Economical and Environmental Factors in Light Alloys Automotive Applications

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The effects of mass reduction through substitution of ferrous components by equivalent Al or Mg alloy components on the vehicle's cost and CO_2 emissions are discussed using M.F. Ashby's penalty functions and exchange constants method. The viability of substitutions of Al alloys by Mg alloys is also considered. Substitutions of cast components at equal volume and panels and beams at constant stiffness are considered. Substitutions of cast ferrous components are economically the only viable ones in terms of the CAFE (Corporate Average Fuel Economy) liability, although the cost penalty can be fully offset by the gasoline savings over the life of the car for most other forms of light alloy substitutions. When primary alloys are used, the gasoline savings over the lifetime of a lighter car offset the CO_2 footprint of Al alloys in all cases. Because of their larger CO_2 footprint, the environmental feasibility is somewhat restricted for electrolytic Mg, and more so for Mg produced by the Pidgeon process. Due to their high recyclability, Al casting alloys have a significant environmental advantage over all other light alloy applications. Viable substitutions of existing Al components by Mg components are largely restricted to castings of electrolytic Mg.

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I. INTRODUCTION

A vehicle[1,2] designed to maximize the use of aluminum alloys may be up to 36 pct lighter than a conventional steel car, with a concomitant fuel economy improvement, and hence reduced emissions, of over 20 pct. Magnesium is less dense than aluminum, and extensive[3–10] use of magnesium alloys may lead to even greater mass reduction and increased fuel efficiency. Carpenter *et al.*[11,12] pointed out that mass reduction may also prove crucial to the performance of vehicles with hybrid and fuel cell powertrains, which are expected to be heavier than internal combustion powertrains.

Aluminum alloys, currently with over 100 kg average use per car, have a clear lead over magnesium alloys at only about 6 kg.[3,5,13,14] In part, this is so because despite a continuously decreasing cost over the past few years, Mg alloys are still relatively expensive in comparison with Al alloys and polymers.[8,11,15,16] Indeed, the relatively high cost of both Al and Mg alloys in relation to steel is normally identified as the single most important deterrent to a wider use in motor cars,[1,3,12,15,17–21] especially when the liability arising from CAFE (Corporate Average Fuel Economy[22]) standards is considered. From the environmental point of view, for metals like Al and Mg, which are "dirty" products to make, but are "clean" to use, initial emissions will be higher than those of a metal such as Fe, which is clean to make but dirty in use.[23] The difference between the two emissions impact totals must be fully offset over a time shorter than the vehicle's expected lifespan to make any substitutions environmentally feasible.[1,4,6,18,21,23–28]

In this article, the cost and environmental viability substitutions of ferrous components by Mg and Al alloy components are discussed by using M.F. Ashby and coworkers' method of analysis, which involves material indices, penalty functions, and exchange constants.[29,30,31] The viability of substituting Mg components for existing Al components is also examined.

Sivertsen *et al.*[6] reviewed a number of recent publications dealing with the lifecycle assessment (LCA) of automotive light alloys, pointing out some of the difficulties inherent to this sort of analyses, which ultimately limit their practical value, namely, lack of reliable data, lack of an accepted method for weighing the environmental impact, the methodologies used being too comprehensive and rigorous (*i.e.*, too time and resource consuming) for widespread application, difficult translation of conclusions into information useful for decision making, and lack of transparency due to the incorporation of weight factors within the analysis. In addition, they pointed out inconsistent definitions of what constitutes recycled metal and generally insufficient sensitivity analysis.

To avoid some of these shortcomings in the present work, the environmental data for the light alloys have been taken from recent comprehensive studies.[24,32,33] To maintain consistency and fairness in the comparison between Mg and Al, the analysis is initially based on the use of primary metal, and sensitivity analyses to the effect of recycling and to the source of primary energy are carried out subsequently. The mechanical function of the components, namely, castings, beams, and panels, is

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made explicit from the outset in order to identify which applications are more suitable for substitution, conferring on the analysis' outcomes immediate practical value. In addition, the differential nature of the method makes a full inventory of the cost and environmental burden unnecessary, greatly simplifying the task and leaving the conclusions as sole functions of the difference in the materials' cost and the amount of primary energy embodied. The power of the method of analysis lies in its transparency and simplicity, and, because no other assumptions are involved aside from those embedded in the determination of the primary energy or the vehicle's use phase data, it leads to robust conclusions.

II. STRUCTURAL AUTOMOTIVE APPLICATIONS

Three types of ferrous components are considered for substitution: cast iron parts, and beams and flat panels of prescribed stiffness made of stamped steel. Valve covers,[3,15] torque converter and transmission housings,[9,10,12,26] crankcases,[34,35,36] cylinder heads, and engine blocks[12,13] are examples of cast components, whereas steering wheels,[10,37] space frames,[13,19,38] door frames,[3] dashboards,[3,9,10,15] and roof, door, and hood sheet panels[3,10,13,19] are examples of steel beams and panels currently considered amenable to substitution by light alloys. The replacement of cast components is assumed to occur at nearly equal volume, whereas[39] the beams' cross-sectional area is varied at constant shape, and the panels' thickness is adjusted at constant width, to meet the stiffness constraint. Examples of Mg substitutions for existing Al components are engine blocks and cradles, torque converter housings, *etc*.[9–12,26,34,35,40,41]

Representative structural aluminum[19,42] (A356, A380, A319, or A6111) or magnesium[5] (AM50 or AZ91) alloys are considered for the analysis. Three polymeric materials commonly used in cars,[15] and a titanium alloy that is also considered[43,44] as a viable weight-saving option for passenger cars because of its high specific elastic modulus and strength and high corrosion resistance, have also been included to provide a wider reference frame.*

A car in which ferrous parts are replaced by functionally equivalent light alloy components, as assumed in this exercise, is heavier than the one designed to maximize the use of light alloys,[1,2,5] hence the conclusions regarding beams and panels substitutions are likely to be biased toward steel. In the case of castings, minimum cross sections are generally determined by process constraints[1] rather than by mechanics, hence they tend to be bigger, that is, heavier than necessary, and the overall weight ratio is essentially that of the respective densities. An exception is that of cylinder heads, which are designed for strength, and relatively thicker sections (*i.e.*, heavier castings) would be required for actual substitutions using Al and Mg; thus, the conclusions based solely on the density ratio may be slightly biased in favor of the light alloys in these cases.[1] The strength of the materials is not considered in the analysis, as it has been shown that[1,3] substitutions of Mg and Al alloys for mild steel sheet require larger cross sections (*i.e.*, they are heavier) at constant bending stiffness than those at constant bending strength. The reader is referred to the articles by Stodolsky *et al.*,[1] Luo,[3] and Schumann[10] for more detailed discussions on specific substitutions.

It is often pointed out that decreasing the mass of a component has a compounding effect on the rest of the vehicle, as the overall loads are decreased. Estimates put the mass compounding effect at about 50 pct of the primary mass savings;[1,2,25,45] *i.e.*, for every kilogram saved in the substitution, an extra 0.5 kg can be removed from the rest of the car. In practice, however, the primary mass reductions have systematically been used in new cars to offset the added mass of safety, comfort, or pollution control devices,[12,19,25,45] and the average curb weight has actually increased over the past 20 years.[9,12,45] In other words, while actual gasoline savings have resulted from not having to increase the mass of the frame, drive train, *etc*., because of the additional devices,[21,25] no mass compounding effects can be claimed for current vehicles. There are no mass compounding effects on trucks, trains, airplanes, or other forms of transportation involving payload.[25] Thus, unlike other works,[1,2,25] mass compounding has not been incorporated into the discussion, although its potential benefit is accounted for in the closing section of the article (Figure 9).

