International **A**luminium **I**nstitute

Improving Sustainability in the Transport Sector Through Weight Reduction and the Application of Aluminium

The application of aluminium in passenger vehicles and light trucks manufactured in 2006 will lead to potential savings of approximately 140 million tonnes of CO_2eq emissions and to energy savings of equivalent to 55 billion litres of crude oil over the lifecycle of these vehicles. This is vital because the transport sector today generates about 19% of all manmade greenhouse gas emissions. This industry, along with its suppliers has an essential role in assuring future generations the means needed to move people and their goods in a safe, energy efficient and environmentally-friendly manner.

This paper examines the role that weight reduction can play in enabling the transportation industry and members of its supply chain to meet their sustainability objectives. Aluminium is one of the most viable light-weighting options available to original equipment manufacturers in all areas of transport for weight reduction applications. Aluminium offers significant benefits in both the use stage and in the recycling stage of a vehicle.

Primary energy and greenhouse gas savings realised from light-weighting specific components of cars are quantified in this study based on life cycle assessment methodology. The model applied for cars to quantify these savings is also applicable for light duty trucks, commercial road vehicles, buses, ships and trains, represented here by a subway/metro car.

All modern vehicles are made up of many components produced through a range of processes. Most undergo different types of end-of-life operations. This document, produced by the IAI Sustainable Aluminium Working Group in cooperation with the European Aluminium Association (EAA) and the Aluminium Association (AA), does not compare a generic aluminium-intensive vehicle with a standard vehicle. Rather it uses a pragmatic approach based on specific examples of components where aluminium has been specified and manufactured.

The goal of this analysis is to quantify the value of mass reduction in the effort to improve vehicle sustainability and to show specifically how transport aluminium can advance this objective.

european aluminium association

The Aluminum Association

Points to make

1. Climate change is a subject of growing global concern. Based on International Energy Agency research, about 19% of man made greenhouse gas emissions are generated by the transportation sector. The reduction of the weight of transportation vehicles is an important method of improving fuel efficiency, reducing energy consumption and greenhouse gas emissions. Other measures are improved engines, lower air friction, better lubricants, etc...
2. Transport related greenhouse gas emissions amount to 7.6 billion tonnes annually. A 2004 study by Helms and Lambrecht concluded that about 660 million tonnes of greenhouse gas could be saved during the use phase if all transport units (including road vehicles, trains and aircraft) were replaced by lightweight vehicles of current design with the same functional properties. Approximately 870 million tonnes were possible with advance designs.
3. A vehicle’s life cycle covers three discrete parts: production; use; and end-of-life. With the ability of aluminium to be recycled, this process is better described as “cradle to cradle” rather than “cradle to grave”. The use stage dominates energy consumption and correspondingly carbon dioxide (CO_2eq) emissions, while production and end-of-life stage represent less than 20% of the CO_2eq burden. The focus of measures to reduce energy consumption during the life cycle of a vehicle should therefore concentrate on the use stage.
4. Since its introduction to transport aluminium has made an impressive contribution to the light-weighting of land and marine vehicles and will continue to do so. The demand for aluminium in transportation has been increasing year by year. In 2005, about 30% of aluminium used globally was used in transportation. In 2000 each automotive vehicle contained between 100 and 120 kg of aluminium and in 2006 between 110 and 145 kg.
5. The aluminium industry has consistently sought to develop and optimise components for the transportation sector in terms of weight savings through the replacement of heavier materials -saving fuel and reducing greenhouse gases.
6. Substitutions by aluminium are made component by component in different vehicle series. Each component is subjected to individual life cycle analysis providing a detailed profile of the energy and greenhouse gas savings.
7. A life cycle model developed by the aluminium industry can be used for these component specific calculations for all modes of transport, including automotive, trucks, trains and ships. All of the results have been generated utilizing public available information on aluminium production, usage and recycling and observing the principles of life cycle assessment per ISO standard 14044 with regards to energy and greenhouse gas emissions.

