Proceedings of the 2008 IEEE International Symposium on Electronics and the Environment, San Francisco, USA, May 19th-21st
(DOI: 10.1109/ISEE.2008.4562897) p. 1-6.

Model of Cost and Mass for Compact Sized Lightweight Automobiles using Aluminum & High Strength Steel

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Abstract— **In this paper, we consider interactions between life cycle emissions and materials flows associated with lightweighting automobiles. The study begins by developing scenarios for lightweighting a specific compact sized vehicle based on a Ford Focus. Both aluminum and high strength steel are used, and specific levels of lightweighting are considered between 6% and 23% based on literature references and discussions with industry experts. Using automotive simulations and literature estimations for cost, we estimate improvements in fuel economy and increases in cost relative to the baseline vehicle. By incorporating emissions factors associated with producing aluminum and high strength steel, over a range of possible values dependent for instance on region of the world where these materials are produced, we compare the increased emissions associated with producing the vehicle with the saved emissions during use following from lightweighting. This yields a calculation of how many years it takes to recover the extra greenhouse gas GHG emissions required in production to create the lightweight vehicle. We observe a 2-12 year GHG payback for the 6% lightweighting scenario, a 2-7 year GHG payback for the 11% lightweighting scenario, and a 4-9 year GHG payback for the 23% lightweighting scenario. We also observe that the cost to remove GHG emissions per kilogram by lightweighting is lowest for the 23% case. In principle, these payback times can be shortened for aluminum intensive vehicles by closed-loop recycling of wrought aluminum (i.e., using secondary wrought aluminum), which is not practiced today. However, over a 15-year time horizon this is unlikely to make much difference due to a lack of secondary wrought aluminum and the expected growth in the demand for vehicles. Cost analyses demonstrate that lightweight vehicles have favorable economics for consumers.**

Index Terms—**Life Cycle Assessment, Vehicle Lightweighting, Greenhouse Gas, Aluminum, High Strength Steel.**

I. INTRODUCTION

Since pre-industrial times, increasing emissions of greenhouse gases (GHG) due to human activities have led to a marked increase in atmospheric GHG concentration. These emissions have grown 70% between 1970 and 2004 [1]. Even with climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades [1]. The IPCC study [1] indicates that there is substantial economic potential for the mitigation of GHG emissions over the coming decades that could offset the projected growth of global emissions or reduce emissions below current levels [1]. In order to stabilize the concentration of GHGs in the atmosphere, emissions would need to peak and decline thereafter. The lower the stabilization level, the more quickly this peak and decline would need to occur. Mitigation efforts over the next two and three decades will have a large impact on opportunities to achieve lower stabilization levels [1].

Recent policy proposals aimed at reducing GHG emissions from automobiles have accelerated efforts to significantly improve vehicle fuel efficiency. One option is reducing the overall mass of a vehicle. Such lightweighting (LW) of the vehicle presents an opportunity for cutting both petroleum consumption and GHG emissions. Among the potential LW materials, high strength steel and aluminum have been proven to achieve weight reduction while meeting vehicle safety and performance requirements. Despite potential LW advantages of these metals, their displacement of traditional materials such as mild steels has been slow because of their higher costs, as well as institutional and technical barriers. The purpose of this study is to understand how widespread market penetration of lightweighted vehicles could lead to unintended life cycle emissions and materials flows consequences. We analyze this question by considering the detail design and modeling of a compact vehicle.

A number of prior studies have been undertaken to explore the systemic impacts of increased use of lightweight metals in vehicles [2,3,4]. The common conclusion among studies is that a LW strategy should be accompanied by the creation of a closed-loop recycling system for the resulting end-of-life (EoL) scrap [2,3]. In fact, the LCA of LW vehicles has assumed a closed-loop recycling of major materials utilized in the vehicle structure and powertrain [2]. Currently such a market does not exist in the sense that lightweighted vehicles today require the input of primary metals owing to a lack of infrastructure for producing secondary wrought metals that can be used in the vehicle structure.

