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# Analysis of greenhouse gas emissions related to aluminium transport applications

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**Abstract**

*Background, aim and scope* Climate change is a subject of growing global concern. Based on International Energy Agency (IEA 2004) research, about 19% of the greenhouse gas emissions from fuel combustion are generated by the transportation sector, and its share is likely to grow. Significant increases in the vehicles fleets are expected in particular in China, India, the Middle East and Latin America. As a result, reducing vehicle fuel consumption is most essential for the future. The reduction of the vehicle weight, the introduction of improved engine technologies, lower air friction, better lubricants, etc. are established methods of improving fuel efficiency, reducing energy consumption and greenhouse gas emissions. Continued progress will be required along all these fronts with light-weighting being one of the most promising options for the global transport sector. This paper quantifies greenhouse gas savings realised from light-weighting cars with aluminium based on life cycle assessment methodology. The study uses a pragmatic approach to assess mass reduction by comparing specific examples of components meeting identical performance criteria. The four examples presented in this analysis come from practical applications of aluminium. For each case study, the vehicle manufacturer has supplied the respective masses of the aluminium and the alternative component.

*Material and methods* A full life cycle assessment with regards to greenhouse gas emissions and savings has been carried out for different aluminium applications in cars as compared to the same applications in steel or cast iron. The case studies reference real cases, where aluminium is actually used in series production. The studies are based on a greenhouse gas lifecycle model, which has been developed following the ISO standard 14040 framework. For each component, sensitivity analysis is applied to determine the impact of lifetime driving distance, driving characteristics (impact of air friction) and recycling rate.

*Results* Life cycle results show that in automotive applications, each kilogram of aluminium replacing mild steel, cast iron or high strength steel saves, depending on the specific case (bumper and motor block of a compact car, front hood of a large family car, body-in white of a luxury car), between 13 and 20 kg of greenhouse gas emissions.

*Discussion* The performed sensitivity analysis finds that even with 'worst case' scenarios savings are still significant.

*Conclusions* The results not only demonstrate significant benefits of aluminium with regard to greenhouse gas savings but also show that these are very sensitive to variations of the recycling rate, the life-time driving distance and the driving behaviour.

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This paper only covers two impact categories and has not undergone a critical review procedure as specified in ISO 14044. Therefore, it does not intend to make a comparative assertion, i.e. state the overall environmental superiority of one alternative versus another, nor should it be used by others for comparative assertions.

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*Recommendations and perspectives* Good care is needed to gather life-cycle data and to make informed estimates, where no data are available. Furthermore, greenhouse gas savings for additional components should be calculated using this life cycle model to sustain the findings.

**Keywords** Aluminium · Automotive · Climate change · Greenhouse gas emissions · ISO standard 14044 · LCA · Light-weighting · Transport sector

## 1 Background, aim and scope

Climate change is a subject of growing global concern. Based on International Energy Agency (IEA 2004) research, about 19% of the greenhouse gas emissions from fuel combustion are generated by the transportation sector as shown in Fig. 1, and its share is likely to grow. Significant increases in the vehicles fleets are expected in particular in China, India, the Middle East and Latin America. As a result, reducing vehicle fuel consumption is most essential for the future. The reduction of the vehicle weight, the introduction of improved engine technologies, lower air friction, better lubricants, etc. are established methods of improving fuel efficiency, reducing energy consumption and greenhouse gas emissions. Continued progress will be required along all these fronts with light-weighting being one of the most promising options for the global transport sector.

While several materials can be used to reduce vehicle mass, light-weighting with aluminium offers not only significant advantages during the use stage, but also in the end-of-life stage. Aluminium from transport applications is part of an established recycling system. Recycled aluminium can be utilised for almost all applications, preserving raw materials, reducing emissions and leading to considerable energy savings. Currently, the profitability of the end of life vehicles processing relies heavily on its metal content, especially aluminium due to the high value of the aluminium scrap, which is on a per kilogram basis approximately ten times higher than steel scrap (White 2006).