8. The transport light-weighting study references real cases, where aluminium is used and can be used in the design of new vehicles. For each component a sensitivity analysis is applied to determine the impact of the lifetime driving distance. 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 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. The case for metro/subway car has shown savings of approximately 26 (operating in Europe) and 51 (operating in the USA) kg of greenhouse gas emissions.
9. In 2006, about 65 million passenger cars and light trucks were produced globally. The achieved weight savings due to aluminium will lead to potential global CO_2eq savings of 140 million tonnes. The total primary energy saved due to the application of aluminium during the life cycle of passenger cars and light trucks produced in 2006 is equivalent to about 55 billion litres of crude oil.
10. The specific case studies and the life cycle model can be ordered from the International Aluminium Institute to calculate primary energy and greenhouse gas savings for similar cases, just by replacing the relevant parameters.

Table of content

1 The Issue

1.1 A growing transport sector and vehicle weight changes

After the first and second oil crises in the early 1970’s, legislation as well as customers’ demand required the automotive industry to improve the fuel efficiency of their products. One prominent option in this pursuit was to reduce vehicle weight. In the United States, when Corporate Average Fuel Economy (CAFE) standards were put in place, the weight of the average vehicle was reduced by about one thousand pounds.

However, in past two decades, cars have become heavier and heavier, see Figure 1.1. The popularity of light trucks, luxury high performance cars, mini-vans and SUVs has accelerated this development. In addition to changes in fleet mix, consumer demands for increased safety, comfort and convenience without any sacrifice in overall performance have also contributed to the weight spiral of current vehicles.

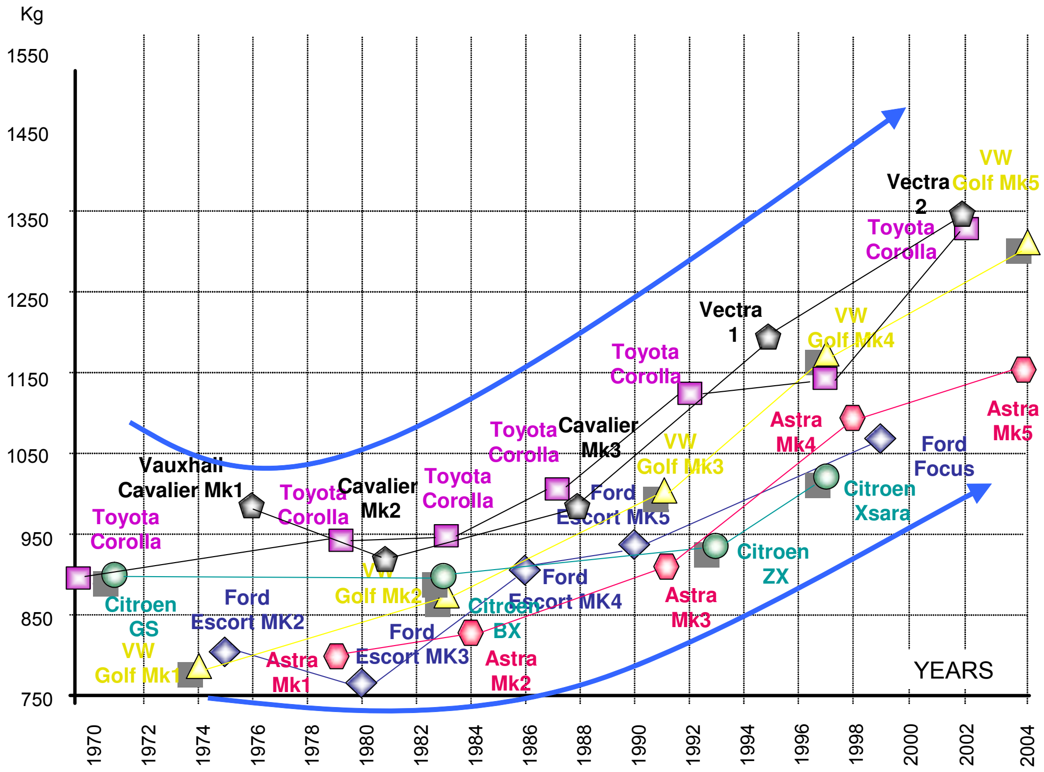


Figure 1.1: Evolution of weight in compact-class cars (Jaguar, permanently updated)

The rise in vehicle weight is compounded by a significant increase in the number of cars that will be manufactured in the future. Significant increases in the vehicles fleets are expected in China, India, the Middle East and Latin America as shown in Figure 1.2. As a result, reducing vehicle fuel consumption has become essential for the future.

