25% lighter than conventional steel [22].

2.3.2 Automotive Initiatives

As new automotive regulations emerge, new standards for safety and environmental protection are also being released. In this regard, new designs for vehicles have become necessary, in which weight reduction is considered to be the driving force. The desire to achieve weight reduction led to further research and new lighter material alternatives such as titanium, magnesium, aluminum or plastics, capable of satisfying the new standards and having the potential to replace successfully the traditionally heavier materials, used for decades by automotive sector, have come forefront.

Even though aluminum has been long used as major structural material in the aerospace industry [16, 30, 41], the manufacturing processes commonly used in aircraft industry are completely unrelated to those for automotive mass production [16]. Cost was a critical impediment which slowed down the use of aluminum by automotive industry. Aluminum presently costs between two and five times as much as automotive steel pound for pound [12, 28, 41]. Apart from cost disadvantage, another critical limitation which withstands aluminum from being currently used in automotive bodies is its stiffness: it is only one-third as stiff as steel. There are two ways to increase the aluminum stiffness, either by changing the geometry of the design (curved shapes) or making the body panels thicker than the actual steel panels to ensure that they perform equally well. Both alternatives have drawbacks since shape and style are important sales concepts and increasing thickness imposes higher material costs and offsets to some extent the weight advantage [41]. However, a major advantage for aluminum, compared with other competing lightweight materials, which makes the automotive industry to consider switching to aluminum, is that it can be formed using many techniques already applied in making automobiles out of steel. Designing for aluminum is another advantage for aluminum since it is not drastically different from designing for steel [41].

The new regulations set by Federal Motor Vehicle Safety Standards and Environmental Protection Agency [42] pushed the automobile manufacturers to face growing pressure from consumers and government agencies to produce vehicles that perform better, and are easier to recycle and repair, create less pollution, and are less expensive, more comfortable, durable, fuel-efficient, maintenance-free and safer. The Partnership for New Generation of Vehicles (PNGV) program launched in 1993, which involved the "Big 3" US automakers (General Motors, Ford and Chrysler), several government agencies, and several national research laboratories, stated as one of its major thrusts the use of lightweight materials to attain the primary goals of a 40% reduction in curb weight and a fuel efficiency of 80 miles per gallon (mpg) [43, 44]. The key to achieve the new challenge is hidden in reducing the total weight of the vehicle, which in turn will improve its fuel consumption.

Among multiple methods available to improve fuel economy for a passenger car, weight savings are proven to offer the most spectacular results. Reducing the weight of the vehicle has other important benefits for automobiles such as reduced CO_2 emissions, better acceleration and shorter stopping distance, lower center of gravity and improved vehicle control, reduced noise and vibration or keeping the vehicle's size while reducing its weight [27, 45]. Moreover, the structural stiffness and crashworthiness of aluminum bodies are equal to or superior to steel. Since aluminum has an excellent resistance to corrosion, the crashworthiness of aluminum structures will not deteriorate with time [27].

Aluminum's record of reducing vehicle weight to help protect our environment is very well-known. Despite the fact that producing virgin aluminum is a more expensive process than producing other competing materials, aluminum has some properties that make it attractive. Its unique properties such as light weight, high strength, resistance to corrosion and recyclability have determined researchers from automotive industry to investigate the possibility of substituting aluminum for steel in auto body structures. It is as simple as this: less weight to move leads to greater fuel economy, and less energy consumed means fewer greenhouse gas emissions. Eventually, all these requirements are today's challenges for automakers all over the world.

2.4 Problem Identification for Thesis Work

Road transportation for many years have impacted the world positively. However, this impact has been possible at the expense of our environment. In addition to being one of the greatest contributors to global warming, the air and water pollution, vehicles have a significant impact on public health contributing to cancer, premature deaths, and the aggravation of chronic respiratory illnesses [46].

Therefore, it is in our hands and should be our responsibility to ask for environmentally friendly vehicles capable to help protect our health and preserve our planet. From the extraction of materials to the final use and disposal, all the vehicles on the road spread pollution and use up huge quantities of natural resources. By applying the best practices currently available in the auto industry, it is possible to manufacture vehicles that produce less pollution from the assembly line on through road use and to end-of-life disposition.

The key to achieve this goal is by using lighter materials which can be easily recycled or reused. Initial material cost difference between the traditionally used materials in automotive industry and the competing materials such as aluminum, which can potentially replace the heavier materials such as steel in vehicle's construction, is not a complete indicator of the total cost of substituting aluminum for steel or other materials. By evaluating the entire material usage and the manufacturing system as a whole as well as its environmental benefits, aluminum's true value becomes apparent. Since the use of lightweight aluminum body structures also allows automakers to downsize other parts of the car such as smaller engine and the use of lighter chassis components, there are additional savings in the vehicle's weight and cost, and further reductions in exhaust emissions during its use. It has been shown that greater than 85% of the life-cycle CO_2 emissions occur during the use phase of the vehicle [27]. These secondary cost savings often can be substantial and can offer benefits never thought before.

As a general rule, motor vehicles are classified as "clean" if they conform to three basic standards: fuel efficiency, low tailpipe emissions and the manufacturing process uses fewer and non-toxic recyclable materials [2].

CHAPTER 3

LIFE-CYCLE COST ANALYSIS OF ALUMINUM AUTO BODY PARTS: A PRELIMINARY STUDY

3.1 Cost Model Development: Aluminum vs. Steel in Passenger Cars

Since the benefits of using aluminum to reduce vehicle's weight are very well-known, the present chapter is aimed at developing a methodology to compare the costs encountered during the entire life-cycle of a vehicle, considering two different material scenarios, namely aluminum versus steel, used in body-in-white (BIW) structures and exterior body panels, for a typical vehicle family. The analysis covers all four major stages of the life-cycle: pre-manufacturing (material processing), manufacturing, use, and post-use. To some extent the work also quantify the environmental impact of material substitution.

Knowing that the greatest opportunity for weight savings comes from the body structure and exterior closure panels, and that additional weight reduction can be achieved by downsizing the other components such as engine components [12], the proposed model considers achieving weight reduction by replacing the conventional material used in vehicle's construction (i.e., steel) with a lighter mass equivalent material (i.e., aluminum), maintaining the same vehicle design and using the same manufacturing processes for body components [12,39]. The basic assumptions for this study are listed in Table 3.1.

The starting value for gas price is assumed to be $2.30 per gallon, a value which is considered to be closer to the current gas price. The gas price can fluctuate, and a 20 percent increase or decrease for the current value has been considered in the current study. Thus, the resulting price ranges between $1.84 and $2.76 per gallon as shown in Table 3.1.

For the pre-manufacturing stage, the cost calculations for both materials are based on the assumption that 308 kg of aluminum sheet would be required to produce the completed 193 kg aluminum body structure and 565 kg steel sheet would be needed to produce 371 kg steel body structure [20]. According to Stodolsky [12], the primary material used in the typical passenger car today is steel, which can be purchased for a cost between $0.77 to $1.20/kg. A 20 percent increase or decrease for steel sheet cost has also been considered, with a range of values between $0.63 – $1.17/kg.

Table 3.1: The basic assumptions of major parameters used in the current study

Parameter	**Starting value**	**Range**
Gas Price ($/gal)	2.30	1.84 – 2.76
Cost of Steel ($/kg)	0.90	0.63 – 1.17
Cost of Aluminum ($/kg)	3.30	2.31 – 4.29
Price of scrap ($/kg) Steel Aluminum	 0.09 0.93	 0.069 – 0.129 0.657 – 1.221
Fuel Consumption (mpg) Steel BIW Aluminum BIW	 20 22	
Total Vehicle Weight (kg) Steel BIW Aluminum BIW	 1,418 1,155	
Body-in-White weight (kg) Steel Aluminum	 371 193	
Life of the Car (years)	14	
Miles driven in Year 1	15,220	
Lifetime Miles Driven	174,140	
Recycling Percentage Steel Aluminum	 90 90	

Since aluminum is a material which is likely to replace steel in automotive body components [17], the starting value for aluminum sheet has been chosen as $3.30/kg [12]. A 20 percent increase or decrease in aluminum sheet cost has also been considered, giving a range of values between $2.31 - $4.29/kg. The starting values for both materials are considered to be in agreement with the generally known fact that the cost to produce primary aluminum is between 2 to 5 times more expensive than the cost to produce primary steel [12, 28, 41].

For the manufacturing stage of the life-cycle, the calculations are based on Technical Cost Modeling software developed at Massachusetts Institute of Technology (MIT) for a production volume of 150,000 vehicles per year. The analysis considers both fabrication costs and assembly costs encountered by the body-in-white (BIW) structure and the exterior panels during the manufacturing stage.

The fuel consumption of vehicles is assumed to be constant throughout the use stage, with a lower vehicle weight providing improved fuel efficiency. It is assumed that 5 % fuel efficiency can be achieved from a 10 % weight-reduction [17, 34]. In the case of steel BIW, the fuel economy has been assumed to be 20 mpg, whereas the fuel efficiency for aluminum BIW is assumed to be 22 mpg [39].

The life time of the vehicle has been assumed 14 years [22]. The total number of miles driven over the life time of the vehicle is 174,140 miles, with the assumption that in the first year, the vehicle is driven 15,220 miles, and that the number of miles driven annually decreases as the vehicle age increases as shown in Table 3.2.

Table 3.2: Estimated annual miles driven by the vehicle age

Vehicle Age (Years)	**Annual Miles Driven**	**Total Miles Driven**
1	15,220	15,220
2-5	14,250	72,220
6-10	12,560	135,020
10-14	9,780	174,140

The price values of scrap material and recycled material are listed in Table 3.3 for both materials [18]. Once the vehicle reaches its end-of-life, it is considered that the owner sells the vehicle to a dismantler and that 90 percent of the BIW material is recycled [36, 38]. It is also considered closed-loop recycling of obsolete automotive BIW materials, where the recycled materials are returned to their original usage through further processing.

Table 3.3: Material databases for aluminum and steel

Material	Price ($/kg)	Scrap ($/kg)	Recycle($/kg)
Steel	0.9	0.09	0.12
Aluminum	3.3	0.93	1.32

Apart from the cost analysis, the model also quantifies the amounts of carbon dioxide emissions generated during the processing of the materials, manufacturing the body structures, use of the vehicle, and in recycling the materials. For all four life-cycle stages, carbon dioxide emissions for both materials are listed in Table 3.4 and these values are derived from [21]. The current model tracks only carbon dioxide emissions associated with fuels used for aluminum and steel operations during each stage. Other fuel-related emissions such as carbon monoxide, nitrous oxides, sulfur dioxide, and other compounds are not considered in this study.

Table 3.4: Total carbon dioxide emissions for steel and aluminum BIWs.

Stage	Steel (kg CO_2/BIW)	Aluminum(kg CO_2/BIW)
Pre-manufacturing	1,913.5	2,689
Manufacturing	19.5	18.6
Use	6,772.5	6,139.5
Post-use	282.5	75.7

Being a highly energy-intensive process, producing virgin aluminum generates more carbon dioxide emissions than producing virgin steel. Since their manufacture and assembly processes are assumed to be similar, the amounts of carbon dioxide generated during the manufacturing stage differ slightly, being the result of using electricity to operate the machinery.

The vehicle's operational (use) stage has the greatest environmental impact in terms of carbon dioxide emissions. Fuel economy, the number of years the vehicle is used on the roads and the emissions rate are among the most common factors contributing to the amount of carbon dioxide generated over the operational stage. The lighter alternative is proven to emit less gaseous substances since it needs less power to move and therefore less fuel. Credits for emission rates are given in accordance with the U.S. Environmental Protection Agency recommendations [47].

For post-use stage, the amounts of carbon dioxide generated by both materials, are based on the assumption that 90 percent of the material is recycled once the vehicle reaches its end-of-life [36, 38] and that the recycled aluminum saves 95 percent of the energy to produce virgin aluminum [26, 29] whereas the recycled steel saves between 40 - 75 percent of the energy required to produce virgin steel [38].

All the above values are illustrative, not definitive and they are derived from published sources which helped in developing the model. By changing the starting values according to the actual consent and realistic estimates, the model will recalculate all the costs encountered by the BIW structures over the entire life-cycle of the vehicle.

3.2 Preliminary Results Discussion

Fuel economy, gas price variation and the number of miles driven on the roads are important parameters which make up for the total cost encountered by the vehicle during the use stage. The cost of gasoline encountered over the operational (use) stage of the vehicle is a function of the gas price variation, for both material scenarios, and is shown in Figure 3.1. As expected, aluminum substitution would provide important savings over the entire range of the gas price variation. At a price of $2.30 per gallon and a fuel economy improvement of 10 percent, it is shown that over the life time of the vehicle (14 years), approximately 791.5 gallons of gasoline can be saved. This number translates into about $1,820 saved over the same period of time. This is possible merely due to the fact that aluminum being a lighter material contributes to lightening the overall vehicle mass, which in turn leads to fuel improvement. It can also be noticed that once the gas price increases, as expected in the future, the savings increase accordingly following the trends shown in the figure below.

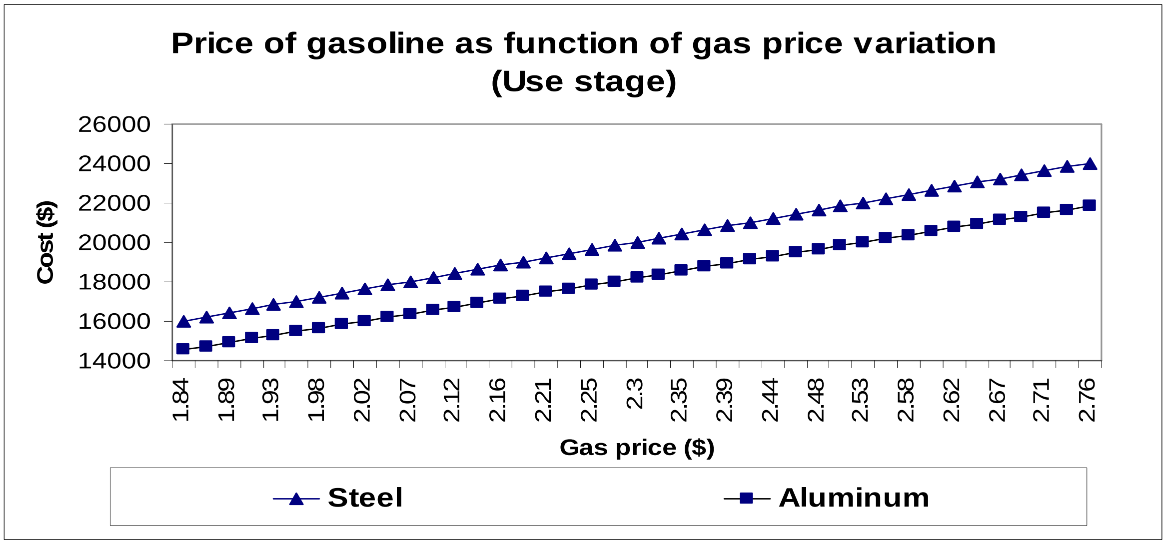

Figure 3.1: Cost of gasoline as function of gas price variation (Use stage)

Since the cost encountered during the "use" stage has the highest impact on computing the total ownership cost and the number of miles driven, the recycling content (R) and the price of gas are important parameters to compute the total cost encountered by the vehicle over its life-cycle, this study compares the total costs encountered by vehicle for three different mileage scenarios (15,220 miles, 57,970 miles, and 135,020 miles). Four different levels of recycled material, for each mileage case scenario, are also considered: 0, 25, 75, 100 percent, both recycled materials (steel and aluminum), and a special case scenario, in which 75 percent aluminum and 25 percent steel is recycled material.

Pre-manufacturing costs depend greatly on the percent of material recycled. With the increased use of recycled material, the material cost becomes smaller. The manufacturing costs consider both the cost of body fabrication and the cost of final assembly. The cost functions for aluminum and steel sheets and the fabrication costs for body components differ, and it is shown that steel fabrication cost is less than the fabrication cost for aluminum body components. Since the assembly cost for aluminum body structure is higher than the assembly cost for steel body structure, the manufacturing costs to produce steel body structure are generally lower than the manufacturing costs to produce the aluminum body structure.

Costs encountered during the “use” stage of the vehicle are functions of the number of miles driven, fuel consumption, and price of gasoline. An improvement in fuel consumption, and the increase in the number of miles driven by vehicle lead to an increase in the difference between the number of gallons of gas used by the steel structured vehicle and the number of gallons of gas used by the aluminum structured vehicle, thus, making aluminum BIW vehicle much cheaper in terms of the money spent on gasoline during this stage.

The “post-use” stage costs consider only obsolete scrap from end-of-life vehicle. Since both materials are considered to be 90 percent recycled, and because aluminum has a higher scrap value, \$0.94 per kilogram compared to \$0.10 per kilogram for steel, aluminum has a higher post-use value.

Figure 3.2 refers to the first mileage case scenario (15,220 miles driven) for Year 1, and it shows the ratio of the total cost for aluminum versus the total cost for steel over the entire life-cycle of the vehicle as function of gas price variation. Excepting the case scenario in which both materials have 100 percent material recycled content, all the other scenarios assumed, have the plots above the unit value for the entire range of gas price variation. Since the ratio total costs for aluminum to total costs for steel is more than unit value, steel body structured vehicle is proven to be a more economical option.