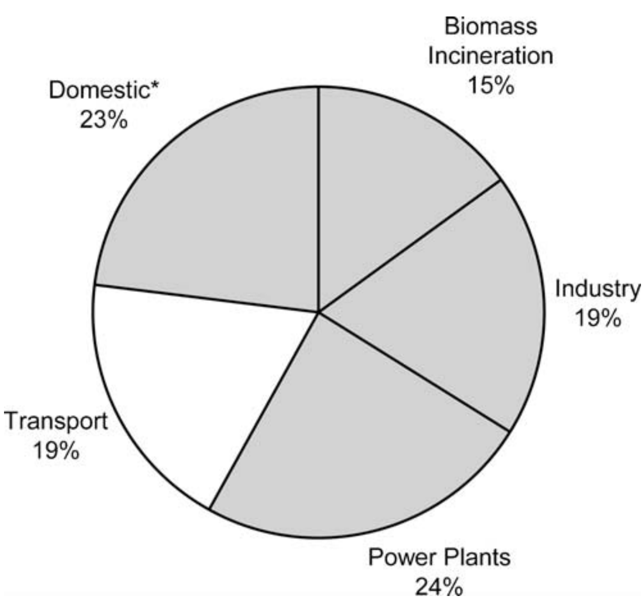


**Fig. 1** Greenhouse gas emissions from fuel combustion (IEA 2004). *Asterisk* Includes soil, oceans, vegetation, burning of biomass, human activity

Today, many cars contain significant amounts of aluminium, and its share is strongly growing as designers become increasingly aware of the metal's demonstrated advantages. More than 20% of the cars produced in Europe already have an aluminium hood, including the Peugeot 307 as a small family car and other aluminium hang-on parts are following. The Jaguar XJ model exhibits the first aluminium body-in-white (the car's metal structure) in a sheet-based design to employ structural adhesive bonding and self piercing riveting as joining methods. Several high-performance car bodies, such as Audi, Ferrari and Lotus, are also produced in aluminium using in addition extruded and cast parts.

The increase in automotive aluminium content is illustrated in Table 1, which shows that the growth is primarily the result of replacement of cast iron (engine blocks, transmission housings, suspension parts, etc.), mild steel (car bodies and wheels) and copper (radiators) products. While aluminium has historically been employed in automobiles primarily in the form of castings, in recent years engineers have "discovered" a wider variety of aluminium products for automotive applications, in the form of extrusions, stamped sheet parts and forgings, the use of which have consistently increased in car body, chassis and suspension, crash management and other structural applications.

## 2 Methodology and dataset

The quantitative determination of the environmental parameter does not only include the use stage of the component but also considers material production (from ore to ingot), fabrication (from ingot to semi-fabricated product), manufacturing (from semi-fabricated product to final product) and end-of-life recycling. For this purpose, life cycle assessment methodology is used to calculate greenhouse gas savings.

For metal products, the metal is generally not consumed during a use stage but only used and subsequently recycled (Atherton 2007). The life cycle starts with the ingot (cradle), from which a final product is manufactured. The life cycle ends again with the recycled ingot (cradle). Any material losses, mainly within the recycling processes, have

**Table 1** Average content of aluminium in new vehicles by component

| Component aluminium form | North America | | Europe | | Japan | |
|---|---|---|---|---|---|---|
| | 2002 kg/car | 2006 kg/car | 2002 kg/car | 2006 kg/car | 2002 kg/car | 2006 kg/car |
| Engines **Castings** | 42.0 | 51.6 | 36.6 | 40.3 | 44.5 | 45.8 |
| Transmission and driveline **Castings** | 28.1 | 31.5 | 15.4 | 16.3 | 20.5 | 21.8 |
| Chassis, suspension and steering **Castings**/Forgings/Extrusions/Sheets | 6.2 | 10.1 | 8.2 | 12.5 | 2.9 | 3.7 |
| Wheels and spares **Castings**/Forgings/(Sheets) | 22.4 | 23.6 | 14.2 | 17.7 | 17.8 | 18.9 |
| Heat exchanger **Sheets**/Extrusions | 14.5 | 14.5 | 11.0 | 12.3 | 12.0 | 13.6 |
| Brakes **Castings**/Forgings | 2.5 | 3.5 | 2.7 | 3.7 | 1.7 | 3.4 |
| Closures **Sheets**/Extrusions/(Castings) | 2.0 | 2.5 | 2.4 | 4.0 | 0.3 | 1.6 |
| Body and IP beams **Sheets**/Extrusions/Castings | 0.5 | 0.5 | 1.8 | 2.8 | 0.1 | 0.2 |
| Heat shields **Sheets** | 1.7 | 1.8 | 1.2 | 1.4 | 0.5 | 1.0 |
| Bumper beams **Extrusions** | 0.6 | 0.8 | 1.4 | 2.8 | 0.8 | 0.8 |
| All other components Sheets/Extrusions/Castings/Forgings | 4.1 | 4.1 | 3.9 | 3.9 | 2.8 | 3.2 |
| Total | 124.6 | 144.6 | 98.8 | 117.6 | 103.9 | 114.0 |