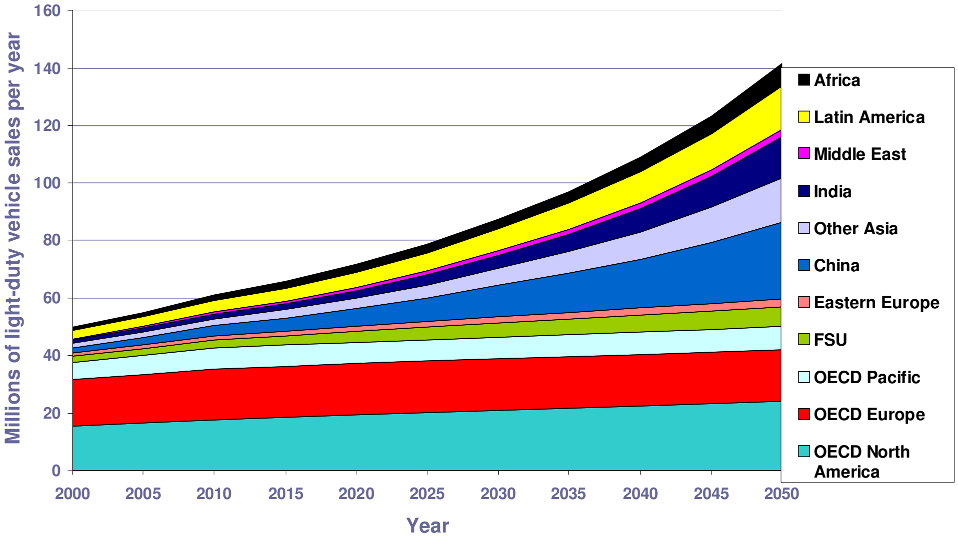


Figure 1.2: Predicted future growth in car and light truck sales (IEA, 2004)

1.2 Other transport means

Growing global population and income is increasing the number of cars. Cities are also substantially increasing their public transport system in terms of commuter trains, subways, trams and city buses. High-speed trains and long-distance buses serve medium distances. For long distances the aircraft industry is booming.

Moreover, globalisation and the growth in international trade have increased container transport by trucks, rail and ships and aircraft significantly, permitting more goods to be transported over longer distances.

1.3 How to meet the challenge of the impact of a growing transport sector on climate change and energy resources

The transport sector contributes significantly to the total global energy consumption and to greenhouse gas emissions (Figure 1.3). The International Energy Agency states that about 19% of the global greenhouse gas emissions are generated by this sector. If emissions generated by electricity and fuel supply processes, which are related to transport, were to be added, the share would even be higher.

In light of the growing demand for energy and the simultaneous desire to reduce climate change, the need to improve the overall energy efficiency and reduce the environmental impact of global transportation is critical. The introduction of increasingly stringent regulatory and legislative measures can therefore be expected in the near future.

At the third session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in 1997 in Kyoto, Japan, the text of the so-called “Kyoto Protocol” was adopted. With the “Kyoto Protocol” many states have made the commitment to comply with targets for climate protection and the conservation of natural resources.

As an anticipatory measure, a coalition of the car industry (ACEA, JAMA & KAMA) has envisaged a reduction of the CO_2eq emissions of their average fleet in Europe down to 140 g CO_2eq/km by 2008 (2009 respectively for JAMA and KAMA). Since the voluntary agreements targets will most likely not be met, political initiatives are expected. The European Commission, for example, has proposed legislation to reduce the average CO_2eq emissions of new vehicles to 130g/km.

