WHY SHOULD ALUMINUM CONTINUE TO REPLACE STEEL IN CARS? AN LCA (LYFE CYCLE ASSESSMENT) COMPARISON

Gustavo Zini
School of Engineering – University of Buenos Aires
Argentina
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ABSTRACT

"To achieve more sustainable production and consumption patterns, we must consider the environmental implications of the whole supply-chain of products, both goods and services, their use, and waste management, i.e. their entire life cycle from 'cradle to grave' ". (Preface to the ILCD Handbook: General guide for Life Cycle Assessment)

Though conventional wisdom states that more fuel-efficient vehicles are lighter and smaller, yet less safe than their less fuel-efficient counterparts, another point of view will be shown. Aluminum and other materials have proven to replace steel with a good trade-off of fuel efficiency against safety. Yet steel is predominant in mass production automobiles, representing around 65% of their weight. The reasons behind this choice could be explained through both cost effectiveness and technology expertise, but they will not be thoroughly analyzed in this paper. However, it can be argued that a complete assessment of the ecological impact of using aluminum instead steel has not been done up till now, or at least has not been taken into full consideration. The use of lighter yet impact-efficient materials will certainly improve both safety and fuel economy, so a comprehensive study in this issue is proposed.

Therefore, this paper will compare the LCA (Life Cycle Assessment) of two different cars, one with a steel chassis group and body-in white, and another one having these parts made out of aluminum. This comparison has already been made by the University of California [1]. Nevertheless, a different approach is hereby proposed, so that both conclusions can be contrasted.

To conclude, a new LCA model will be developed, and two hypothetical vehicles will be compared on a theoretical approach, pointing out some aspects that should be developed thoroughly within the corresponding settings and using appropriate resources.

INTRODUCTION

"Design is the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are: the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation." (ABET: Accreditation Board for Engineering and Technology, 1988)

Weight does matter.

On the one hand, lighter automobiles mean lower fuel consumption and therefore minor impact to the Environment. Yet this is only partly true, because in order to fully understand the mentioned impact an assessment of the complete product life-cycle must be done. For example, an electric motor generates no CO_2 emissions, yet the electricity that is stored in the batteries could have been generated in power plants that use either more energy or green-house gasses than an internal combustion energy. A life cycle assessment is a technique to assess each and every impact associated with all the stages of a process from cradle-to-grave. LCA's can help avoid a narrow outlook on environmental, social and economic concerns.

On the other hand, fuel-efficient engines also generate lower impact to the Environment. As time passes, automobile engines are getting smaller, lighter, and more fuel-efficient than ever.

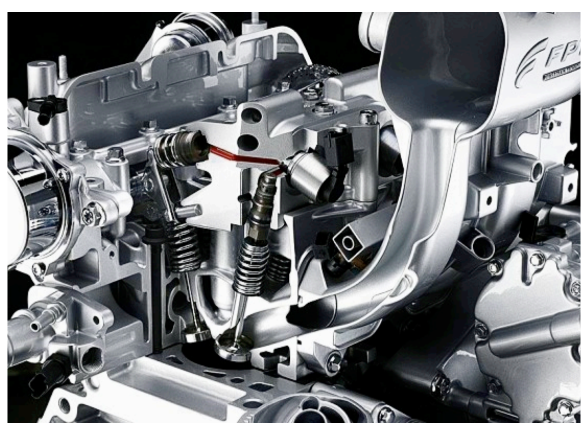


Figure 1. FIAT's new Twin-Air engine.

For example, using next-generation technology, the new Fiat "Twin-air" engine implements a revolutionary system, taking the concept of downsizing to the extreme and masterly tuning the basic mechanics, the new family –delivering from 65 to 105 HP– emits 30% less CO_2 than an engine of equal performance.

Therefore, it can be stated that modern engines are both less fuel-consuming devices and more environmentally-friendly. Yet, and this can be highlighted as one of the key issues discussed in this paper, automobiles are getting heavier and heavier. For example, and as expressed by the European Aluminium Association, the average mass of European vehicles has dramatically increased. The weight increase is basically due to more stringent legislative requirements and changing customer demands (growing vehicle size, extra comfort and safety devices, etc) that, in turn, have caused an increase weight of other components to reach the envisaged performance level. This "weight spiral" is shown in the next figure [2].