The use cost for aluminum BIW vehicle, at a gas price of \$2.30 per gallon, is \$1591 compared with \$1,750 for steel BIW vehicle. For 0 percent material recycled content the costs to procure aluminum and steel sheets are \$ 1,016 for aluminum, respective \$508.7 for steel. Since manufacturing costs depend greatly on variable costs such as material cost per piece, manufacturing and assembly costs for aluminum BIW are \$2,138 compared with \$1,115 for steel BIW. Post-use costs are \$163 for aluminum respective \$ 33 for steel. Computing all the costs encountered by the vehicle over the entire life-cycle result a total cost for aluminum of \$4,475 compared with \$3,322 for steel and a ratio between total costs for aluminum to total costs for steel of 1.37. The ratio is inverse proportional with the price for gasoline, because once the gas price increases the ratio decreases following the trend in Figure 3.2. At a gas price of $2.76 per gallon the ratio becomes equal to 1.32.

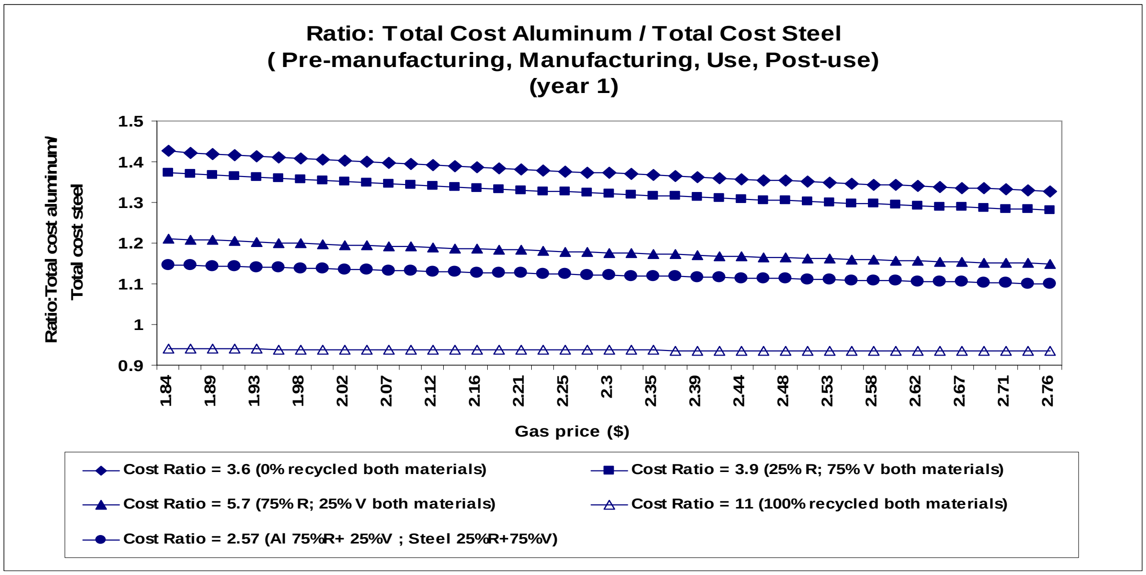

Figure 3.2: The ratio of the total cost for aluminum versus the total cost for steel (Year 1)

As content of material recycled is increased, for instance from 25 % to 75 % material recycled, the ratio becomes closer to the unit value, but still the total cost for steel BIW is smaller than the total cost for aluminum BIW for the entire range of gas price variation. Considering 75 % both materials recycled, after one year or 15,220 miles driven, the total cost for aluminum drops to $3,602 compared to $3,062 for steel and the ratio total cost for aluminum to total cost for steel becomes1.17. This drop is possible because increasing the content of material recycled the initial costs to fabricate sheets drop significantly ($559.3 for aluminum and $178 for steel). The costs to manufacture and assembly body components also decrease ($1,614 for aluminum and $1,167 for steel). The use costs remain the same, since only the content of material recycled is increased not the number of miles driven. For 100 % both materials recycled content, the ratio is below the unit value, and decreases slightly, for all range of gas price variation.

Considering the case scenario (aluminum75 % and steel 25 % material recycled content), at a gas price of $2.30 per gallon, the ratio drops to 1.12, since the difference between pre-manufacturing costs for aluminum sheet ($559) and steel sheet ($398) becomes smaller. The manufacturing costs for steel BIW ($1,097) are still lower than the manufacturing costs for aluminum BIW ($1,614). The decreasing trend toward the unit value shows that once the difference between the use costs becomes bigger, aluminum structured vehicle has the potential to offset the initial cost advantage of steel structured vehicle gained in pre-manufacturing and manufacturing stages. Material sheet cost, fuel cost and the number of miles driven have a crucial influence upon the total cost ratio.

Increasing the number of miles driven to 57,970 miles or after four years of vehicle usage the difference between the total costs for aluminum and the total costs for steel reduces, as the difference between "use" stage costs becomes bigger (Figure 3.3).

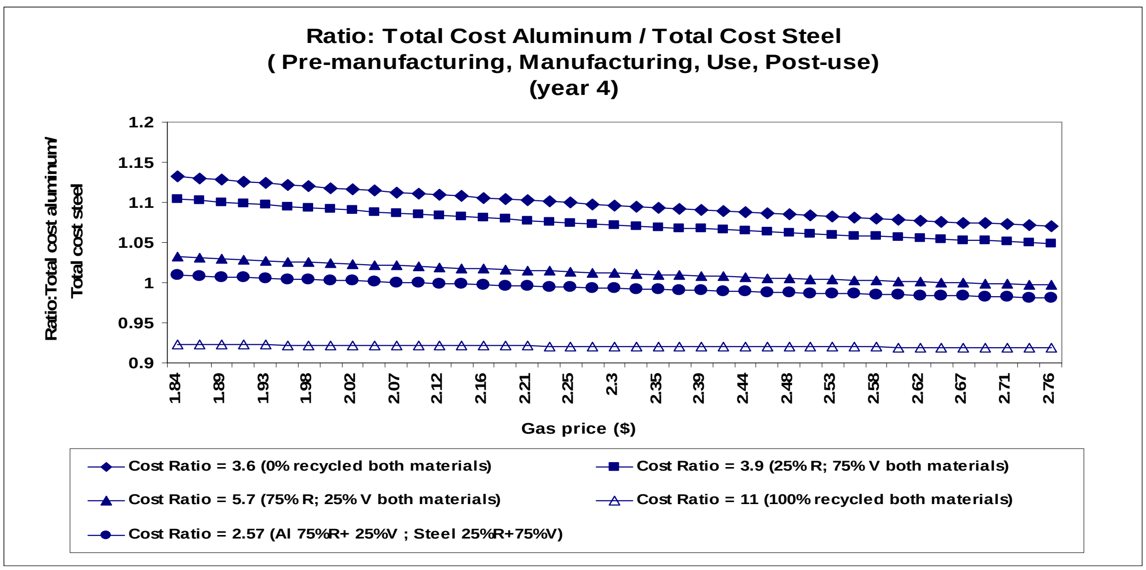

Figure 3.3: The ratio of the total cost for aluminum versus the total cost for steel (Year 4)

For zero percent both materials recycled content, at a gas price of $2.30 per gallon, the aluminum total cost is $9,052 compared with $8,257 total cost for steel, making the ratio equal to 1.09. Increasing the content of recycled material to 25 percent the ratio becomes even closer to the unit value. For 75 percent both materials recycled, the aluminum total cost ($ 8,071) becomes almost similar to the total cost for steel ($7,978), giving a total cost ratio equal to 1.01. It is important to notice that for a gas price of $2.64 the total cost for aluminum ($8,983) becomes equal to the total cost for steel ($8,981). For the case scenario (aluminum 75 % and steel 25 % material recycled content), the total cost ratio is below unit value, for almost the entire range of gas price variation. In other words, it takes four years for an aluminum structured vehicle to offset the initial steel structured vehicle's cost advantage, from pre-manufacturing and manufacturing stages, under the special case scenario, no matter the price for gas.

After 135,020 miles driven (year 10), the total cost ratio is less than the unit value, for almost all material recycled content scenarios. At zero percent both materials recycled content the total cost ratio is close to the unit value, showing the impact of the use stage in general, and gas price in particular, in computing the total cost encountered by vehicle over its life-cycle. At $2.30 per gallon under the zero percent material recycled the total cost ratio becomes 0.99. (Figure 3.4)

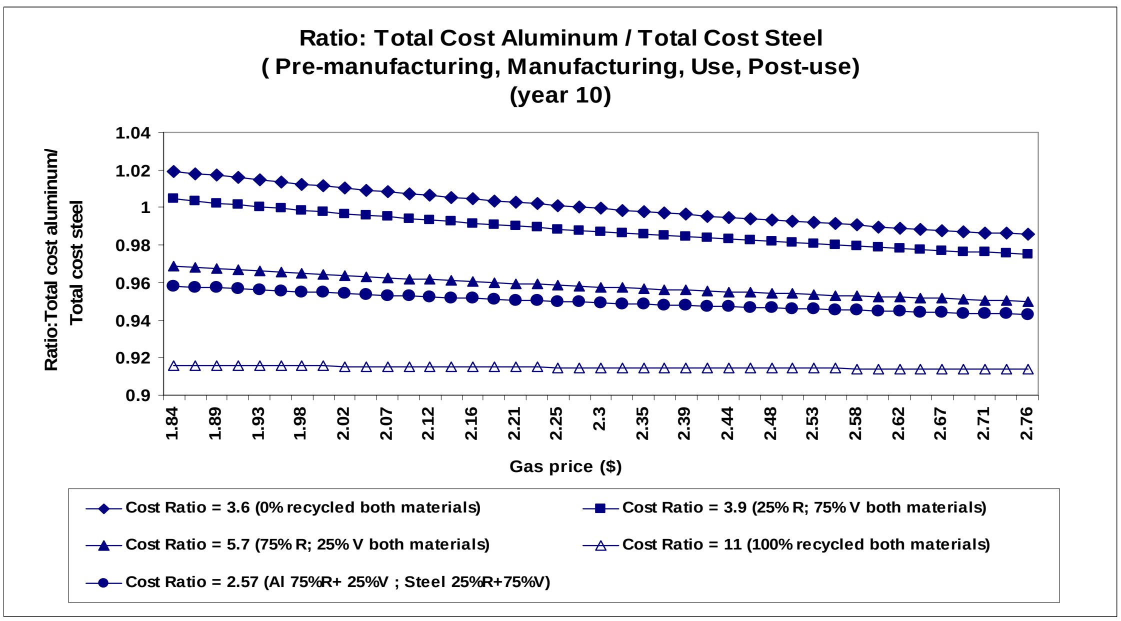

Figure 3.4: The ratio of the total cost for aluminum versus the total cost for steel (Year10)

Considering the case scenario (aluminum 75 % and steel 25 % material recycled content) and a gas price of $2.30, Figure 3.5 shows the total ownership cost breakdown for both materials. Being a cheaper material to produce and manufacture, for the first four years of vehicle usage, steel BIW structure is shown to be a more economical option. Once the vehicle's usage is increased, the difference between the use costs for both materials becomes significant, making aluminum BIW structure a more economical option. After ten years, the aluminum structure has a cost advantage of about 5 percent over the steel structure.

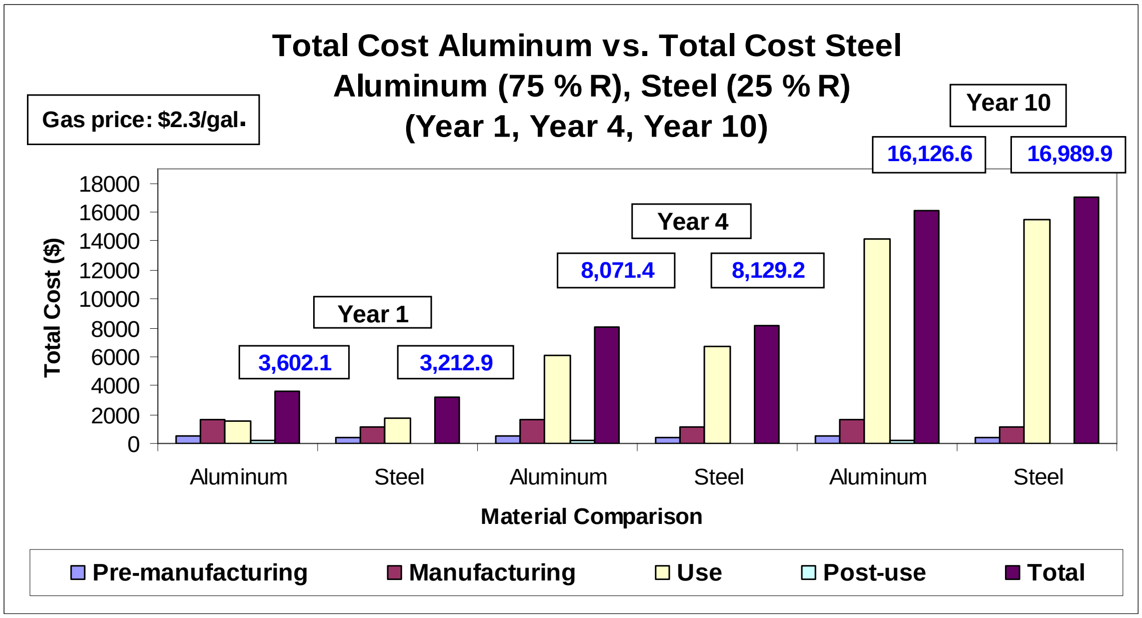

Figure 3.5: Total cost breakdown (Aluminum versus Steel)

Another benefit of using lighter, easy to recycle materials in the construction of body structures for passenger cars is the reduction of gaseous emissions associated with the vehicle's life-cycle. Since energy use and greenhouse gas emissions are closely related [31] the fuel-related emissions during the operational stage of the vehicle are considerable less for aluminum structured vehicle than those for steel structured vehicle.
According to Martchek [48], vehicle usage generates considerable more greenhouse gas emissions than in the production of materials, vehicle manufacturing and end-of-life recycling. Therefore, reducing fuel consumption in vehicle's operation has a great effect on reducing the tailpipe emissions, making the vehicles on the roads "green".

For pre-manufacturing stage, the amount of carbon dioxide generated is calculated based on the content of material recycled. Table 3.5 and Figure 3.6 show the amounts of carbon dioxide generated during this stage for increasing recycling rate for both materials.

Table 3.5: The amounts of carbon dioxide generated during pre-manufacturing stage as a function of the content of material recycled

Percent Recycled	CO_2 Emissions (kg)	
	Aluminum	Steel
0 % Material Recycled	2,689	1,913
25 % Material Recycled	2,050	1,554
75 % Material Recycled	773	837
100 % Material Recycled	134	478
Aluminum 75 % R Steel 25 % R	773	1,554

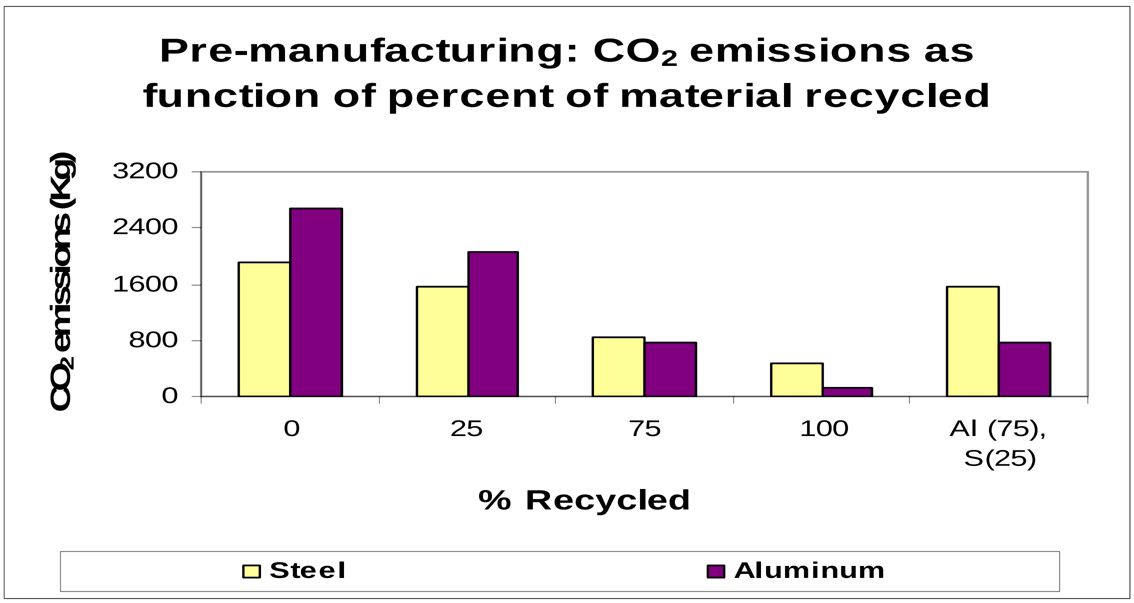

Figure 3.6: Carbon dioxide emissions as function of the percent of material recycled

For manufacturing stage, the amounts of carbon dioxide emissions are quite similar (19.5 kg CO_2 emissions for manufacturing aluminum BIW structure and 18.6 kg CO_2 emissions for manufacturing steel BIW structure) since the manufacturing processes are not assumed to be different.

The carbon dioxide emissions for the “use” stage, depend on the number of miles driven, fuel economy, and emissions rate. According to the US Environmental Protection Agency, it is assumed 0.916 pounds of CO_2 emissions per mile for a passenger car’s fuel consumption of 21.5 miles per gallon. Since carbon dioxide emissions are directly proportional to fuel economy, each 1% increase (decrease) in fuel consumption results in a corresponding 1% increase (decrease) in carbon dioxide emissions [47].Therefore, this study considers for aluminum BIW structured vehicle, 0.88 pounds CO_2 emissions per mile and for steel BIW structured vehicle 0.98 pounds CO_2 emissions per mile. The carbon dioxide (CO_2) emissions generated during the use stage as function of the number of miles driven are shown in Table 3.6.

