Guidelines for the market competitiveness of sustainable lightweight design by magnesium solution: a new Life Cycle Assessment integrated approach

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Abstract

Recent changes to the Corporate Average Fuel Economy (CAFE) are driving automakers to seek more aggressive methods for fuel consumption reductions. In the long term, policy appears to focus on conversion of the dominant 20th century internal combustion engine (ICE) to a different engine that is partially or fully hydrocarbon-free. As the future of automotive propulsion is the subject of some debate, whatever the vehicle power source will be, weight reduction of the car is sure to be a key factor to meet energy saving requirements. The need to cut CO_2 emissions by reducing fuel consumption on ICE vehicles may also benefit market penetration of hydrocarbon free battery powered vehicles. A major factor in this decision will be the success in reducing battery cost for travel ranges that will make electric vehicles attractive to consumers. For the next few years, the purchase price of a hybrid or fully electric car is expected to be several thousand Euros higher than the average price of the gas-fuelled vehicle. It is worth noticing that price difference is largely due to the cost of battery (EU Commission targets a reduction in the cost of batteries by 6-8% annually together with improved chemistry and the economies of scale). To speed up the reduction in unitary mileage costs for full or hybrid electric vehicles lightweighting is again a key for success, however, a successful lightweight design will only be possible through a balanced solution that takes into account conflicting factors such as manufacturing costs, safety and crashworthiness, recycling and life cycle considerations. Life cycle considerations, particularly, have led to a large number of Life Cycle Assessment (LCA) studies to determine the carbon footprint of using lightweight materials. Three key-factors for the assessment of environmental impact of lightweight design for conventional ICE vehicle are the materials substitution factor; the fuel-mass correlation factor; and the energy intensity and recycling factors of materials production. In this work a material substitution scenario has been developed for assessing the net environmental impact of adoption of magnesium alloy panels instead of heavy steel panels, and competitive weight saving CRFP panels. Clean-up strategies for the LCA magnesium model for the fossil-fueled automotive sector will also be discussed.

Introduction

Recent changes to the Corporate Average Fuel Economy (CAFE) are driving automakers to seek more aggressive methods for fuel consumption reductions. Weight reduction is one of the most cost-effective means to reduce fuel consumption and greenhouse gases from the transportation sector powered by Internal Combustion Engine (ICE). There is a high emphasis on greenhouse gas reductions and improving fuel efficiency in the transportation sector, all car manufacturers, suppliers, assemblers, and component producers are investing significantly in lightweight materials research and development and commercialization. Light weighting of vehicles will be a factor in meeting these requirements due to the inherent relationship between mass and fuel consumption. Lighter weight materials have the advantage of providing sustained greenhouse gas emission reductions over the use cycle of the vehicle. All are moving towards the objective of increasing the use of lightweight materials and to obtain more market penetration by manufacturing components and vehicle structures made from these materials. The reasoning behind this is because it takes less work to accelerate and move a lighter object. It has been estimated in simulations that for every 10% of weight eliminated from a vehicle's total weight, fuel economy improves by 7%[1]. Lighter weight materials have the advantage of providing sustained greenhouse gas emission reductions over the use cycle of the vehicle. The ability to introduce new lightweight materials into vehicles is not a trivial matter. Many see a new concept, or limited production, vehicle introduced to the market with lightweight “space-aged” materials and feel that its adoption by mass produced vehicles is a simple matter of “remove and replace.” However, this is not the case; factors such as existing infrastructure, material cost, and high volume capacity become of great importance for mass production vehicles. In addition, many of the low production vehicles incorporate these lightweight materials as a method for gaining experience on their performance. Without significant data to support durability, the risk-averse automotive culture will not adopt new materials. Reducing the steel and cast iron share in the weight onboard an average internal combustion engine motor vehicle is not easy, because they carry load types that make it difficult to find lightweight solutions in the substitution of materials. For this reason, it is really difficult to reduce the weight of conventional 1,400kg vehicle even by 20-50kg, a very low percentage. But by decreasing gear components, avoiding crankshafts and reducing chassis elements, that is, by decreasing the number of components that cannot be made of light materials, the potential light-weight share increases. This is thinkable in new battery charged electric vehicles or fuel cell powered cars where about 200kg are reasonable target. While light weighting is crucial in reducing direct emissions produced by travelling, it may benefit also battery-powered vehicles attractiveness: benefits go beyond the power saving which positively impact on operational costs (i.e. cost for electricity sourced per mile travelled), but lighter structures allows to downsize batteries, thus reducing ownership costs while keeping high the long-range no-refuel driving. A car which is limited in range, and that need infrastructure to frequently charge it, along with ownership costs are main barriers automakers have been facing to put on market electric vehicles which can compete with conventional fossil fuel powered vehicles. Another strategy used to reduce vehicle mass is through a complete vehicle redesign. Examples of redesign may be a switch from body-on-frame to unibody construction or reducing non-structural elements of vehicles. In this case, the recent example of *BMW-i* is worth noting; it has an architecture that was actually custom-built for electric cars: it is made up of two separate units, the passenger cell (made of carbon fiber composite) and the drive module with suspension and drive components and the high-voltage battery. There is no tunnel running through the middle of the car, thus leaving more room for passengers and the desired compact design. However, in many instances this is not possible. For example, changing the body construction affects the overall volume of vehicles produced and may increase costs due to complex assembly techniques. Obstacle in the application of lightweight materials is their high cost, priority is given to activities to reduce costs through the development of new materials, forming technologies, and manufacturing processes. Comparable cost and increased functionality, is a major marketability objective to pursue in order to push wide spreading use of advanced lightweight materials capable of matching customers’ wishes of larger volumes with increased fuel economy, respectfully of high safety requirements.