Source: Ducker Research 2006. Most important form is marked in bold letters, least important is in brackets

to be substituted by primary material from ore. Crucial in this methodology is, therefore, the amount of metal that is extracted from a discarded product and put back on the market. If no metal is recycled from a discarded product, 100% of the environmental burden will be based on the primary production route. In case the primary and the recycled ingots have a different market value, a correction factor can be applied (Werner and Richter 2000).

The cradle-to-cradle life cycles of aluminium, steel and cast iron are subdivided into independent information modules (Buxmann et al. 2009), for which the greenhouse gas emissions (direct and indirect) are calculated individually, and the resulting parameters are finally added up.

The use stage is the stage of the life cycle of vehicles, which has by far the highest environmental impact, in particular when focusing on energy consumption and greenhouse gas emissions (Schmidt et al. 2004). In this study, final energy savings per 100 kg weight savings and 100 km driving distance are calculated using Eq. 1 based on Helms et al. (2003), Helms and Lambrecht (2004) and Helms and Lambrecht (2007). For road and rail vehicles, there are four resistance factors, namely the rolling resistance, the gradient resistance, the acceleration resistance and the aerodynamic resistance. The first three factors are proportional to the mass of the vehicle. The aerodynamic resistance factor depends on the dimensions and the form of the vehicle and not on the mass of the vehicle.

$$S = E \times 100/M \times (1 - W) \qquad (1)$$

where

- $S$ Final energy savings (litres of fuel or kWh of electricity)
- $M$ Mass of the vehicle (kg)
- $E$ Energy consumption of the vehicle for 100 km (l/100 km or kWh/100 km)
- $W$ Portion of the aerodynamic resistance to the total resistance of the vehicle for an average driving cycle (%)

Table 2 shows some typical savings for gasoline cars, which vary between 300 and 2,600 l. Based on the final energy (fuel and electricity) savings in the use stage, the corresponding greenhouse gas savings caused by weight savings of 100 kg are calculated.

The potential of aluminium as a light-weighting material becomes obvious when looking at the specific weight (2.7 g/cm$^3$), which is significantly lower than that of iron (7.6 g/cm$^3$) and copper (8.5 g/cm$^3$). Such a comparison is of course a simplistic view, since application-specific

**Table 2** Final energy savings by weight savings for different passenger car examples using gasoline

| Vehicle type | Weight *t* | Average gasoline consumption l/100 km | Gasoline consumption/ 100 kg weight l/100 km | Percentage air friction % | Gasoline savings/ 100 kg weight savings l/100 km | Lifetime performance km | Lifetime gasoline savings/100 kg weight savings l |
|---|---|---|---|---|---|---|---|
| Small car, mainly long distances | 1.0 | 6.0 | 0.60 | 40 | 0.36 | 200,000 | 720 |
| Small car, mainly urban | 1.0 | 8.5 | 0.85 | 35 | 0.55 | 150,000 | 829 |
| Medium sized car, mainly long distances | 1.6 | 9.0 | 0.56 | 50 | 0.28 | 300,000 | 844 |
| Luxury car, mainly long distances | 2.0 | 12.0 | 0.60 | 50 | 0.30 | 100,000 | 300 |
| Medium sized car, Taxi | 1.6 | 11.0 | 0.69 | 25 | 0.52 | 500,000 | 2,578 |

design and performance criteria have to be considered for every vehicle component. These criteria are related to specific performance metrics, such as mechanical strength and stiffness, crash performance, etc. Therefore, each component must be individually evaluated based on all its required performance criteria.

Furthermore, the reduction of the total vehicle weight offers the potential for indirect weight savings. When Audi designed the first A8 model in 1994, it had to choose between a steel body-in-white with a mass of 441 kg and an aluminium alternative of 247 kg (Buxmann 2002). Such light-weighting possibilities offer the potential to realise additional weight-saving measures, e.g. the use of a smaller engine or a smaller fuel tank in order to fulfil the given requirements for the car (acceleration, mileage per tank filling). In case of the Audi A8, the secondary weight savings potential was estimated to reach 23%.