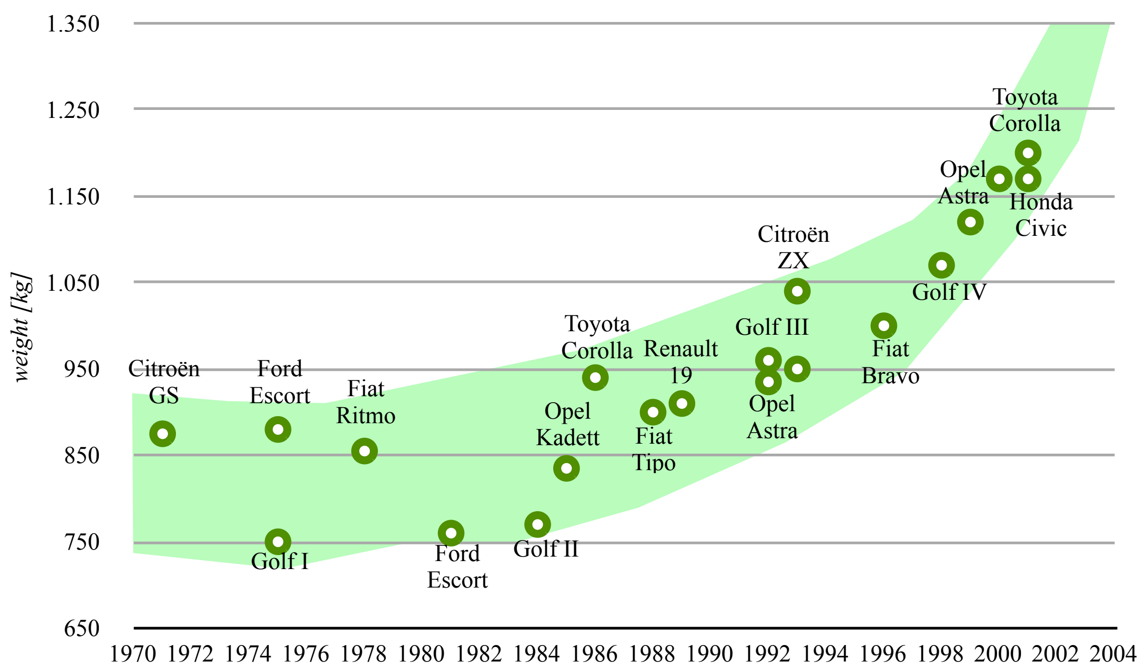


Figure 2. Passenger car mass distribution from 1970.

Consequently, if there is a clear advantage in weight reduction. why are innovation efforts concentrated on designing better engines but not lighter automobiles? Why is it that no high-volume mass-production vehicle is made entirely in aluminum? These answers exceed the purpose of this paper, but it has to be pointed out that even though it is crystal clear that wider use of aluminum will mean lighter vehicles and lower fuel consumption, is it worthy to outclass every technological and economical motive that excluded aluminum from high-volume production? Will the Environmental impact of this action compensate the disadvantages that have until nowadays maintained steel as the principal material used for automobile manufacturing? These two latest questions are the ones that will be answered, or at least an outline of the answers will be given.

In order to do so, two papers [1]; [3] will be used as a basis to perform this particular study.

Figure 3. AUDI's A2 had an all-aluminum body frame.

The first one of them will give an indication of the percentage that each part of an automobile bears in terms of weight distribution:

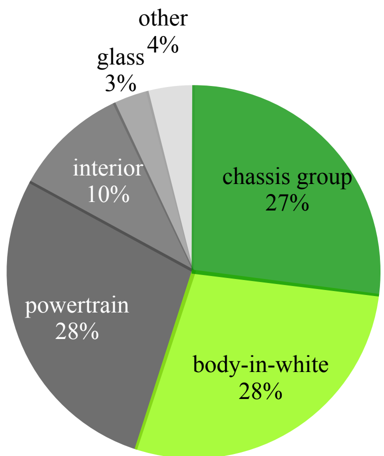


Figure 4. Passenger car mass distribution [3].

It also states that aluminum has reached its limit in substituting steel both in the powertrain and in the interior parts, but has a very minor use in the chassis group and in the body-in.white, which represent 55% of an automobile mass.

The other paper, developed by the World Steel Association analysis the LCA of three types of automobiles, two made out mainly of steel and one of aluminum [1].

A key finding of the latter paper is that with reasonable assumptions and inputs for the specific application and manufacturing processes, the material production phase can be a significant percentage of the vehicle's total carbon footprint. In fact, it becomes even more important as the vehicle's footprint is diminished through advanced powertrains and fuel sources. It also says that significant improvements in reducing automotive GHG emissions will not be achieved by material substitution alone; investment in new powertrains and fuels contribute to the greatest emissions reductions.

In other words, this study indicates that the use-phase of LCA has a lower impact than the other phases, which will be proven in this paper that could be an inaccurate statement.

Consequently, the calculation logic of the World Steel Association paper will be studied and remade, not to expose its probable inaccuracy, but to show that the energy consumed and the green-house gasses emissions during the product-use phase are several times higher than the ones of the other three phases of the LCA, and that this reason alone may justify a wider use of aluminum in the chassis group and in the body-in-white.

MODEL CARS AND TYPE OF ANALYSIS

"External goods have a limit, like any other instrument, and all things useful are of such a nature that where there is too much of them they must either do harm, or at any rate be of no use". (Aristotle, Politics, Bk 7 Chapter 1)

As said before, most of the findings of this paper are based on a reinterpretation of the data of papers [1] and [3]. An interesting issue to be mentioned is that the eventual substitution of steel by aluminum is analyzed by using a study from a Steel Association, thus minimizing the eventual bias that could be introduced if the data where taken from an Aluminum Association.