The Life Cycle Assessment of lighter automotive parts

Environmental impacts associated with fossil fuel powered automobiles are dominated by the consumption of fuel, and this indicate that any improvements that are capable to contribute reduce fuel consumption are environmentally preferable. For example it is known that the choice of lighter materials to put onboard a vehicle fueled by gasoline can contribute to reducing emissions, namely the

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[1] Recent literature on lightweight design in automotive has been using data provided by ADVISOR (Advanced Vehicle Simulator) simulator developed by U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) with industry partners that simulates and analyze conventional, advanced, light and heavy vehicles, including hybrid electric and fuel cell vehicles.

carbon footprint of the vehicle over its life. A fuel-mass correlation factor (Ridge, 1998, sets to 1.08x10-4 kgCO2eq/Km·kg) can help to point out how the linear function emissions over travel distance. On the other hand, lighter components can vanish partially – sometimes totally – benefits of reduction of direct emissions as they are put onboard travelling vehicles when they are made of metallic materials that are primarily extracted with pollutant and energy intensive processes (e.g. aluminum, magnesium and titanium) or produced by non-environmental friend raw materials (e.g. carbon fiber reinforced polymers composite materials). The emissions “stored” in extracting and/or fabrication phases have, therefore, to be accounted for in the net balance between the cleaner and dirtier phase when, in order to make a decision we compare a lighter scenarios with that of the baseline. It is not only the sustainability consciousness of material specialists, product development engineers and designers that drives them to make product plans and de-signs to minimize the consumption of energy during manufacture and use, to in-crease energy consumption from renewable sources, maintaining water and air quality at the highest purity levels. On the market domain, reducing emissions is becoming a further added value in competitiveness. The U.S. government is making important progress toward reducing GHG emissions. A large number of U.S. states and localities are implementing clean energy incentives and clean energy targets—from voluntary emission goals and green building standards to mandatory cap-and-trade laws similar to the carbon taxes of EU Directives, which give polluters a financial incentive to reduce their GHG emissions and encourage the reduction of negative externalities in their own production processes. To evaluate the net balance of environmental impacts - both positive and negative impacts – of using lighter components onto internal combustion vehicles, use of standard Life Cycle Assessment (LCA) can help industry to get aware of quantifying energy and direct emissions of materials entering in manufacturing process so to evaluate actual balance over product life in terms of environmental impacts. Accounting the net environmental impact of product can reveal, for example, that use of lighter materials can be only beneficial for consumers. This is the case when light materials are actually capable to reduce fuel-consumption, but quantity of pollutants emitted in upstream phases - namely those phase before lighter vehicle is born – cannot be balanced over reasonable travel distance covered by vehicle. For this scope LCA in automotive sector shall assess the impact of the product throughout its life. Generally LCA starts with the compilation of relevant environmental exchanges during the life cycle of a product, with the evaluation of the potential environmental impact expressed by global warming potential (GWP) measured in kgCO$_{2eq}$, that can be estimated and calculated for all the exchanges. As stated, the production of manufactured products results from the overall supply of raw materials (e.g. mineral resource extraction for metals), some intermediate phases for mixing/processing raw materials, and following secondary manufacturing processes, it can be critical for the potential release of pollutant emissions and the consumption of a significant number of various sources of non-renewable energy. On the other side the reduction of emissions realized by lighter material in *usage phase* must be addressed. A well-structured Life Cycle Assessment (LCA) addresses life cycle of manufactured products divided into 3 stages [2]: a) *cradle-to-entry gate* (raw material extraction and refining); b) *entry gate-to-exit gate* (product manufacture); *c) exit gate-to-grave* (product use, recycling and disposal). Particularly for vehicle component, the rationale of assessing the emissions and energy consumed in life cycle of a component onboard vehicles is schematically shown in Figure 1.