Table 3 lists the data used for all case studies in this study. Most of the data result from data collection campaigns of the relevant industrial association and can be received from data providers. Other data are best estimates based on industrial experience. Such data often have a lower data quality and should be replaced by better data as soon as they are available.

This study tries to use a pragmatic approach to assess mass reduction by comparing specific examples of components meeting identical performance criteria. The four examples used in this analysis come from practical applications of aluminium. For each case study the vehicle manufacturer has supplied the relevant masses of the aluminium and the alternative component.

## 3 Case studies

The product system captured all life cycle stages of four car components made out of either aluminium or steel or cast iron. Each component examined uses different fabrication and manufacturing processes and was recycled by different end-of-life operations. All components are real cases but the name of the vehicle manufacturer and the vehicle type had been eliminated in order to provide confidentiality.

### 3.1 Bumper beam of a compact car

The examined vehicles have similar weight (1,100 to 1,200 kg) and similar diesel consumption of about 6 l/100 km. Both cars were commercialised in late 2005/early 2006 to the same crash testing requirements. Manufacturer A used an aluminium solution for the front bumper and crash boxes; manufacturer B used a high strength steel system. The aluminium solution gives 45% direct weight savings as shown below:

- Mass of Al component: 3.2 kg (Manufacturer A)
- Mass of high strength steel component: 5.8 kg (Manufacturer B)
- Mass difference: 2.6 kg

While the majority of automotive aluminium applications do not occur in isolation but as part of an overall light-weighting concept, the authors understand that in case of the introduction of a single bumper beam, little or no opportunity for indirect weight savings is being offered. Indirect weight savings are therefore not included in the base case (Fig. 2).

Results show in Fig. 2a, after a lifetime driving distance of 200,000 km, savings of approximately 48 kg $CO_2$ eq, when using the aluminium bumper solution.

Future developments will increase the weight savings when using both aluminium and steel. With the same crash management requirements, it is estimated that the use of existing high strength aluminium alloys could bring the weight down to 2.8 kg, compared with 5.5 kg for an ultra high strength steel solution (Personal communication with

**Table 3** Data used in the study

| | Value | Unit |
|---|---|---|
| Energy data | | |
| Direct $CO_2$ eq emission of gasoline[a] | 2,310 | g/l |
| Direct $CO_2$ eq emission of diesel[a] | 2,590 | g/l |
| Direct $CO_2$ eq emission of biofuel[b] | 0 | g/l |
| Direct $CO_2$ eq emission of natural gas[b] | 2,230 | g/Nm$^3$ |
| Life cycle greenhouse gas emissions of gasoline[a] | 2.81 | kg $CO_2$ eq/l |
| Life cycle greenhouse gas emissions of diesel[a] | 2.93 | kg $CO_2$ eq/l |
| Life cycle greenhouse gas emissions of biofuel[b] | 1.46 | kg $CO_2$ eq/l |
| Life cycle greenhouse gas emissions of natural gas[b] | 2.23 | kg $CO_2$ eq/Nm$^3$ |
| Life cycle greenhouse gas emissions of electric energy[a] | 0.12–0.43 | kg $CO_2$ eq/kWh |
| Fabrication of semi-finished products | | |
| Production of semis-finished products, aluminium[c] | 0.64–1.38 | kg $CO_2$ eq/kg |
| Production of semis-finished products, steel or cast iron[d] | 0.15–0.90 | kg $CO_2$ eq/kg |
| Fabrication of final products from semis | | |
| Electricity consumption for forming and machining operations[b] | 0.40 | kWh/kg |
| Electricity consumption for assembling of vehicle[a] | 0.10 | kWh/kg |
| Shredding and sorting operations | | |
| Electricity consumption for shredding of dismantled parts and sorting[b] | 0.05 | kWh/kg |
| Electricity consumption for electromagnetic sorting[b] | 0.04 | kWh/kg |
| Electricity consumption for car shredding and sorting[b] | 0.05 | kWh/kg |
| Electricity consumption for sink float sorting[b] | 0.06 | kWh/kg |
| Gas consumption for sink float sorting[b] | 0.01 | Nm$^3$/kg |
| Substitution of lost material | | |
| Cradle-to-gate greenhouse gas generation for basic oxygen furnace/blast furnace process (primary steel/iron production)[d] | 2.02 | kg $CO_2$ eq/kg |
| Cradle-to-gate greenhouse gas generation for primary aluminium production[e] | 10.40 | kg $CO_2$ eq/kg |
| Remelting of scrap | | |
| Cradle-to-gate greenhouse gas generation for electric arc furnace process (recycling steel or cast iron production)[d] | 0.37 | kg $CO_2$ eq/kg |
| Cradle-to-gate greenhouse gas generation for aluminium refining and remelting[c] | 0.32–0.51 | kg $CO_2$ eq/kg |
| Other | | |
| End-of-life recycling rate for steel or cast iron[b] | 91 | % |
| End-of-life processing rate for aluminium[f] | 89–95 | % |
| End-of-life re-melting rate for aluminium[g] | 95–96 | % |
| Percentage air friction[h] | 40 | % |
| Life-time driving distance[h] | 200,000 | km |