Table 3.6: Carbon dioxide emissions as function of the number of miles driven

Vehicle Age (Years)	**Cumulative Annual Miles**	**Steel Fuel Consumption (gal)**	**Aluminum Fuel Consumption (gal)**	**Steel CO_2 Emissions (kg)**	**Aluminum CO_2 Emissions (kg)**
1	15,220	761	696.4	6,772.5	6,139.5
2	29,470	1,473.5	1,348.4	13,113.3	11,887.8
3	43,720	2,186	2,000.4	19,454.2	17,636.1
4	57,970	2,898.5	2,652.5	25,795.1	23,384.4
5	72,220	3,611	3,304.5	32,136	29,132.6
6	84,780	4,239	3,879.2	37,724.9	34,199.2
7	97,340	4,867	4,453.9	43,313.8	39,265.7
8	109,900	5,495	5,028.6	48,902.6	44,332.3
9	122,460	6,123	5,603.3	54,491.5	49,398.9
10	135,020	6,751	6,178	60,080.4	54,465.4
11	144,080	7,240	6,625.5	64,432.3	58,410.5
12	154,580	7,729	7,073	68,784.1	62,355.7
13	164,360	8,218	7,520.5	73,136	66,300.8
14	174,140	8.707	7,968	77,487.8	70,246

Carbon dioxide estimations to recycle both materials are: 75.7 kg carbon dioxide for aluminum recycling and 282.5 kg carbon dioxide for steel recycling.

Figure 3.7 illustrates the difference between the amounts of carbon dioxide emissions over the use stage of the vehicles. Having a fuel improvement of 2.0 mpg aluminum BIW vehicle generates less carbon dioxide than steel BIW vehicle for the whole range of operational years.

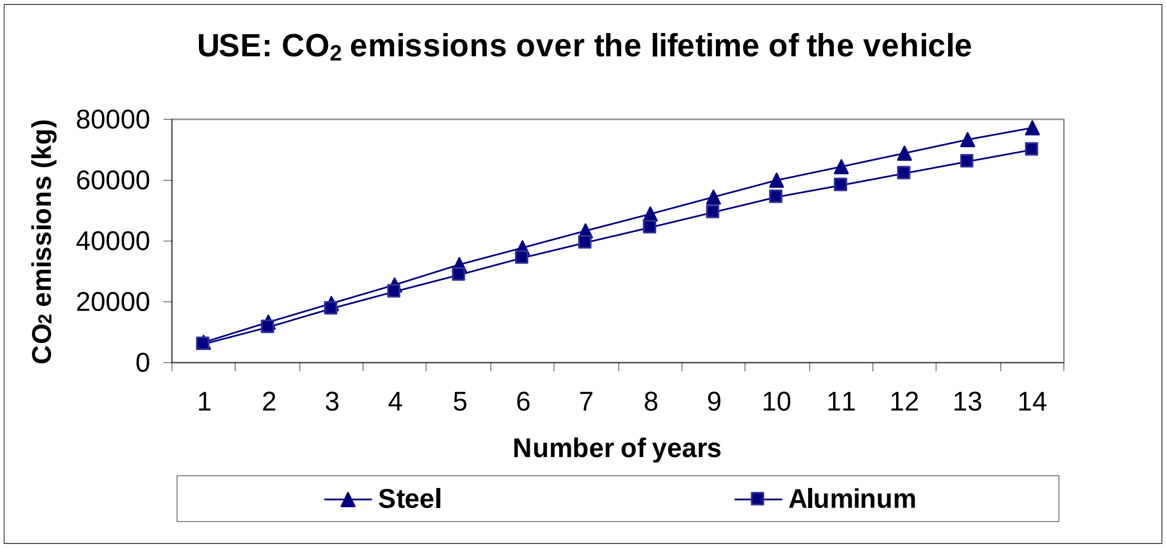

Figure 3.7: Carbon dioxide emissions over the lifetime of vehicle

Table 3.7 and Figure 3.8 show the carbon dioxide emissions for three different years, for the case scenario in which both materials have zero percent material recycled content.

Table 3.7: Total carbon dioxide emissions (0 % R both materials).

Stage	**Year 1**		**Year 4**		**Year 10**	
	Aluminum CO_2 (kg)	**Steel CO_2 (kg)**	**Aluminum CO_2 (kg)**	**Steel CO_2 (kg)**	**Aluminum CO_2 (kg)**	**Steel CO_2 (kg)**
PM	2,689.0577	1,913.561	2,689.0577	1,913.5611	2,689.0577	1,913.561
M	19.510036	18.63846	19.510036	18.638457	19.510036	18.63846
U	6,139.66	6,772.511	23,384.407	25,795.170	54,465.458	60,080.454
PU	75.782699	282.5929	75.782699	282.5929	75.782699	282.5929
Total	8,923.917	8,987.304	26,168.757	28,009.963	57,249.809	62,295.246

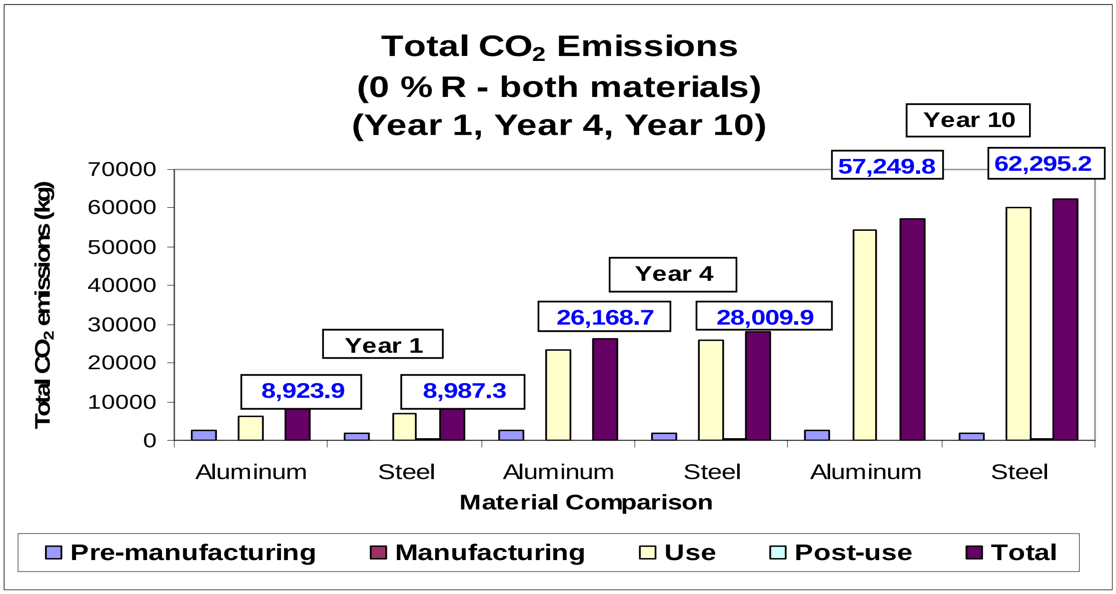

Figure 3.8: Total carbon dioxide emissions breakdown (0 % R both materials)

Even though the production of virgin aluminum is highly energy-intensive, it takes only one year of vehicle usage for aluminum to offset the carbon dioxide (CO_2) emission disadvantage from pre-manufacturing stage, as a result of fuel consumption improvement.

Table 3.8 and Figure 3.9 show the carbon dioxide emissions for three different years for the case scenario in which aluminum is 75 percent and steel 25 percent material recycled content.

Table 3.8: Total carbon dioxide emissions (Aluminum 75 % R, Steel 25 % R)

Stage	Year 1		Year 4		Year 10	
	Aluminum CO2 (kg)	Steel CO2 (kg)	Aluminum CO2 (kg)	Steel CO2 (kg)	Aluminum CO2 (kg)	Steel CO2 (kg)
PM	773.1041	1,554.768	773.1041	1,554.768	773.1041	1,554.768
M	19.510036	18.63846	19.510036	18.638457	19.510036	18.63846
U	6,139.566	6,772.512	23,384.407	25,795.171	54,465.459	60,080.45
PU	75.782699	282.5929	75.782699	282.5929	75.782699	282.5929
Total	7,007.96	8,628.51	24,252.8	27,651.17	55,333.85	61,936.45

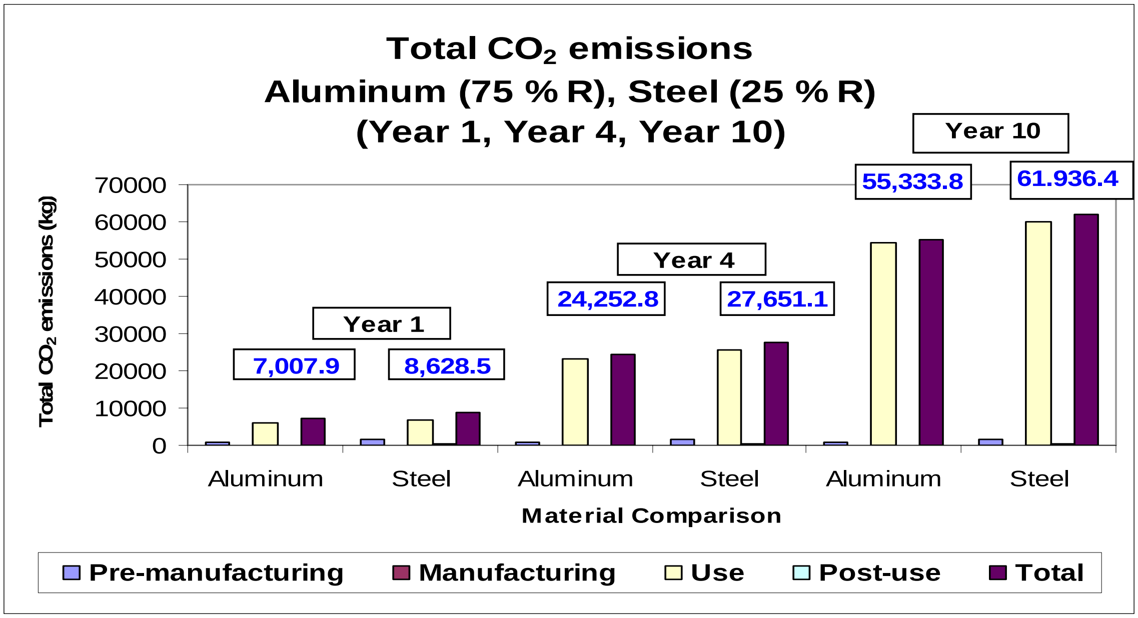

Figure 3.9: Total carbon dioxide breakdown (Aluminum 75 % R, Steel 25 % R).

Fuel consumption improvement and energy savings from recycling reduces dramatically the total amount of carbon dioxide generated by aluminum BIW structure over the entire life-cycle. The carbon dioxide emissions for aluminum BIW structure are about 22 percent smaller than those for steel BIW structure after only one year of vehicle usage.

3.3 Conclusion

This study considers material-substitution as a means to achieve weight reduction, and shows its benefits by considering the entire life-cycle of the vehicle, from fabrication of raw materials to the final disposal. This work highlights the advantage of using aluminum in auto body structures from both economical and environmental points of view by using a case study at a single-product level. Reducing the weight of the vehicle has a significant effect upon its lifetime monetary cost, since the cost at the "use" stage presently constitutes a dominant portion of the overall cost. As real gasoline price increases and vehicle lives are extended, the light weight issue becomes even more important. Previous research has demonstrated the cost advantage of producing automotive components from virgin steel. The other two stages (use and post-use) were not considered significant for computing the total life-cycle cost, since the gas price was considered to be low and recycling facilities for metals were not very well developed [17].

Considering zero percent recycled content both materials, the initial fabrication and manufacturing cost advantage for steel structure is offset by the lower costs for gasoline, and the higher metal scrap value for aluminum structure in the use and post-use stages. This model shows that it takes 9 years or 122,460 miles, at a gas price of $2.53 per gallon for aluminum structured vehicle to offset the total cost for steel structured vehicle. As the gas price increases, at a value of $2.76, the total cost for aluminum structured vehicle ($18,355) becomes lower than the total cost for steel structured vehicle ($18,490). Furthermore, increasing the content of material recycled to 25 percent for both materials, the number of years the aluminum BIW needs to offset the total costs encountered by steel BIW drops to 7. It is shown that after 97,340 miles, at a gas price of $2.76 per gallon, aluminum structured vehicle offsets the total cost of steel structured vehicle. For 75 percent both material recycled, it takes only 4 years or 57,970 miles at a gas price of $2.66 for aluminum structure to offset the total cost for steel structure.

Under the most likely case scenario, (aluminum 75 percent and steel 25 percent recycled), the model shows that after 3 years or 43,720 miles at a gas price of $2.76 per gallon, aluminum BIW structure offsets the total costs of steel BIW structure as shown in Table 3.9 and Figure 3.10.

Table 3.9: Total cost breakdown (Aluminum 75% R, Steel 25 % R) (Year 3)

Stage	**Aluminum cost ($)**	**Steel Cost ($)**
Pre-manufacturing	559.3	398.4
Manufacturing	1,614.8	1,097.5
Use	5,484.8	6,033.3
Post-use	163.2	33.8
Total Cost	7,495.7	7,496.05

Figure 3.10 shows the total ownership cost breakdown encountered by both materials during each stage after three years, at a gas price of $2.76.

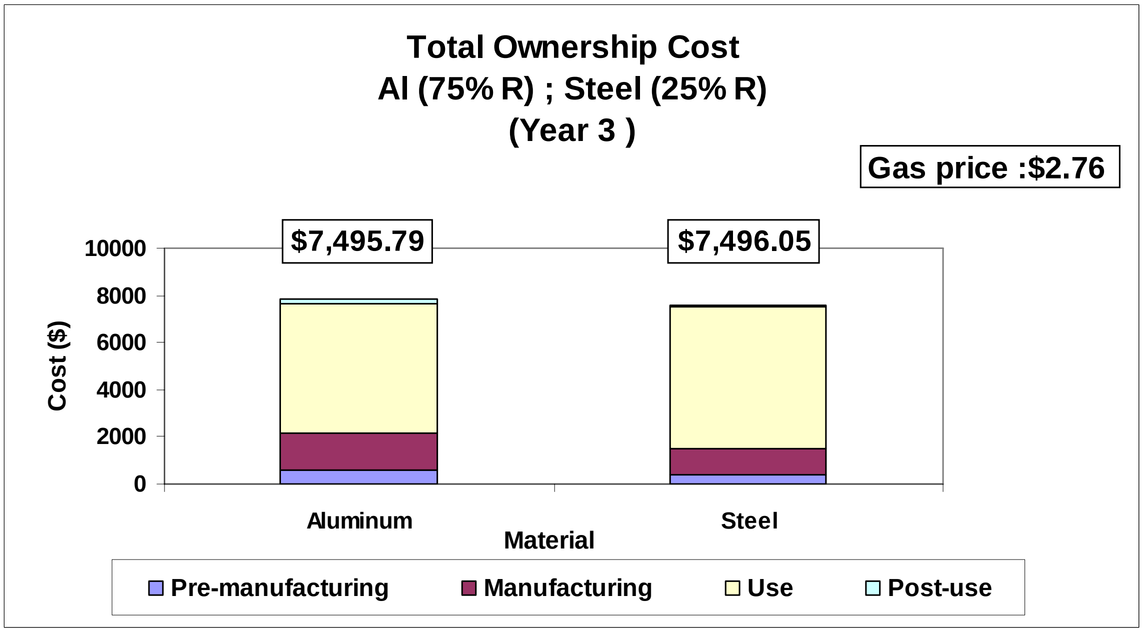

Figure 3.10: Total ownership cost

Regarding carbon dioxide emissions, the model shows the benefit of using lighter materials in the body construction of vehicles. Figure 3.11 illustrates the total carbon dioxide emissions, over the vehicle's life-cycle considering that are virgin materials. Despite the emission disadvantage from pre-manufacturing stage, it is found that only one year or 15,220 mile driven, needs for aluminum BIW structure to emit less carbon dioxide than the steel counterpart. The energy savings from the recycled steel are not as dramatic as the energy savings from recycled aluminum. The amount of carbon dioxide generated in producing the steel sheet with increased content of material recycled is not so drastically low, as that of the amount of carbon dioxide generated in producing aluminum sheet with increased content of recycled material. Using increased content of aluminum recycled material in the vehicle's body, which dramatically reduces the amount of carbon dioxide generated in the process of making virgin material, aluminum BIW structure is proven to emit about 22 % less carbon dioxide than what steel BIW structure does emit, after only one year of vehicle usage. As the vehicles continue to "age", the carbon dioxide savings from the "use" stage increase, and after ten years, there will be about 12 % carbon dioxide emissions savings from the use of recycled aluminum in the vehicle's body structure (Figure 3.12).