While previous research has intensively studied trade-offs between aluminum and high-strength steel, this comparison has not been performed in the context of detailed modeling of a specific vehicle. Therefore while the qualitative trade-offs

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are understood, we do not have a complete sense of the magnitude of the trade-offs and therefore the potential for unintended consequences of policies that incentivize manufacturers to pursue LW strategies. As a result, we do not have a quantitative sense regarding how important these trade-offs are in the context of meeting societal goals for reducing carbon emissions from the automotive sector as quickly as possible. This paper is a beginning towards closing this gap.

II. APPROACHES AND METHODS

To achieve these objectives, we have constructed four models specific to the:

- **Materials and components**: [2,5] were used to develop a component and material model for the baseline vehicle of investigation with example of a compact sized vehicle. This vehicle was lightweighted by component substitution for aluminum [2,6,7] and by integrated re-design for high-strength steel [8,9]. Component and sub-system level analysis was performed to assure feasible weight reductions and realistic inputs of LW materials.
- **Technical Performance:** Fuel economy for vehicles with varying degrees of lightweighting was modeled using AVL CRUISE (AVL LIST GmbH).
- **Life Cycle Cost**: [2,5] were used to develop a cost model for the baseline vehicle and its LW variants. Industry experts also provided updated information and improved estimates for the specific vehicle considered here. [10,11,12,13] were compiled into a cost model for the acquisition and manufacturing of lightweight materials. The cost model also includes estimated producer costs for LW vehicles, costs to establish collection and recycling infrastructure, sorting costs per unit, production costs using secondary vs. primary materials, and scenarios for material value at EOL.
- **Life Cycle GHG Emissions and Materials Use:** Previous LCA studies of aluminum and steel production were utilized [14,15,16,17] to estimate added upstream emissions associated with LW of the vehicle. The use-phase emissions were estimated based on travel demand models from the literature [18]. A separate model was created for treating end-of-life emissions and re-use of materials. We also consider EOL scenarios such as business-as-usual recycling, regulated vehicle recycling targets (e.g., European ELV regulation), and closed loop recycling (Fig. 1).

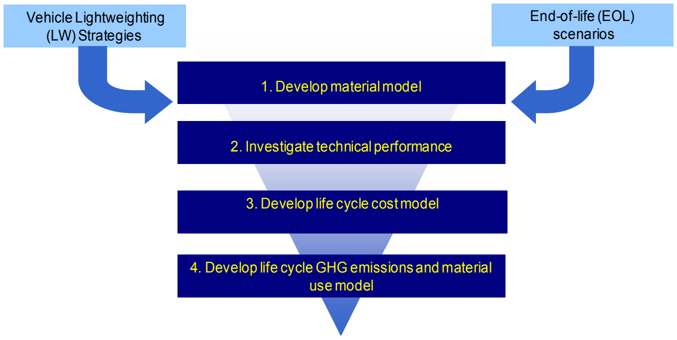

Fig. 1. Research Approach

III. SCENARIO DEVELOPMENT

Taking a compact sized baseline vehicle based on a Ford Focus, we evaluate the magnitude of vehicle lightweighting that is technologically feasible in the future and postulate realistic scenarios for degree of LW achievable and the associated amount of aluminum or high strength steel required. Starting with a curb weight of 1150kg, we estimated that the baseline vehicle has a steel/iron mass of 737kg, a light metals mass of 115kg, and an aluminum mass of 86kg. These calculations are based on [5]. Relative to the baseline vehicle, we assume the baseline vehicle Body In White (BIW) sub-assembly has a lightweighting potential of up to 11% with aluminum based on [5, 6] and up to 6% with high strength steel (HSS) based on [9]. Lightweighting with aluminum beyond the BIW can achieve a total curb weight reduction of up to 23% relative to the baseline vehicle [9].

Based on this information, we created 5 LW scenarios: 3% and 6% weight reduction with HSS and 11%, 19% and 23% weight reduction with aluminum. This results in a total curbweight of 1116kg for a weight reduction of 3%, 1081kg for a weight reduction of 6%, 1018kg for a weight reduction of 11%, 940kg for a weight reduction of 18%, and 901kg for a weight reduction of 23%. A summary of the scenarios is provided in Fig. 2.