"The Impact of Material Choice in Vehicle Design on Life Cycle Greenhouse Gas emissions - The Case of HSS and AHSS versus Aluminum for BIW applications." compares three different cars, and there LCA. Herein, only two of the vehicles will be used, for simplification matters. The characteristics of the two automobiles that will be analyzed can be summarized in the following chart:

Table 1.
Characteristics of two of the automobiles used in reference [1].

	chassis group and body-in-white	
	steel	aluminum
steel [kg]	819,0	437,4
aluminum [kg]	88,2	282,6
other [kg]	352,8	352,8
total mass [kg]	**1.260,0**	**1.072,8**

It is interesting to point out that although the specific mass of aluminum is 1/3 of the one of steel (around 2.700 kg/m3 for Al versus 7.800 kg/m3 for Fe), lower tension- resistance results in that an automobile with a chassis group and body-in-white made out of aluminum will no be 65% lighter, but 30% instead. This statements is shared both by references [1] and [3]. And this reduction is not meant to be considered for the whole vehicle, but only for the chassis group and the body-in-white.

Hence, on the one hand, only two automobiles will be compared, one with its chassis group and body-in-white made out completely of steel, the other one made out completely of aluminum. To further simplify the analysis, all other materials will be taken out of the equations, as to perform a marginal analysis. It can be stated that this method of comparison will show the relative impact of the use of each material with a higher precision and with a simpler and more accurate vision.

The following table, which is derived from table 1, shows the new material distribution of the two vehicles that will be analyzed in this paper:

Table 2.
Characteristics of two of the automobiles used in this paper.

	chassis group and body-in-white			
	steel		aluminum	
steel [kg]	819,0	90%	437,4	61%
aluminum [kg]	88,2	10%	282,6	39%
total mass [kg]	**907,2**		**720,0**	
			-20,6%	

It is very important to highlight that even though the “aluminum” car has a chassis group and a body-in-white made out of this material, 61% of its weight is all the same represented by steel, since there are some parts of the vehicle where steel cannot be substituted. Similarly, the “steel” car has 10% of its weight in aluminum components. Bottom line, the two vehicles which LCA will be analyzed can be sketched as follows:

Figure 5. Car 1 - ”Steel” vehicle to be analyzed.

Figure 6. Car 2 - ”Aluminum” vehicle to be analyzed.

To conclude, and as shown in table 2, the difference in weight between the two hypothetical vehicles is around 20%, again a number far lower than the 65% difference between Al and Fe specific mass.

LCA: ADOPTED PROCEEDINGS

According to Wikipedia, the goal of LCA is to compare the full range of environmental and social damages assignable to products and services, to be able to choose the least burdensome one. At present it is a way to account for the effects of the cascade of technologies responsible for goods and services. It is limited to that, though, because the similar cascade of impacts from the commerce responsible for goods and services is unaccountable because what people do with money is unrecorded. As a consequence LCA succeeds in accurately measuring the impacts of the technology used for delivering products, but not the whole impact of making the economic choice of using it.

The term 'life cycle' refers to the notion that a fair, holistic assessment requires the assessment of raw material production, manufacture, distribution, use and disposal including all intervening transportation steps necessary or caused by the product's existence. The sum of all those steps –or phases– is the life cycle of the product. The concept also can be used to optimize the environmental performance of a single product (ecodesign) or to optimize the environmental performance of a company.

Common categories of assessed damages are global warming (greenhouse gases), acidification (soil and ocean), smog, ozone layer depletion, eutrophication, eco-toxicological and human-toxicological pollutants, habitat destruction, desertification, land use as well as depletion of minerals and fossil fuels.

LCA includes four stages:

1. Goal and Scope
2. Life Cycle Inventory
3. Life Cycle Impact Assessment
4. Interpretation

The stage that will be considered in this paper is the third one (Life Cycle Inventory), and the chosen variant is the one named “Cradle-to-grave”. Furthermore, impact assessment has been divided into four phases:

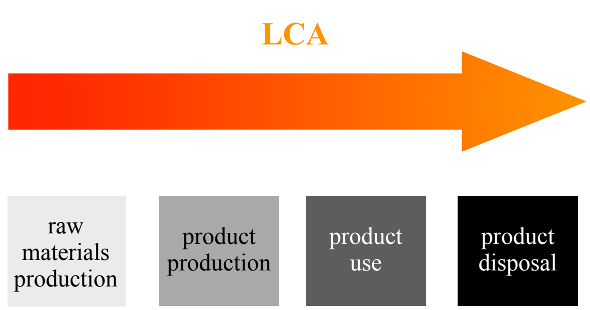


Figure 7. LCA impact assessment as considered in this paper.