In the USA, legislation is pending in both the House of Representatives and the Senate to raise gasoline mileage standards substantially to 35 miles-per-gallon (15 km/l) by 2020 – and some bills contain requirements for 4% annual increases in the standards for ten years after that. Some bills also contain requirements that medium- and heavy-duty trucks be subjected to a new CAFE standards program; others also contain a cap-and-trade system to allow companies to buy and sell CO_2eq emissions credits in order to meet greenhouse gas emissions reductions requirements. While some requirement for higher CAFE standards is almost certain to be enacted, it is unclear at this time just how steep those increases will be.

Over the past few years, auto manufacturers have succeeded in maintaining or in many cases reducing the fuel consumption of vehicles despite the aforementioned consistent increase in vehicle weight. Different methods, including improved engines and power trains, lower air friction, better lubricants, have been used.

But continued progress will be required along all these fronts to meet what are certain to increased demands for ever more fuel efficiency and environmental friendliness. Weight reduction is one of the most desirable and realizable options for the global transport sector.

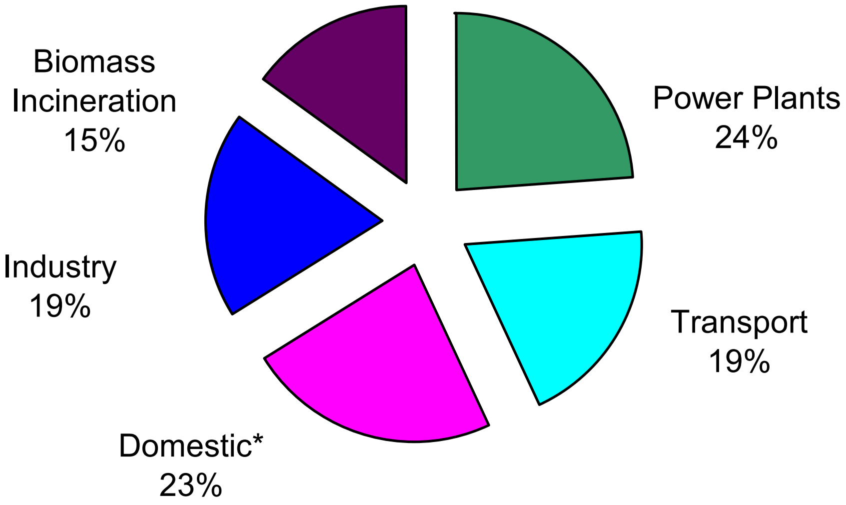


Figure 1.3: Greenhouse gas emissions from different sources (IEA, 2005)
***Includes soil, oceans, vegetation, burning of biomass, human activity**

2 Aluminium in transport

2.1 General

Over the life cycle of any transport vehicle, the use of aluminium results in economic, social and environmental benefits. Aluminium is light, it ensures and often enhances safety, it is recyclable from one product generation to the next and it keeps its value and properties after recycling.

As shown in Figure 2.1, the demand for aluminium in the transport sector has been increasing year by year. In 2005, up to 30% of wrought and casting alloys used globally were used in cars, commercial vehicles, aircraft, trains, ships etc...

While several materials can be used to reduce vehicle mass, aluminium offers not only significant advantages during the use stage, but in particular, also in the end-of-life stage. The excellent recyclability of aluminium, together with its high scrap value and the low energy needs during recycling (only about 5% energy need required by primary production), make aluminium lightweight solutions highly desirable.