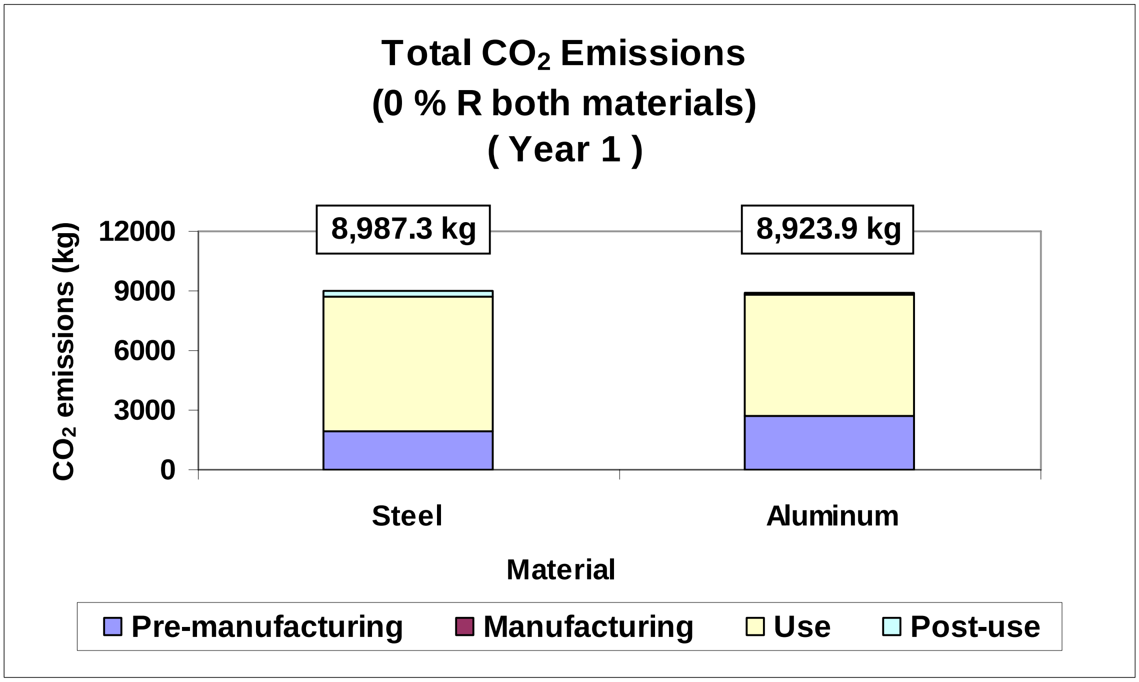

Figure 3.11: Total carbon dioxide emissions (0 % R both materials)

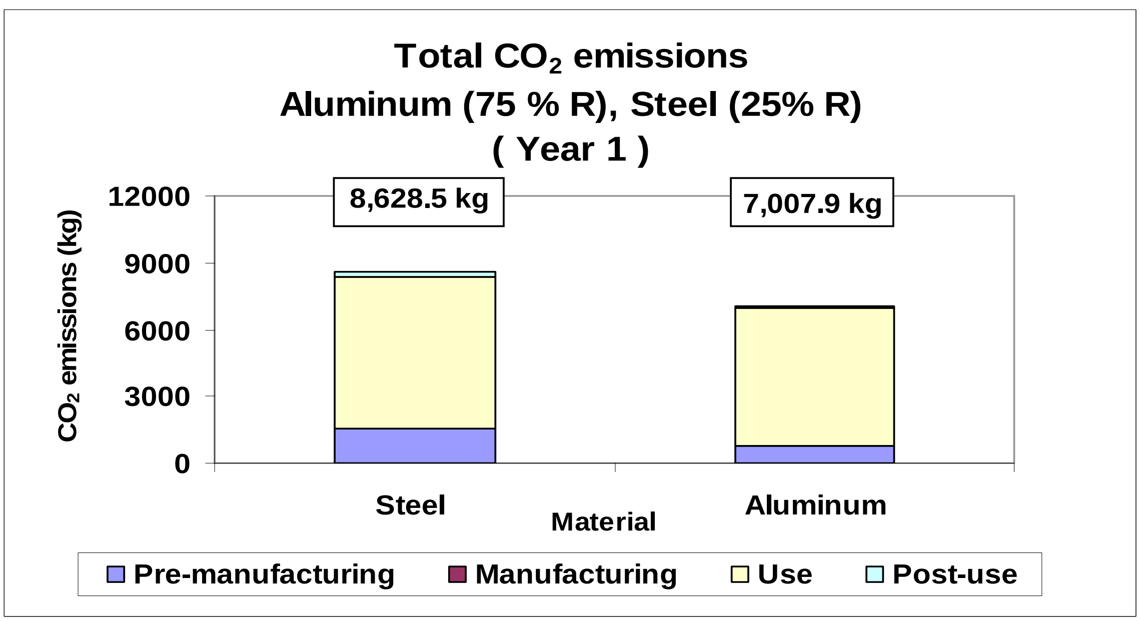

Figure 3.12: Total carbon dioxide emissions (Aluminum 75 % R, Steel 25 % R)

CHAPTER 4

DEVELOPMENT OF A SUSTAINABILITY SCORING METHOD: A CASE STUDY OF AUTO BODY PANELS

4.1 Assessment Criteria for Product Sustainability

Motor vehicles are no doubt the most complex and environmentally damaging consumer products on the planet. According to Jawahir and Wanigarathne [5] when computing the "level of sustainability" build in any product, six major contributing elements need to be taken into consideration. These six elements are: Environmental Impact, Societal Impact, Functionality, Resource Utilization and Economy, Manufacturability and Recyclability/Remanufacturability (Figure 4.1). Each of the six sustainability elements is characterized by a sub-element level and each sub-element depends in turn upon a range of influencing factors.

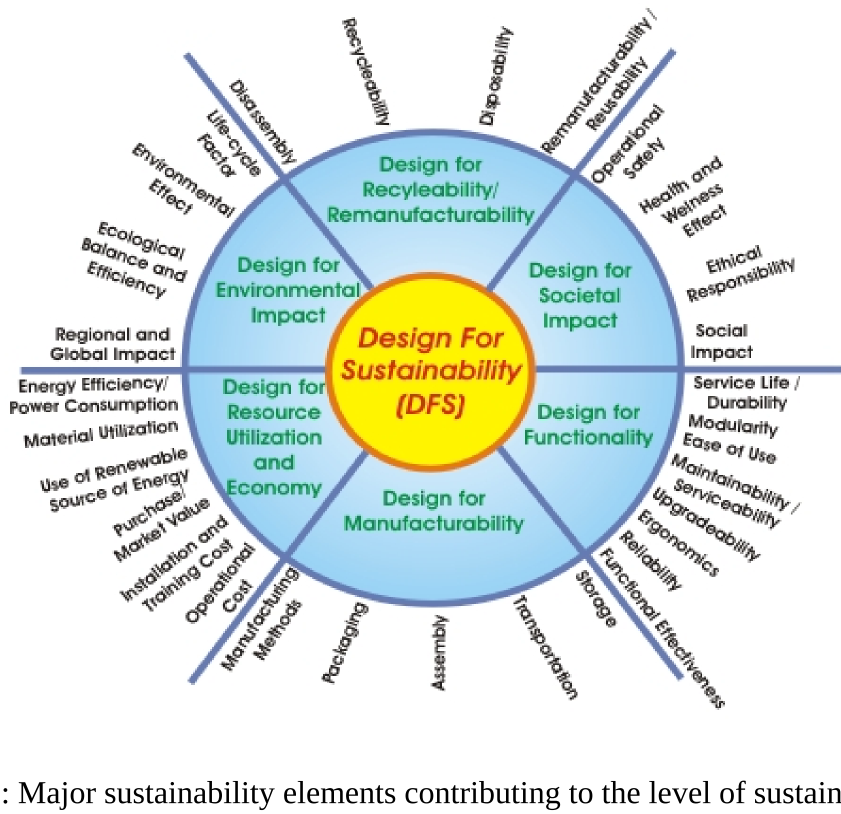

Figure 4.1: Major sustainability elements contributing to the level of sustainability in a manufactured product [49]

To assess the overall product sustainability, there can be many other sub-elements stemmed from the six sustainability elements. However, all sub-elements chosen for developing this model are believed to suit the best in the automotive field since proven safety, reduced emissions, enhanced performance, increased miles per gallon, durability, improved design and manufacturability, are important requirements for the future automobiles. Therefore, 19 influencing factors belonging to 14 sub-elements are considered as the most representative for this analysis - see Table 4.1.

Table 4.1: The proposed elements, sub-elements and influencing factors for automotive sustainability evaluation

Sustainability element	**Sub-elements of sustainability**	**Influencing factors**
Environmental Impact	Adverse Environmental Effect	CO_2 emissions
Economic Impact	Energy Efficiency Material utilization Operational cost	Pre-manufacturing energy Manufacturing energy Recycling energy Cost of material Cost of gasoline
Societal impact	Operational safety Health and wellness	Energy absorption in collision Stopping distance Noise, Vibration, Harshness (NVH)
Functionality	Service life/Durability Handling & Performance	Atmospheric conditions Repairability Acceleration Stability
Manufacturability	Manufacturing Methods Assembly Storage	Technological advancements Number of parts Cost of storage
Recyclability/ Remanufacturability	Recyclability Remanufacturability/Reusab. Disposability	Value of material recycled Number of recovered parts Disposable options.

Introducing three new sustainability elements (Manufacturability, Functionality, and Recycling/Remanufacturing) to the conventional three elements for sustainability (Environment, Economy, and Society) provides a new comprehensive framework for the sustainability of manufactured products. Functionality is important since service life/durability, performance, ease to use, upgradeability, modularity, and reliability, contribute to sustaining any product. Manufacturability refers to the manufacturing capability without compromising the quality requirements of products and the tooling sustainment, and it includes other related activities such as storage, transportation, assembly, and packaging where new legislative drivers are continuing to emerge. Recyclability/remanufacturing is a very broad element which include redesigning, remanufacturing, reusing, reducing, recycling, and recovering of materials and product parts. This element is extremely important since the automotive industry has to focus heavily on waste minimization and resource preservation.

4.1.1 Environmental Impact

The environmental element quantifies the gaseous emissions generated by the vehicle over its operational use stage. The only sub-element considered for this element is the adverse environmental effect, and it can be described as:

$$\textit{Environmental impact} = K_1\,(\textit{Adverse Environmental Effect}) \qquad (4.1)$$

K_1 is a constant which can be calculated as the adverse environmental sub-element is assessed. Since the environmental element has only one influencing factor, K_1 it is considered equal to1.

In order to calculate the adverse environmental effect, the only influencing factor employed is the carbon dioxide emissions generated during the use stage. The amount of emissions generated during this stage depends greatly on the number of miles driven, which in turn, depends on the number of gallons of gasoline used and eventually on the vehicle's fuel economy. The more miles driven, the more emissions are generated with increased fuel consumption required. Therefore, the relationship of carbon dioxide (CO_2) emissions – amount of gasoline consumed is used to assess the adverse environmental effect sub-element. As shown in Figure 4.2 this relationship follows an increasing trend, and using the best fitting curve method and the equation of the line, the following generic mathematical relationship can be developed.

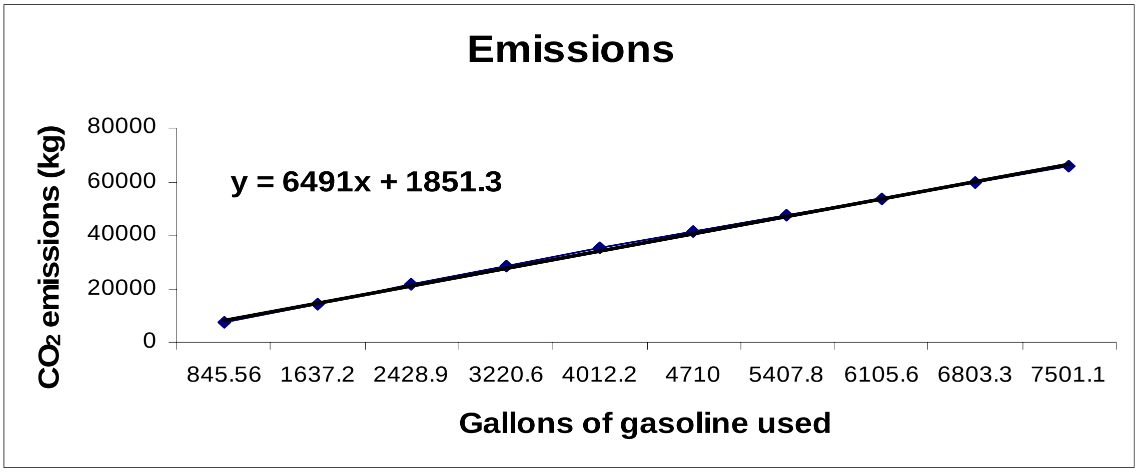

Figure 4.2: Carbon dioxide emissions as a function of the amount of gasoline used

$$\textit{Adverse Environmental Effect} = K_2\,(\textit{Carbon dioxide emissions}) \qquad (4.2)$$

K_2 is a constant which can be calculated as the influencing factors are assessed. Since the adverse environmental effect sub-element has only one influencing factor, K_2 it is considered equal to1.

Using the best fitting curve, the relationship of carbon dioxide emissions to number of gallons used follows a linear trend and it can be expressed as:

$$Y_1 = A_1X_1 + B_1 \qquad (4.3)$$

where Y_1 is the amount of CO_2 emitted over the use stage, A_1, B_1 are constants, and X_1 is the number of gallons used. The slope in the above figure is positive since the carbon dioxide emissions increase as the amount of gasoline used increases.

Therefore, the sub-element adverse environmental effect can be written in generic form as:

$$\textit{Adverse Environmental Effect} = A_1X_1 + B_1 \qquad (4.4)$$

Since there is only one sub-element, the environmental element can be written generic as:

$$Environmental\ impact = A_1X_1 + B_1 \quad (4.5)$$

4.1.2 Material Utilization and Economy

The material utilization and economy element of sustainability includes such sub-elements as energy efficiency/power consumption, material utilization, and vehicle's operational cost. All three sub-elements are considered of equal importance in calculating the final material utilization and economy element of sustainability. The generic equation for this sub-element can be written as:

$$Material\ Utilization\ and\ Economy = K_3\ [(Energy\ Efficiency) + (Material\ Utilization) + \\ + (Operational\ Cost)] \quad (4.6)$$

K_3 is a constant which will be determined when all three sub-elements of this element are calculated. Since all the sub-elements are considered as having equal importance, the constant K_3 is equal to 1/3.

The energy efficiency sub-element is function of the energy needed to produce the materials, to manufacture and assemble the vehicle, and to recycle the vehicle when it reaches its end-of-life. Therefore, the following generic equation may be developed:

$$Energy\ Efficiency = K_4\ (Pre\text{-}Manufacturing\ Energy + Manufacturing\ Energy + \\ + Recycling\ Energy) \quad (4.7)$$

K_4 is a constant which will be determined when the three influencing factors of this sub-element are calculated. Since all the influencing factors are assessed as having equal importance, the constant K_4 is equal to 1/3.

The energy needed in these processes is mainly in the form of electricity which can be assessed in terms of the monetary cost [21]. Knowing that producing virgin aluminum is a highly energy-intensive process [12], increasing the content of recycled material will significantly reduce the amount of energy required to produce virgin material. Consequently, the electricity cost to produce the material will be reduced [12]. An efficient process is considered to be a process which needs less electricity to operate, thus, the electricity cost for operating the machinery will be kept low. A simple mathematical relationship between the energy requirements to operate the machinery and the electricity cost as a result of operating the machinery can be developed to assess the energy efficiency sub-element, and it follows the trend shown in Figure 4.3.

Since the relationship between the energy use and the electricity cost employed to assess this sub-element follows a linear trend, the energy requirement for each stage: pre-manufacturing, manufacturing/assembly and recycling can be generic written as:

$$Y_2 = A_2X_2 - B_2 \tag{4.8}$$

where Y_2 represents the electricity cost, A_2, B_2 are constants and X_2 is the energy requirement for each stage considered.

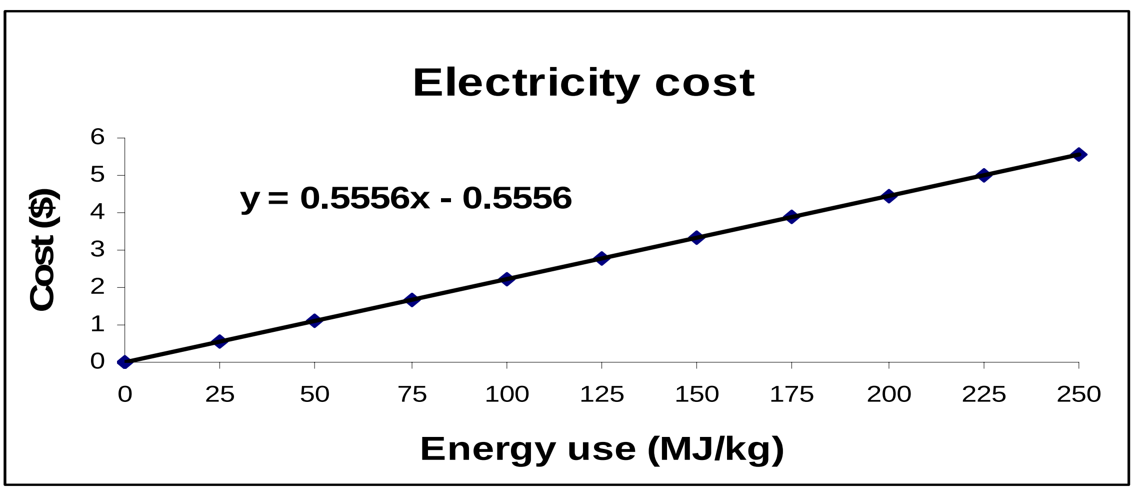

Figure 4.3: Energy use as a function of electricity cost

Therefore, the following equations can be developed for the energy use in all three stages of relevant product life-cycle.

$$Pre\text{-}manufacturing\ Energy = A_3X_3 - B_3 \quad (4.9)$$

$$Manufacturing/Assembly\ Energy = A_4X_4 - B_4 \quad (4.10)$$

$$Recycling\ Energy = A_5X_5 - B_5 \quad (4.11)$$

Since each stage is considered to carry equal weight in computing the total energy requirement, the final equation for the energy efficiency sub-element is computed as:

$$Energy\ Efficiency = (1/3)\ [(A_3X_3 - B_3) + (A_4X_4 - B_4) + (A_5X_5 - B_5)] \quad (4.12)$$

Since the energy needed to power the vehicle during its operational (use) stage is the result of burning gasoline, the operational cost sub-element includes the use stage energy cost.