FIRST PHASE:
RAW MATERIALS PRODUCTION

The first assessment of the LCA is the energy and the amount of CO_2 that are consumed and released during the raw materials productions. The following table summarizes both parameters:

Table 3.
Energy consumption and green-house gas emissions for the production of primary and secondary steel and aluminum [1].

	total energy consumption [MJ/kg]	green-house gas emissions [$kgCO_2eq/kg$]
primary steel (basic oxygen)	21,7	2,0
secondary steel (electric arc furnace)	7,1	0,4
primary aluminum (electrolysis)	193,7	12,7
secondary aluminum (foundry)	10,3	0,6

Yet, every single part made out of aluminum or steel uses a certain percentage of primary and secondary metal. It can be stated, using as a general an very approximative rule that 40% of the steel used in the world is secondary, and that 30% of aluminum is secondary. Thereby, further considerations have to be made, starting by separating the above figures for primary and secondary metals:

Tables 4/5.
Use and energy consumption and green-house gas emissions for the production of primary and secondary steel and aluminum [1].

	primary		
	use	total energy consumption	green-house gas emissions
	%	[MJ/kg]	[$kgCO_2eq/kg$]
steel	60	21,7	2,0
aluminum	70	193,7	12,7

	secondary		
	use	total energy consumption	green-house gas emissions
	%	[MJ/kg]	[$kgCO_2eq/kg$]
steel	40	7,1	0,4
aluminum	30	10,3	0,6

After this, both total energy consumption and green-house emissions for the steel and aluminum used to build automobiles are integrated:

Table 6.
Energy consumption and green-house gas emissions for the production of steel and aluminum used in automobiles (considering the percentage of primary and secondary materials).

	primary and secondary	
	total energy consumption	green-house gas emissions
	[MJ/kg]	[$kgCO_2eq/kg$]
steel	15,9	1,4
aluminum	138,7	9,1

Thus, the figures for each hypothetical car result in:

Tables 7/8.
Energy consumption and green-house gas emissions for each of the hypothetical cars analyzed in this study (phase 1 of LCA).

	car 1		
	mass	total energy consumption	green-house gas emissions
	[kg]	[MJ]	[$kgCO_2eq$]
steel	819,0	13.022	1.147
aluminum	88,2	12.233	803
total	**907,2**	**25.255**	**1.949**

	car 2		
	mass	total energy consumption	green-house gas emissions
	[kg]	[MJ]	[$kgCO_2eq$]
steel	437,4	6.955	612
aluminum	282,6	39.197	2.572
total	**720,0**	**46.151**	**3.184**

The first issue to be highlighted is that the “steel” car has a lower environmental impact as far as phase 1 of the LCA is considered. This difference origins in the two completely different technologies used to obtain each metal from their mineral ore (basic-oxygen vs. electrolysis). The numbers from tables 7 and 8 can be transferred into a bar-chart that will be used throughout the entire paper:

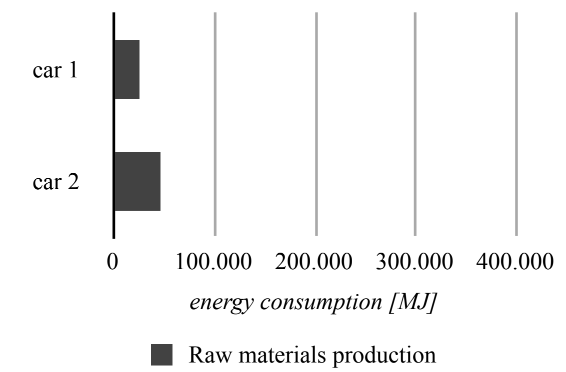


Figure 8. Energy consumption for LCA phase 1.

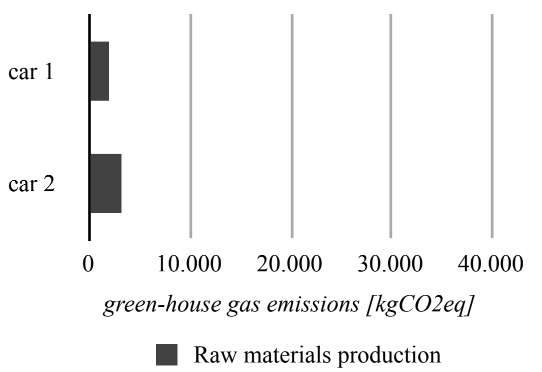


Figure 9. Green-house gas emissions for LCA phase 1.

SECOND PHASE: PRODUCT PRODUCTION

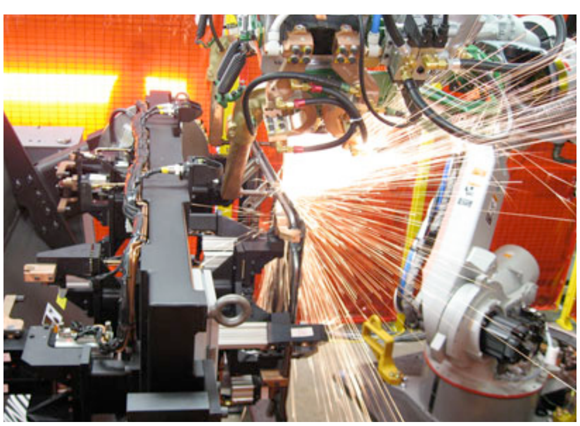


Figure 10. Production phase of an automobile.