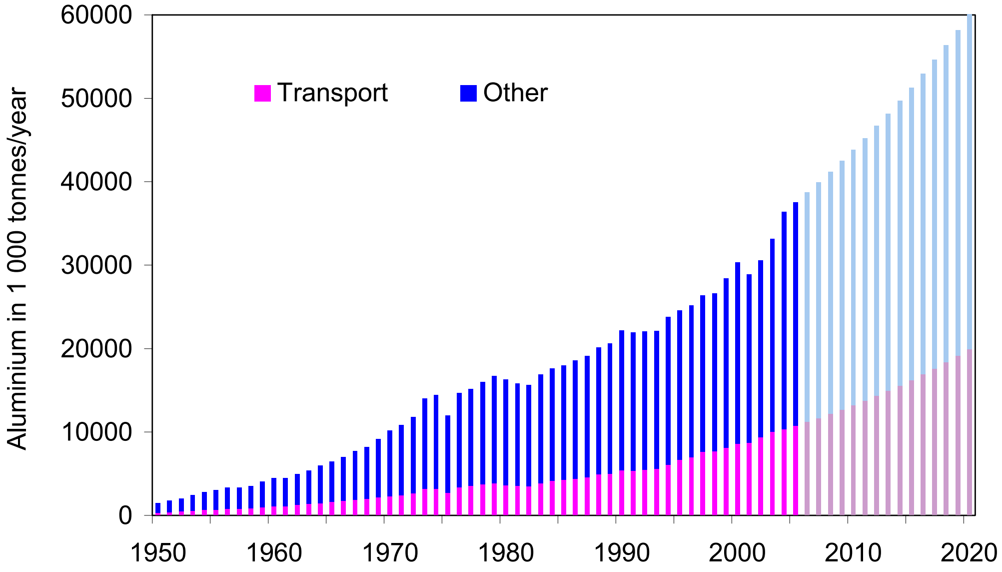


Figure 2.1: Global total and transport related aluminium use (1990 – 2020)

Aluminium from transport applications is part of an established recycling system. Recycled aluminium can be utilized for almost all applications, preserving raw materials, reducing emissions and leading to considerable energy savings. At the moment metals, with aluminium being the most significant one, play an important role in funding the end-of-life processing of vehicles

2.2 Automotive

Carl Benz built the first combustion engine driven car in 1886. Then, in 1899, a small sports car with an aluminium body was unveiled at the Berlin international car exhibition. In 1948, Land Rover made intensive use of aluminium outer skin sheets and, in 1953, the Panhard Dyna was the first volume-produced car to have an aluminium body. It was in 1965 that large-scale production of aluminium engine blocks began, while 1975 saw accelerated application of aluminium hoods in US cars. In 1994, Audi launched the all-aluminium passenger car in its Audi A8 with a space frame body concept.

Today, many cars contain significant amounts of aluminium, as designers have become increasingly aware of the metal's demonstrated advantages. More than 20% of the cars produced in Europe have an aluminium hood, including the Peugeot 307 as a small family car. The Jaguar XJ is the first aluminium body-in-white (the car's metal structure) in a sheet-based design to employ structural adhesive bonding as one of its joining methods. Several high-performance sports car bodies, such as Ferrari and Lotus, are also produced in aluminium.

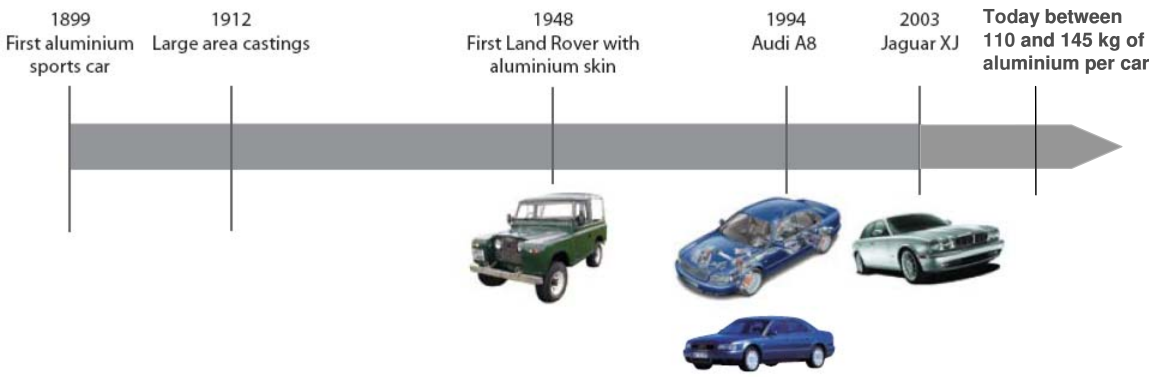


Figure 2.2: Historical evolution of aluminium in cars

In the case of automotive & light truck shipments, the increase in aluminium content is illustrated in Figure 2.3 and Table 2.1.

