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Life-cycle Cost Analysis*:* *Aluminum versus Steel in Passenger Cars*

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Abstract

In light of escalating fuel prices and the ongoing climate change discussion, sustainability considerations are currently taking a more prominent role in material selection decisions for automotive applications. This paper presents a new methodology for total life-cycle cost analysis and employs a case study involving the use of aluminum in automotive applications. This study is aimed at developing a new sustainability model to quantify the total cost encountered over the entire life-cycle of a vehicle considering all four life-cycle stages: (1) pre-manufacturing, (2) manufacturing, (3) use and (4) post-use. Also, the paper presents a quantitative evaluation of the environmental impact of using aluminum material in a vehicle. The paper compares the use of aluminum with the traditional use of steel alloys in a given automotive application by providing details of economic and environmental performance of the vehicle over the total life-cycle.

Introduction

Reducing manufacturing costs and tailpipe emissions by using light-weight materials which can easily be recycled or reused are among the major issues in today’s automobile industry. The growing emphasis on total cost and environmental impact has forced the life-cycle cost issue to be the driving factor. Weight savings in the overall car mass is considered to be a major research focus. Aluminum is proven to be among the potential materials capable of achieving weight reduction without sacrificing the vehicle safety and performance. Despite significant technological advantages in aluminum alloys, the use of aluminum alloys to replace traditional materials such as steels has been slow due to lack of comprehensive economic analysis of the entire life-cycle of automotive products.

In considering the total life-cycle of an automobile covering four stages (pre-manufacturing, manufacturing, use, and post-use), it is apparent that during the operational (use) stage of a vehicle, aluminum is proven to be a reliable alternative for traditional materials currently used in automotive body structures largely due to its cost-effectiveness and superior performance due to light weight. With the gas price variation, the initial cost advantage of using steel in body components gained in pre-manufacturing and manufacturing stages can be overcome during the operational (use) stage of the vehicle, since the lighter alternative provides significant savings in terms of fuel consumption and consequently generation of airborne gas emissions. Also, the superior recyclability and reusability of aluminum in the post-use stage outweighs the traditional materials despite the higher cost involved in producing primary aluminum.

This paper presents a systematic study of the total life-cycle cost analysis and the environmental impact of using aluminum-based automotive products. This study is aimed at developing a new model to quantify the total cost encountered over the entire life-cycle of a vehicle considering material substitution in the body structure of the vehicle, since the so-called body-in-white (BIW) structure plus exterior closure panels represent an important group where significant weight savings can be achieved. Also, the environmental impact over the lifetime of the vehicle is being quantified. Overall, the study concludes that considering the entire life-cycle of an automobile, from extraction of materials to the final disposal including recycling and reuse applications, aluminum proves to be a potential alternative for steels in future automotive applications.

Major Assumptions

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 [1, 2], 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. The major assumptions for this study are listed in Table 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 range is between $1.84 and $2.76 per gallon as shown in Table 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 are needed to produce 371 kg steel body structure. According to Stodolsky [1], the primary material used in the typical passenger car today is steel, which can be purchased for a cost between $0.77 and $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. Since aluminum is a material which is likely to replace steel in automotive body components [3], the starting value for aluminum sheet has been chosen as $3.3/kg [1]. 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 [4, 5].

For the manufacturing stage of the life-cycle, the calculations use Technical Cost Modeling software developed at MIT [3, 6] 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 [3, 5]. 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 [2].

Table 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	

The life time of the vehicle has been assumed 14 years [7]. 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 2. The price values of scrap material and recycled material are listed in Table 3 for both materials [8].

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 [9, 10]. 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 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

Table 3: Material price database 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 4 and these values are derived from [11]. 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 4: Total carbon dioxide emissions for steel and aluminum BIW (Year 1)

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 direct 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 [12]. For the 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 [9] and that the recycled aluminum saves 95 percent of the energy to produce virgin aluminum [13, 14] whereas the recycled steel saves between 40-75 percent of the energy required to produce virgin steel [10]. 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.

Preliminary Results

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 1. As expected, aluminum substitution would provide important savings over the entire range of the gas price variation. At a price of only $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.