Once the production of raw materials has been assessed, the transformation of these metals into the parts of an automobile will be analyzed. To do so, the proceedings of reference [1] will be adopted, as well as its data.

As in the previous and future phases of this LCA analysis, both the energy required to produce the mentioned parts and their carbon footprint during the production phase will be considered. The next two tables show the energy consumption and the green-house gas emissions for every type of steel and aluminum used in automobiles (namely flat carbon steel, cast iron, rolled aluminum, extruded aluminum):

Table 9.
Energy consumption during manufacturing for each type of material used in both hypothetical cars [MJ/kg].

	raw material	manufac-turing	**material in car**
flat carbon steel		9,8	**25,2**
long & special steel	15,4	5,4	**20,8**
cast iron		2,0	**17,4**
rolled aluminum		17,8	**156,5**
extruded aluminum	138,7	19,8	**158,5**
cast aluminum		12,2	**150,9**

Table 10.
Green-house gas emissions for each type of material used in both hypothetical cars [kgCO2eq/kg].

	raw material	manufac-turing	**material in car**
flat carbon steel		0,6	**2,0**
long & special steel	1,4	0,3	**1,7**
cast iron		0,2	**1,6**
rolled aluminum		1,2	**10,3**
extruded aluminum	9,1	1,2	**10,3**
cast aluminum		0,7	**9,8**

The above figures can be combined with the amount of each type of material used in the hypothetical cars that are been assessed (taking into consideration the proceedings of reference [1]) and merged into the following tables that show the results of the second phase of the LCA:

Table 11.
Energy consumption and green-house gas emissions during manufacturing for car 1.

	mass [kg]	total energy consumption [MJ]	green-house gas emissions [$kgCO_2eq$]
flat carbon steel	504,0	4.939	302
long & special steel	189,0	1.021	57
cast iron	126,0	252	25
rolled aluminum	12,6	224	15
extruded aluminum	12,6	249	15
cast aluminum	63,0	769	44
total car 1	**907,2**	**7.454**	**459**

Table 12.
Energy consumption and green-house gas emissions during manufacturing for car 2.

	mass [kg]	total energy consumption [MJ]	green-house gas emissions [$kgCO_2eq$]
flat carbon steel	167,0	1.637	100
long & special steel	144,4	780	43
cast iron	126,0	252	25
rolled aluminum	159,5	2.839	191
extruded aluminum	73,1	1.447	88
cast aluminum	50,0	610	35
total car 1	**720,0**	**7.565**	**483**

In the same way that it was done after the first phase evaluation, the figures in the above tables will be transferred into a bar-chart that will show in a graphical way the differences between the environmental impact of each hypothetical car, for phases 1 and 2. Once more, and due to higher energy demanded on behalf of aluminum parts to be welded, a "steel" car proves to be more "environmentally friendly" than its "aluminum" counterpart, as it can be seen in the following graphs:

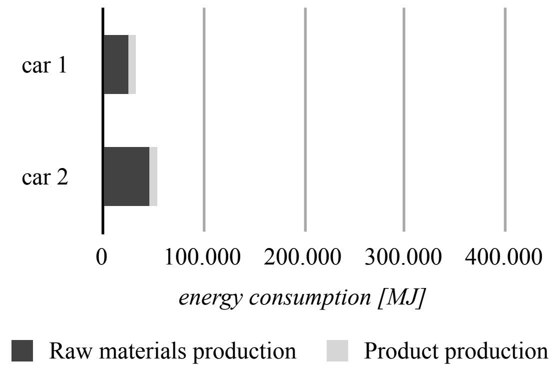


Figure 11. Energy consumption for LCA phases 1 and 2.

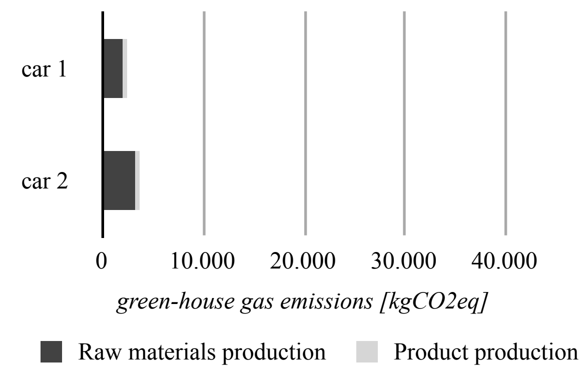


Figure 12. Green-house gas emissions for LCA phases 1 and 2 .

THIRD PHASE: PRODUCT USE

This phase of the assessment that marks the difference between the proceedings in reference [1] and this paper. As it will be shown in the conclusions, reference [1] takes into consideration that despite the fact that the "aluminum" car is lighter than the "steel" car, both fuel consumptions over the product use result in the same figures.