[a] IFEU 2001
[b] Informed estimate
[c] EAA 2008
[d] IISI 2006
[e] IAI 2007
[f] Julius and Mutz 2008
[g] Boin and Bertram 2005
[h] Helms et al. 2003

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### 3.2 Front hood of a large family car

The front hood of a North American family car has been calculated. This car has a mass of 2,041 kg with gasoline consumption of 11.2 l/100 km. The car manufacturer has studied the following masses from which the effective savings were calculated:

- Mass of Al component: 10.1 kg
- Mass of high strength steel component: 17.5 kg
- Mass difference: 7.4 kg

Results for this large family car show, after a lifetime driving distance of 200,000 km, savings of about 130 kg

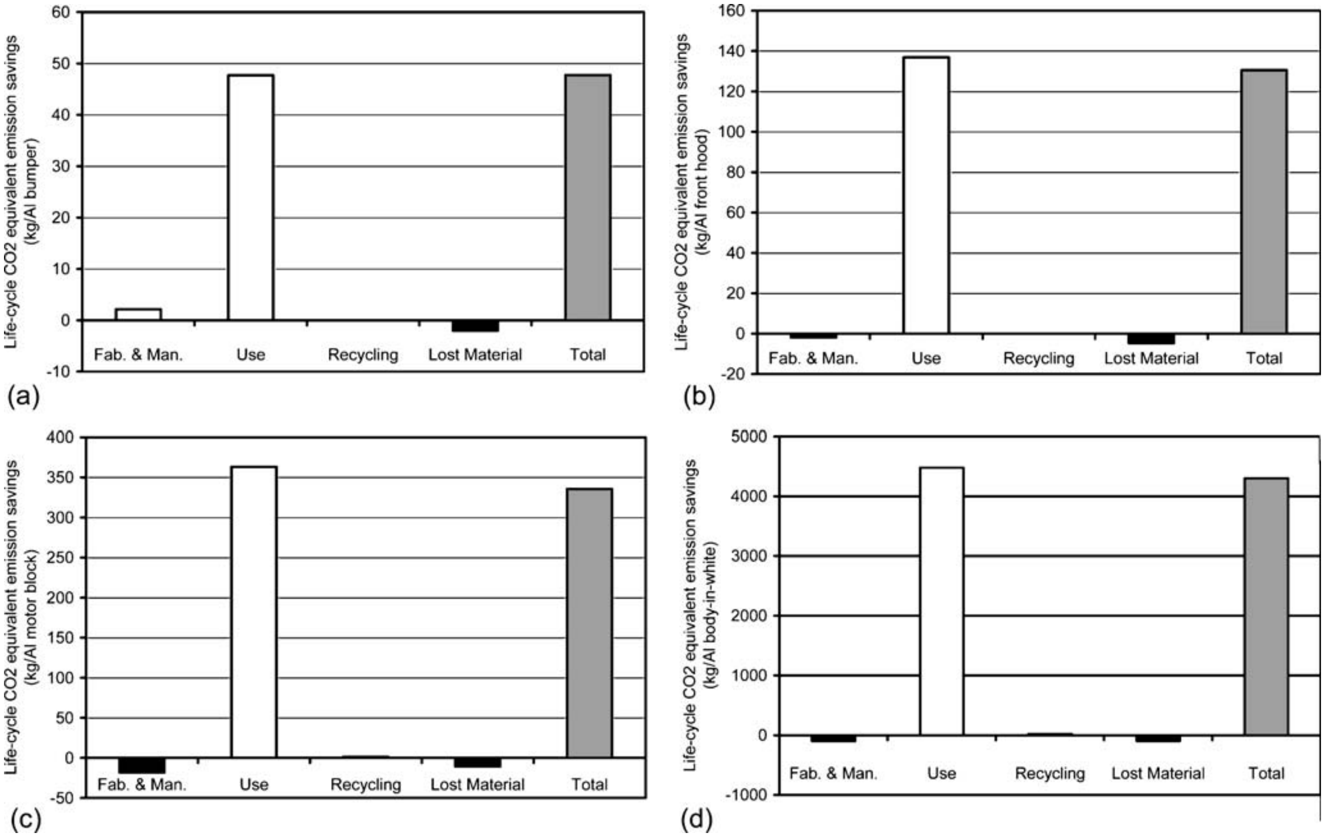


**Fig. 2** Life-cycle greenhouse gas emission savings for different **a** bumper, **b** front hood, **c** motor block, **d** body-in-white materials. '*Fab. & Man.*' includes all production stages from ingot to final product. '*Lost Material*' refers to the amount of metal that is lost during recycling and has to be replaced by primary metal

$CO_2$ eq, when choosing the aluminium front hood (see Fig. 2b).

### 3.3 Motor block of a compact car

This medium weight compact car has a mass of 1,250 kg and a gasoline consumption of 7.5 l/100 km. The car manufacturer has studied an aluminium version and a cast iron version with identical performance characteristics and specified the following masses from which the effective savings were calculated:

- Mass of Al component: 16.4 kg
- Mass of steel component: 31.0 kg
- Mass difference: 14.6 kg
- Indirect mass savings: 23% of 14.6 kg=3.4 kg
- Effective weight savings: 18.0 kg

Results for this compact car show in Fig. 2c that, after a lifetime driving distance of 200,000 km, savings of approximately 340 kg $CO_2$ eq are achieved when using the aluminium motor block.

### 3.4 Body-in-white of a luxury car

The body-in-white represent the car's metal structure. This luxury car has a mass of 1,700 kg and a gasoline consumption of 10.2 l/100 km. The car manufacturer has studied the following masses from which the effective savings were calculated:

- Mass of Al component: 295 kg
- Mass of steel component: 475 kg
- Mass difference: 180 kg
- Indirect mass savings: 23% of 180 kg=41 kg
- Effective weight savings: 221 kg

The resulting greenhouse gas savings are shown in Fig. 2d. They lead, after a lifetime driving distance of 200,000 km, to savings of about 4,300 kg $CO_2$ eq for the aluminium body-in-white.

### 3.5 Sensitivity analysis

Sensitivity analysis shows to which extent the results of the study depend on the informed estimates made. Therefore, the assumptions are systematically varied and the resulting data are shown in Figs. 3, 4 and 5.

The base case assumes a recycling rate (including collection, processing and scrap melting) of 91% for aluminium, steel and cast iron. In the sensitivity analysis the recycling rate for aluminium was varied between 0% (no recycling) and 100%. The recycling rate for steel or cast iron was kept constant at 91%. The results are shown in Fig. 3. The influence of the recycling rate is significant. However, because of the high market value of the aluminium contained in an end-of-life car, it would be unrealistic to assume a 0% recycling rate.

The influence of the life time driving distance is shown in Fig. 4. Even with a low life time driving distance of 100,000 km, savings of 6 to 9 kg $CO_2$ eq/kg of aluminium used are made. On the other side, if the life time driving distance is increased, the savings increase to 20 to 32 kg $CO_2$ eq/kg of aluminium used.

The savings by light-weighting depend on the gasoline consumption and the assumed air friction. The base case assumes a contribution of air friction of 40% to the total driving resistance, which is representative of a mixture of city, country road and highway driving. Twenty percent air friction is representative of city driving, while 60% is corresponding to driving on highways. If a car is used in an urban environment, savings increase to 17 to 28 kg greenhouse gas emission/kg of aluminium. If the car is predominantly used on a highway, then the saving will be reduced to 8 to 13 kg greenhouse gas emissions/kg of aluminium (Fig. 5).