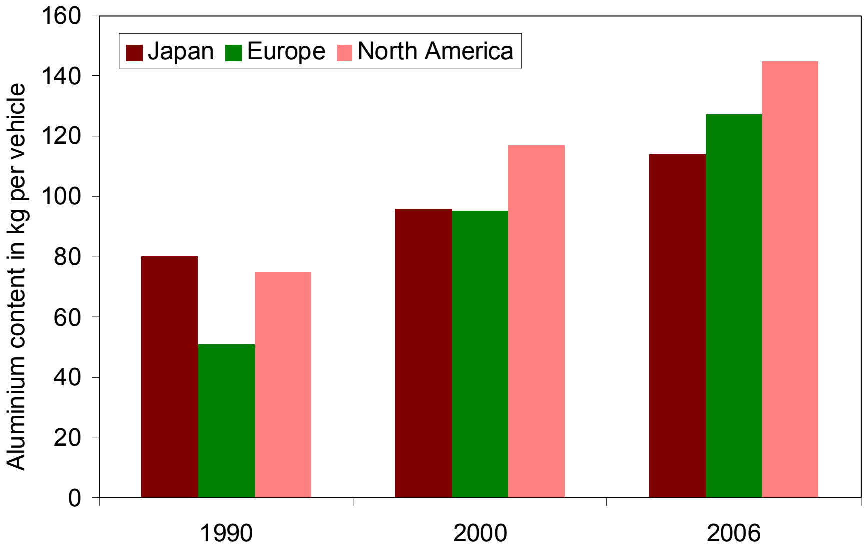


Figure 2.3: Aluminium vehicle content in North America, Europe and Japan (Ducker Research, 2005)

In the last 50 years, additional aluminium content has been the result of replacing cast iron (engine blocks and transmission housings), mild steel (car bodies and wheels), and copper (radiators). While in the past aluminium was used in automobiles primarily the form of castings, in recent years engineers have increasingly “discovered” the wide variety of aluminium product forms for automotive applications as extrusions, stamped sheet parts and forgings have consistently grown in chassis and suspension, crash management and other structural applications.

Component Aluminium form*	North America		Europe*		Japan	
	2002	2006	2002	2006	2002	2006
	kg/car	kg/car	kg/car	kg/car	kg/car	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

Table 2.1: Average content of aluminium in new vehicles by component (Ducker Research, 2005)

* Most important form is marked in bold letters, least important is in brackets

**Based on Knibb, Gormezano & Partners (2006) about 130 kg per car in 2005.

2.3 Trucks, trailers and buses

Having made its debut in Parisian buses in 1910, aluminium was used for a variety of elements in road and rail transport in the 1930s, when the industrial development of components actually began. The 1950s saw the first aluminium superstructures for tankers, vans and tipping vehicles. For commercial vehicles, traditionally "heavy duty", the advantages of aluminium were put to good use with the manufacture of the first aluminium systems to meet weight sensitive transport requirements in the 1970s.

Today, the superstructures of most tankers and silo semi-trailers are made entirely of aluminium. Aluminium is also frequently used for vans, tipping and self-discharging bodies.

In an average articulated truck aluminium components can reduce the weight of a truck trailer by up to 2 000 kg. With this weight advantage an aluminium-intense truck can carry a heavier load without exceeding statuary weight limits. This increase of the load capacity of vehicles means, in the case of weight limited transport, that fewer trips are necessary which contributes to additional reduction of CO_2eq emissions.

In North America, aluminium hoppers and gondolas have displaced steel cars in unit trains hauling coal. The switch has brought substantial savings to the electricity utility companies. In many cases the investment in aluminium rolling stock is covered in under two years.