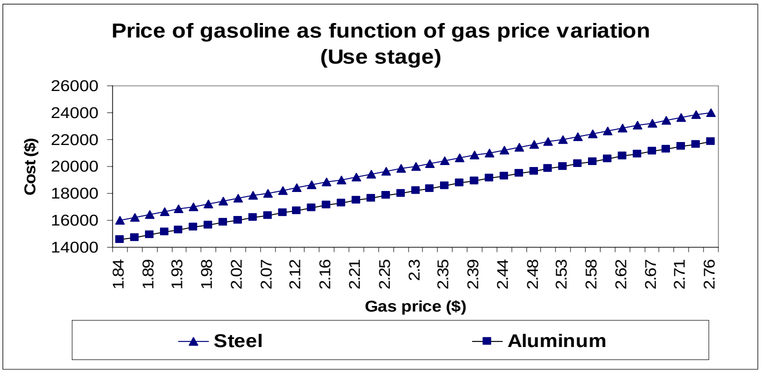

Figure 1: Cost of gasoline as a function of gas price variation (Use stage, 14 years)

The carbon dioxide emissions for the "Use" stage depend on the number of miles driven, fuel economy, and the 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 [12].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 CO_2 emissions generated during the use stage as function of the number of years are shown in Figure 2.

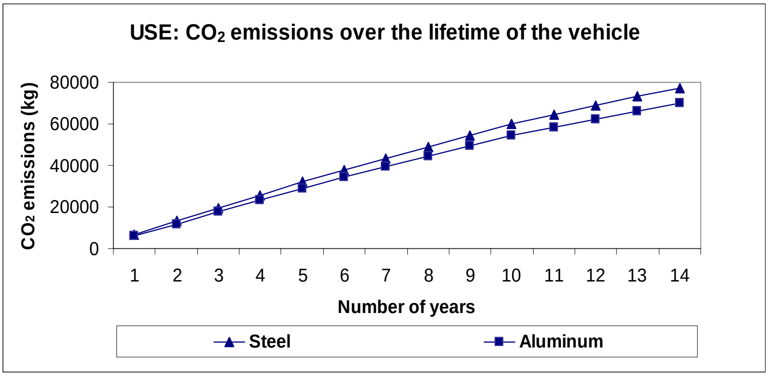

Figure 2: Carbon dioxide emissions over the lifetime of vehicle

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 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 the 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 the end-of-life vehicle. Since both materials are considered to be 90 percent recycled, and that 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 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. As content of material recycled is increased, for instance from 25 % to 75 % material recycled, the ratio becomes closer to the unity 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. However, a 100% recycled material us for both materials would give a cost advantage for aluminum.

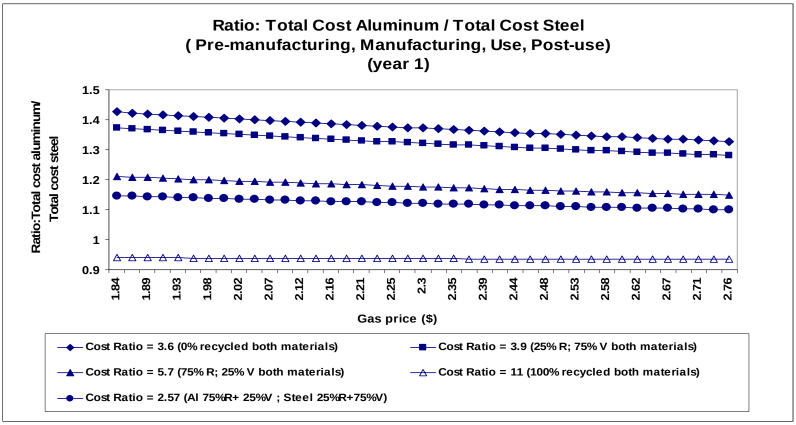

Figure 3: The ratio of the total cost for aluminum versus the total cost for steel (Year 1)

Figures 4 and 5 show the same decreasing trend for all scenarios of recycled material content, but for different number of miles driven: 57,970 miles (Figure 4) and 135,020 miles (Figure 5), driven at Year 4 and Year 10, respectively. The difference between the total costs for aluminum and the total costs for steel reduces, as the difference between the “Use” stage costs becomes larger. After 135,020 miles driven (Year 10), the total cost ratio is less than the unity value, for almost all scenarios of recycled material content. Considering the case scenario where aluminum 75 percent and steel 25 percent material recycled, Figure 6 shows the total ownership cost breakdown for both materials.