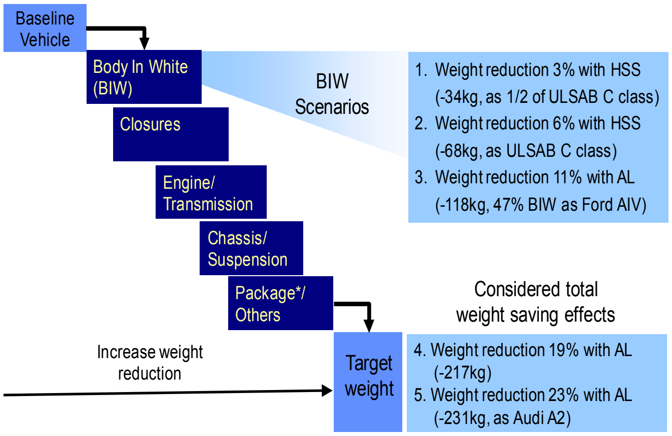

Fig. 2. Definition of lightweighting scenarios

IV. VEHICLE MODELING

A reasonable prediction of GHG emissions from the use phase requires two major elements: a prediction of fuel economy under various lightweighting strategies, and assumptions about vehicle miles travelled (VMT) as a function of fuel economy. We utilized the simulation software AVL Cruise to predict the fuel economy associated with the five lightweighting strategies. The simulations are necessary because the fuel economy improvements are non-linear. We provide the estimated fuel economy of each LW scenario in Fig. 3. Here we see that the baseline vehicle has a fuel economy of 33 miles per gallon (mpg) for the FTP75 drive cycle. In the 3% and 6% weight reduction scenario, the fuel economies are increased to 33.6 mpg and 34.2 mpg respectively. The fuel economy is increased to 36.9 mpg, 39.7 mpg and 41.3 mpg in the 11%, 19%% and 23% mass reduction scenarios respectively.

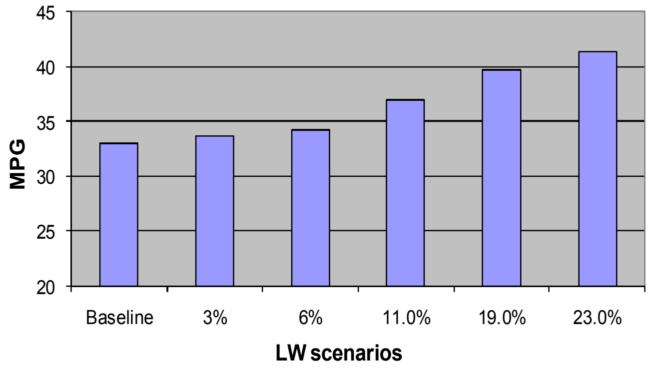

Fig. 3. Fuel Consumptions

V. Life Cycle Costs

We also estimated the material and manufacturing costs associated with substituting HSS and aluminum for conventional steel. For materials, we used [13] to estimate purchase costs for mild steel ($0.80/kg), HSS ($0.95/kg), cast Al ($1.52/kg), and wrought aluminum alloy ($2.75/kg for alloy 5X, and $3.25/kg for 6XXX). With this information we can bound added material costs for each LW scenario. Noting that the baseline vehicle (1150 kg) is comprised of conventional stamped steel, we then set about the task of estimating costs associated with manufacturing. The assumptions for production capital investment cost and manufacturing cost for steel and aluminum body-in-white (BIW) are based heavily on the approach of [11]. We report a range of values due to the significant uncertainty in the approach.

Table I lists the estimated vehicle manufacturing cost and net additional manufacturing cost compared with the baseline vehicle. The baseline vehicle has $776~$940 for BIW manufacturing cost, and its capital investment cost is assumed $871M for the production volume 200,000 vehicles per year. The BIW manufacturing cost for the 11.4% LW scenario is $1193~$1961, and its investment cost is $954M (200,000 vehicles per year).