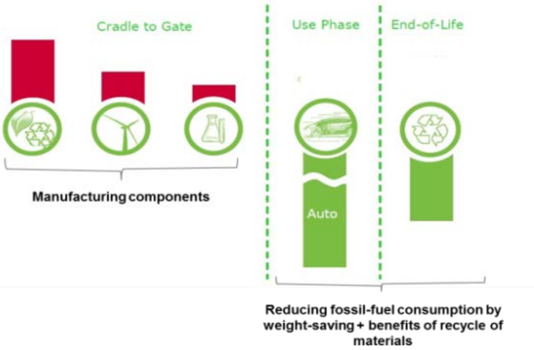
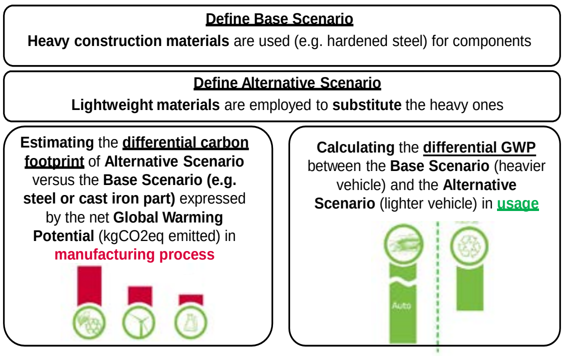


Figure 1 – Scheme for assessment of net GHG emissions in automotive sector.

A summarizing scheme for calculation of LCA for fossil-fuel vehicle is show in Figure 2. The model of the product system to employ in LCA calculation is typically a static simulation model. This means that a manufacturing process is schematized of basic process units, or stages, and each stage represents one or several activities performed such as production processes, transport, or retail. For each stage, data is recorded on the inputs of natural resources, the emissions, waste flows, and other environmental exchanges.



Define Base Scenario

Heavy construction materials are used (e.g. hardened steel) for components

Define Alternative Scenario

Lightweight materials are employed to **substitute** the heavy ones

Estimating the **differential carbon footprint** of **Alternative Scenario** versus the **Base Scenario (e.g. steel or cast iron part)** expressed by the net **Global Warming Potential** (kgCO2eq emitted) in **manufacturing process**

Calculating the **differential GWP** between the **Base Scenario** (heavier vehicle) and the **Alternative Scenario** (lighter vehicle) in **usage**

Figure 2 –The LCA assessment for fossil-fuel vehicles: scheme for calculation.

For the sake of simplicity, environmental exchanges of activities performed in single stage are typically assumed to be linearly related to one of the product flows of the unit process throughout its life. Each stage of the process activity is therefore schematized as a black box. Here materials flow in to be transformed, thus they flow out changed with the eventual production of some waste material. To make such modifications, energy is generally used, natural sources are consumed, some direct emissions could be produced by chemical reactions developing, etc. Any energy usage is therefore converted into indirect emissions, since a non 100% renewable energy (non- renewable electricity, steam, fossil fuels, etc.) powering the process in stage impact onto environment with their own global warming potential. For example, for each kW of electricity used, its environmental price is paid in terms of CO2 emitted to produce that one kW: it is low when electricity is produced by hydroelectric plants, it is very high when generated by fossil fuel power station that burns fossil fuels such as coal, natural gas or petroleum. The majority of the calculation model here illustrated is performed using the CCaLC software, a specific free-tool developed by The University of Manchester reviewed with the collaboration of several industries. The tool is based on two databases for material and energy inventories, the specifically developed CCaLC and Ecoinvent databases. As we are interested in investigating comparative scenarios between (multiple) candidate solutions and basic option (refer once again to scheme in Fig.2), calculation of petroleum consumption emissions saved in usage phase (i.e. car travelling) thanks to weightsaving shall considers how is mass we can reasonably save by substituting heavier components with lighter solution. Two are the factor to be considered, as it follows:

i) Material substitution factor which represents the mass ratio to calculate how much new material is required to substitute baseline material to achieve similar mechanical response (i.e. satisfy design requirements)[2];

ii) Fuel-mass correlation factor which describes the rate of fuel consumption during vehicle operation that can be presented as a simple linear function of vehicle mass, M (Keoleian and Sullivan, 2012) as follows:

(eq.1) $FCv = A \times Mv + B$

where *FCv* is the fuel consumption rate in L/km, constant A characterizes the fuel consumption associated with rolling, gradient, and acceleration resistance in L/(km·kg), Mv is vehicle mass in kg, and constant *B* represents parasitic loss in L/km mostly related to aerodynamic drag. The constant A here is often called *fuel reduction value (FRV)* or *fuel consumption reduction coefficient (FRC)* and is used as a measure of fuel-mass correlation. It varies depending on driving cycle, vehicle design, mass, powertrain type, and whether the powertrain is rematched for performance equivalence of the lightweight vehicle. According to a literature survey and simulations by Whohlecker et al. [3] the *FRV* of internal combustion engines lie in the range 0.15−0.7 L/(100 km·100 kg) depending on the factors discussed above, while the LCA studies reviewed here used values in the range 0.3÷0.6 L/(100 km·100 kg). Thus, considering 2.31 kgCO2eq are CO2 emissions resulting from each liter of motor fuel consumed, the above range can be represented in terms of reduction of carbon dioxide emission per each km when 1 kg is saved on board with respect to baseline scenario, namely $3.47x10^{-5}$÷ $1.62x10^{-4}$ $KgCO_{2eq}$/ (km·kg). Within this range is therefore $1.083x10^{-4}$ $kgCO2_{eq}$/(Km·kg), namely one major literature reference that we refer to in the following impact analysis [4].

The case study of lighter pans for vehicle

Case study here discussed addresses LCA of a floor pan in the automotive sector as produced by three different manufacturing process cycles, namely:

- *Cycle 1* - Conventional stamped steel floor pan;

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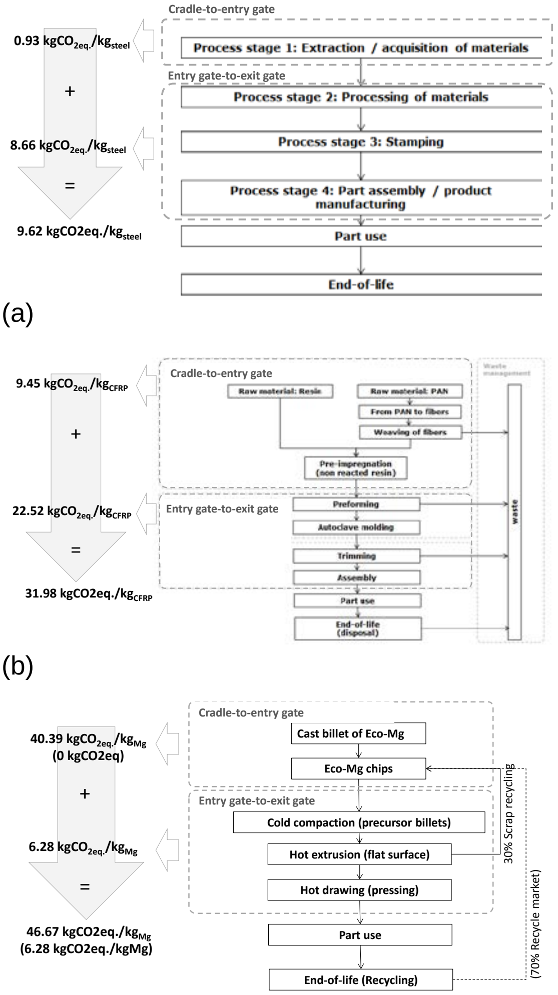
[2] The material substitution factors for this case study are explained in the next section and are given in the Table I.