Usually, there are several materials such as rubber, glass, plastics and metals are used to make up the entire vehicle. However, in our analysis, only the material used in body construction is being considered. The material utilization sub-element depends on the material cost used in vehicle's body construction.

$$Material\ Utilization = K_5\ (Cost\ of\ material) \quad (4.13)$$

K_5 is a constant which will be calculated when the influencing factors are assessed. Since the material utilization sub-element has only one influencing factor, K_5 it is considered equal to1.

The material cost depends on the type of material and the quantity used in body construction and may be estimated as a function of the percent of material recycled. Low material cost is always preferred by the automotive manufacturers. Figure 4.4 shows the material cost as a function of the percent of material recycled.

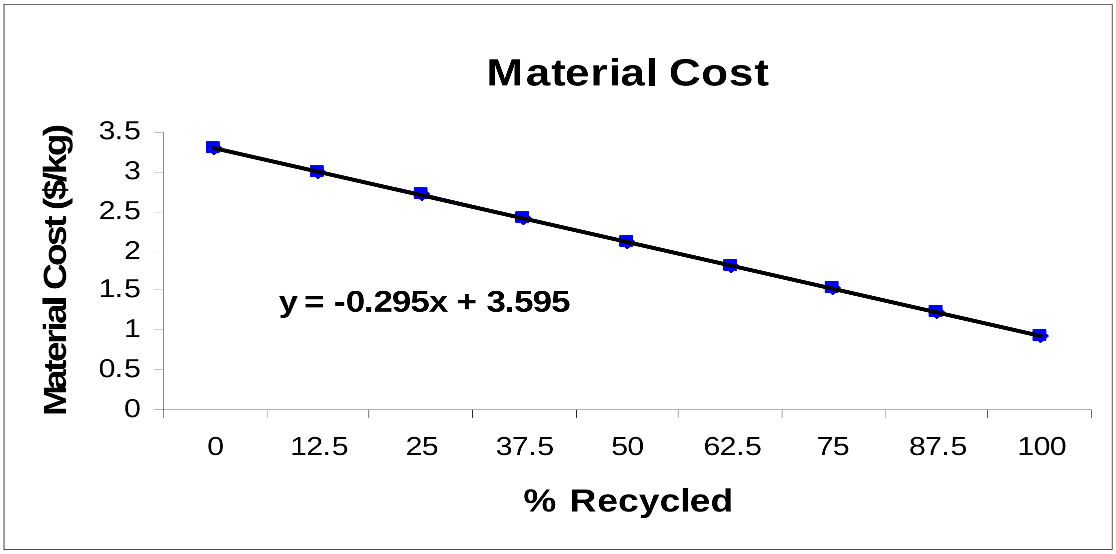

Figure 4.4: Material cost as a function of the percent of material recycled

Since the material cost decreases as the amount of recycled material used increases, the trend in the above figure has a negative slope. The following generic equation can be derived.

$$Y_6 = -A_6X_6 + B_6 \tag{4.14}$$

where Y_6 is material cost, X_6 is the content of material recycled and A_6, B_6 are constants. Therefore, the sub-element material utilization can be written in generic form as:

$$\textit{Material utilization} = -A_6X_6 + B_6 \tag{4.15}$$

The cost to operate the vehicle has a high impact upon the economic element of sustainability. Cost to operate the vehicle is a function of the amount of gallons used and the gasoline price. Fewer gallons used will lead to increased cost savings.

$$\textit{Operational Cost} = K_6\ (\textit{Cost of gasoline}) \tag{4.16}$$

K_6 is a constant which will be calculated as the influencing factors are assessed. Since the operational cost sub-element has only one influencing factor, K_6 is considered equal to1.

The relationship between the amount of used gasoline and its cost is employed to assess the operational cost sub-element and it follows the same trend as shown in Figure 4.2. The generic equation can be expressed as:

$$Y_7 = A_7X_7 + B_7 \tag{4.17}$$

where Y_7 is the money spent on gasoline, X_7 is the number of gasoline gallons used, and A_7, B_7 are constants.

Since the operational cost sub-element is derived only from one influencing factor, gasoline cost, the final equation for operational cost can be the following:

$$Operational\ Cost = A_7X_7 + B_7 \tag{4.18}$$

Since there are three sub-elements of equal importance for this element, the final equation can be written in a generic form as:

$$Material\ Utilization\ and\ Economy = (1/3)\{(1/3)[(A_3X_3 - B_3) + (A_4X_4 - B_4) + (A_5X_5 - B_5)] + [-A_6X_6 + B_6] + [A_7X_7 + B_7]\} \tag{4.19}$$

4.1.3 Societal Impact

Operational safety and health and wellness are considered two important sub-elements which define the societal element of sustainability when automotive applications are involved. The generic equation for this element can be written as:

$$Societal\ impact = K_7\ [Health\ and\ wellness + Operational\ safety] \tag{4.20}$$

K_7 is a constant which will be determined as the two sub-elements of this element are calculated. Since both sub-elements are assessed as having equal importance, the constant K_7 is equal to 1/2.

Health and wellness sub-element depends greatly not only on the air pollution produced by the vehicles, but also on other elements such as the level of vibration or the level of noise generated by the vehicle‘s use. The vehicle body’s resistance to twisting forces, also called torsional rigidity, influences the way road-generated noise and vibrations are amplified and transmitted to the vehicle occupants. The challenge here is to obtain a high torsional rigidity without building a heavier car. According to the Aluminum Association, Inc. [50] well-designed aluminum body structures provide increased torsional rigidity with significant reductions in weight. Therefore, increased torsional rigidity lead to reduced noise and vibration transmitted to the occupants. The relationship between the torsional rigidity and the level of noise or vibration transmitted to the occupants may follow a linear trend as shown in Figure 4.4, and is used to assess the health and wellness sub-element.

$$\textit{Health and Wellness} = K_8\ (\textit{Level of noise, vibration and harshness}) \qquad (4.21)$$

K_8 is a constant which will be calculated once the influencing factors will be assessed. Since the health and wellness sub-element has only one influencing factor, K_8 is considered equal to 1.

Therefore, the relationship level of noise, vibration, and harshness (NVH) - torsional rigidity may be expressed as:

$$Y_8 = -A_8X_8+B_8 \qquad (4.22)$$

where Y_8 is the level of noise and vibration transmitted to the occupants, X_8 is torsional rigidity and A_8, B_8 are constants. The negative slope is the result of the fact that the level of noise and vibration transmitted to the occupants decreases as the torsional rigidity increases.

Therefore, the sub-element health and wellness can be generic written as:

$$\textit{Health and Wellness} = -A_8X_8 + B_8 \qquad (4.23)$$

Apart from cost considerations, which are the primary barrier to the widespread substitution of aluminum for steel in automobiles, another concern for automakers is that in crash situations, aluminum structures may not perform as well as those made of steel [27]. However, according to The Aluminum Association, Inc. [51], studies confirm that size, not weight is more important for a vehicle safety. This means that aluminum can make a vehicle safer by making it larger (to extend crush space for crash protection), while reducing the weight (to boost fuel economy). Lightweight design also improves maneuverability and stopping distance, allowing the driver to avoid many potential collisions. Using technologies for energy absorption, force-limiting occupant restraints, and rigid passenger compartment design, even ultralight vehicles can surpass the safety standards of today's cars in many types of collisions [44]. In a crash, aluminum is proven to act much like steel since the principal energy-absorbing components of an aluminum structure fold or collapse in a highly predictable manner, absorbing kinetic energy through the resulting work of deformation [27]. This allows the vehicle, not the passengers to absorb the crash forces. According to the Aluminum Association, Inc. aluminum can absorb 55-80 percent more crash energy than steel and can be two and a half times stronger than steel. Since the consequences in the event of crash are a function of the material's properties used in its body construction, the passenger is considered safer if the material has the ability to absorb more crash energy (forces) so they are not passed along to the vehicle occupants.

The operational safety can be determined as:

$$Operational\ safety = K_9\ [(Crash\ energy\ absorption) + (Stopping\ distance)] \qquad (4.24)$$

K_9 is a constant which will be calculated as the influencing factors are assessed. Since the operational safety sub-element is considered to have two influencing factors of equal importance, K_9 is considered equal to1/2.

The more crash energy absorbed, the safer the vehicle occupant will be, and a lighter vehicle leads to reduced stopping distance. A similar linear relationship as in Figure 4.3 between occupant safety - crash absorption and vehicle mass – stopping distance can be developed and the generic equations can be written as:

$$Y_9 = A_9X_9 - B_9 \quad (4.25)$$

$$Y_{10} = A_{10}X_{10} - B_{10} \quad (4.26)$$

where Y_9, Y_{10} are the occupant safety and the stopping distance, X_9, X_{10} are crash energy absorbed and vehicle's body weight, and A_9, B_9, A_{10}, B_{10} are constants.
Therefore,

$$Operational\ Safety = 1/2\ [(A_9X_9 - B_9) + (A_{10}X_{10} - B_{10})] \quad (4.27)$$

Since there are two sub-elements of equal importance, the generic final equation for this element of societal impact may be written:

$$Societal\ impact = 1/2\ [(-A_8X_8 + B_8) + 1/2\ (A_9X_9 - B_9) + 1/2\ (A_{10}X_{10} - B_{10})] \quad (4.28)$$

4.1.4 Manufacturability

The manufacturability element of sustainability includes such sub-elements as manufacturing methods, packaging, assembly, transportation and storage. Since the model refers to the autobody applications, manufacturing methods, assembly and joining techniques and storage of products are considered to be the most important sub-elements. Even though, aluminum can be manufactured largely employing the same manufacturing methods as used for steel sheet panels [52], the sub-element manufacturing methods depend greatly on the technological advancements introduced by steel and aluminum experts from the automotive industry, and therefore, are difficult to assess. Consequently, in this work, the manufacturability element is assessed using only two sub-elements such as assembly and storage.

$$Manufacturability = K_{10}\ [Assembly + Storage] \quad (4.29)$$

K_{10} is a constant which will be determined as the two sub-elements of this element are calculated. Since both sub-elements are assessed as having equal importance, the constant K_{10} is equal to 1/2.

Regarding assembly, the number of parts employed to produce the entire body assembly is considered the most important influencing factor.

$$Assembly = K_{11}\,(Number\ of\ parts) \quad (4.30)$$

K_{11} is a constant which will be calculated as the influencing factors are calculated. Since there is only one influencing factor considered K_{11} is equal to1.

Fewer parts to be assembled means less welding points and it is always desired in the assembly of any product. A linear relationship can be applied following the trend from Figure 4.3.

$$Y_{11}= A_{11}X_{11} – B_{11} \quad (3.31)$$

where Y_{11} represents the number of welds, X_{11} the number of parts, and A_{11}, B_{11} are constants. Since there is only one influencing factor, the generic equation for this sub-element can be written as:

$$Assembly = A_{11}X_{11} – B_{11} \quad (4.32)$$

The storage sub-element largely depends on only one influencing factor, the cost of storage. Less storage time means less storage cost and eventually greater company profits. The following equation can be developed.

$$Storage=K_{12}\,(Cost\ of\ storage) \quad (4.33)$$

K_{12} is a constant which will be calculated as the influencing factors is calculated. Since there is only one influencing factor considered K_{12} is equal to1.

The relationship cost of storage-time of storage follow the trend shown in Figure 4.3 and is employed to assess the storage sub-element.

$$Y_{12}= A_{12}X_{12} – B_{12} \quad (4.34)$$

where Y_{12} represents the cost of storage, X_{12} the time of storage, and A_{12}, B_{12} are constants. Since there is only one influencing factor, this sub-element can be written as:

$$Storage = A_{12}X_{12} - B_{12} \tag{4.35}$$

Therefore, the final equation for this element of manufacturability can be written in generic form as:

$$Manufacturability = (1/2)\,[(A_{11}X_{11} - B_{11}) + (A_{12}X_{12} - B_{12})] \tag{4.36}$$

4.1.5 Functionality

Service life or durability and handling and performance are considered two important sub-elements for auto body components when the functionality element is assessed. Even though, aluminum has a higher resistance to corrosion, the service life/durability sub-element depends greatly on the atmospheric conditions the vehicle is driven and the proper equipment and properly trained repair personnel. Advancements in joining, metalworking, and finishing technologies have been made by automakers and transferred to the point of repair. However, this sub-element is difficult to assess since the influencing factors are difficult to quantify. Handling and performance sub-element is then, the only one sub-element considered to assess this element. The following generic equation can be developed:

$$Functionality = K_{13}\,(Handling\ and\ Performance) \tag{4.37}$$

K_{13} is a constant which will be determined as all the sub-elements of this element is calculated. Since there is one sub-element, the constant K_{13} is equal to1.

Two influencing factors are taken into account when we assess the handling and performance sub-element: acceleration and stability.

$$Handling\ and\ performance = K_{14}\,[(Acceleration\ time) + (Stability)] \tag{4.38}$$

K_{14} is a constant which will be assessed as the influencing factors are calculated. Since both influencing factors are considered of equal importance the constant K_{14} is 1/2.

According to the Aluminum Association, Inc. lighter vehicle weight leads to both better acceleration and improved stability and turning response. Thus, a linear relationship between vehicle's body weight and each of the two influencing factors can be developed and it follows the trend shown in Figure 4.3.

Therefore,

$$Y_{13} = A_{13}X_{13} - B_{13} \quad (4.39)$$

$$Y_{14} = A_{14}X_{14} - B_{14} \quad (4.40)$$

where Y_{13}, Y_{14} are acceleration time and stability, X_{13}, X_{14} vehicle's body weight, and A_{13}, A_{14}, B_{13}, B_{14} are constants. The final equation for handling and performance sub-element may be written as:

$$\text{Handling and performance} = 1/2\ [(A_{13}X_{13} - B_{13}) + (A_{14}X_{14} - B_{14})] \quad (4.41)$$

Since there is one sub-element, the final equation for this element may be:

$$\text{Functionality} = 1/2\ [(A_{13}X_{13} - B_{13}) + (A_{14}X_{14} - B_{14})] \quad (4.42)$$

4.1.6 Recyclability and Remanufacturability

At the end-of-life, all vehicles usually enters the recycling system. Dismantling followed by transportation to the shredding facilities where the "hulk" or what is left from vehicle body is transformed into small pieces for recycling the material, defines the basis for this sustainability element. Therefore, reusability/remanufacturability, recyclability, and disposability are considered the most important sub-elements.

The following relationship can be developed:

$$Recyclability/Remanufacturability = K_{15} [(Reusability/Remanufacturability) + + (Recyclability) + (Disposability)] \quad (4.43)$$

K_{15} is a constant which will be calculated when all the sub-elements are assessed. Since all three sub-elements are considered of equal importance the constant K_{15} will be equal to 1/3.

Reusability/Remanufacturability sub-element depends greatly on the number of parts recovered.

$$Reusability/Remanufacturability = K_{16} [Number\ of\ parts\ recovered] \quad (4.44)$$

K_{16} is a constant and because there is only one influencing factor K_{16} is equal to1.
The relationship of number of parts recovered with manufacturing costs is employed to assess this sub-element and it follows a linear trend as shown in Figure 4.4. The line has a negative slope since more recovered parts leads to reduced manufacturing costs.

$$Y_{15} = -A_{15}X_{15} + B_{15} \quad (4.45)$$

where Y_{14} is manufacturing cost, X_{14} is number of parts recovered, and A_{14}, B_{14} are constants. Since there is one influencing factor this sub-element can be written as:

$$Reusability/Remanufacturability = -A_{15}X_{15} + B_{15} \quad (4.46)$$

Recyclability sub-element is a function of one influencing factor the value of recycled material or scrap value.

$$Recyclability = K_{17} [Value\ of\ Material\ Recycled] \quad (4.47)$$

K_{17} is a constant and because there is only one influencing factor K_{17} is equal to1.

The relationship of percent of material recycled with the scrap value is employed to assess this sub-element and it follows a linear trend as shown in Figure 4.3. It has a positive slope since more material recycled leads to higher scrap value. The following equation can be developed:

$$Y_{16} = A_{16}X_{16} - B_{16} \tag{4.48}$$

where Y_{16} is scrap value, X_{16} is percent of material recycled, and A_{16}, B_{16} are constants. Since there is one influencing factor this sub-element can be written as:

$$Recyclability = A_{16}X_{16} - B_{16} \tag{4.49}$$

A disposal option is a key factor contributing to the disposability sub-element. It could also be seen as linear since having more disposable options will be always preferred.

$$Disposability = K_{18}\ [Disposable\ options] \tag{4.50}$$

K_{18} is a constant and because there is only one influencing factor K_{18} is equal to1.

$$Y_{17} = A_{17}X_{17} – B_{17} \tag{4.51}$$

where Y_{17} is disposability sub-element, X_{17} is number of disposable options, and A_{17}, B_{17} are constants. Since there is one influencing factor this sub-element can be written as:

$$Disposability = A_{17}X_{17} - B_{17} \tag{4.52}$$

The final equation for this element of recyclability/remanufacrurability can be generic written as:

$$Recyclability/Remanufacturability = 1/3\ [(-A_{15}X_{15} + B_{15}) + (A_{16}X_{16} - B_{16}) + \\ + (A_{17}X_{17} - B_{17})] \tag{4.53}$$

All shown relationships are subjective and all used constants are based on imaginary data which has been used to help develop the model. All the sub-elements contributing to corresponding elements and all influencing factors which contribute to sub-elements are considered of equal importance. Therefore, as the actual data is made available these relationships and constants may change their values.