The parameters that can be found in different LCA assessments for the product use phase of an automobile consider traveling 200.000 km over a 10-year period. These figures are the same one used in reference [1] for the assessment, and in that case, the energy required to and the carbon footprint during the use phase for the "steel" car characterized in table 1 are the following:

➡ total mass [kg]: 1.260

➡ use [km]: 200.000

➡ energy consumption [MJ]: 407.700

➡ green-house gas emissions [kgCO2eq]: 36.600

Nevertheless, it can be argued that it is very important to reconsider the difference in fuel consumption for different masses (as it may be obvious that lighter cars consume less fuel that heavier ones). Therefore, is it possible to conclude the percentage of fuel-consumption reduction that results from a mass reduction of an automobile?

To answer this question, the next chart shows that there is a statistically relevant correlation between car mass and fuel consumption:

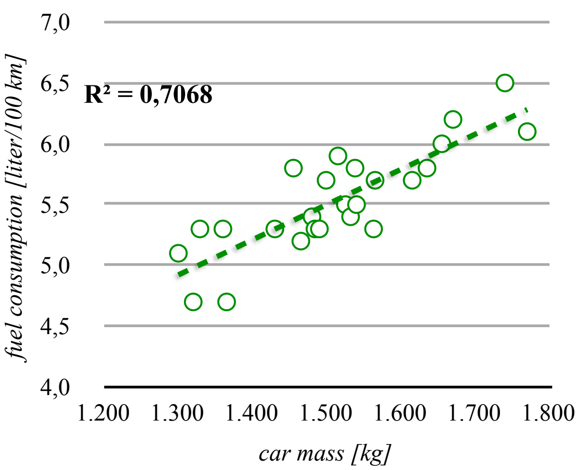


Figure 13. Correlation between car mass and fuel consumption for a sample of selected 2.0 (170 CV) diesel engine automobiles.

Every point of the chart is based on information provided by car manufacturers, for an average fuel consumption, has been taken from Quattroruote Magazine [4] and can be seen in Appendix I. Pearson's coefficient of 0,71 shows that there is a statistical relevant correlation between both parameters. From the regression equation it can be stated that for every 1% of mass reduction there is a 0,75% fuel consumption reduction:

➡ **1% mass reduction ⇒ 0,75% fuel consumption reduction.**

Using this parameter as an input to estimate the energy consumption and the green house gas emissions, which are directly related to fuel consumption, table 13 shows the figures for the original car in reference [1], and for the two hypothetical cars proposed in this paper, considering the above relationship between mass and fuel consumption. This figures can be considered as the key difference between the two studies herein compared.

Table 13.
Energy consumption and green-house gas emissions during product-use phase for cars 1 and 2.

	mass [kg]	total energy consumption [MJ]	green-house gas emissions [kgCO2eq]
"steel" car from ref. [1]	1.260,0	407.700	36.600
car 1	907,2	**322.083**	**28.914**
car 2	720,0	**272.237**	**24.439**

As established, these numbers will be again transferred to a bar-chart:

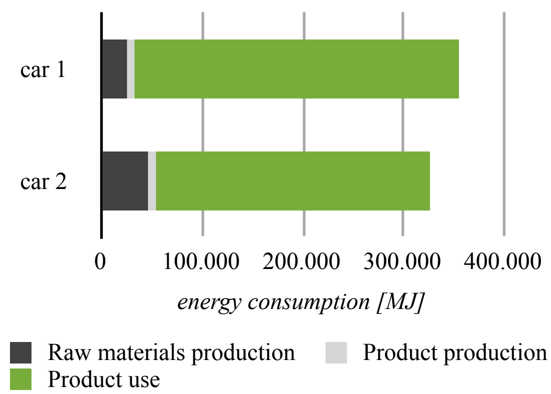


Figure 14. Energy consumption for LCA phases 1 to 3.

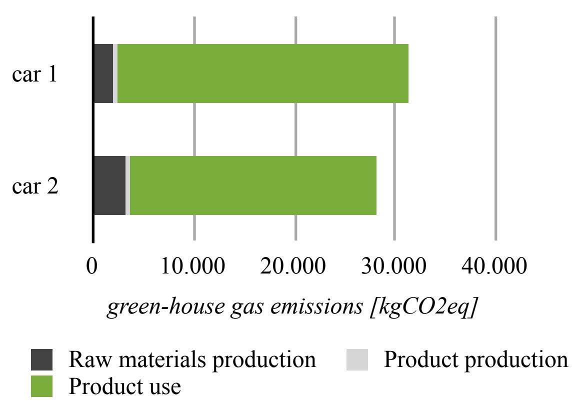


Figure 15. Green-house gas emissions for LCA phases 1 to 3.

For the first time in the analysis of this paper, the "aluminum" car proves to be more "ecologically-friendly". Furthermore, figures 14 and 15 show to what extent the product-use phase is by far the one that consumes more energy and emits more green-house gasses.

FORTH PHASE: PRODUCT DISPOSAL

In order to complete the LCA analysis in the variant called "Cradle-to-grave", product disposal must be assessed.