Differences in operational costs and energy usage between cast iron, steel, Al, and Mg components have generally been deemed to be very small,[1,3,10,12,15,20,21,25,46,47] so the only cost and energy differences are those of the materials themselves, with proper accounting for scrap. Because of the differential nature of the analysis (Eq. [4]), labor and process cost and energy can thus be assumed to cancel each other out when the exchange constants are calculated. Ongstad *et al.*[47] noted that this assumption is valid as long as the primary energy is much larger than any other quantity involved; *i.e.*, it may not extend to those cases where the recycled fraction is very large.

III. MATERIALS AND SOURCES OF DATA

The data for the study, listed in Table I, are from the 2006 Cambridge Engineering Selector (CES) database,[48] except for the cost of Mg, which refers only to the United States market and was obtained from other sources,**[49,50] and the CO_2 footprints, *h*, of Al and Mg, which are as explained subsequently and in Appendix A.

In order to compare Al and electrolytic Mg on an equal footing, the respective smelters are assumed connected to the same electric power grid. The *h* values

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*Because the method of analysis is essentially graphical (Figs. 2 through 7), other materials can be easily added.

**The price of Mg has recently dropped to near parity with Al in the world markets, but local tariffs imposed in 2005 have kept the price in the United States a factor 1.5 to 1.6 above that of Al.[12]

Table I. The Materials Studied and the Upper-Lower Limits of their Relevant Properties; Unless Stated Otherwise, the Data are from the 2006 CES[48] Software Data Base; an Asterisk Identifies Data for Mg Produced by the Pidgeon Process

Material	Key	Density, ρ (Mg/m^3)	Cost, $c^{\#}$ ($/kg)	Elastic Modulus, E (GPa)	Yield Strength, YS (MPa)	CO$_2$ Footprint, h (kg/kg)	Typical Automotive Applications
Gray cast iron	cast Fe	6.9 to 7.4	0.19 to 0.68	80 to 150	65 to 293	1.0	engine blocks, transmission cases
Low-carbon steel sheet	steel	7.8 to 7.9	0.47 to 0.85	200 to 215	250 to 395	1.9 to 2.1	galvanized sheet for body panels
Al casting alloys, alloys A356, A319, A380, and A6111	A356	2.6 to 2.7	1.4 to 2.3	71 to 75	228 to 252	$12^{\#\#}$	engine blocks, valve covers, outerbody panels, space frames
Mg casting alloys, alloys AZ91 and AM50	AZ91	1.8 to 1.84	3.3 to 3.5†	40 to 45	155 to 165	17.5 to 28,4$^{\#\#}$ 37* to 47*,‡	transmission cases, instrument panels, engine blocks, steering wheels
Ti-6Al-4V	Ti	4.4 to 4.45	28 to 47	110 to 117	827 to 1069	50.2 to 55.5	Con rods, brake pins, camshafts, exhaust systems, valves
PA 6 (30 pct glass)	nylon	1.6 to 1.7	4.3 to 4.8	8.3 to 1.7	144 to 159	7.7 to 8.5	valve covers, instrument panels
BMC (30 pct glass)	BMC	1.7 to 2.1	2.3 to 2.5	10.3 to 17.2	25.1 to 55.2	7.7 to 8.5	
SMC (30 pct glass)	SMC	1.8 to 2.2	2.9 to 3.2	9.7 to 17.2	62.6 to 137.6	7.7 to 8.5	

$^{\#}$Prices are in $US/kg through the article.
$^{\#\#}$Assumes that 55 pct of the energy for smelting is generated from fossil fuels. Refer to Appendix A.
†Data from Refs. 49 and 56.
‡Data from Ref. 53.

given in Table I for both Al and Mg assume that ~55 pct of the electric energy is obtained by burning fossil fuels, reflecting the current western world mixture of energy sources for the smelting of aluminum[24] (Appendix A provides the details).

Magnesium produced by the silicothermic Pidgeon process, used mostly in China, accounts for nearly 70 pct of the world production,[51,52] and because of its very large CO$_2$ footprint, needs to be considered separately. Values from recent estimates by Ramakrishnan *et al.*[26,33,53] are used (data for Pidgeon Mg are identified by an asterisk in Table I and throughout the article). A more thermally efficient Pidgeon process described in the recent literature[52] is also considered in Appendix A.

IV. MATERIAL INDICES TO MINIMIZE MASS, COST, AND CO$_2$ EMISSIONS

The material indices used to minimize the relevant performance metrics, namely, mass, cost, and CO$_2$ emissions, are listed in Table II. An example of derivation of a generic material index is given in Appendix B. The reader is referred to recent publications[31,39,54,55] for detailed derivations of material indices involving both mechanical and environmental performance.

Table II. Material Indices for the Performance Metrics Mass, Cost, and Gasoline Equivalent CO$_2$ Footprint (h_q, Defined by Eq. [7]); Maximizing Any Given Index Minimizes the Relevant Metric

Function	Mass	Cost	Gasoline Equivalent CO$_2$ Footprint
Castings	ρ^{-1}	$(\rho c)^{-1}$	$(\rho h_q)^{-1}$
Beam	$E^{1/2}/\rho$	$E^{1/2}/(\rho c)$	$E^{1/2}/(\rho h_q)$
Panel	$E^{1/3}/\rho$	$E^{1/3}/(\rho c)$	$E^{1/3}/(\rho h_q)$

CO$_2$ is the major[57] contributor to the greenhouse effect, and other emissions effects are usually accounted for as CO$_2$ equivalents. Thus, the environmental impact of the light alloys substitutions is assessed by comparing (in gasoline equivalent units) the CO$_2$-emissions penalty of the primary alloys substitutions with the potential savings in gasoline burnt powering a lighter car.

V. PENALTY FUNCTIONS AND EXCHANGE CONSTANTS

A material that makes a car inexpensive to produce, such as steel, is not necessarily the one that makes it environmentally friendly to produce or drive. This creates conflicts between the performance metrics used to optimize the design, in this case, between cost, mass, and CO$_2$ emissions, if they are to be minimized simultaneously. Conflicts of this sort can be solved in a systematic and unambiguous way following the multiple objective minimization method prescribed by Ashby and co-workers.[29,30,31] The approach involves the use of a locally linear function, Z, called the penalty, value, or utility function, to combine the design metrics, P_i, through exchange constants α_i. These are defined as

$$Z = \alpha_1 P_1 + \alpha_2 P_2 + \alpha_3 P_3 + \ldots \qquad [1]$$

and

$$\alpha_i = \left(\frac{\partial Z}{\partial P_j}\right)_{P_j, j \neq i} \qquad [2]$$

A minimum of Z identifies the most preferable solution to the conflicts in design goals.

The exchange constants measure the change in Z per unit change in a given metric, all others being held constant. Thus, for the performance metrics mass and cost, α measures the change in Z caused by 1 kg of mass reduction, and should Z be expressed in \$, the units for α will be \$/kg.

The approach is illustrated for the two-dimensional case in the trade-off graph of Figure 1. The metrics, P_1 and P_2, represent in this example the mass and cost of panels of given stiffness, respectively. The circles are all the candidate materials, and the shaded ones define the trade-off surface (thick dashed line). The penalty function takes the form

$$Z = \alpha_1 P_1 + P_2 = GF\left[\frac{\alpha_1}{M_1} + \frac{1}{M_2}\right] \qquad [3]$$

where G and F are constants (Appendix B), and M_1 and M_2 are material indices from Table II. For the family of parallel lines, materials A and B are a better option than any other material such as C, as they sit on a line with lower Z, given by the y-intercept in this example.

The simultaneous minimization of all three metrics, mass, cost, and environmental impact, can be done by numerical methods using Eqs. [1] and [2]. This is an appealing possibility, useful when the overall goal is to simply rank the candidate materials (for instance, the work by Ermaloeva *et al.*[58] with regard to automotive composite panels). In the present case, however, the discussion of the mass-cost interaction was kept separated from that of the mass-CO_2 emissions to enable individual sensitivity analyses. Simultaneous consideration of all three metrics is made at a later stage (Figure 8).