- *Cycle 2* - Conventional Polyacrylonitrile (PAN) carbon fiber blended with epoxy resin;
- *Cycle 3* - Alternative low-impacting manufacturing technology process addressed by recycled Eco-Magnesium that uses a high recycling rate for magnesium machined chips as precursor materials [1]. A double scenario is assumed: i) 30% in situ recycled mixed with 70% of fresh material[3]; ii) 30% in situ recycled mixed with 70% of recycled chips from (future) Eco-Mg recycling market.

In Figure 3 are shown the 3 process cycles and relative GWP per kg of material produced.



(a)

(b)

(c)

Figure 3 – Process cycles and GWP results by CCalC software calculation: a) LCA of conventional steel floor pan; b) LCA of CFRP floor pan; c) LCA for novel process route of extrusion of in-situ recycled Eco-chips. GWP values outside parenthesis represent the GWP values (at various process stages, i.e. entry gate and exit gate) in case 70% virgin material Eco-Mg series alloys produced in Korea - best case of master alloy ingots produced in Korea with non-SF6 gas process [1] – starting from primary raw Mg imported from China - enters the process with 30% in-situ recycled chips; thus, the value in parenthesis refers to GWP impact of Eco-Mg recycled chips that enters [1].

As stated, first step is calculate the *materials substitution factor*, the mass ratio between the lightweight and baseline-component. The materials substitution factor is determined by the physical properties of the material, design constraints and economic considerations. Fig.4 represents a simply case study here analyzed. A panel subjected to bend momentum *Mf* where design constraints fix the width *a* and the length *L* (namely the size and geometry) while the thickness *b* of the cross-section is free. The problem of reducing the mass would be solved by simply reducing the cross-section, but there is a constraint: the section-area *A* must be sufficient to carry the bending moment *Mf*.

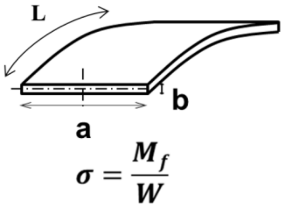


Figure 4 - Critical stress to calculate in order to compare the resistance of a material in case of bending load.

Such an optimization problem is therefore managed by material change. It is usually solved this way. The state of stress σ induced by the external momentum Mf is easily calculated by the formula in Fig.4 as:

$$\sigma_{appl} = M_f / W \qquad \text{(eq.2)}$$

where W is the moment of resistance to bending. For the study case it is calculated as:

$$W = \frac{a \cdot b^2}{6} = \frac{a}{a} \cdot \frac{ab^2}{6} = \frac{A^2}{6a} \qquad \text{(eq.3)}$$

In the eq.3 the W parameter is expressed in a more convenient way, as the function of the area A and the geometry constraint we have for the design, as the width of the panel *a*. The design load constraint that requires the pan to resist safely to the bending moment Mf can therefore be expressed by a relationship that states that the strength of material σ_f, the stress to failure, shall be higher than the maximum stress applied to panel σ_{appl} when it

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[3] In the short term a more realistic scenario requires considerable primary production at very high GWP to get that much magnesium metal into the vehicle materials stream and develop the recycling market.

is supporting the external load bending momentum Mf:

(eq.4) $$\sigma_f \geq \sigma_{appl}$$

Combining the design failure constraint in (eq.4) with (eq.2) and (eq.3), we can rewrite (eq.4) as the following:

(eq.5) $$\sigma_f \geq \frac{6a \cdot M_f}{A^2}$$

This last relationship means that the panel should be designed by a cross-area *A* capable of keeping the second member below the threshold σ_f, which is the strength limit of the chosen material. Thus, considering that we are addressing a minimizing weight problem, the larger the area A is, the heavier the component will be. Thus (eq.5) will actually be considered with its lower bound value, namely:

(eq.6) $\sigma_f = \frac{6a \cdot M_f}{A^2}$

As our first step consists in calculating the substitution factor for alternative materials, we need to write the ratio between the mass *m* (obtained multiplying density ρ, by section area *A* to be expressed by inverting the eq.6, by the length of panel *L*, in case of constant thickness) of the alternative panel against the mass of the baseline panel, that is:

(eq.7) $\frac{m_{alternative}}{m_{baseline}} = \frac{\varrho_{alt} \cdot}{\varrho_{base}} \cdot \frac{{\sigma_{base}}^{1/2}}{{\sigma_{alt}}^{1/2}}$

Table I gathers the results of the calculation of the mass of alternative panels made in two new materials against baseline steel, considering the constraint of thickness for the alternative light panel that will be limited to twice the baseline steel panel.