## 4 Results

The life cycle model developed by the aluminium industry (IAI 2008) can be used for component specific calculations.

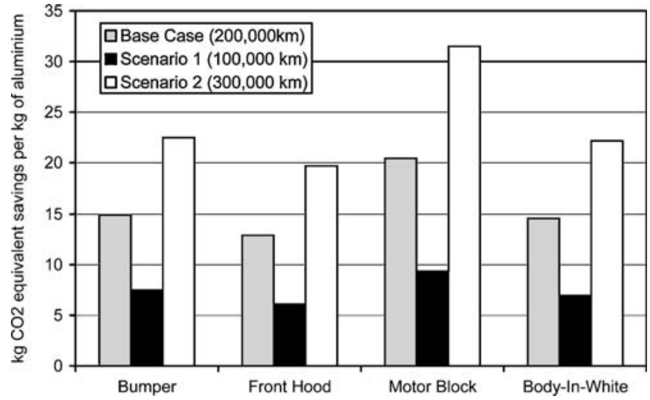


**Fig. 4** Influence of life time driving distance

Each component is subjected to individual life cycle analysis providing a detailed profile of greenhouse gas savings. All of the results have been generated utilising public available information on aluminium production, usage and recycling and observing the principles of life cycle assessment per ISO standard 14044 with regards to greenhouse gas emissions.

In all case studies, greenhouse gas emissions saved during the use stage because of aluminium's light-weighting potential far outreach the burden during production. Even with a non-realistic recycling rate of 0%, the achieved savings are significant.

Life cycle results show that for the cases studied here (bumper and motor block of a compact car, front hood of a large family car, body-in-white of a luxury car) that each kilogram of aluminium replacing mild steel, cast iron or high strength steel, under standard conditions, saves between 13 and 20 kg of greenhouse gas emissions.

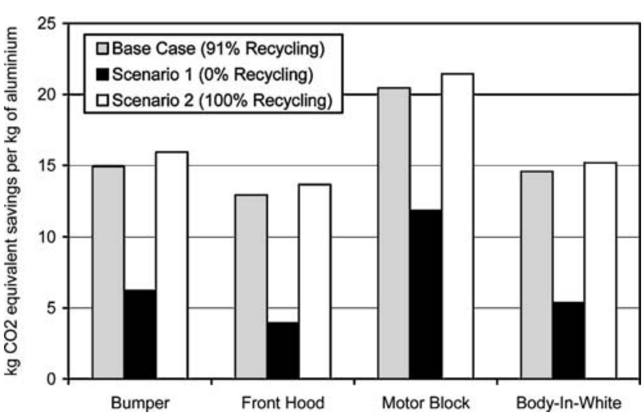


**Fig. 3** Influence of the end-life-recycling rate. The steel or cast iron recycling rate is kept at 91% for all three cases

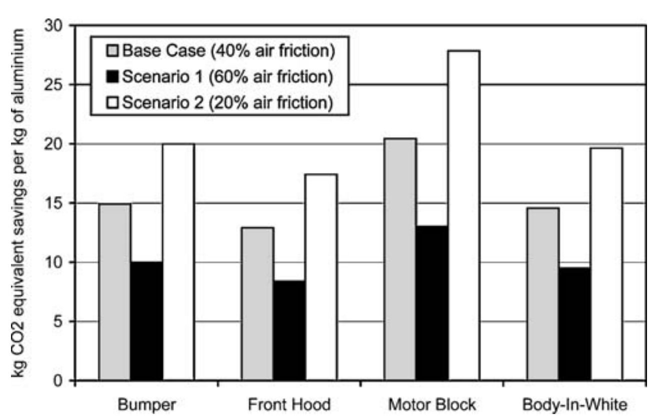


**Fig. 5** Influence of the driving behaviour

## 5 Conclusions

The study demonstrates the benefits of aluminium with regards to greenhouse gas savings and finds that even with 'worst case' scenarios savings are still significant. Nevertheless, the results are very sensitive to variations in of the recycling rate, the life time driving distance and the driving behaviour. Hence good care is needed to gather life-cycle data and to make informed estimates, where no data are available. Furthermore, greenhouse gas savings for additional components should be calculated using this life cycle model to sustain the findings.

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