With reference to Figure 1, the present analysis addresses the substitution of an incumbent material, such as A (steel), for one of two alternative materials, B or D (Mg or Al). Each substitution defines a particular exchange constant, α_1 or α_2, and in either case, the substitution is feasible provided the following condition is met:

$$\alpha_1, \alpha_2 = -\frac{\Delta P_2}{\Delta P_1} \leq \alpha_u \qquad [4]$$

where α_u is the relevant upper bound. Equation [4] is a most valuable tool[29,30,31] to assess potential candidates against an incumbent material while maintaining functional equivalence through the performance indices.

The main thrust of this article can now be restated as, on the one hand, the calculation of the exchange constants involved in the substitution of cast iron or steel by Mg or Al alloys in functionally equivalent components, and on the other hand, the determination of the relevant upper bounds.

This article is organized as follows: the upper bounds to the exchange constants are determined first, followed by analyses of the mass-cost interaction (Figures 2 through 4) and the mass-CO_2 emissions interaction (Figures 5 through 7). A graphical way of co-minimizing cost and CO_2 emissions is then presented (Figure 8), followed by a discussion of the effect of recycling (Figure 9). A sensitivity analysis of the environmental data is carried out in Appendix A.

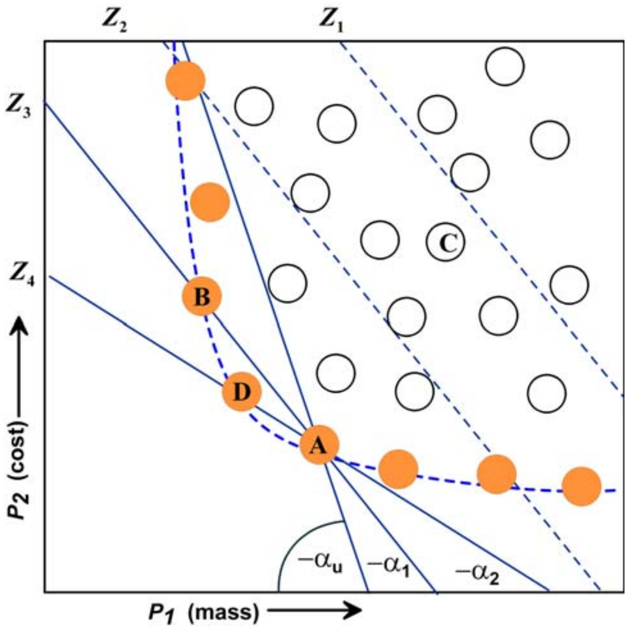

Fig. 1—Trade-off graph.[29,30,31] The x and y axes represent the performance metrics to be minimized (P_1 = mass, and P_2 = cost, both for given stiffness). The circles represent suitable materials; the shaded ones determine the trade-off surface (thick dashed line). The y intercepts, Z_j, are the values of the respective penalty functions (Eq. [3]), the α_i values are the exchange constants (Eq. [2]), and α_u is an upper bound to the exchange constants.

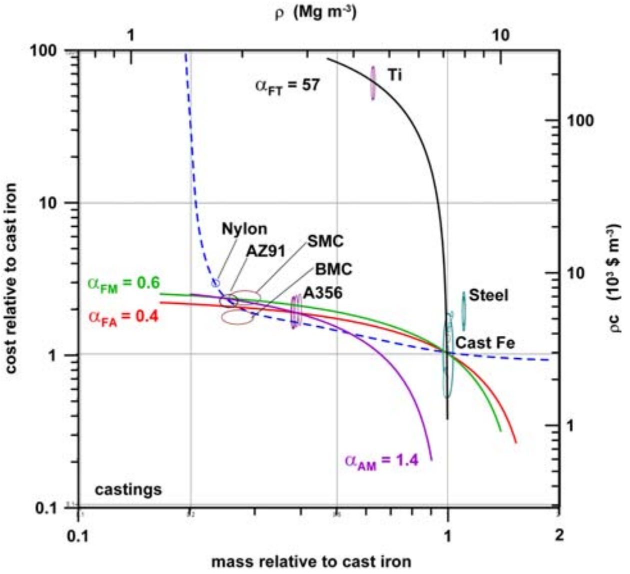

Fig. 2—The relative cost of castings as a function of their relative mass. The α values (\$US/kg) indicate the cost penalty per kilogram of mass reduction. The first subscript indicates the incumbent material, the second its replacement, namely, F = iron, A = aluminum, M = magnesium, and T = titanium. In this and Figures 3 through 7, the logarithmic scales cause the penalty function lines to appear curved.

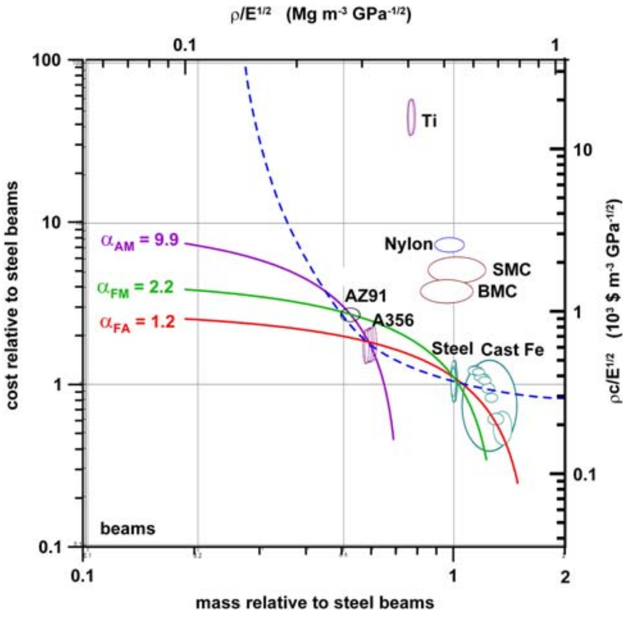

Fig. 3—The relative cost of beams of prescribed stiffness, as a function of their relative mass.

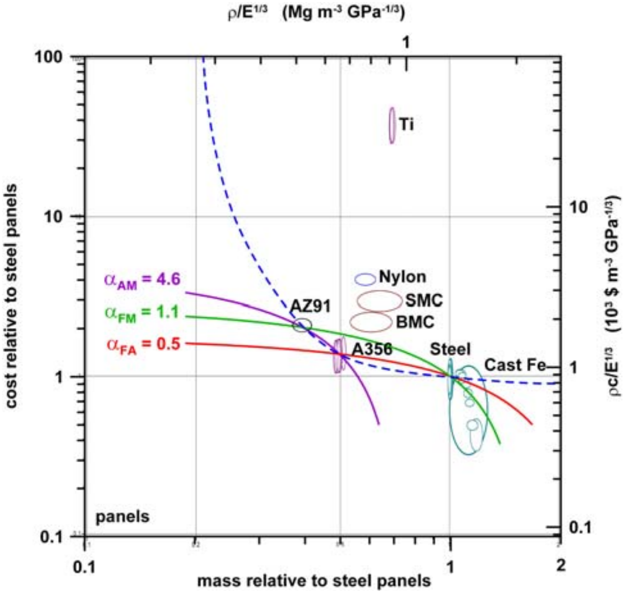

Fig. 4—The relative cost of panels of prescribed stiffness, as a function of their relative mass.