Table I**.** Comparison of weight saved onboard when either Eco-Magnesium considered in this case study are used to substitute a steel large pan loaded in bending mode to external momentum M_f.

Features	**CFRP**	**Magnesium alloy (type Eco-Mg AZ31B) [ref]**	**Steel (type AISI 4140)**
Density (kg/dm^3)	1.60	1.81	7.87
Resistance limit (MPa)	120	125	450
Substitution factor (kg$_{alternative}$/kg$_{baseline}$)	0.39	0.44	1.00
a (dm)	15.30	15.30	15.30
b (dm)	0.014	0.013	0.007
L (dm)	15.30	15.30	15.30
Volume (dm^3)	3.17	3.11	1.64
Total weight onboard (kg)	5.08	5.63	12.90
Weight saved (kg)	7.82	7.27	-
	60.6%	56.4%	-

Discussion: the net "cradle-to-grave" GWP of the pan

The first impact scenario addresses what happens when substituting the baseline case, the 7.7 kg steel metal floor pan, with about 5 kg of CFRP-made floor pan or about 5.7 kg of Mg pan in a vehicle, thus satisfying same design specifications (refer again to Table I). Assessing the net global warming potential of a lighter component vs a heavier component works with differential analysis between the two scenarios, the new and baseline one. Scope is to calculate the net value of kgCO$_{2eq}$ for the new component over its life cycle (from "cradle" to "grave").

Calculation of net "cradle-to-exit gate" global warming potential due to material substitution

The first step consists in calculating the net "cradle-to-exit gate" GWP of the alternative material component (namely the functional unit of this LCA analysis) expressed as kgCO$_{2eq}$ per kg of component to be put on board to substitute the steel made component, i.e. the baseline case.

The net "cradle-to-exit gate" GWP for CFRP floor pans put on board

By the GWP value 31.98 kgCO$_{2eq}$ / kg$_{CFRP}$ calculated by use of CCalC software over the cradle-to-exit gate process stages (refer to Fig.3b), it is possible to determine that 159.89 kgCO$_{2eq}$ is the GWP of 5kg of CFRP pans. Starting from this value, we are interested in calculating the Net Value of GWP over the "cradle-to-exit gate" phase, namely the adjusted value as it is compared to the baseline scenario consisting in a 13 kg steel pan, due to substitution factor 0.39 kg$_{CFRP}$/kg$_{steel}$ in Table I. It means we have to subtract from the above calculated CO$_{2eq}$ emissions for the manufacturing of the CRFP-made floor pan, the total CO$_{2eq}$ emissions of the baseline steel component. By this assumption, the net "cradle-to-exit gate" GWP for the 5kg CFRP floor pan calculated referring to the baseline scenario 13 kg steel made pan accounts for each 5 kg of CFRP pan:

(eq.8) $[31.48 \mathrm{kgCO_{2eq}/kg_{CFRP}} \times 5.07 \mathrm{kg_{CFRP}/pan}] - [2.56 \mathrm{kg_{steel}/kg_{CFRP}} \times 5.07 \mathrm{kg_{CFRP}} \times 9.59 \mathrm{kgCO_{2eq}/kg_{steel}}] = 34.97 \mathrm{kgCO_2eq/pan_{(CFRP)}}$

The net "cradle-to-grave" GWP for total of floor pans onboard made of CFRP

By combining literature data referring to average fuel consumption – i.e. 8.5 liter per km - for a medium size vehicle and the kgCO2 emitted per liter consumed – 2.85 kgCO$_2$eq per liter of motor fuel consumed - it is easy to estimate the emissions produced during the life-long standard travel distance of a vehicle (literature considers 200,000 km the average travel distance of a vehicle until it ends its life and being disposal and several construction materials recycled after dismantling). This value is around 48,500 kgCO$_2$eq emitted over total 200,000 km. Finally it is considered in the GWP model the potentialities of CO$_2$ emission reduction per km once weight is reduced from the above baseline scenario by use of the fuel-mass correlation factor; by using 1.08x10^{-4}kgCO$_2$eq/(Km·kg) as above stated, the linear function emissions vs travel distance is scaled down by constant value. This result is clearly shown in the graph of Fig.5:

- The "baseline case scenario", the A-line represents the linear correlation between emissions and travel distance for baseline scenario (baseline vehicle);
- The B-line represents the shift of correlation between emissions and travel distance when a weight reduction is achieved on-board, but realized with material that has a certain impact in its production phase (see the "net GWP" interception to y-axis).