4.2 Preliminary Results for a Case Study of Auto Body Panels

In the absence of available data from industry, the illustration of assessing the level of “sustainability” built in a vehicle is based on data gathered from published papers related to automotive body applications. Therefore, the model compares the “level of sustainability” incorporated in automobiles when the vehicle’s body structure and exterior closure panels are made from two different materials: aluminum and steel.

The assumed sub-elements are chosen so that each of the six sustainability elements is represented by at least one sub-element. The following sub-elements are, therefore, assumed to be important for the automotive industry: adverse environmental effect, energy efficiency, material utilization, operational cost, operational safety, assembly, performance, and recyclability. More sub-elements can be added for each element as more data from automotive industry becomes available. The influencing factors for each sub-element along with the methods used to quantify each sub-element are listed in Table 4.2. Each influencing factor within each sub-element is assessed on a scale rating from 0 to 1 with one being the best. All influencing factors are assumed to be of equal importance within each sub-element. Once the influencing factors have been assessed, they can be combined to produce a single, comprehensive rating for each sub-element. Similarly, all sub-elements pertaining to each element are computed so that each element will be assessed with a unique rating. The overall “sustainability indicator” of the product is then developed as the composite rating of all six elements.

Table 4.2: The proposed sub-elements and influencing factors for evaluation of the sustainability level build in autobody panels.

Sub-Elements	**Influencing Factors**	**Method of Quantifying**
Adverse Environmental Effect	CO_2 Emissions	CO_2 Emissions Generated during Vehicle's Use Stage
Energy Efficiency	Pre-manufacturing Energy	Pre-manufacturing Energy Cost
	Manufacturing Energy	Manufacturing Energy Cost
	Recycling Energy	Recycling Energy Cost
Material Utilization	Cost of Material	Percent of Material Recycled
Operational Cost	Gasoline Cost	Cost of Gasoline during Use Stage
Operational Safety	Energy Absorption in Collision	Crash Energy Absorbed
Assembly	Number of Parts	Number of Parts for BIW
Handling & Performance	Acceleration	Acceleration Time
Recyclability	Value of Material Recycled	Scrap value of material

The following assumptions, based on the results obtained in Chapter 3 and gathered from published papers, are employed to compute the "level of sustainability" build in automobiles having aluminum and steel body-in-whites.

Table 4.3: Major assumptions used to compute the level of sustainability build in aluminum versus steel structured body vehicles

Parameter	**Assumptions**
Service life	10 years
Miles driven	135,020
Gasoline price	2.30 $/gal
Aluminum fuel economy	22 mpg
Steel fuel economy	20 mpg
Energy to produce virgin aluminum	230 MJ/kg
Energy to produce recycled aluminum	52 MJ/Kg
Energy to produce virgin steel	65 MJ/kg

Energy to produce recycled steel	52 MJ/kg
Energy to manufacture and assembly aluminum body components	4.8 MJ/kg
Energy to manufacture and assembly steel body components	4.5 MJ/kg
Electricity cost	0.08 $/KWh
Aluminum recycled material	75 %
Steel recycled material	25 %
Aluminum virgin material cost	3.30 $/kg
Aluminum recycled cost	1.32 $/kg
Steel virgin material cost	0.90 $/kg
Steel recycled cost	0.12 $/kg
Aluminum energy absorption for spot-welded hexagonal box beams	22.4 kJ/kg
Steel energy absorption for spot-welded hexagonal box beams	14.5 kJ/kg
Number of aluminum parts for BIW	288
Number of steel parts for BIW	200
Acceleration time (from 0 to 60 mph):	
3400 lb. vehicle weight	10 seconds
3300 lb. vehicle weight	9.1 seconds
Steel scrap value	0.10 $/kg
Aluminum scrap value	0.94 $/kg

Adverse Environmental Effect considers the environmental damage generated by the vehicle usage such as tailpipe emissions, which are estimated by the amount of CO_2 generated from combustion of gasoline. The vehicle's life is assumed ten years and function of the fuel economy, aluminum structured vehicles consumes about 6,178 gallons of gasoline whereas steel structured vehicle consumes about 6,751gallons of gasoline.

Adverse Environmental Effect Index = CO_2 emissions Index (4.54)

Since there is only one sub-element for this element the index for this element will be:

Environment Impact Index = Adverse Environmental Effect Index (4.55)

Energy efficiency considers the pre-manufacturing, manufacturing, and recycling energy used to produce the materials, to manufacture and assembly the body structure and exterior closure panels, and to recycle the materials used in body construction. Energy during the "use" stage is the result of burning gasoline and it is considered with the operational cost sub-element. Electricity is the only form of energy associated with mining/refining the raw material, fabrication of body components, and recycling the materials. The cost for electricity needed to power all the equipment is set to 0.08 $/kWh [19]. The energy credits for each stage are listed in Table 4.3 [12]. Since the machinery operational costs are assumed to be a linear function of the amount of energy used in each stage, and since each influencing factor is considered of equal importance, the index for this sub-element will be:

Energy efficiency Index = 1/3(Pre-Manufacturing Energy Cost Index +Manufacturing Energy Cost Index + Recycling Energy Cost Index) (4.56)

Material utilization considers the material cost, and it is a function of the percentage of material recycled. Assuming that aluminum and steel material have 75% and 25% recycled content respectively, the index for this sub-element will be:

Material utilization Index = Material Cost Index (4.57)

Operational cost considers only the money spent on gasoline during the use stage of the vehicle. The gasoline price has been assumed at $2.30 per gallon and aluminum versus steel fuel economy is shown in Table 4.3 [39]. The index for this sub-element will be:

Operational cost Index = Gasoline Cost Index *(4.58)*

Since all the sub-elements for material utilization and economy element are of equal importance, the final index for this sub-element will be:

Material Utilization and Economy Index = 1/3 (Energy Efficiency Index + Material Utilization Index + Operational Cost Index) *(4.59)*

Operational safety considers the ability of the material to absorb the crash forces. It is estimated that aluminum is two times stronger than steel (pound for pound) and it can fold predictably allowing the vehicle not the passengers to absorb the crash energy [51]. According to the Aluminum Association, aluminum can absorb 55 – 80 percent more crash energy when compared with steel. Credits for energy absorption for aluminum and steel hexagonal box beams are listed in Table 4.3 [53].Therefore, the index for this sub-element can be assessed as:

Operational Safety Index = Crash Energy Absorption Index *(4.60)*

Since there is only one sub-element for this element the index for this element will be:

Societal Impact Index = Operational Safety Index *(4.61)*

Assembly considers the number of parts or components which make up the body assembly. According to Kelkar and Clark [20] the number of parts needed to assemble a mid-size steel unibody design vehicle is 200. For aluminum uniboby design, the number of parts is 288 and for aluminum space-frame design the number of parts is 300 [20]. The number of welds needed to achieve a comparable structural stiffness gives 20 percent more welds for aluminum unibody than for the similar steel unibody[17]. Therefore, the index for this sub-element can be assessed as:

Assembly Index = Number of Parts Index *(4.62)*

Since there is only one sub-element for this element the index for this element will be:

Manufacturability Index =Assembly Index *(4.63)*

Handling and performance refers to the ability of the vehicle to accelerate from 0 to 60 mph. within a certain amount of time. According to the Aluminum Association, Inc., the lighter the vehicle the better the acceleration and the higher the stability and handling response [50]. Therefore, the index for this sub-element can be assessed as:

Handling and Performance Index = Acceleration Time Index *(4.64)*

Since there is only one sub-element for this element the index for this element will be:

Functionality Index = Handling and Performance Index *(4.65)*

Recyclability considers the value of material recycled. The higher recycled content of aluminum in automobiles is the result of a successful, sustained history of recovery and recycling. Material recycled value is a function of the percent of material recycled and the market value for the recycled material. Considering 90 percent both vehicles recycled [36, 38], the index for this sub-element can be assessed as:

Recyclability Index = Material recycled value Index *(4.66)*

Since there is only one sub-element for this element the index for this element will be:

Recyclability/Remanufacturability Index = Recyclability Index *(4.67)*

Once all influencing factors have been assessed and all sub-elements have been calculated, each element can be given a unique index or value which represents the level of sustainability incorporated by product for that specific element. Table 4.4 shows the computation results and the total score obtained by aluminum structured body vehicle and steel structured body vehicle, considering all elements are of equal importance for the automotive field.

Table 4.4: Calculated product sustainability index

Sustainability Calculations			
Sustainability element	**Sustainability Sub-element**	**Index**	
		Aluminum BIW	**Steel BIW**
Environment	Adverse Environmental Effect	0.60	0.30
Material Utilization and Economy	Energy Efficiency	0.80	0.85
	Material Utilization	0.60	0.90
	Operational Cost	0.60	0.30
Society	Operational Safety	0.70	0.30
Manufacturability	Assembly	0.30	0.70
Functionality	Handling and Performance	0.90	0.50
Recyclability/ Remanufacturability	Recyclability	0.60	0.10
Total		0.62	0.43

As shown in Table 4.4, the calculated product sustainability index for aluminum structured body vehicle is 0.62, which is by far a more acceptable index than the score of 0.43 obtained for steel structured body vehicle. Even though, the existing technology and knowledge to manufacture and assemble steel components, reflected by the manufacturability element or the lower cost to produce virgin material reflected by the material utilization and economy element, seem to be in favor of steel, the other elements such as environment, functionality, safety, and recyclability, show the overall potential benefit of using aluminum in automotive body applications. Once the manufacturing methods employed by steel industry can be applied efficiently for aluminum [52], and taking advantage of the unique property of aluminum, that of being recycled again and again without loss of quality and performance [26], the overall index obtained by aluminum, recommends it as a potential future material used in vehicle body applications. Figures 4.5 and 4.6 show the detailed breakdown of the six sustainability components.

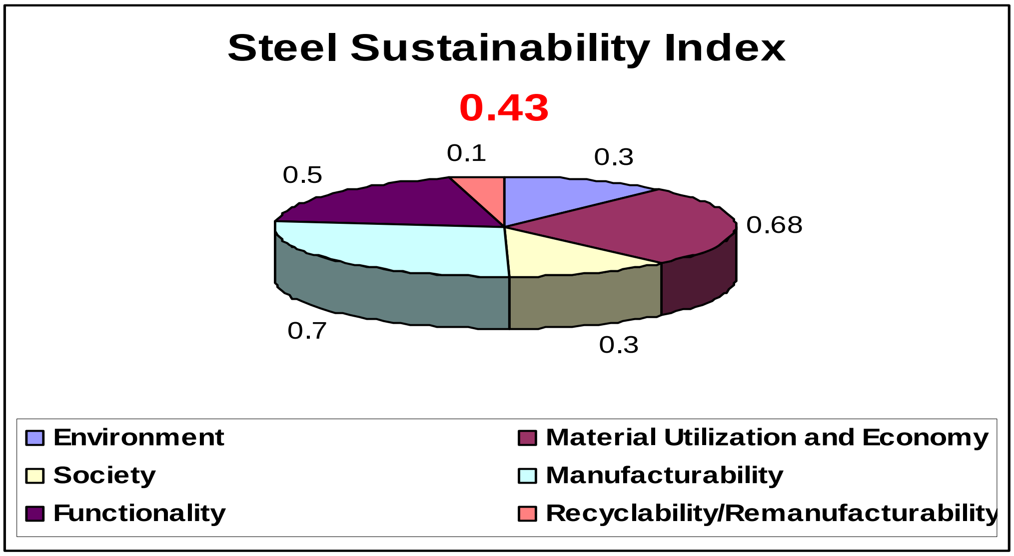

Figure 4.5: Steel sustainability index

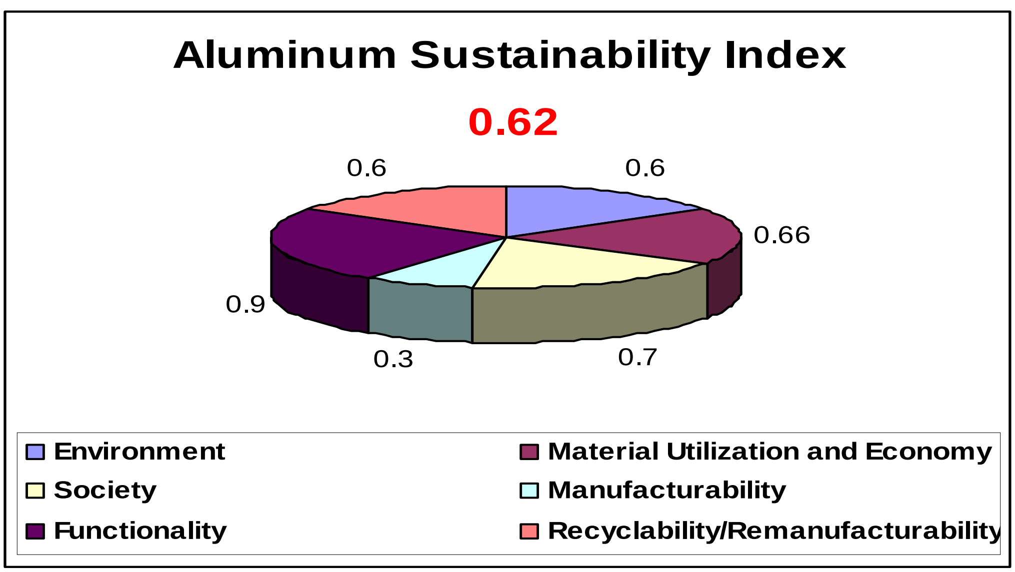

Figure 4.6: Aluminum sustainability index

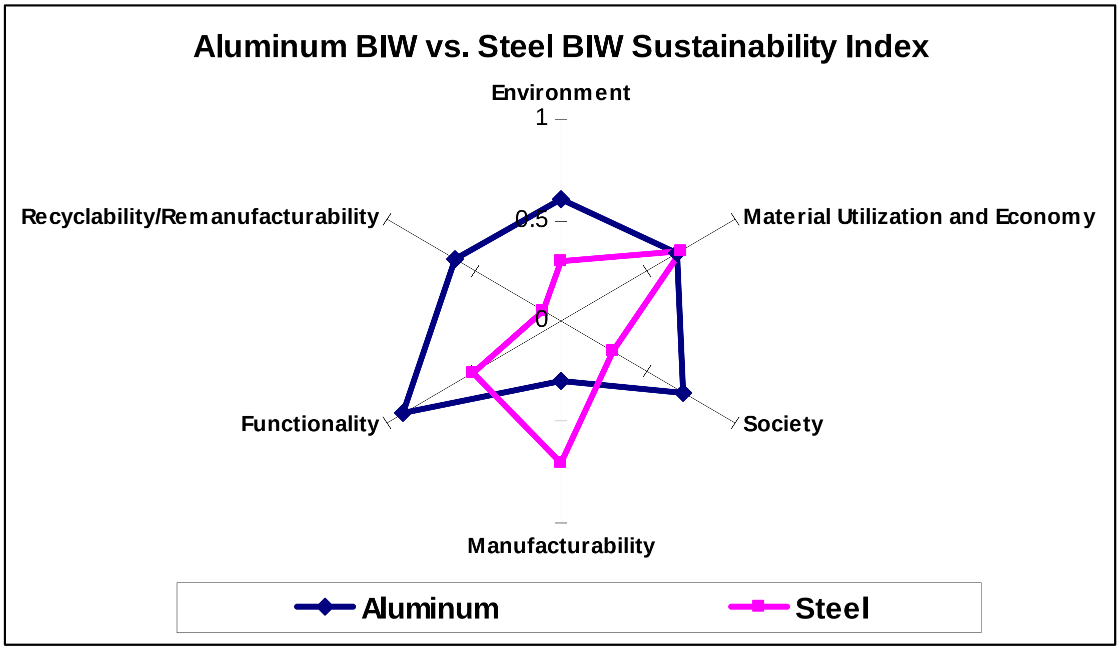

Figure 4.7: Aluminum versus steel sustainability index comparison

Figure 4.7 shows a comparison of BIW sustainability in these two materials.

4.3 Conclusion

Looking at all sustainability elements, aluminum has proven to be a material of choice for the new generation of vehicles. Due to its unique property of being recycled again and again without loss of quality and performance, aluminum has the potential to replace steel in auto body applications. Being a lighter material, aluminum contributes to reducing dramatically the weight of the vehicle, which in turn reduces the generation of pollutant compounds during operational stage of the vehicle. Being lighter, the vehicle needs less power to move and therefore reduces the money spent on gasoline. Safety is proven to be good since Audi A8, an all aluminum vehicle, earned a five star rating from the National Highway Traffic Safety Administration (NHTSA), which means 10 percent or less chance of serious injury in a vehicle collision [51]. However, some areas need improvement in order to make aluminum a sustainable choice for automotive industry. The existing manufacturing and assembly equipment, used by automotive industry, being set for steel components, need to be redesigned to fit the aluminum characteristics and the recycling system need to focus on finding ways to recycle the materials efficiently in order to take advantage of the all material properties. Once these barriers are overcome, and aluminum can be produced at a lower cost, the vehicles on the roads can be made using increased content of aluminum plus other lighter materials, keeping their utility and contributing to preserving our environment and natural resources through efficient recycling.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

Chapter one briefly addresses the stringent issue of developing and implementing sustainability models and principles in any manufactured product.

Chapter two briefly reviews the previous research done in automotive autobody applications and summarizes the current industry practice and possible future automotive initiatives.

Chapter three is aimed at developing a methodology to compare the costs encountered during the entire life-cycle of the vehicle under two different material scenarios used in body-in-white structures for a typical passenger car.

Chapter four extends the analysis from chapter three, including new sustainability elements (i.e.,Manufacturability, Functionality, Recyclability/Remanufacturability) and it is aimed at developing a new methodology to quantify all the sustainability elements.