VI. UPPER BOUNDS TO THE EXCHANGE CONSTANTS

A. *Curb Weight and Fuel Economy*

The cost penalty resulting from the CAFE standard is currently the main driving force[†] for incorporating lighter materials in automobiles in the United States.[17] Car manufacturers are liable for a civil penalty of \$5 for each 40 metres per litre of gasoline (0.1 miles per gallon (mpg)) if a fleet falls below the CAFE standard[22] of 9.4 km/lg[‡] as of 2007 (equivalent to 22.2 mpg). Gasoline

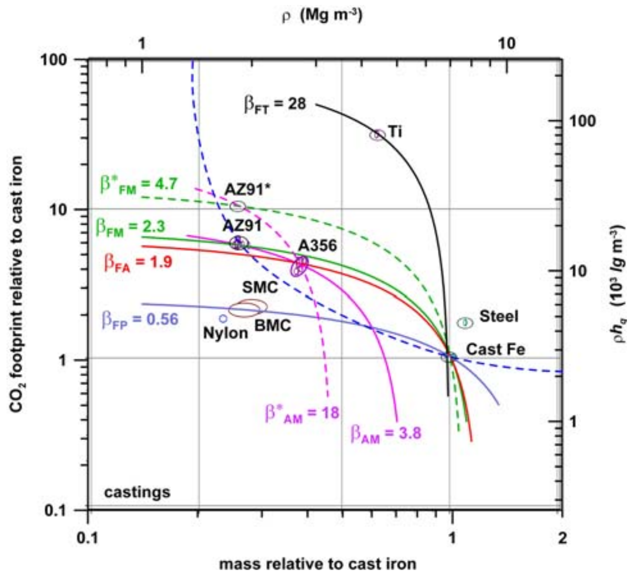

Fig. 5—The relative CO_2 footprint of castings as a function of their relative mass. In Figures 5 through 7, the β values (lg/kg) indicate the CO_2 gasoline equivalent per kg of mass reduction. (*indicates Pidgeon Mg). The subscripts to the β values indicate F = iron, A = aluminum, M = magnesium, T = titanium, and P = polymers.

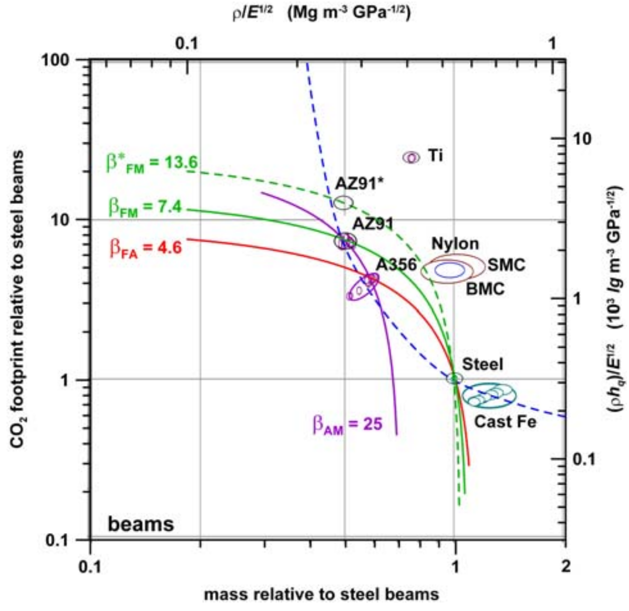

Fig. 6—The relative CO_2 footprint of beams of prescribed stiffness, as a function of their relative mass.

[†] The vagaries of dealing with the CAFE liability, including the so-called "Tiffany syndrome," have been described by Davis[59] and Mezoff.[7]

[‡] The term "lg" is used throughout the article for liters of gasoline.

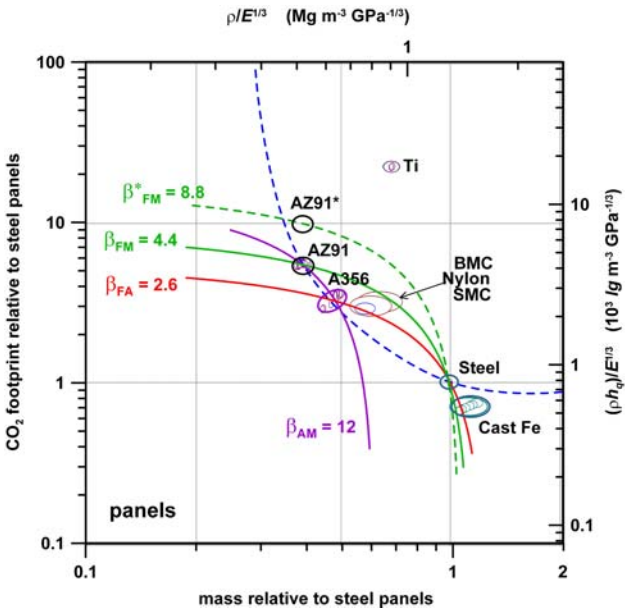

Fig. 7—The relative CO_2 footprint of panels of prescribed stiffness as a function of their relative mass.

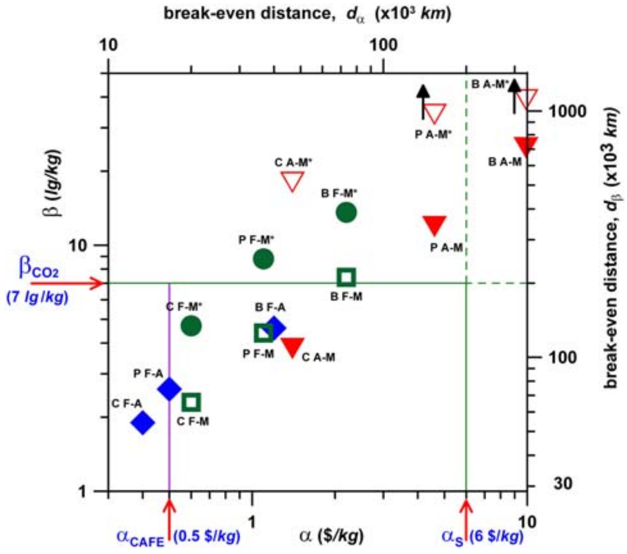

Fig. 8—The exchange constants of Figures 2 through 7 plotted as functions of each other and compared with the relevant upper bounds (Eqs. [5], [6], and [8]). The top and right axes are the driving distances to breakeven calculated with Eqs. [11a] and [11b], respectively. (Key: P = panel, B = beam, and C = casting). The P A-M* and B A-M* data points are off the vertical scale (Appendix C provides the numeric values to the exchange constants).

consumption may be decreased by curb weight reduction, and it is estimated[15,25] that a 10-kg reduction in the mass of the average family car is necessary to increase its fuel efficiency by 40 m/lg. Eberle and Franze[60] pointed out that these savings are realized only when the car's final drive ratio is also optimized. Combining these figures, the CAFE liability becomes

$$\alpha_{\mathrm{CAFE}} = 0.5\,\$/\mathrm{kg} \qquad [5]$$

Equation [5] is the upper bound to the car manufacturer's exchange constant, because any material substitution costing more than 0.5 \$/kg is not economically feasible.

A lighter car, being more fuel efficient,[60] benefits the driver in the long run even if the substitution costs more than the CAFE liability. Over an assumed[24,61] lifespan of 200×10^3 km, increasing the car efficiency by 40 m/lg results in savings of about 70 lg, *i.e.*, 7 lg/kg.§ With gasoline selling in the United States at ~\$0.8 per liter,§§ a car driver's upper bound to the exchange constant based on lifespan savings, α_s, is thus obtained:

$$\alpha_s \approx 6\,\$/\mathrm{kg} \qquad [6]$$

B. *Fuel Efficiency and CO_2 Emissions*

The primary alloys' CO_2 footprint (the parameter h in Table I) is measured for this analysis in terms of the equivalent amount of gasoline, h_q, as

$$h_q(\mathrm{lg/kg}) = h/2.85 \qquad [7]$$

where the numerical factor* 2.85 is the amount (kg/lg) of CO_2 created by the extraction, processing, transportation and combustion of 1 L of gasoline.[24,65] The relevant material indices incorporating h_q are listed in Table II, while the average h_q values are given in Table III.

It was shown in relation to Eq. [6] that curb weight reduction entails a lifespan gasoline savings of 7 lg/kg. This implies that a material substitution leading to an exchange constant (the Greek letter β will used for exchange constants involving CO_2 emissions) larger than 7 lg/kg is not viable, because the gasoline saved is insufficient to offset the (gasoline equivalent) footprint penalty of the substitution. Thus, the upper bound** to

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§This estimate excludes the gasoline burnt to overcome the air and rolling resistance.[15,25,60] When dragging effects are not removed, a much larger figure (11 to 12 lg/kg) is obtained.[24–27,62]

§§The price of gasoline went through a maximum[63] of \$0.8 per litre on September 2005. This value has been used for the analysis.