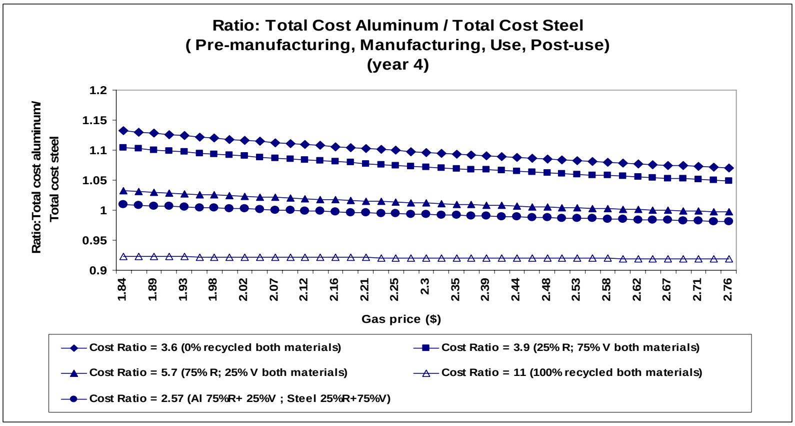

Figure 4: The ratio of the total cost for aluminum versus the total cost for steel (Year 4)

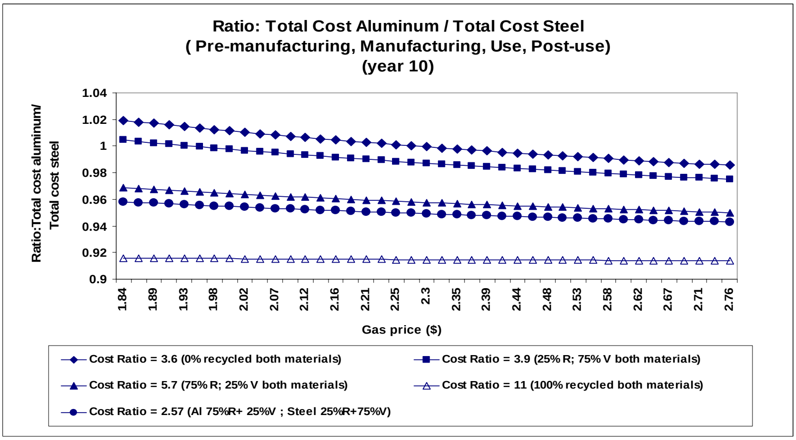

Figure 5: The ratio of the total cost for aluminum versus the total cost for steel (Year 10)

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.

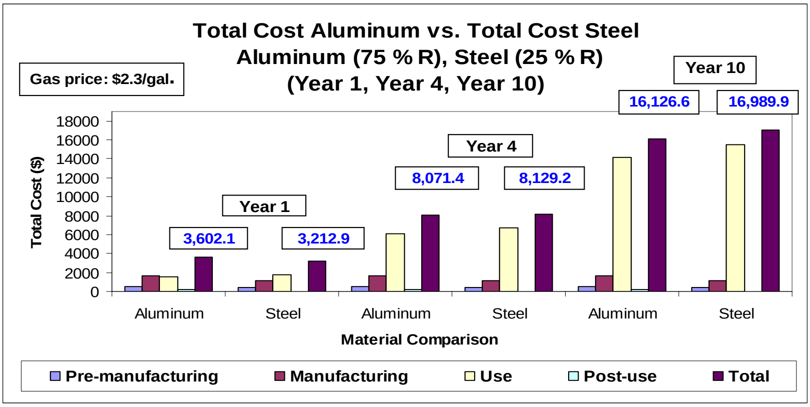

Figure 6: Total cost breakdown (Aluminum vs. Steel) for all four life-cycle stages

For the pre-manufacturing stage, the amount of carbon dioxide generated is calculated based on the content of material recycled. Figure 7 shows the amounts of carbon dioxide generated during this stage for increasing recycling rate for both materials.