Using the figures from table 3, that indicate both energy consumption and green-house gasses emissions for secondary steel and aluminum, it is assumed that the entire mass of each hypothetical cars is scrapped as secondary metal. Hence, the impact of the fourth phase can be calculated as follow:

Tables 14/15.
Energy consumption and green-house gas emissions during product-disposal phase for cars 1 and 2.

	car 1		
	mass	total energy consumption	green-house gas emissions
	[kg]	[MJ]	[$kgCO_2eq$]
steel	819,0	5.815	328
aluminum	88,2	908	53
total	**907,2**	**6.723**	**381**

	car 2		
	mass	total energy consumption	green-house gas emissions
	[kg]	[MJ]	[$kgCO_2eq$]
steel	437,4	3.106	175
aluminum	282,6	2.911	170
total	**720,0**	**6.016**	**345**

As it could be already be deducted from table 3, there is practically no difference for each material, since both the energy required and the carbon footprint for recycling steel in an electric arc furnace and aluminum in a foundry are very similar.

To conclude, the numbers form tables 14 and 15 are added to the previous figures and shown in the following bar-charts. The final result of the LCA for both cars show that the "aluminum" one consumes 8,2% less energy during its life, while emitting 10,3% less green-house gases.

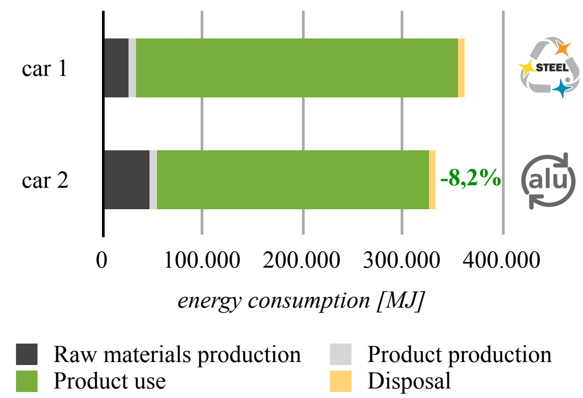


Figure 16. Energy consumption for entire LCA impact assessment stage.

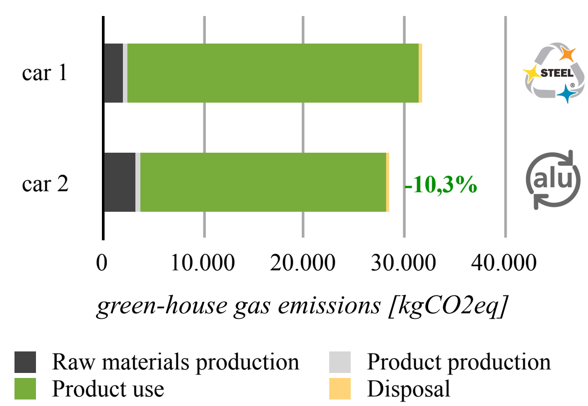


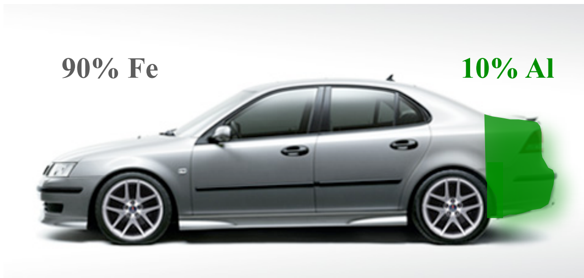
Figure 17. Green-house gas emissions for entire LCA impact assessment stage.

CONCLUSIONS

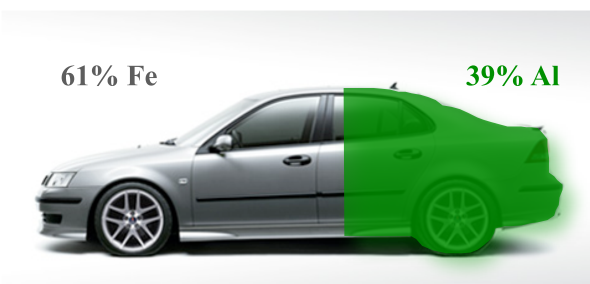
The aim of this paper was to compare the LCA of two different cars, one with a steel chassis group and body-in white, and another one having these parts made out of aluminum. As pointed out, this comparison has already been made by the University of California [1]. Nevertheless, the assessment in this paper had a different approach, so that both conclusions could be contrasted.