*The burning of 1 L of gasoline creates[64] ~2.34 kg of CO_2; the rest is created during the extraction, refining, and transportation of oil and fuel.[24,65]

**Note that the upper bounds α_s and β_{CO_2} can be much larger for commercial vehicles, such as taxis or trucks, because of high payload returns[29] (in \$/kg) and because the vehicle is likely to be driven well beyond the 2×10^5 km assumed for passenger cars.

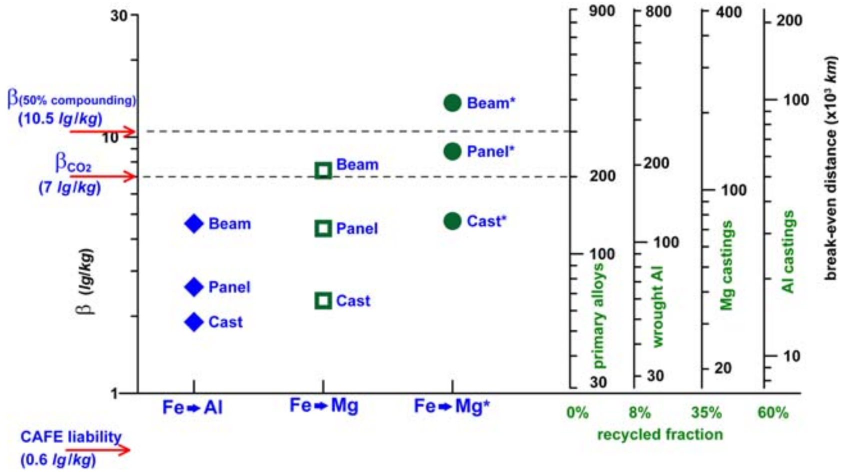

Fig. 9—The β values of Figs. 5 through 7 correlated with the driving distance to breakeven (calculated with Eqs. [11b] and [12] assuming $f^* = 80$ pct for all alloys) for light alloy substitutions for ferrous components. Note the CAFE liability expressed in lg/kg, and the compounding effect of mass reduction on the upper bound to the β values. An asterisk indicates Pidgeon Mg.

the exchange constant for the (gasoline equivalent) CO_2-footprint, β_{CO_2}, is

$$\beta_{CO_2} = 7 \text{ lg/kg} \qquad [8]$$

VII. DETERMINATION OF EXCHANGE CONSTANTS

The trade-off charts of Figures 2 through 4 are used to relate the mass and cost of components for castings, beams, and panel substitutions, respectively, while those of Figures 5 through 7 serve the same purpose for mass and CO_2-footprint equivalent. Each chart includes a number of bubbles representing the respective range of properties for each material, the penalty lines relevant to each substitution, and the corresponding exchange constants (α values for mass-cost, and β values for mass-CO_2 emissions). The left and bottom axes are the performance metrics relative to the incumbent ferrous component, while the top and right axes are the reciprocal of the relevant material indices. The subscripts to the α and β values identify the materials involved in the substitution, with the incumbent material being the first one. For clarity, the quantitative analysis has been restricted to substitutions of ferrous components by Mg or Al alloy components and Al alloys substituted by Mg alloys. Examples of exchange constants for Ti are given in Figures 2 and 5, and in Figure 5 for the polymers. The exchange constants have been plotted in Figure 8, and the numeric values have been summarized in Appendix C (Table C1).

A. *Mass-Cost Exchange Constants*

With reference to Figure 2, $\alpha_{FA} = 0.4$ \$/kg is the additional cost involved when, for example, an Al alloy engine block substitutes a ferrous one of similar volume. A magnesium engine block would impose a similar penalty, $\alpha_{FM} = 0.6$ \$/kg. Both α values are of the order of the CAFE liability (0.5 \$/kg), and this makes the substitution of cast iron by cast Al and Mg economically viable. Substitution of cast Al by cast Mg entails a larger penalty (1.4 \$/kg). The chart shows that polymers can make good economic choices as well, while Ti, with $\alpha = 57$ \$/kg, is too expensive to compete.

The analysis applied to beams (Figure 3) shows that substitution of steel by either Mg or Al incurs penalties higher than in the case of castings. Note also the very high exchange constant ($\alpha_{AM} = 9.9$ \$/kg) involved by Mg substitutions for Al. Neither the polymers (due to their low elastic modulus) nor Ti (due to its elevated cost) are viable options for beams.

When applied to panels (Figure 4), the analysis presents a more positive situation for the light alloys than the beams, due to the dominant effect of a low density on the indices of Table II, although, in practice, only Al substitutions for steel incur a penalty on the order of the CAFE liability. The polymers also perform

Table III. Average (Gasoline Equivalent) CO_2 Footprint, h_q, per Unit Mass (Calculated with Equation [7]) and per Unit Volume, ρh_q (Numerals in Brackets are Values Relative to Cast Fe), for the Materials Studied

Material	Cast Fe	Steel	A356	AZ91	AZ91*	Ti	Polymers
h_q (lg/kg)	0.35	0.70	4.21	8.07	14.74	18.54	2.84
ρh_q (lg/m^3)	2.53 (1)	5.51 (2.17)	11.36 (4.49)	14.6 (5.77)	26.67 (10.54)	81.59 (32.25)	5.40 (2.13)

*Pidgeon process.

better as panels than as beams, because of their low density, although they are no match for Al or Mg. The high cost of Ti still keeps it out of bounds.

B. *Mass-CO_2 Emissions Exchange Constants*

Figures 5 through 7 include two families of bubbles for Mg alloys, according to the method of production, *i.e.*, electrolytic or Pidgeon, the latter identified by an asterisk. As for the cost analysis, it is seen that substitutions of cast iron by light alloys are the most environmentally feasible, followed by panels and beams, in that order. Figure 5 shows that, due to their small CO_2 footprint, the polymers are a much better option than Al or Mg as a substitution for ferrous castings. Figures 6 and 7 show that the polymers compete with the Al and Mg in panel applications, but underperform for beams, due to their low E value. Titanium's high h value results in extremely high exchange constants (β_{FT} = 28 lg/kg in Figure 5), eliminating this material as a viable option in all cases. Substituting Al by Mg generally leads to very high β values, particularly when Pidgeon Mg is used. For clarity, the penalty lines joining Pidgeon Mg and Al alloys have been deleted from Figures 6 and 7, but the β^*_{AM} numeric values can be found in Appendix C (Table C1).

VIII. COMPARISON WITH THE UPPER BOUNDS

Figure 8 compares the α and β values of Figures 2 through 7 with the relevant upper bounds (Eq. [5], α_{CAFE}; Eq. [6], α_s; and Eq. [8], β_{CO_2}). With regard to the α values (the x-axis of Figure 8), it is seen that the light alloys fall mostly on the expensive side of the CAFE liability (α_{CAFE}), as concluded in other studies.[1,17] However, the savings over the life of the car (α_s) fully offset the cost penalty in all but two cases (B A-M and B A-M*).

With reference to the β values (the y-axis of Figure 8), Al substitutions for cast iron (C F-A) and steel panels (P F-A), together with castings of electrolytic Mg (C F-M), are the most viable. The viability is limited for Al beams (B F-A), electrolytic Mg panels (P F-M), Pidgeon Mg castings (C F-M*), and castings of electrolytic Mg substituted for Al (C A-M). Several substitutions for ferrous components (B F-M, P F-M*, and B F-M*) are above the upper bound (β_{CO_2}) and are not feasible, nor are electrolytic Mg substitutions for Al panels and beams (P A-M and B A-M). Pidgeon Mg (C A-M*, P A-M*, and B A-M*) is not an option for existing Al components. All in all, 8 out the 15 applications considered in Figure 8 are environmentally not viable as far as primary alloys are concerned.