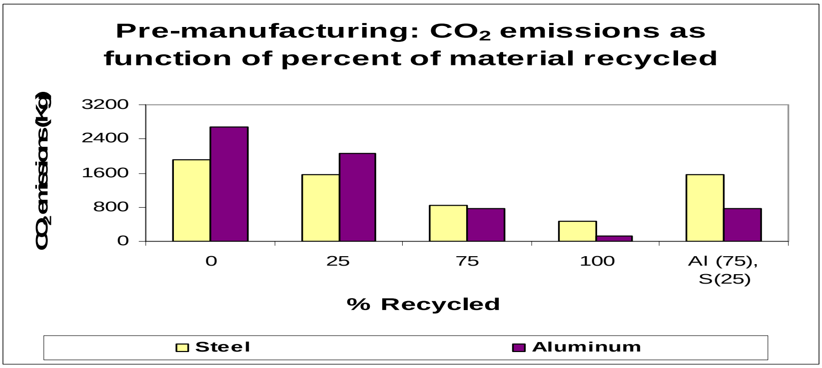

Figure 7: Carbon dioxide emissions as a function of recycled material content during the pre-manufacturing stage

For the 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) while the manufacturing processes are assumed to be different.

Figure 8 shows the carbon dioxide emissions in all four life-cycle stages, for three different years, for the case of using zero percent recycled materials.

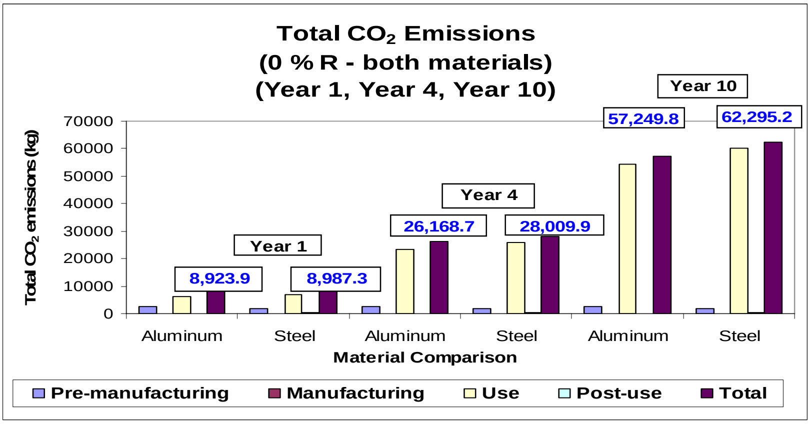

Figure 8: Total carbon dioxide emissions breakdown (0 % R both materials)

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 emission disadvantage from the pre-manufacturing stage, as a result of fuel consumption improvement. Figure 9 shows the carbon dioxide emissions for three different years for the case scenario in which aluminum has 75 percent material recycled content and steel has 25 percent material recycled content.

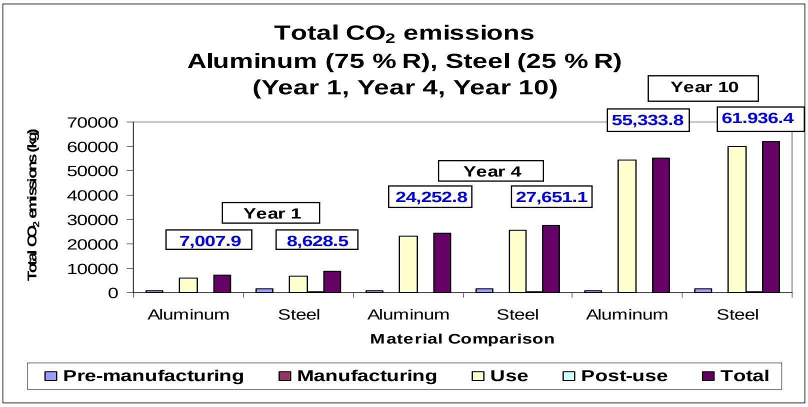

Figure 9: Total carbon dioxide emissions breakdown (Al. 75 % R; steel 25 % R

Fuel efficiency and energy savings from the use of recycled materials reduce 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 8 percent lower than those for steel BIW structure after only one year of vehicle usage.

Summary and Future work

This study considers material-substitution as a means to achieve weight reduction, and the 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 the real gasoline price increases and vehicle life is 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 [3].
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 5.