TABLE I
VEHICLE MANUFACTURING COST OF THE LW SCENARIOS

LW Scenario	Estimated manufacturing cost ($)	Net additional manufacturing cost compared with the Baseline ($)
Baseline Vehicle	776~940	
3% LW HSS	1176~1400	400~460
6% LW HSS	1182~1506	406~566
11% LW Al	1193~1961	417~1021
19% LW HSS	1350~2050	574~1110
23% LW Al	1500~2150	724~1210

Here we estimate the masses of recovered materials based on the type of recycling process employed. For currently available recycling processes, we investigated today's averages and that 8.5% (by mass) of vehicle components are disassembled. Only about 2% of the components, such as the alternator and starter motor, are reused or remanufactured [19]. The rest of the components (91.5%) are usually shredded. A typical recovery rate from the shredding process is 95% for steel and 89% for aluminum. The mass of recoverable steel and aluminum in the 22.6% lightweighting scenario is 48 kg and 399 kg, respectively.

Fig. 4 summarizes the ELV recycling costs (including shredder and sorting costs) and the expected recovery revenue for the LW scenarios compared with the baseline vehicle [20]. By way of trends, it is observed that as lightweighting is intensified, the ferrous material value at EoL decreases substantially while the aluminum material value increases substantially. Due to the higher value of aluminum than steel, the overall EoL value of the vehicle increases significantly, despite (slightly) lower recovery efficiencies for aluminum vs. steel. Currently, wrought aluminum alloys, which have high purity of aluminum, are mostly recycled with cast aluminum, because wrought aluminum sorting and recycling infrastructure is not widely available on the metal recycling market. Recycling of separated wrought aluminum alloys directly into high quality secondary wrought aluminum alloys would avert new aluminum production and improve the life cycle GHG profile of LW vehicles. To understand the magnitude, we considered such a scenario and discuss it below. Based on discussions with industry experts, we assume that investment to recover 150 million kg/yr of separated alloy aluminum costs about $100 Million.

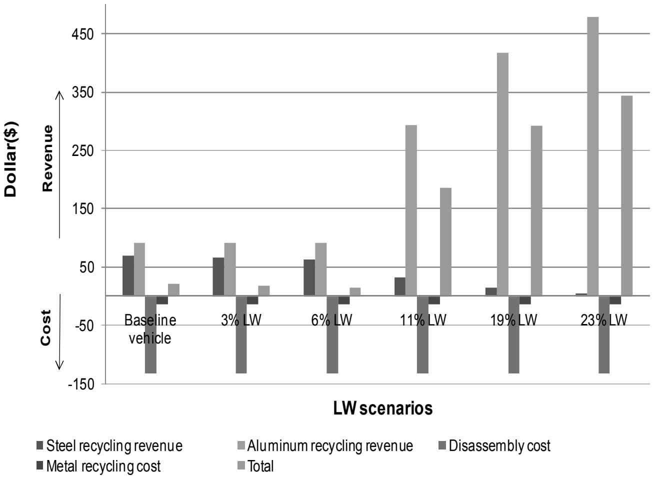

Fig. 4. Recycling costs and revenues

VI. Life Cycle Emissions

A. Material Production and Manufacturing

Here we consider primary and secondary production of steel and aluminum, as well as the manufacturing processes required producing finished LW components. Table II summarizes greenhouse gases emission factors for primary and secondary steel and aluminum. The table provides different emission factors of cast and wrought alloys for aluminum [1, 21, 25]. We consider a "typical" emission factor for primary aluminum to be the U.S. average emission factor, and we consider a "high" estimate for emission factor to be the Chinese average emission factor for primary aluminum. The high estimate of the emission factor represents a country using almost 100% coal-generated electricity.

We compare life cycle emissions considering both "closed loop recycling" (where all the iron, steel, and aluminum are sorted by alloy and recycled into new vehicles) and conventional recycling as practiced today. We use an allocation approach that is a slight modification of [22]. We assume that 95% of all LWs are collected at the end of life [23] and that 95% and 89% of the steel and aluminum, respectively, are recovered after disassembling, shredding, separating, and sorting. Metallic recovery of scrap melting was assumed to be 95% for steel and 91% for aluminum.