When both cost and CO_2 emissions penalties are considered simultaneously, Figure 8 shows that castings of Al and electrolytic Mg, and Al panels (C F-A, P F-A, and C F-M), are the most feasible substitutions as far as primary alloys are concerned.

The chart in Figure 8 may be applied to other cases; for instance, utility vehicles have larger α_s values,[29] so the material of choice will not necessarily mean cast Al or Mg when only cost is an issue. Similarly, for vehicles that start and stop more often than passenger cars, such as buses or garbage trucks, or fleet cars and taxis, which are driven beyond 200×10^3 km, higher β_{CO_2} values apply, and the selection of mass reducing materials will be less restricted.

IX. EFFECT OF RECYCLING

The analysis so far assumed the exclusive use of primary alloys, while in practice most ferrous and nonferrous alloys contain some amount of recycled metal.[66] Recycling may decrease the cost of most alloys by a small amount,[5,18,27] generally improving the economical viability of all substitutions. More importantly, reusing[14,18,26,67–70] Al or Mg requires only about 5 to 8 pct of the energy necessary to produce the same amount of primary metal, although other estimates put these figures at about 20 pct.[1,18,70] In any case, recycling can be expected to drastically reduce some of the h values of Table I, increasing the environmental viability of the corresponding substitutions.

The use of scrap in iron and steelmaking greatly lowers the cost, energy consumption, and environmental burden resulting from both ore mining and metal production.[66] However, unlike for the light alloys, recycling is an integral part of the production process, as scrap is a major component of the raw materials[66] for steelmaking. That is, the cost and h values given in Table I for iron and steel already incorporate the effect of recycling,† and any additional effects on the exchange constants may only stem from the light alloys' side.

The effect of recycling on the β values is given by Eq. [9], which is easily derived from Eq. [4]:

$$\beta^r = \beta\left(1 + \frac{(1-e_r) f\, M_L^{-1}}{M_F^{-1} - M_L^{-1}}\right) \qquad [9]$$

where β^r is the exchange constant of material containing a recycled fraction f; e_r is the fractional energy required to recycle the material involved; and ML and M_F are the gasoline equivalent CO_2-footprint material indices of Table II for the light alloy and ferrous components, respectively.

When it comes to recycling light alloys, it is necessary to distinguish between castings and wrought products, because castings are more receptive of secondary metal than the wrought alloys. This fact is often ignored, and unrealistically high recycling fractions have been assumed in automotive LCA of substitutions of steel by Mg and Al irrespectively of whether the substitutions involve castings, wrought products, or a mixture of both. The proportion of castings to wrought alloys can vary widely: current automotive Al products consist of a mixture of[14,24,42] 72 pct castings, 22 pct extrusions, and 6 pct rolled products. In contrast, wrought products are

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†This fact has been sometimes overlooked in automotive LCAs, and additional recycling factors have been applied to steel.

dominant in Audi's space frame: 71 pct of extruded products and only 8 to 15 pct of castings.[19,71] Magnesium alloys in cars are predominantly high pressure die castings,[72,73] although efforts are being put into the development of wrought Mg alloys for sheet panels.[10,12]

Another important factor[6] often ignored in automotive LCA is the need to distinguish between industrial, or new scrap, and postconsumers, or old scrap. The recycling of industrial scrap is carried out very efficiently (close to 100 pct) in most developed countries, for both Al and Mg,[18,73,74] and is integrated into closed loops of the metal's production. The critical step, as far as material (or primary energy) conservation is concerned, is the recycling of old scrap.[18,42,61,70,74] Following Sibley *et al.*,[74] the recycling rate, f, will be defined excluding metal recovered from new scrap, as $f = s_o/(p + s_o)$, where s_o is the amount of old scrap and p the amount of refined metal consumed.

The ability to recycle old scrap sets apart Al from Mg casting alloys. A coincidental advantage for Al casting alloys is that the current mixture of wrought and cast alloys in fragmentized automotive scrap naturally matches the composition of the 3××.0 and 4××.0 alloys.[42,75] An extreme example of recyclability is alloy A319, which is often produced with as much as 95 pct of secondary metal.[42,71,76] In more realistic terms, however, it is estimated that recycled Al can only supply about 50 to 60 pct of the demand from the car industry,[14,61] setting the upper bound for f (Al castings) at 50 to 60 pct. Due to stringent composition specifications, especially, regarding the Cu and Ni contents, old scrap of Mg is still very difficult to recycle,[72,73,77] and as a result, only 20 to 30 pct of secondary Mg is from old scrap.[18,72–74,78] The overall content of secondary metal (old and new scrap combined) in the Mg die casting industry is about[17] 64 pct; thus, the maximum value for f (Mg die castings) is 26 to 35 pct. These f values will be considered valid for gravity castings of Mg as well.

The wrought Al alloys, again due to tight composition specifications, contain only between 10 and 15 pct of secondary metal, of which about half is old scrap,[18,61,71,79] setting f (wrought Al) at 5 to 8 pct. Wrought automotive Al is currently shredded with, and recycled into, castings.[1,61] The recycling of Mg[72,73,77] is currently aimed at castings only, *i.e.*, f (wrought Mg) = 0 pct. To sum up, recycling can be expected to drastically reduce the β values for Al and (to a lesser degree) Mg casting alloys, while the benefits are minute for the wrought Al and nil for the wrought Mg alloys.

It is of interest to calculate the critical recycling rate, f^*, that nullifies the exchange constants for substitution of ferrous components by light alloys. Setting $\beta^r = 0$ in Eq. [9] and solving for f:

$$f^* = \frac{1}{1 - e_r}\left(1 - \frac{M_L}{M_F}\right) \qquad [10]$$

Calculated f^* values, with $e_r = 0.05$, are given in Table IV. It is seen that recycling rates of the order of 70 to 80 pct are necessary to nullify the β values for Al, in agreement with the estimates by Carle and Blount,[21] while recycling rates of over 80 and 90 pct are necessary for electrolytic and Pidgeon Mg, respectively. It is apparent that the recycling rates of Al casting alloys, and particularly that of alloy[76] A319, can potentially approach f^*, while those for the wrought Al alloys and all of the Mg alloys remain well below.

Table IV. Critical Recycling Rates (Percent) of Al and Mg when Substituted for Ferrous Components, Computed with Equation [10]

Material	Castings	Panels	Beams
Al	82	69	75
Mg	87	82	87
Mg*	95	93	96

X. DRIVING DISTANCE TO BREAKEVEN

The minimal driving distance, d_e, to offset either the cost or the CO_2 emissions penalty involved in any given substitution (using primary alloys) can be calculated directly from the α and β values of Figure 8 (assuming a 200×10^3 km lifespan for the car) as

$$d_\alpha\,(10^3\text{km}) = 200\,\alpha/\alpha_s = 33.3\,\alpha \qquad [11a]$$

$$d_\beta\,(10^3\text{km}) = 200\,\beta/\beta_{CO_2} = 28.6\,\beta \qquad [11b]$$

Equations [11a] and [11b] have been used to calculate the d_α and d_β scales in Figure 8 and the numeric values in Appendix C (Table C1). The top x-axis of Figure 8 shows that all but one of the light alloy substitutions financially breakeven during the life of the car. The right-hand y-axis of Figure 8 indicates that, for an average driving distance of 20×10^3 km per year, the car needs to be driven some 3 to 4 years to environmentally breakeven in the most favorable cases (C F-A, C F-M, and P F-A). For the rest of the possible substitutions, the breakeven distance implies between 6 and > 100 years of driving, the largest distance for Pidgeon Mg beams (B A-M*). These figures are generally consistent with estimates by Buxman,[61] Field *et al.*,[23] and Carle and Blount[21] for Al alloys and Koltun *et al.*[26] for Mg castings.[‡]