5.2 Concluding Remarks

- In light of escalating fuel prices and ongoing climate change discussions, sustainability considerations are taking a more prominent role in material selection decisions for automotive applications.

- Since life-cycle assessment methods requires an extensive amount of data and quantify mainly the environmental impact of any product over its life-cycle, the need to develop comprehensive models to include all the major elements of sustainability such as social impact, economic impact, environmental impact manufacturability, functionality, and recyclability has become essential.

- From both economic and environment point of views, this work concludes that over the entire life-cycle of an automobile, aluminum proves to be a potential alternative for steels in future automotive applications.

- Recycling plays an important role and once take back initiatives will place the responsibility of product disposal on the product manufacturer, designers will be asked to develop products that are reusable, made of recycled materials, and are recyclable.

- This study proved the overall benefit of using lighter materials such as aluminum in autobody structures with respect to environment, society, economy, manufacturability, functionality and recyclability/remanufacturability since each year in the U.S., 15 millions cars and trucks reach the end of their useful lives entering the recycling stream [9].

5.3 Future Work

Based on these findings, and from the economical and environmental benefits of using both materials, future work should be focused on determining the right combination of materials in automotive structures. This would help to reduce total costs and greenhouse gas emissions over the life-cycle of the vehicle and to improve safety and performance. Since use and post-use costs associated to the vehicle's body are incurred over the lifetime of the vehicle, these costs must first be discounted to a present value in order to be possible to compare them to the manufacturing and pre-manufacturing costs. Since take-back options are fast becoming inevitable and unavoidable for car makers, it would be essential to quantify and estimate the total life-cycle cost encountered by the vehicles by considering the other options such as reuse and remanufacturing of parts. More "sustainability" sub-elements might be added to refine the "sustainability" model and some weight might be placed on different sub-elements or influencing factors.

APPENDICES

APPENDIX A

‘Life-Cycle Cost Analysis:
Aluminum vs. Steel in Passenger Cars

‘Set spreadsheet 1

‘Assumptions
‘Gas price = [C9]
[C9] = [C7] + ([C7]*([C8]/100))
‘Cost of steel = [C14]
[C14] = [C12] + ([C12]*([C13]/100))
‘Cost of aluminum = [C19]
[C19] = [C17] + ([C17]*([C18]/100))
‘Life of car = [C21]
‘Total miles driven = [C22]
[C22] = IF ([C21] =1, Sheet1! [K7], IF ([C21] =3, Sheet1! [K9], IF ([C21] =4, Sheet1! [K10], IF ([C21] =7, Sheet1! [K13], IF ([C21] =9, Sheet1! [K15], IF ([C21] =10, Sheet1! [K16], IF ([C21] =12, Sheet1! [K18], IF ([C21] = 14, Sheet1! [K20]))))))))
‘Steel fuel consumption = [C25]
‘Aluminum fuel consumption = [C26]
‘Steel curb weight = [C34]
‘Aluminum curb weight = [C35]
‘Steel Body-in-white weight = [C38]
‘Aluminum Body-in-white weight = [C39]
‘Steel scrap price = [C46]
[C46] = [C42] + ([C42]*[C44]/100))
‘Aluminum scrap price = [C47]
[C47] = [C43] + ([C43]*[C45]/100))
‘Percent recycling
‘Steel = [C50]
‘Aluminum = [C51]
‘Steel recycled price = [C58]
[C58] = [C54] + ([C54]*[C56]/100))
‘Aluminum recycled price = [C59]
[C59] = [C55] + ([C55]*[C57]/100))
‘Steel gallons used = [C65]
[C65] = [C22]/ [C29]
‘Aluminum gallons used = [C66]
[C66] = [C22]/ [C31]
‘Gallons difference = [C67]
[C67] = [C66] – [C65]
‘Steel use cost = [C68]
[C68] = [C65]*[C9]
‘Aluminum use cost = [C69]

[C69] = [C66]*[C9]

‘Set Spreadsheet 2

‘Ratio: Total (Pre-manufacturing, Manufacturing, Use, post-use) cost steel vs. Total (Pre-manufacturing, Manufacturing, Use, Post-use) cost aluminum

‘Number of years = [C15]
‘Miles driven = [C16]
[C16] = IF ([C15] =1, Sheet1! [K7], IF ([C15] =3, Sheet1! [K9], IF ([C15] =4, Sheet1! [K10], IF ([C15] = 7, Sheet1! [K13], IF ([C15] = 9, Sheet1! [K15], IF ([C15] = 10, Sheet1! [K16], IF ([C15] = 12, Sheet1! [K18], IF ([C15] = 14, Sheet1! [K20]))))))))

‘0 % RECYCLING
‘Aluminum cost = [C53]
[C53] = Sheet2! [C13]
‘Steel cost = [C54]
[C54] = Sheet2! [C9]
‘Cost ratio aluminum/ steel = [C56]
[C56] = [C53]/ [C54]

‘PRE-MANUFACTURING STAGE
‘Aluminum sheet = [C60]
‘Cost of aluminum sheet = [C61]
[C61] = [C60]*[C53]
‘Steel sheet = [C62]
‘Cost of steel sheet = [C63]
[C63] = [C62]*[C54]

‘MANUFACTURING STAGE
‘Annual production = [C66]
‘Steel BIW Production cost = [C67]
‘Steel BIW assembly cost = [C68]
‘Steel total manufacturing cost = [C69]
[C69] = [C67] + [C68]
‘Aluminum BIW Production cost = [C73]
‘Aluminum BIW Assembly cost = [C74]
‘Aluminum total manufacturing cost = [C75]
[C75] = [C73] + [C74]

‘USE STAGE
‘Aluminum gallons used = [C80]
[C80] = [C16]/ [C20]
‘Steel gallons used = [C81]
[C81] = [C16]/ [C18]
‘Aluminum use cost = [C82]

[C82] = [C80]* Sheet1! [C9]
‘Steel use cost = [C83]
[C83] = [C81]* Sheet1! [C9]

‘POST-USE STAGE
‘Steel Scrap from EOL = [C87]
[C87] = ([C35]/100)*[C23]
‘Steel Scrap value = [C88]
[C88] = [C87]*[C31]
‘Aluminum Scrap from EOL = [C91]
[C91] = ([C36]/100)*[C24]
‘Aluminum Scrap value = [C92]
[C92] = [C91]*[C32]

’25 % RECYCLING + 75 % VIRGIN
‘Aluminum cost = [C102]
[C102] = {(0.75*[C13]) + (0.25*[C44])}
‘Steel cost = [C103]
[C103] = {(0.75*[C9] + (0.25*[C43])}
‘Cost ratio aluminum/ steel = [C105]
[C105] = [C102]/ [C103]

‘PRE-MANUFACTURING STAGE
‘Aluminum sheet = [C108]
‘Cost of aluminum sheet = [C109]
[C109] = [C108]*[C102]
‘Steel sheet = [C110]
‘Cost of steel sheet = [C111]
[C111] = [C110]*[C103]
‘MANUFACTURING STAGE
‘Annual production = [C114]
‘Steel BIW Production cost = [C115]
‘Steel BIW assembly cost = [C116]
‘Steel total manufacturing cost = [C117]
[C117] = [C115] + [C116]
‘Aluminum BIW Production cost = [C121]
‘Aluminum BIW Assembly cost = [C122]
‘Aluminum total manufacturing cost = [C123]
[C123] = [C121] + [C122]

‘USE STAGE
‘Aluminum gallons used = [C128]
[C128] = [C16]/ [C20]
‘Steel gallons used = [C129]
[C129] = [C16]/ [C18]
‘Aluminum use cost = [C130]

[C130] = [C128]* Sheet1! [C9]
‘Steel use cost = [C131]
[C131] = [C129]* Sheet1! [C9]

‘POST-USE STAGE
‘Steel Scrap from EOL = [C135]
[C135] = ([C35]/100)*[C23]
‘Steel Scrap value = [C136]
[C136] = [C135]*[C31]
‘Aluminum Scrap from EOL = [C139]
[C139] = ([C36]/100)*[C24]
‘Aluminum Scrap value = [C140]
[C140] = [C139]*[C32]

’75 % RECYCLING + 25 % VIRGIN
‘Aluminum cost = [C151]
[C151] = {(0.75*[C44]) + (0.25*[C13])}
‘Steel cost = [C152]
[C152] = {(0.75*[C43] + (0.25*[C9])}
‘Cost ratio aluminum/ steel = [C154]
[C154] = [C151]/ [C152]

‘PRE-MANUFACTURING STAGE
‘Aluminum sheet = [C157]
‘Cost of aluminum sheet = [C158]
[C158] = [C157]*[C151]
‘Steel sheet = [C159]
‘Cost of steel sheet = [C160]
[C160] = [C159]*[C152]
‘MANUFACTURING STAGE
‘Annual production = [C163]
‘Steel BIW Production cost = [C164]
‘Steel BIW assembly cost = [C165]
‘Steel total manufacturing cost = [C166]
[C166] = [C164] + [C165]
‘Aluminum BIW Production cost = [C170]
‘Aluminum BIW Assembly cost = [C171]
‘Aluminum total manufacturing cost = [C172]
[C172] = [C170] + [C171]

‘USE STAGE
‘Aluminum gallons used = [C177]
[C177] = [C16]/ [C20]
‘Steel gallons used = [C178]
[C178] = [C16]/ [C18]
‘Aluminum use cost = [C179]

[C179] = [C177]* Sheet1! [C9]
‘Steel use cost = [C180]
[C180] = [C178]* Sheet1! [C9]

‘POST-USE STAGE
‘Steel Scrap from EOL = [C184]
[C184] = ([C35]/100)*[C23]
‘Steel Scrap value = [C185]
[C185] = [C184]*[C31]
‘Aluminum Scrap from EOL = [C188]
[C188] = ([C36]/100)*[C24]
‘Aluminum Scrap value = [C189]
[C189] = [C188]*[C32]

‘100 % RECYCLING
‘Aluminum cost = [C200]
[C200] = Sheet2! [C44]
‘Steel cost = [C201]
[C201] = Sheet2! [C43]
‘Cost ratio aluminum/ steel = [C203]
[C203] = [C200]/ [C201]

‘PRE-MANUFACTURING STAGE
‘Aluminum sheet = [C206]
‘Cost of aluminum sheet = [C207]
[C207] = [C206]*[C200]
‘Steel sheet = [C208]
‘Cost of steel sheet = [C209]
[C209] = [C208]*[C201]
‘MANUFACTURING STAGE
‘Annual production = [C212]
‘Steel BIW Production cost = [C213]
‘Steel BIW assembly cost = [C214]
‘Steel total manufacturing cost = [C215]
[C215] = [C213] + [C214]
‘Aluminum BIW Production cost = [C219]
‘Aluminum BIW Assembly cost = [C220]
‘Aluminum total manufacturing cost = [C221]
[C221] = [C219] + [C220]

‘USE STAGE
‘Aluminum gallons used = [C226]
[C226] = [C16]/ [C20]
‘Steel gallons used = [C227]
[C227] = [C16]/ [C18]
‘Aluminum use cost = [C228]

[C228] = [C226]* Sheet1! [C9]
‘Steel use cost = [C229]
[C229] = [C227]* Sheet1! [C9]

‘POST-USE STAGE
‘Steel Scrap from EOL = [C233]
[C233] = ([C35]/100)*[C23]
‘Steel Scrap value = [C234]
[C234] = [C233]*[C31]
‘Aluminum Scrap from EOL = [C237]
[C237] = ([C36]/100)*[C24]
‘Aluminum Scrap value = [C238]
[C238] = [C237]*[C32]

‘ALUMINUM 75 % R + 25 % V; STEEL 25 % R + 75 % V
‘Aluminum cost = [C249]
[C249] = Sheet2! [C151]
‘Steel cost = [C250]
[C250] = Sheet2! [C103]
‘Cost ratio aluminum/ steel = [C252]
[C252] = [C249]/ [C250]

‘PRE-MANUFACTURING STAGE
‘Aluminum sheet = [C255]
‘Cost of aluminum sheet = [C256]
[C256] = [C255]*[C249]
‘Steel sheet = [C257]
‘Cost of steel sheet = [C258]
[C258] = [C257]*[C250]
‘MANUFACTURING STAGE
‘Annual production = [C261]
‘Steel BIW Production cost = [C262]
‘Steel BIW assembly cost = [C263]
‘Steel total manufacturing cost = [C264]
[C264] = [C262] + [C263]
‘Aluminum BIW Production cost = [C268]
‘Aluminum BIW Assembly cost = [C269]
‘Aluminum total manufacturing cost = [C270]
[C270] = [C268] + [C269]

‘USE STAGE
‘Aluminum gallons used = [C275]
[C275] = [C16]/ [C20]
‘Steel gallons used = [C276]
[C276] = [C16]/ [C18]
‘Aluminum use cost = [C277]

[C277] = [C275]* Sheet1! [C9]
‘Steel use cost = [C278]
[C278] = [C276]* Sheet1! [C9]

‘POST-USE STAGE
‘Steel Scrap from EOL = [C282]
[C282] = ([C35]/100)*[C23]
‘Steel Scrap value = [C283]
[C283] = [C282]*[C31]
‘Aluminum Scrap from EOL = [C286]
[C286] = ([C36]/100)*[C24]
‘Aluminum Scrap value = [C287]
[C287] = [C286]*[C32]

‘Set Spreadsheet 3

‘Total Ownership Costs (ALUMINUM 75 % R + 25 % V; STEEL 25 % R + 75 % V)

‘Gas price = [C6]
[C6] = IF (Sheet1! [C8]= -20, Sheet 1! [C9], IF ([Sheet1! [C8] = -10, Sheet1! [C9], IF (Sheet1! [C8] = 0, Sheet1! [C9], IF (Sheet1! [C8] = +10, Sheet1! [C9], IF (Sheet1! [C8] = +20, Sheet1! [C9])))))
‘Aluminum
‘Pre-manufacturing stage = [G7]
[G7] = Sheet2! [C256]
‘Manufacturing stage = [G8]
[G8] = Sheet2! [C268]
‘Use stage = [G9]
[G9] = IF (Sheet3! [C7] = 1, [C15], IF (Sheet3! [C7] =3, [D15], IF (Sheet3! [C7] = 4, [E15], IF (Sheet3! [C7] = 7, [F15], IF (Sheet3! [C7] = 9, [G15], IF (Sheet3! [C7] = 10, [H15], IF (Sheet3! [C7] = 12, [I15], IF (Sheet3! [C7] = 14, [J15]))))))))
‘Post-use stage = [G10]
[G10] = Sheet2! [C290]
‘Steel
‘Pre-manufacturing stage = [H7]
[H7] = Sheet2! [C258]
‘Manufacturing stage = [H8]
[H8] = Sheet2! [C264]
‘Use stage = [H9]
[H9] = IF (Sheet3! [C7] = 1, [C16], IF (Sheet3! [C7] =3, [D16], IF (Sheet3! [C7] = 4, [E16], IF (Sheet3! [C7] = 7, [F16], IF (Sheet3! [C7] = 9, [G16], IF (Sheet3! [C7] = 10, [H16], IF (Sheet3! [C7] = 12, [I16], IF (Sheet3! [C7] = 14, [J16]))))))))
‘Post-use stage = [H10]
[H10] = Sheet2! [C282]
*********************************END*********************************

APPENDIX B

Life-Cycle CO_2 emissions analysis: Aluminum vs. Steel in Passenger Cars

'Set Spreadsheet 1

'Assumptions
'Steel curb weight = [C7]
'Aluminum curb weight = [C8]
'Weight reduction = [C9]
[C9] = 100 – ([C8]*100/ [C7])
'Steel BIW weight = [C12]
'Aluminum BIW weight = [C13]
'Body in white savings = [C14]
[C14] = [C13] – [C12]
'Fuel economy = [C16]
[C16] = 5*[C9]/10
'Steel fuel efficiency = [C21]
'Aluminum fuel efficiency = [C23]
[C23] = [C21] + ([C21]*[C22]/100)
'Pounds CO_2 emissions per mile = [C25]
'Steel CO2 emissions per mile = [C26]
[C26] = [C25] + (0.07*[C25])
'Aluminum CO2 emissions per mile = [C27]
[C27] = [C25] – (0.03*[C25])

'CO_2 emissions over the lifetime of the vehicle (USE stage)
'Steel fuel consumption = [C32]
'Aluminum fuel consumption = [C33]
'Steel CO_2 emissions = [C36]
[C36] = [Gi]*[C26]*[C29]
'Aluminum CO_2 emissions = [C38]
[C38] = [Gi]*[C27]*[C29]
I = [G9], [G10]… [G22]

'CO_2 emissions during PRE-MANUFACTURING stage
'Kilograms steel sheet to produce steel BIW = [C77]
'Kilograms aluminum sheet to produce aluminum BIW = [C78]
'Kilograms CO_2 to produce virgin steel sheet = [C81]
'Kilograms CO_2 to produce 1 Kg virgin steel sheet = [C82]
'Kilograms CO_2 to produce 1 Kg recycled steel sheet = [C84]
[C84] = (.25)*[C82]
'Kilograms CO_2 to produce virgin aluminum sheet = [C87]
'Kilograms CO_2 to produce 1 Kg virgin aluminum sheet = [C88]
'Kilograms CO_2 to produce 1 Kg recycled aluminum sheet = [C90]
[C90] = (.05)*[C88]

‘CO_2 emissions during MANUFACTURING stage
‘Kilograms CO_2 to manufacture steel BIW = [C122]
‘Kilograms CO_2 to manufacture aluminum BIW = [C126]