Table 5: Total cost breakdown for (aluminum 75%, steel 25 % material recycled)

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

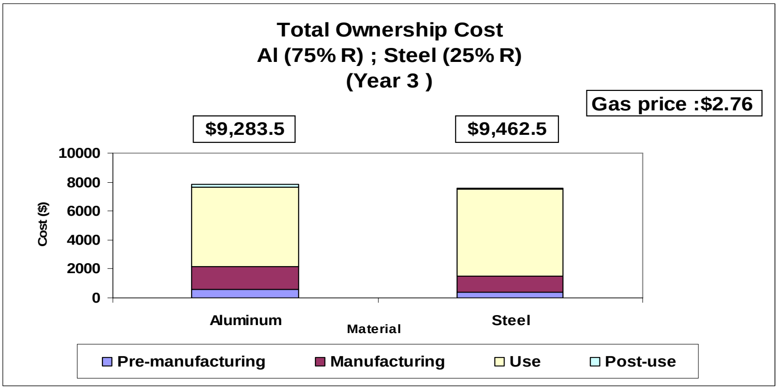

Figure 10: Total ownership cost

Regarding carbon dioxide emissions, the model shows the benefit of using lighter materials in the body construction of vehicles. Figure 11 illustrates the total carbon dioxide emissions, over the vehicle's life-cycle considering that both are virgin materials. Despite the emission disadvantage from the 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.

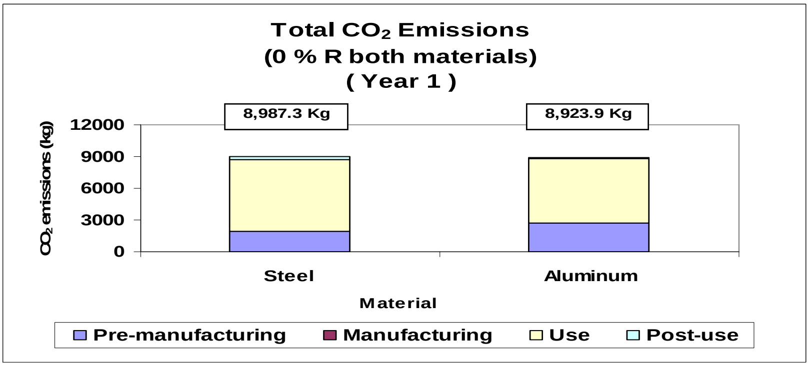

Figure 11: Total CO_2 emissions (both are virgin materials)

The energy savings from the recycled steel are not as dramatic as the energy savings from the 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 the 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 aluminum, aluminum BIW structure is proven to emit about 7 percent less carbon dioxide than what steel BIW structure does emit, after only one year of vehicle usage. As the vehicle continues to "age", the carbon dioxide savings increase, and after ten years, there will be about 11 percent carbon dioxide emissions savings from the use of recycled aluminum in the vehicle's body structure (Figure 12).

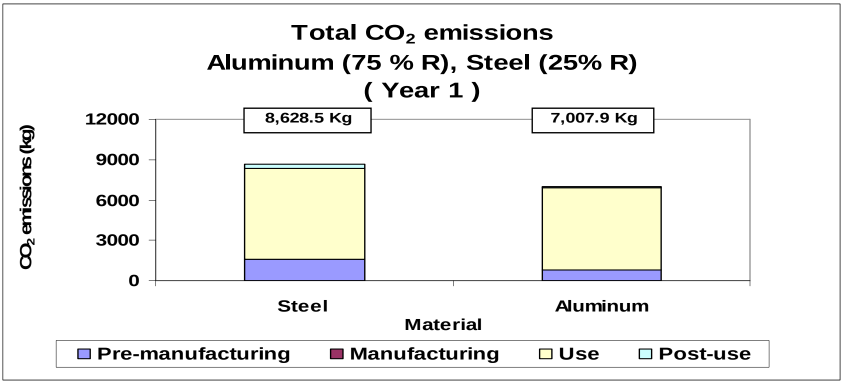

Figure 12: Total carbon dioxide emissions (Aluminum 75 % R, Steel 25 % R)

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 these two materials in automotive industry. This would help to reduce total costs and greenhouse gas emissions over the life-cycle of the vehicle and to improve the safety and performance. Since take-back options are fast becoming an 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 two options: reuse of parts, and the use of recycled materials.

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