The d_β value (Eq. [11b]) is greatly reduced if secondary metal is included in the substitution. The effect of recycling on the distance to breakeven can be accounted for by modifying Eq. [11b] to

$$d_{\beta r}(\times 10^3\text{km}) = 28.6\ \beta^r = 28.6\,\beta(1 - f/f^*) \qquad [12]$$

with f^* given by Eq. [10]. Equations [11b] and [12] have been used to compute scales to the breakeven distances

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[‡] The reader's attention is directed to Field *et al.*'s fleet-based analysis[23] of the temporal distribution of emissions as light alloy components are substituted for ferrous ones in an existing production car. The total emissions at any time reflect the dynamic balance between newer, lighter, cars coming in, and older, heavier, cars reaching the end of their life.

of Figure 9, for the recycling fractions stated (a common $f^* = 80$ pct was assumed in Eq. [12] for all alloys). The recycling fractions of Figure 9 have been selected to represent primary alloys (0 pct) and the current maximum recycling fractions (old scrap only) for wrought Al products (8 pct), Mg castings and die castings (35 pct), and Al castings (60 pct). The CAFE liability (in lg/kg) has also been included in Figure 9 to highlight its negligible environmental significance. Note that 8, 35, and 60 pct scales apply to substitutions of ferrous components only, *i.e.*, they exclude substitutions of Al by Mg, which are considered later.

Figure 9 shows that a cast Al alloy comprising 60 pct recycled metal requires only ~15 × 10^3 km to breakeven when substituted for cast iron. The next most viable cases are electrolytic Mg castings and Al panels, with breakeven distances of 35 × 10^3 and 70 × 10^3 km at their current recycling rates of 35 and 8 pct, respectively. Pidgeon Mg castings require about 75 × 10^3 km on the 35 pct scale. The viability of wrought Al beam and Mg panel components is far more limited, both with a breakeven distance of ~120 × 10^3 km on the 8 and 0 pct scales, respectively.[§] Beams of wrought electrolytic Mg and panels and beams of wrought Pidgeon Mg are all out of bounds, unless the car's life is extended well beyond 200 × 10^3 km. Figure 9 also shows that only recycling rates of at least 30 pct have meaningful effects on the breakeven distance.

Recycled metal may be involved in different proportions in both the incumbent and replacement component when Al is substituted by Mg, and a case by case calculation is required in these cases. As an example, a Mg engine[11,12,34,35] cast with a recycling rate f_{Mg} will be considered as a replacement for a current production Al block containing a fraction f_{Al} of old scrap. Rewriting Eq. [4] for castings (with $e_r = 0.05$),

$$\beta^r_{\mathrm{AM}} = -\frac{(1 - 0.95 f_{\mathrm{Al}})(\rho h_q)_{\mathrm{Al}} - (1 - 0.95 f_{\mathrm{Mg}})(\rho h_q)_{\mathrm{Mg}}}{\rho_{\mathrm{Al}} - \rho_{\mathrm{Mg}}} \qquad [13]$$

Using ρh_{q} data from Table III, for electrolytic Mg, β^r_{AM} varies between[§§] –1.9 and 5.6 lg/kg when f_{Al} is varied between 0 and 60 pct and f_{Mg} between 0 and 35 pct; hence (Eq. [12]), $d_{\beta r}$ varies between–53 × 10^3 and 160 × 10^3 km. For Pidgeon Mg, β^{r*}_{AM} varies between 7.5 and 25 lg/kg, hence $d_{\beta r}$ between 214 × 10^3 and 724 × 10^3 km. That is, while electrolytic Mg may be a viable substitution in some favorable cases, Pidgeon Mg is always out of bounds. The same conclusion may be made for cast Mg beams and panels substituted for Al components, which have occasionally been considered for mass reduction in upmarket cars.[9,10,12,40]

A. *Mass Compounding Effects*

Although, as explained earlier, no mass compounding effects of structural mass reductions can be claimed in current cars, potentially its effects can be large. This is shown in Figure 9 by the line labeled $\beta_{50\ \mathrm{pct\ compounding}}$. The position of the line has been determined assuming an additional 50 pct mass reduction over the primary mass savings, which is equivalent to increasing the relevant upper bound, $\beta_{\mathrm{CO_2}}$ (Eq. [8]), from 7 to 10.5 lg/kg.

XI. THE RELATIVE POSITION OF AL AND MG ALLOYS

Because of their high recyclability, Al casting alloys have the advantage as far as CO_2 emissions are concerned, leaving Mg casting alloys as less viable options. It must be kept in mind, however, that although as much as 90 pct of Al in cars is recycled back into automotive applications, due to the continued expansion in the Al content of new cars, as well as the continued increase in the number of cars, recycled Al can only supply about 50 to 60 pct of the demand from the car industry.[14,61] The 60 pct driving distance scale in Figure 9 therefore represents a realistic upper bound for Al castings. In addition, the possible applications for castings seem to be approaching saturation,[42] and further growth is mostly expected in the use of wrought alloys.[1,42] Thus, any further improvements over current levels of recycling of Al can only come from increased recycling rates of the wrought alloys.[42,61]

It has been stated that Mg is[72,77] unlikely to attain the same levels of recyclability of Al, but, as Mg is a newcomer, many components still need to complete their life cycle in order to become available as old scrap.[70] This, and increases in Mg usage, are likely to support the development and installation in scrap yards of new recycling techniques and dedicated facilities,[5,17,18] as happened with Al,[42] and the relative position of Mg should improve over time, even if the two-tier system of Al alloys, *i.e.*, primary and secondary, is unlikely[72] to develop due to the tighter compositional restrictions.

Magnesium may benefit from other factors as well: the imposition by the European Union of taxes on CO_2 creation in the near future seems likely,[80] and this may enhance again the production of electrolytic Mg, while more extensive use of a cover gas with low global warming potential,[81,82,83] or a wider use of alloys less reliant on cover gas[84] would generally decrease Mg's CO_2 footprint. In turn, increased availability of clean energy sources would benefit both, Al and electrolytic Mg. A sensitivity analysis of the exchange constants to the nature of the energy sources is presented in Appendix A.

Overall, it is evident that increasing the (old scrap) recycling rate of Mg casting alloys, as well as that of Al

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[§] Wrought Al is used in space frames and body panels, so the 8 pct scale applies. Magnesium panels and beams (*e.g.*, steering wheels, seats, and dashboards) are likely to be die cast to shape, rather than stamped or extruded. The 35 pct scale in these cases yields $d_{\beta r} \approx 70 \times 10^3$ and 105×10^3 km, respectively.

[§§] Negative β^r_{AM} or $d_{\beta r}$ values are obtained for $f_{\mathrm{Al}} = 0$ and $f_{\mathrm{Mg}} = 35$ pct.

and Mg wrought alloys, is crucial to generally improve the environmental viability of all light alloy automotive applications. Current efforts in this sense[4,13,14,19,61,71,72,73,77,85,86] seem amply justified.

XII. CONCLUSIONS

The cost and environmental viability of light alloy substitutions in automotive applications strongly depend on the mechanical function of the component. Substitution at equal volume (castings) for ferrous components takes maximum advantage of Al and Mg's low densities, both in terms of cost and CO$_2$ emissions. Substitution for stiff steel panels is the second best option, followed by substitutions of stiff steel beams. Substituting Mg for existing Al components is environmentally feasible for electrolytic Mg, but it is not for Pidgeon Mg.

The CAFE liability is too small to fully offset the cost penalty of light alloy substitutions in most applications, although the potential gasoline savings over the car's lifespan make viable all of the Al and Mg substitutions for iron and steel, as well as Mg substitutions for cast Al components.

Aluminum and magnesium's large CO$_2$ footprints constitute a heavy environmental drawback as far as primary alloys are concerned. This is especially true for Mg produced by the Pidgeon process.

Under the current technology, recycling primarily benefits Al casting alloys. Increasing the recyclability of cast Mg alloys as well as that of wrought Al and Mg alloys is necessary to correct the present imbalances. Production methods with a smaller CO$_2$ footprint, both in terms of cleaner energy sources and the use of a cover gas with low global warming potential, seem equally important to make Mg more competitive.