TABLE II
GREENHOUSE GAS EMISSION FACTORS

	Metals	Emission Factor
Baseline estimate	Primary Steel	2.2 kg CO_2-eq/kg Steel [21]
	Secondary Steel	0.6 kg CO_2-eq/kg Steel [21]
	Primary cast Al	9.72 kg CO_2-eq/kg Al [25]
	Primary wrought Al	9.45 kg CO_2-eq/kg Al [25]
	Secondary cast Al	1.18 kg CO_2-eq/kg Al [25]
	Secondary wrought Al	0.90 kg CO_2-eq/kg Al [25]
High estimate	Primary Steel	3.8 kg CO_2-eq/kg Steel [1]
	Primary cast Al	26.6 kg CO_2-eq/kg Al [25]

Aluminum manufacturing processes are divided into casting, extruding and rolling. For aluminum casting, an average of the lost foam, die, and sand casting processes is calculated as 5.5 kg CO_2-eq/kg [14]. Aluminum rolling and extruding are assumed to have emission factors of 0.26 kg CO_2-eq/kg and 0.34 kg CO_2-eq/kg, respectively [15]. No additional manufacturing processes are assumed for the finished cold rolled coil steel. Here we do not include manufacturing scrap rates for either steel or aluminum. Based on these estimates, the GHG emission factors and resulting emissions for the production and manufacture of aluminum and steel LW components are summarized in Table V (after Section VII).

B. *GHG Emissions: Use-Phase*

For the baseline and LW scenario vehicles, a vehicle lifetime from 11 years [15] to 14 years [21] is assumed. It is also assumed that the lifetime vehicle miles traveled (VMT) for each vehicle ranges from 120,000 miles to 181,195 miles [21]. Based on the assumed VMT and the modeled fuel economy of each vehicle, it is possible to calculate lifetime gasoline consumption. Subsequently, life cycle CO_2 emissions from gasoline consumption are calculated using an emission factor of approximately 10.4 kg CO_2/gallon gasoline. This emission factor includes emissions from both the combustion of gasoline (8.79 kg CO_2/gallon [17]) and the production and delivery of gasoline (1.58 kg CO_2-eq/gallon [18]).

C. *GHG Emissions: EoL Treatment*

Greenhouse gas emissions are calculated for the ELV processes of disassembly, shredding, and non-ferrous separation based on energy consumption data and an assumed CO_2 emission per unit energy delivered (totally as electricity) [14]. Transportation emissions are also calculated for the movement of material between each process stage, as well as transport of automotive shredder residue (ASR) to landfill disposal [14]. Total emissions in the EoL treatment are provided in the summary table (Table V).

D. *Life Cycle GHG Emissions Associated with LW Scenarios*

Based on the previous sections, total life cycle GHG emissions are calculated for the baseline compact vehicle and the five LW scenarios. As expected, the use phase dominates the total emissions for each vehicle. Use phase emissions decrease with increased lightweighting, while material production and manufacturing emissions increase due to the additional use of aluminum. Table V summarizes the vehicle GHG emissions by life cycle phase. Section VII discusses these results in detail.

VII. EFFECTS ON VEHICLE LIGHTWEIGHTING

A. *Cumulative GHG emissions by carbon intensity in the production*

In this section, we will only consider the 6%, 11% and 23% LW scenarios to simplify the presentation. For each of these scenarios we consider both "baseline" emissions factors (where "baseline" is assumed to be the average GHG emissions factors for aluminum and steel in the U.S. [21,25]) and a "high" emissions factor (where "high" is assumed to be the average GHG emissions factors for aluminum and steel in China [1,25]). These factors are provided in Table II.

Fig. 5 shows the added emissions per year relative to the baseline vehicle (using both baseline and high emissions factors) over 16 years. Subtracted from this is the cumulative emissions savings from all previous vehicles sold and on the road. The results show a clear impact depending on how the material is produced. Depending on the baseline versus high emissions factor, the GHG emission payback times can vary from 2-12 years for 6% LW, 2-7 years for 11% LW, and 4-9 years for 23% LW.