In this case, we can state that the substitution of materials has produced an increase in terms of net CO$_2$ emitted at the manufacturing stage which is then counter-balanced by the reduction in fuel consumption during vehicle life. As it clearly shown by dotted lines, the more is the NET "cradle-to-exit gate" GWP of the material substitution, the more delayed is the break-even point in terms of travelled distance. It could even happen that no interception exists: in this worst case, the lighter solution against baseline solution is not actually convenient in terms of net CO$_2$.

In the Table II are summarized final results that have been calculated considering a total number of 6 CFRP pans put onboard to substitute 6 steel made pans. Starting from the net GWP of CFRP pan, the "break-even point", total mass saved, the net reduced emissions at the end of life (according to literature, 200,000 km).

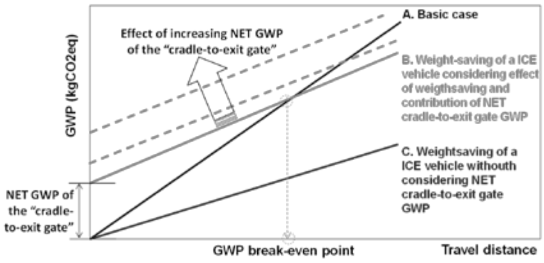

Figure 5 – Scheme for assessment of positive or negative GWP of automotive lighter component: seeking the GWP break-even point.

Table II. Scenario of n.6 CRFP pans versus n.6 steel made pans onboard; relevant results by model (refer to Figure 5 scheme).

Relevant features	Data calculated by model
Mass of CFRP pans (n.6) onboard (kg)	30.48
Mass of substituted steel pans (n.6) onboard (kg)	78.15
Mass saved onboard by substitution (kg)	47.67
NET GWP Break-Even Point (km)	41,500
Net percentage of emissions cut (at end of life, 200,000 km)	-2.10%

The net "cradle-to-grave" GWP of the magnesium made pan against steel made pan

The second impact scenario addressed what happen if 7.7 kg steel metal floor pan are substituted with 5.63 kg magnesium alloy made floor pan fabricated with cycle 3 process route (refer to Fig.3). The first step consists once again in calculating the net "cradle-to-exit gate" GWP of Mg component (namely the functional unit of this LCA analysis) expressed as kgCO2eq per kg of component to put on board to substitute the steel made component. This value has been calculated by considering the average CO$_2$ equivalent emitted for producing 1 kg of component to put on board the vehicle. It has been estimated[4] 40.39 kgCO$_{2eq}$ per kg of semifinished bars is the GWP of 70% Eco-Mg feedstock produced from virgin material fabricated in Korea with no-SF6 gas process enters the process (i.e. cradle-to-entry gate GWP value) starting from primary raw Mg imported from China. Adding 6.28 kgCO2eq per kg bar produced, we obtain 46.67 kgCO$_{2eq}$ per kg of 70% virgin Eco-Mg processed by direct extrusion [1]. Otherwise, we are interested in the net value of GWP over the "cradle-to-exit gate" phase, hence we have

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[4] Chinese origin ingot value was used in Eco-Mg supplied in 2011 to project consortium. The GWP data was calculated as "cradle to gate" by considering average data from plants using Pidgeon process that were in operation in 2011 in China.

to subtract from above calculated CO2 emission for the manufacturing of the CRFP-made floor pan the CO2 emissions of the baseline steel component. Following the calculation scheme above illustrated, we obtain for each 5.63 kg Mg-floor pan:

(eq.9) $[46.67 \mathrm{kgCO_{2eq}/kg_{Mg}} \times 5.63 \mathrm{kg_{Mg}/pan}] - [2.27\ \mathrm{kg_{steel}/kg_{Mg}} \times 5.63 \mathrm{kg_{Mg}} \times 9.59\ \mathrm{kgCO_{2eq}/kg_{\ steel}}] = 140.19\ \mathrm{kgCO_{2eq}\ /\ pan_{(Eco\text{-}Mg\text{-}30\%\ rec.)}}$

In the Table III are summarized the final results obtained considering a total number of 6 Eco-Mg pans produced by cycle 3 with 30% of in-situ recycling put onboard to substitute 6 steel made pans. Starting from the net GWP of CFRP pan, the "break-even point", total mass saved, the net reduced emissions at the end of life (according to literature, 200,000 km).