The first and most important contrast between the two studies is that while in reference [1] both the energy required and the carbon footprint where relatively similar for each automobile, this paper indicates that the lighter vehicle in more environmentally-friendly:

Tables 16/17.
Total energy consumption and green-house gas emissions during the entire Life Cycle of the two hypothetical cars herein proposed.



	car 1	
	total energy consumption	green-house gas emissions
	[MJ/kg]	[$kgCO_2eq/kg$]
raw materials	25.255	1.949
production	7.454	459
use	322.083	28.914
disposal	6.723	381
Total LCA	**361.515**	**31.703**



	car 2	
	total energy consumption	green-house gas emissions
	[MJ/kg]	[$kgCO_2eq/kg$]
raw materials	46.151	3.184
production	7.565	483
use	272.237	24.439
disposal	6.016	345
Total LCA	**331.969**	**28.451**

Moreover, as said before, one of the key findings of reference [1] is that with reasonable assumptions and inputs for the specific application and manufacturing processes, the material production phase can be a significant percentage of the vehicle's total carbon footprint. In fact, it becomes even more important as the vehicle's footprint is diminished through advanced powertrains and fuel sources. This chart also clearly shows that significant improvements in reducing automotive GHG emissions will not be achieved by material substitution alone. Investment in new powertrains and fuels contribute to the greatest emissions reductions.

Yet, on the contrary, this paper clearly shows that the product-use phase impact outweighs by far the rest of the LCA phases, bearing between 80% and 90% of the total LCA impact:

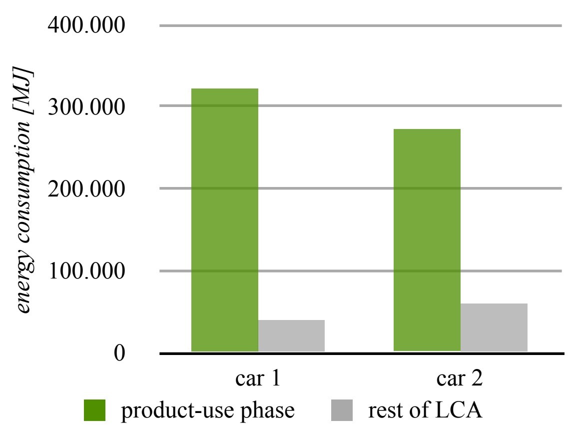


Figure 18. Energy consumption of product-use phase compared with the rest of the LCA phases.

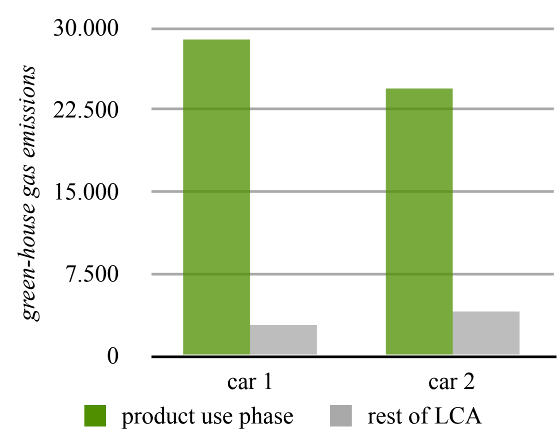


Figure 19. Green-house gas emissions of product-use phase compared with the rest of the LCA phases.

In other words, a car made out of aluminum instead of steel will generate a higher impact during its raw material and production phases, but a much lower impact during its product-use phase, and most important of all, a lower impact in its whole LCA.

On this basis it can be stated that as far as LCA assessment indicates, aluminum should continue to replace steel, specially in the parts of automobiles that is seldom used (chassis group and body-in-white).

To conclude, it is important to mention that the aspects herein pointed out where mostly analyzed in a theoretical and general point of view, and that they should be developed thoroughly within the corresponding settings and using appropriate resources for a proper comparison and conclusion.

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APPENDIX I - Fuel consumption for a sample of engines (2.0 diesel ≈ 170 CV) from reference [4].

brand	model	engine	power [CV]	mass [kg]	mean consumption [liter/100 km]
Alfa Romeo	Giuletta	2.0 JTD	170	1.320	4,7
	159 sedan/Brera			1.480	5,4
	159 SW			1.540	5,5
Audi	A3/A4 sedan	2.0 TDi	170	1.465	5,2
	A4 SW			1.525	5,5
	A6 sedan			1.565	5,7
	A6 SW			1.635	5,8
	A4 Allroad			1.670	6,2
Bmw	Serie 1	20d	177	1.365	4,7
	X1			1.490	5,3
	X3			1.740	6,5
Citroën	C5 sedan	2.0 HDi	163	1.563	5,3
	C8 sedan			1.770	6,1
Fiat	Bravo	2.0 Multijet	165	1.360	5,3
Ford	Mondeo sedan	2.0 TDCi	163	1.484	5,3
	S-Max			1.615	5,7
Lancia	Delta	2.0 MJT	165	1.430	5,3
Opel	Insignia sedan	2.0 CDTi	160	1.538	5,8
	Insignia SW			1.655	6,0
Peugeot	407 coupé	2.0 HDi	163	1.532	5,4
Seat	Exeo sedan	2.0 TDi	170	1.455	5,8
	Exeo SW			1.515	5,9
Volkswagen	Golf sedan	2.0 TDi	170	1.329	5,3
	Passat sedan			1.499	5,7
Volvo	S40	D4 2.0	177	1.300	5,1