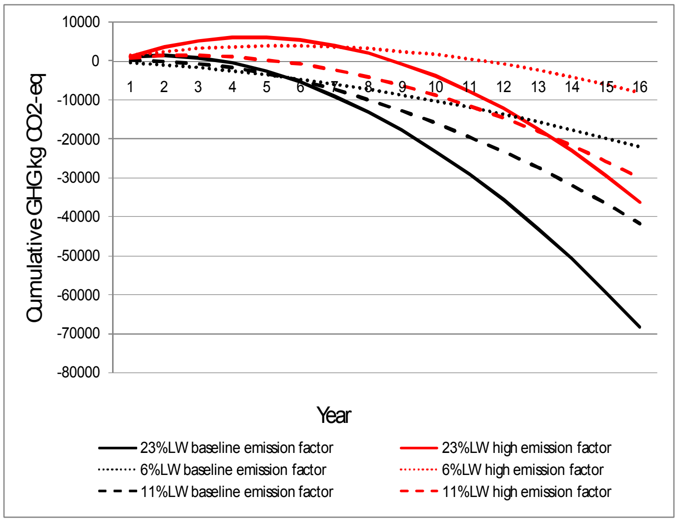

Fig. 5. Cumulative GHG Emissions with different Emission Factors

B. *Cumulative GHG emissions by closed loop recycling*

As seen in Table II, secondary metals need much less GHG emissions per kilogram for production. Therefore in this section we consider possible emissions savings associated with establishing a "closed-loop" infrastructure for recovering wrought aluminum from vehicles and recycling it directly into secondary wrought aluminum. This currently does not occur, as most aluminum recovered from vehicles is recycled as cast aluminum. We begin by assuming an End of Life Vehicle (ELV) scenario similar to [26], where it is assumed that about 60% of the vehicles do not survive past 16 years. We then assume that all ELVs are processed in recycling plants.

Fig. 6 summarizes the cumulative GHG emissions for each 6%, 11% and 23% LW vehicle with and without closed loop recycling. As seen in Table II, the closed-loop recycling should reduce production emissions associated with wrought aluminum by up to 9x. However, this is not achieved since in early years, there is not an appreciable amount of secondary wrought aluminum to use in new vehicles. Therefore the benefits grow over time but cannot be considered integral to a short term solution.

Note here that we assume a truly closed loop system – meaning that only scrapped vehicles produced after the first year are available for the secondary wrought aluminum stream. Naturally other sources may emerge but this appears to be insignificant. So it will take until year 16 before we are able to off-set 60% of the primary wrought aluminum with secondary wrought aluminum. By year 16, closed-loop recycling would off-set 8400 kg CO_2–eq per vehicle under these assumptions in the 23% LW case while off-setting 400kg CO_2–eq per vehicle in the 6% LW case.

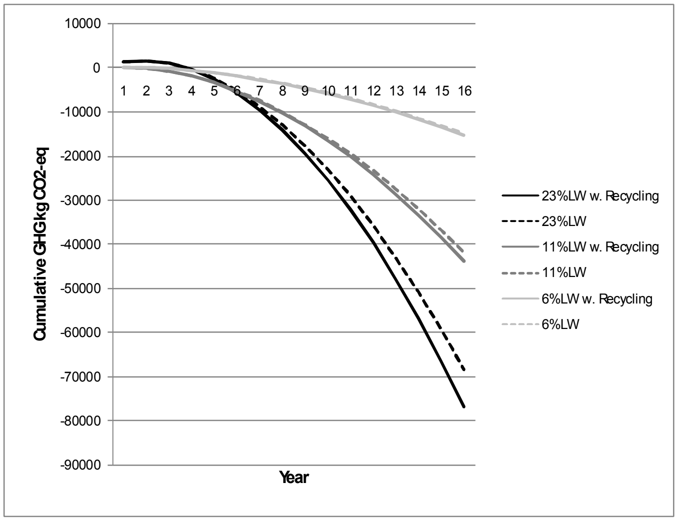

Fig. 6. Cumulative GHG Emissions by closed loop recycling

C. Cost-Benefit analysis

This section considers costs to producers and consumers. On the producer side, we calculate the cost of removing a ton of CO2-eq relative to the baseline vehicle. Under the above assumptions we calculate that for the 11% LW strategy, they must spend an additional \$417~1021 to save 4251~5263 kg CO_2 –eq (for the baseline emission factor case). By calculating the GHG emissions saving per unit LW investment (\$), the result is 5.2~10.2kg/\$ for 11% LW scenario. Table III summarizes the results. The 19% and 23% LW scenarios turn out to be the least expensive from the standpoint of cost to reduce GHG emissions. Naturally, producers care most about profit, so we leave predictions of sales and profitability of these vehicles to future research as in [27].