Table III. Scenario Eco-Mg pans versus steel made pans: relevant results by model calculated with 30% of in-situ recycled scenario and 70% of fresh material (refer to Figure 6 scheme).

Relevant features	Data calculated by model
Mass of Mg pans (n.6) onboard (kg)	33.78
Mass of substituted steel pans (n.6) onboard (kg)	76.77
Mass saved onboard by substitution (kg)	42.99
NET GWP Break-Even Point (km)	~176,500
Net percentage of emissions cut (at end of life, 200,000 km):	-0.20%

In the best but theoretical case 100% recycled chips are used in the process as proposed in the cycle 3 as alternative process path (30% in-situ recycling, 70% from recycling market - not yet developed) [1], the resulting data is aligned with the case of CFRP scenario, as shown in Table IV. Finally a snapshot of variation of net "cradle-to-grave" GWP curves for the 4 scenarios of n.6 pans made of steel (cycle 1), CFRP (cycle 2), Eco-Mg chips with 30% recycling (cycle 3) and Eco-Mg chips with 100% recycling (cycle 3) versus travel distance curve accordingly with Fig.5 are shown limited for facilitating visualization to quarter of lifespan (50,000 km).

Table IV. Scenario Eco-Mg pans versus steel made pans: relevant results by 100% recycling model (refer to Figure 6 scheme, parenthesis values).

Relevant features	Data calculated by model
Mass of Mg pans (n.6) onboard (kg)	33.78
Mass of substituted steel pans (n.6) onboard (kg)	76.77
Mass saved onboard by substitution (kg)	42.99
NET GWP Break-Even Point (km)	0(1)
Net percentage of emissions cut (at end of life, 200.000 km)[1]:	-3.01%

(1) A Net GWP break-even point at 0 km means that component at the exit gate accounts lower CO2eq emissions than steel-made baseline scenario.

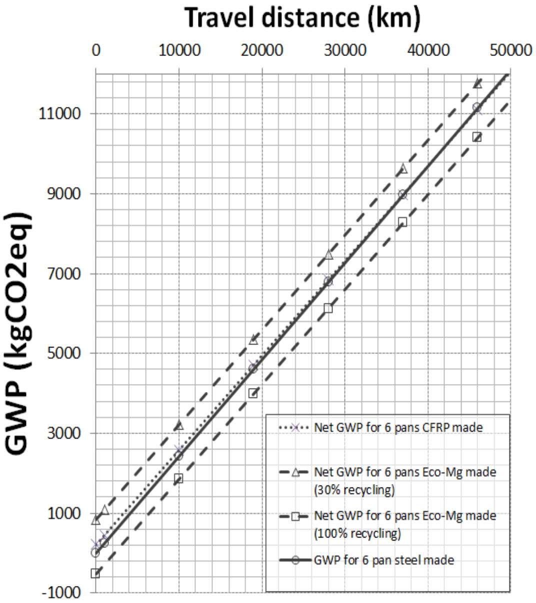

Figure 6 – Scheme for assessment of positive or negative GWP of automotive lighter component: seeking the GWP break-even point

Conclusions

The environmental impact of Eco-Mg series alloy based process used in an experimental pilot plant has been calculated 6.2 $\mathrm{kgCO_2eq/kg}$ when flat extrusion profiles are fabricated by use of recycled chips. This value is valid in theoretical case 100% of recycled material is used in the process (i.e. 30% from the in-situ recycling, 70% supplied by a recycling market) and it leads to best case, superior to CFRP pan. On the other hand, today and for forthcoming years, 100% recycled material is not realistic. A more realistic 30% recycling rate would account for 176,500 break-even point. A 62% is finally accounted for the recycled Eco-Mg fraction for mixing fresh material to make cradle-to-gate GWP of Mg based pan aligned with CRFP part. CRFP are usually less impacting over the total lifespan of vehicle, 200,000 km according to literature. On the other hand, a pilot process has demonstrated the suitability of employing chips of Eco-Mg type as feedstock material and this option allowed to align final global warming potential values of Eco-Mg to those low values typical of a CRFP pan.

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