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APPENDIX A

CO$_2$-footprint: best and worst case scenarios

The burning of fossil fuels to generate energy for the electrolysis of Al and Mg is a major contributor to the respective CO$_2$ footprints. It is thus of interest to examine the sensitivity of the analysis to the ratio between hydroelectricity and power generated with fossil fuels, as it differs greatly between different countries. Table AI has been put together using data from recent References 24, 32, 33, 47, and 87 and the contribution from hydroelectricity to the smelting phase adjusted between 0 and 100 pct to obtain upper and lower bounds for the h values. Any contribution from nuclear power has been ignored. The h values for 55 pct contribution from fossil fuels (the current average for western countries[24]) have been used in Table I and Figures 5 through 9.

The data for aluminum conform to current prebake cell technology, which is more energy efficient and greatly reduces the amount of perfluorocarbon (PFC) emissions in relation to the older Söderberg process.[24,47] For Mg, a rather low bound[87] to the amount of SF$_6$ has been used, (0.25 kg/tonne), following the tendency to reduce the reliance on this cover gas.

Figure A1 reproduces Figure 9, incorporating β values calculated with the h values of Table AI for the three stated proportions of fossil fuels and hydroelectricity (0, 55, and 100 pct fossil fuels).

It seems possible to increase the thermal efficiency of the reduction stage[52] in the Pidgeon process by as much as a factor 1.8. The reduction stage contribution[33] to the overall process' footprint amounts to 15.9 kg/kg (out of a total of 42 kg/kg, average). Thus, increased thermal efficiency would reduce the (average) h value for Pidgeon Mg in Table I to $\approx$ 35 kg/kg. The open diamonds in Figure A1 show the recalculated β values.

Table AI. Contributions to the CO$_2$-Footprint of Al and Electrolytic Mg (in kg/kg), for the Stated Proportions of Hydroelectricity and Fossil Fuels; the h Values are Obtained by Adding the Contribution from Process to the Respective Value from Smelting

		100 Pct Hydroelectricity		55 Pct Fossil Fuels 45 Pct Hydroelectricity		100 Pct Fossil Fuels	
Energy Source	Process*	Smelting	h	Smelting	h	Smelting	h
Al	6.2**	nil	6.2	5.8	12	10.5	16.7
Mg (no SF$_6$)	6.5† to 8.6‡	nil	6.5 to 8.6	11 to 13.8	17.5 to 22.4	20 to 25	26.6 to 33.6
Mg (with SF$_6$)§	12.5 to 14.6	nil	12.5 to 14.6 (10.6)#	17 to 19.8	23.5 to 28.4 (23.0)#	26 to 31.5	32.6 to 39.6 (33.1)#

*Includes all operations from the mining of ores up to casting of ingots, but excludes energy for smelting.

**Includes PFC emissions.

†Assumes processing from sea water.

‡Assumes processing from magnesite.[87]

§Assumes that SF$_6$ is used at a rate of 0.25 kg per tonne, adding 6 kg/kg of CO$_2$ to the process.[87]

#Mean h value (between the minimum without and the maximum with SF$_6$) used to compute the β values of Fig. A1.

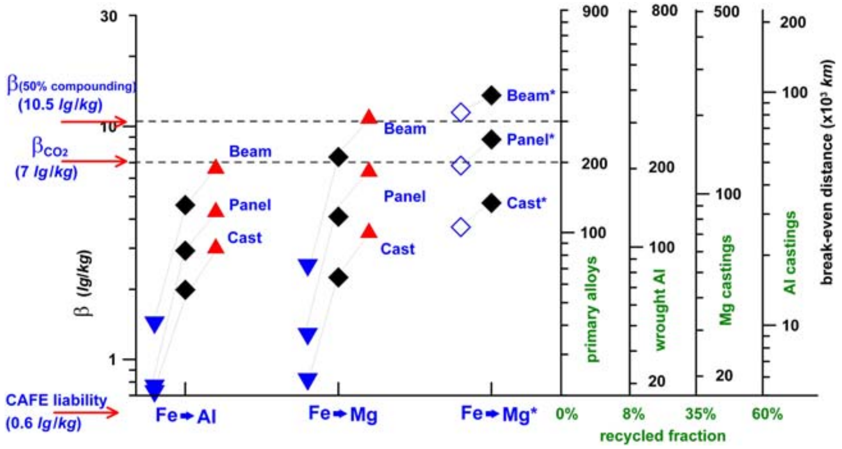

Fig. A1—Same as Fig. 9, with minor adjustments in the scales. The solid diamonds represent the β values of Fig. 9, calculated with h values from Table I (or Table AI, for 55 pct fossil fuels). The pointing down and up triangles are β values calculated with h values from Table AI for 100 pct hydroelectricity and 100 pct fossil fuel, respectively. The open diamonds are values for thermally efficient Pidgeon processing.

Table CI. The Exchange Constants of Figures 2 through 7 (Primary Alloys); Underlined α Values Are of the Order of the CAFE Liability ($\alpha_{\mathrm{CAFE}} = 0.5$ \$/kg); the Bold α and β Values Are within the Savings over a Lifespan of 2×10^5 km ($\alpha_s = 6$ \$/kg; $\beta_{\mathrm{CO_2}} = 7$ lg/kg); the Rest Are Either Economically or Environmentally Not Viable[#]

Metrics Function	Mass–Cost (\$/kg) Figures 2 through 4 and Eq. [9a]			Mass–Gasoline Equivalent Footprint (lg/kg) Figures 5 through 7 and Eq. [9b]				
	α_{FA}	α_{FM}	α_{AM}	β_{FA}	β_{FM}	β^{*}_{FM}	β_{AM}	β^{r*}_{AM}
Beam	**1.2 (40)**	**2.2 (73)**	9.9 (330)	**4.6 (132)**	7.4 (212)	13.6* (389)*	25 (715)	76 (2200)
Panel	$\underline{0.5}$ (17)	**1.1 (37)**	**4.6 (153)**	**2.6 (74)**	**4.4 (126)**	8.8* (252)*	12 (343)	40 (1144)
Casting	$\underline{0.4}$ (13)	$\underline{0.6}$ (20)	**1.3 (43)**	**1.9 (54)**	**2.3 (66)**	**4.7* (134)***	**3.8 (109)**	18 (514)

[#]Numerals in brackets indicate the driving distance to break even (in 10^3 km), calculated with Eqs. [11a] and [11b] (primary alloys). An asterisk indicates Pidgeon Mg. These values have been plotted in Figs. 8, 9, and A1.

APPENDIX B

Material index to minimize the mass of a flat panel of prescribed stiffness.[39]

The performance metric mass, m, of a panel of dimensions, l (length, fixed), w (width, fixed), and t (thickness, free) is

$$m = ltw\rho \qquad [\mathrm{B1}]$$

where ρ is the density.

The panel's structural stiffness is

$$S = \mathrm{C}\frac{Ewt^3}{l^2} \qquad [\mathrm{B2}]$$

where C is a constant and E the elastic modulus. Solving Eq. [B2] for the free panel dimension, t, and substituting into Eq. [B1] yields

$$m = \left(w^2 l^5\right)^{1/3}\left(\frac{S}{\mathrm{C}}\right)^{1/3}\left(\frac{\rho}{E^{1/3}}\right) = GF\left(\frac{\rho}{E^{1/3}}\right) \qquad [\mathrm{B3}]$$

where G and F are constants that lump together the geometric and structural parameters, respectively. The material index, M, of materials that minimize the mass of the panel (of prescribed stiffness S) is

$$M = \frac{E^{1/3}}{\rho} \qquad [\mathrm{B4}]$$

APPENDIX C

Numeric values to the exchange constants

The values to the exchange constants and distance to breakeven of light alloy substitutions using primary alloys have been condensed in Table C1.

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