TABLE III
COST-BENEFIT ANALYSIS: PRODUCER PERSPECTIVE

LW scenario over baseline	Additional cost(\$)	GHG Saving (kg CO_2 –eq)	GHG Saving \$/ton CO2-eq
3%-BL	400~460	1289~1964	-
6% - BL	406~566	2026~3110	179-204
11%-BL	417~1021	4251~5263	98-192
19%-BL	574~1110	6374~7870	90-141
23%-BL	724~1210	7560~9330	96-130

On the consumer side, fuel cost savings are considered relative to added sales cost. For example, consumer can save 626 gallons of fuel with the 11% LW while paying up front an additional \$400-\$1000. If we assume a fuel price of \$3/gallon, the consumers using the LW vehicle can save \$1879 for its total life time, if a discount factor is not considered. Considering the purchase cost the consumer would then save \$859~\$1462. It is notable that the 3% LW scenario yields a loss of \$80~\$140 (again without discounting). By the analysis, 23% LW case is most favorable strategy for consumer point of view. Nevertheless, the gains are relatively small compared to the timescale of the decision and any discounting that may be employed by consumers.

TABLE IV
COST-BENEFIT ANALYSIS: CONSUMER PERSPECTIVE

LW scenario over baseline	Fuel Saving (Gallon)	Fuel Cost Saving at \$3/Gallon	Fuel cost saving-add. manufacturing cost for LW (\$)
3%-BL	106	320	-80 ~ -140
6% - BL	215	645	80~239.6
11%-BL	626	1879	859~1462
19%-BL	1009	3027	1917~2453
23%-BL	1198	3596	2386~2872

TABLE V
LIFE CYCLE GHG EMISSIONS

LW Scenario	Production		Use		EoL	Total	
	Low (all secondary material)	High (all primary material)	Low	High		Low	High
Baseline Vehicle	1668	3585	38,248	57,753	147	40,063	61,485
3% Wt. Reduction w. HSS	1611	3473	37,020	55,905	143	38,774	59,522
6% Wt. Reduction w. HSS	1552	3358	36,347	54,878	138	38,037	58,375
11% Wt. Reduction	1396	4317	34,294	51,782	122	35,812	56,222
19% Wt. Reduction	1699	5366	31,882	48,141	108	33,689	53,615
23% Wt. Reduction	1720	5724	30,683	46,331	100	32,503	52,155

VIII. CONCLUSION

This paper has considered interactions between life cycle emissions and materials flows associated with lightweighting automobiles. The study has developed scenarios for a specific compact sized vehicle based on a Ford Focus. Considering a range of emissions factors associated with lightweighting (LW) this type of vehicle, a 2-12 year GHG payback was observed for the 6% LW scenario, a 2-7 year GHG payback for the 11% LW scenario, and a 4-9 year GHG payback for the 23% LW scenario. In principle, these payback times can be shortened for aluminum intensive vehicles by closed-loop recycling of wrought aluminum (i.e., using secondary wrought aluminum), which is not practiced today. However, over a 15-year time horizon this is unlikely to make much difference due to a lack of secondary wrought aluminum and the expected growth in the demand for vehicles. Over the longer-term (approaching two decades), as lightweight materials become available for recycling and incorporation in to new vehicles, the closed-loop manufacturing can have a very significant impact. Cost analyses demonstrate that lightweight vehicles have favorable economics for consumers for all but the least lightweight intensive approach (3%). For more intensive lightweighting cases, a net positive financial gain is observed (not considering discounting) but the gains are still relatively small compared to the base cost of the vehicle (at most $3000). Finally, it was also observed that the cost to remove GHG emissions by lightweighting the vehicle was lower as the lightweighting intensity increased.

ACKNOWLEDGMENT

This research was supported by the Alcoa Foundation and the National Science Foundation (not subject to agency review). The authors wish to thank Ford Motor Company, International Iron and Steel Institute and Alcoa Inc. for helpful input.

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