‘CO_2 emissions during POST-USE stage
‘Kilograms CO_2 to produce virgin steel BIW = [C134]
[C134] = [C82]*[C13]
‘Percent of BIW recycled = [C135]
[C135] = (.9)*[C13]
‘Kilograms CO_2 to produce 333.9 virgin steel = [C136]
[C136] = [C135]*[C82]
‘Percent of energy saved from recycling steel = [C137]
[C137] = (.25)*[C136]
‘Kilograms CO_2 to produce virgin aluminum BIW = [C140]
[C140] = [C88]*[C14]
‘Percent of BIW recycled = [C141]
[C141] = (.9)*[C14]
‘Kilograms CO_2 to produce 173.7 virgin aluminum = [C142]
[C142] = [C142]*[C88]
‘Percent of energy saved from recycling aluminum = [C143]
[C143] = (.05)*[C142]

‘Set Spreadsheet 2

‘Total CO_2 emissions
‘Number of years = [C149]
‘Total miles driven = [C150]
[C150] = IF ([C149] =1, [G9], IF ([C149] =3, [G11], IF ([C149] =4, [G12], IF ([C149] =5, [G13], IF ([C149] =7, [G15], IF ([C149] =10, [G18], IF ([C149] =12, [G20], IF ([C149] =14, [G22]))))))))

‘Aluminum (75%R + 25%V), Steel (25%R + 75%V)
‘Steel CO_2 emissions
‘Pre-manufacturing stage = [G161]
[G161] = [G85]
‘Manufacturing stage = [G162]
[G162] = [C122]
‘Use stage = [G163]
[G163] = IF ([C149] =1, [G150], IF ([C149] =3, [G151], IF ([C149] =4, [G152], IF ([C149] =5, [G153], IF ([C149] =7, [G154], IF ([C149] =10, [G155], IF ([C149] =12, [G156], IF ([C149] =14, [G157]))))))))
‘Post-use stage = [G164]
[G164] = [C137]
‘Aluminum CO_2 emissions
‘Pre-manufacturing stage = [H161]

[H161] = [H85]
'Manufacturing stage = [H162]
[H162] = [C126]
'Use stage = [H163]
[H163] = IF ([C149] =1, [H150], IF ([C149] =3, [H151], IF ([C149] =4, [H152], IF ([C149] =5, [H153], IF ([C149] =7, [H154], IF ([C149] =10, [H155], IF ([C149] =12, [H156], IF ([C149] =14, [H157]))))))))
'Post-use stage = [H164]
[H164] = [C143]

'0 % R - both materials
'Steel CO_2 emissions
'Pre-manufacturing stage = [G200]
[G200] = [G81]
'Manufacturing stage = [G201]
[G201] = [C122]
'Use stage = [G202]
[G202] = IF ([C149] =1, [G150], IF ([C149] =3, [G151], IF ([C149] =4, [G152], IF ([C149] =5, [G153], IF ([C149] =7, [G154], IF ([C149] =10, [G155], IF ([C149] =12, [G156], IF ([C149] =14, [G157]))))))))
'Post-use stage = [G203]
[G203] = [C137]

'Aluminum CO_2 emissions
'Pre-manufacturing stage = [H200]
[H200] = [H81]
'Manufacturing stage = [H201]
[H201] = [C126]
'Use stage = [H202]
[H202] = IF ([C149] =1, [H150], IF ([C149] =3, [H151], IF ([C149] =4, [H152], IF ([C149] =5, [H153], IF ([C149] =7, [H154], IF ([C149] =10, [H155], IF ([C149] =12, [H156], IF ([C149] =14, [H157]))))))))
'Post-use stage = [H203]
[H203] = [C143]
********************************END********************************

APPENDIX C

Sustainability Calculations

‘Set spreadsheet 1

‘Environmental impact index
‘Adverse environmental effect index
‘Carbon dioxide emissions from a gallon of gasoline = C [17]
‘Aluminum gallons used = D [29]
‘Steel gallons used = D [31]
‘Aluminum adverse environmental effect index = B [35]
B [35] = C [17]*D [29]
‘Steel adverse environmental effect index = B [36]
B [36] = C [17]*D [31]
‘Aluminum environmental impact index = B [35]
‘Steel environmental impact index = B [36]

‘Material utilization and economy index
‘Energy efficiency index
‘Electricity cost = B [54]
‘Aluminum PM energy = C [81]
‘Steel PM energy = C [82]
‘Aluminum PM energy efficiency index = E [81]
E [81] = C [81]*B [54]/3.6
‘Steel PM energy efficiency index = E [82]
E [82] = C [82]*B [54]/3.6
‘Aluminum M energy = C [84]
‘Steel M energy = C [85]
‘Aluminum M energy index = E [84]
E [84] = C [84]*B [54]/3.6
‘Steel M energy index = E [85]
E [85] = C [85]*b [54]/3.6
‘Aluminum R energy = C [87]
‘Steel R energy = C [88]
‘Aluminum R energy index = E [87]
E [87] = C [87]*B [54]/3.6
‘Steel R energy index = E [88]
E [88] = C [88]*B [54]/3.6
‘Aluminum energy efficiency index = B [91]
B [91] = 0.33*(E [81] + E [84] + E [87])
‘Steel energy efficiency index = C [91]
C [91] = 0.33*(E [82] + E [85] + E [88])

‘Material cost index
‘Virgin aluminum material cost = F [134]
‘Virgin steel material cost = F [135]

‘Recycled aluminum material cost	= E [134]
‘Recycled steel material cost	= E [135]
‘Aluminum material cost	= G [134]
‘Steel material cost	= G [135]
‘Aluminum material cost index	= I [134]
I [134] = G [134]/B [134}	
‘Steel material cost index	= I [135]
I [135] = G [135]/B [135]	

‘Operational cost index	
‘Gasoline cost	= A [155]
‘Aluminum gallons used	= C [148]
‘Steel gallons used	= C [150]
‘Aluminum operational cost index	= F [148]
F [148] = A [155]*C [148]	
‘Steel operational cost index	= F [150]
F [150] = A [155]*C [150]	
‘Aluminum material utilization and economy index	= C [172]
C [172] = 0.33*(B [91] + I [134] + F [148])	
‘Steel material utilization and economy index	= C [173]
C [173] = 0.33*(C [91] + I [135] + F [150])	

‘Set Spreadsheet 2

‘Societal impact index	
‘Operational safety index	
‘Aluminum energy absorption	= C [5]
‘Steel energy absorption	= C [6]
‘Aluminum operational safety index	= D [5]
‘Steel operational safety index	= D [6]
‘Aluminum societal impact index	= D [5]
‘Steel societal impact index	= D [6]

‘Manufacturability index	
‘Assembly index	
‘No of parts for aluminum BIW	= B [39]
‘No of parts for steel BIW	= B [40]
‘Aluminum assembly index	= D [39]
‘Steel assembly index	= D [40]
‘Aluminum manufacturability index	= D [39]
‘Steel manufacturability index	= D [40]

‘Functionality index	
‘Acceleration index	
‘Aluminum acceleration time	= G [72]

‘Steel acceleration time	= G [74]
‘Aluminum acceleration index	= H [72]
‘Steel acceleration index	= H [74]
‘Aluminum functionality index	= H [72]
‘Steel functionality index	= H [74]

‘Recyclability/Remanufacturability index
‘Recyclability index

‘Aluminum scrap value	= E [105]
‘Steel scrap value	= E [106]
‘Aluminum recyclability index	= G [105]
‘Steel recyclability index	= G [106]
‘Aluminum recyclability/remanufacturability index	= G [105]
‘Steel recyclability/remanufacturability index	= G [106]

‘Set Spreadsheet 3

‘Aluminum sustainability index = B [11]
B [11] = SUM (B [5]: B [10])/6
‘Steel sustainability index = C [11]
C [11] = SUM (C [5]: C [10])/6
******************************** END **********************************

REFERENCES

[1] The Institute for Market Transformation to Sustainability (MTS),"The Economy and Environment Win", Sustainable Products Corporation, Washington, DC, http://MTS.sustainableproducts.com

[2] The Institute for Market Transformation to Sustainability (MTS), "Sustainable and Green Profits Are Starting to Drive the Economy", Sustainable Products Corporation, Washington, DC, http://MTS.sustainableproducts.com

[3] The Report of the Brundtland Commission," The U.N. World Commission on Environment and Development: Our Common Future", *Oxford: Oxford University Press*, 1987.

[4] Jawahir, I.S., Wanigarathne, P.C., "New Challenges in Developing Science-Based Sustainability Principles for Next Generation Product Design and Manufacture", *Proceedings 8th TMT*, Neum, Bosnia and Herzegovina, September, 15-19, 2004, pp. 1-10

[5] Jawahir, I. S., Wanigarathne, P. C., Wang, X. "Product Design and Manufacturing Processes for Sustainability", *Chapter 12 Mechanical Engineers' Handbook,* Third Edition, 2006, pp. 414-443.

[6] Niranjali de Silva,"A New Comprehensive Methodology for the Evaluation of Product Sustainability at the Design Stage of Consumer Electronics Products", *Master's Thesis*, University of Kentucky, May 2005.

[7] Joshi, K., Venkatachalam, A., Jaafar, I.H., Jawahir, I.S., "A New Methodology for Transforming 3R Concept into 6R Concept for Improved Product Sustainability", *Proceedings 4th Global Conference on Sustainable Product Development and Life-Cycle Engineering*, Sao Carlos, Brazil, October, 3-6, 2006.

[8] Vijay A. Tipnis, "Evolving Issues in Product Life Cycle Design", *Annals of the CIRP* Vol. 42/1/1993, pp. 169-173.

[9] Edward J. Daniels, Joseph A. Carpenter, Jr., Claudia Duranceau, Michael Fisher, Candace Wheeler, and Gerald Winslow,"Sustainable End-of-Life Vehicle Recycling: R&D Collaboration between Industry and the U.S. DOE", *JOM*, August 2004, pp. 28-32.

[10] Pragna N.H. Bhakta, "Recent Technology and Trends in Automotive Recycling", *JOM*, February 1994, pp. 36-39.

[11] Life-cycle thinking, http://www.ami.ac.uk/courses/topics/0109_lct/.

[12] F. Stodolsky, A. Vyas, R. Cuenca, and L.Gaines, "Life-Cycle Energy Savings Potential from Aluminum-Intensive Vehicles", *SAE 1995 Total Life Cycle Conference and Exposition*, Vienna, Austria (October 16 – 19, 1995).

[13] Kurihara Yuri, "The Role of Aluminum in Automotive Weight Reduction – Part I", *JOM*, November 1993, pp. 32-33.

[14] Kurihara Yuri, "The Role of Aluminum in Automotive Weight Reduction – Part II", *JOM*, February 1994, pp. 33-35.

[15] Kurihara Yuri, "The Role of Aluminum in Automotive Weight Reduction – Part III", *JOM*, May 1994, pp. 12-13.

[16] Scot A. Arnold, "Techno-Economic Issues in the Selection of Auto Materials", *JOM*, June 1993, pp. 12-15.

[17] Helen N. Han, Joel P. Clark," Lifetime Costing of the Body-in-Whites: Steel vs. Aluminum", *JOM*, May 1995, pp. 22-28.

[18] Jeff R. Dieffenbach and Anthony E. Mascarin, "Body-in-White Material Systems: A Life-Cycle Cost Comparison", *JOM* ,June 1993, pp. 16-19.

[19] A. Mariano, Floyd R. Tuler, and Walter S. Owen," Comparing Steel and Aluminum Auto Structures by Technical Modeling", *JOM*, June 1993, Stephen Cost pp. 20-22.

[20] Anish Kelkar, Richard Roth, and Joel P. Clark, "Automotive Bodies: Can Aluminum be an Economical Alternative to Steel?", *JOM*, August 2001, pp. 28-32.

[21] Helen N. Han, "The Environmental Impact of Steel and Aluminum Body-in-Whites", *JOM*, February 1996, pp. 33-38.

[22] Sujit Das, "The Life-Cycle Impacts of Aluminum Body-in-White Automotive Material", *JOM* (August 2000), pp. 41-44.

[23] International Aluminum Institute (IAI), "Environment and Health", hhttp://world-aluminium.org/.

[24] International Aluminum Institute (IAI), "Aluminum Sustainability", hhttp://world-aluminium.org/.

[25] William T. Choate, John A.S. Green,"Modeling the Impact of Secondary Recovery (Recycling) on U.S. Aluminum Supply and Nominal Energy Requirements", *TMS*, 2004.

[26] The Aluminum Association, Inc.,"Recyclability and Scrap value", Automotive Aluminum, http://www.aluminum.org/.

[27] The Aluminum Association, Inc., "Aluminum Industry Roadmap for the Automotive market: Enabling Technologies and Challenges for Body Structures and Closures"' May 1999, pp. 1-69.

[28] I.N. Fridlyander, V.G.Sister, O.E. Grushko, V.V.Berstenev, L.M. Sheveleva, L.A. Ivanova, "Aluminum Alloys: Promising Materials in the Automotive Industry", *Metal Science and Heat Treatment*, pp.3-9, September 2002.

[29] Adam Gesing, and Richard Wolanski,"Recycling Light Metals from End-of-Life Vehicles",*JOM*, November 2001, pp. 21-23.

[30] International Aluminum Institute (IAI), "Aluminum for Future Generations", Sustainability Update 2005.

[31] William T. Choate, John A. S. Green, "U.S. Energy Requirements for Aluminum Production: Historical Perspective, Theoretical limits and New Opportunities",*U.S. Department of Energy, Energy Efficiency and Renewable Energy*, Feb. 2003, pp.1-86.

[32] The Aluminum Association's Auto& Light Truck Group (ALTG)," Aluminum Surpasses Iron as Second Most Used Automotive Material Worldwide", http://www.autoaluminum.org/.

[33] Rick Borns, Don Whitacre, "Optimizing Designs of Aluminum Suspension Components Using an Integrated Approach", Alcoa Inc., *SAE Paper 05M-2*.

[34] Frank Field, Randolph Kirchain, and Joel P. Clark, "Life-Cycle Assessment and Temporal Distributions of Emissions", *Journal of Industrial Ecology*, Volume 4, Number 2, 2001, pp. 71-91.

[35] Ducker Worldwide," Aluminum Content for Light Non Commercial Vehicles to be Assembled in North America, Japan and the European Union in 2006", December 2005

[36] Hadley, S.W., Das, S., Miller, J. W., "Aluminum R&D for Automotive Uses and the Department of Energy's Role", *Oak Ridge National Laboratory*, March 2000, pp. 1-28.

[37] The Aluminum Association, Inc.,"Life Cycle Inventory report for the North American Aluminum Industry", *Publication AT 2*, November 1998, pp.1-26.

[38] American Iron and Steel Institute (AISI), Steel Recycling Institute," Recycling Scrapped Automobiles", http://www.recycle-steel.org/

[39] Linda Gaines and Roy M. Cuenca, "Operation of an Aluminum-Intensive Vehicle: Report on a Six-Year Project", SAE Technical Paper, *International Body Engineering Conference and Exhibition*, Paris, France, (July 9-11, 2002), pp.1-9.

[40] Environmental News Network (ENN),"Study crushes idea for aluminum vehicle", http://www.enn.com/, May 1999.

[41] Frank R. Field III and Joel P. Clark, "A Practical Road to Lightweight Cars", *Technology Review*, January 1997, pp. 1-7.

[42] Environmental Protection Agency, "Cars and Light Trucks", http://www.epa.gov/.

[43] Rajive Dhingra, Jonathan G. Overly, Gary A. Davis, Sujit Das, Stan Hadley and Bruce Tonn, "A Life-Cycle-Based Environmental Evaluation: Materials in New Generation Vehicles", SAE Technical Paper, *Environmental Concepts for the Automotive Industry*, Detroit, Michigan (March, 6-9, 2000), pp. 1-10.

[44] Timothy C. Moore, Amory B. Lovins, "Vehicle Design Strategies to Meet and Exceed PNGV Goals", SAE Paper No. 951906, *Future Transportation Technology Conference*, Costa Mesa, CA, August, 4, 1995, pp.1-43.

[45] The Aluminum Association Inc.,"Performance Advantage", Automotive Aluminum, http://www.autoaluminum.org/.

[46] Duke Castle,"A Sustainability Vision for the Automotive Services Industry", *Department of Environmental Quality*, Oregon, June 2001, pp.1-36.

[47] U.S. Environmental Protection Agency, "Emission facts: Average annual Emissions and Fuel Consumption for Passenger Cars and Light trucks", *Office of Transportation and Air Quality*, April 2000.

[48] Martchek, K.J., "The Importance of Recycling to the Environmental Profile of Metal Products", Edited by D.L. Stewart, Jr., J.C. Daley, R.L. Stephens, *TMS*, 2000, pp. 19-28.

[49] Jawahir, I. S., Rouch, K.E., Dillon, O. W. Jr., Holloway, L., Hall, A., Knuf, J., "Design for Sustainability (DFS): New Challenges in Developing and Implementing a Curriculum for Next Generation Design and Manufacturing Engineers", *CIMEC (CIRP International Manufacturing Education Conference) / 3rd SME International Conference on Manufacturing Education*, California Polytechnic State University, San Luis Obispo, June 22-25, 2005, pp. 59-71.

[50] The Aluminum Association, Inc.,"Handling and Performance", Automotive Aluminum, http://www.aluminum.org/.

[51] The Aluminum Association Inc.,"Safety Advantage", Automotive Aluminum, http://www.autoaluminum.org/.

[52] The Aluminum Association, Inc.,"Aluminum for Automotive Body Sheet Panels", *Publication AT 3*, December1998, pp.1-51.

[53] Michael J. Wheeler, "Crashworthiness of aluminum structured vehicles", Alcan International Limited, Canada, *Paper No 98-SI-W-20*, pp. 302-310.

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