Components for tractors & rigid trucks

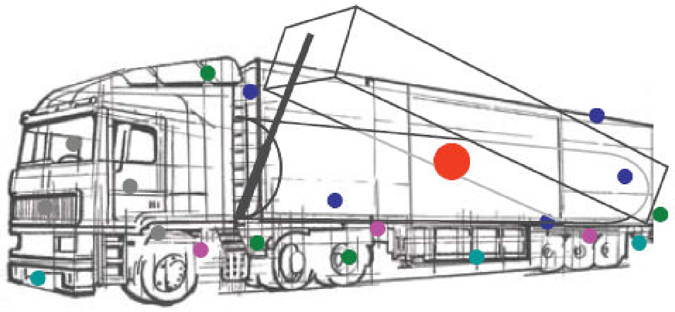
- cabin & doors: -200kg
- chassis: -350kg
- powertrain parts: -125kg
- suspension parts: -110kg

Complete superstructures

- rigid body: 90m² = -800kg
- tipping body: -800 to -2000kg
- ADR fuel tank: 43000l = -1100kg
- self-discharging body
- silo

Components for superstructures

- curtain rails: 2x13.5m = -100kg
- front wall: -85kg
- rear door: -85kg
- side boards: 600mm = -240kg
- stanchions: 10x600mm= -50kg
- reefer floor



Safety parts

- front bumpers: -15kg
- rear bumpers: -15kg
- side bumpers: -20kg
- front and rear under-run protections

Trailers sub-structures

- chassis: 13.5m = -700kg
- chassis: 6m = -300kg
- chassis+floor: 13.5m = -1100kg
- legs: -35kg

Accessories

- air pressure vessels: 6x60l = -54kg
- diesel tank: 600l = -35kg
- toolbox: -15kg
- tail lift: -150kg
- wheels: 14 rims = -300kg

Figure 2.4: Examples for weight savings in trucks

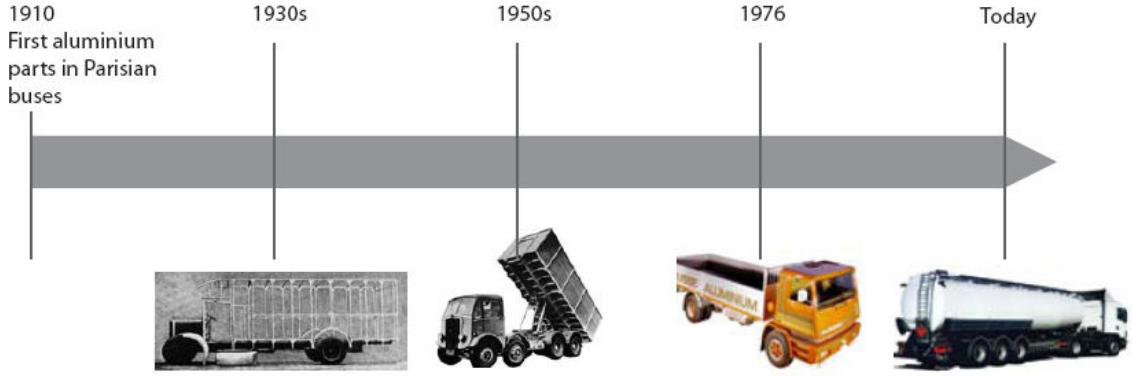


Figure 2.5: Historical evolution of aluminium use in trucks

2.4 Rail transport

In the 1960s, aluminium was used in the niche market for cog railways. Then, in the 1980s, aluminium emerged as the metal of choice for suburban transportation and high-speed trains, which benefited from lower running costs and improved acceleration. In 1996, the TGV Duplex train was introduced, combining the concept of high speed with that of optimal capacity, transporting 40% more passengers while weighing 12% less than the single deck version, all thanks to its aluminium structure.

Today, aluminium metros and trams operate in many countries. Canada's LRC, France's TGV Duplex trains and Japan's Hikari Rail Star, the newest version of the Shinkansen Bullet train, all utilize large amounts of aluminium.

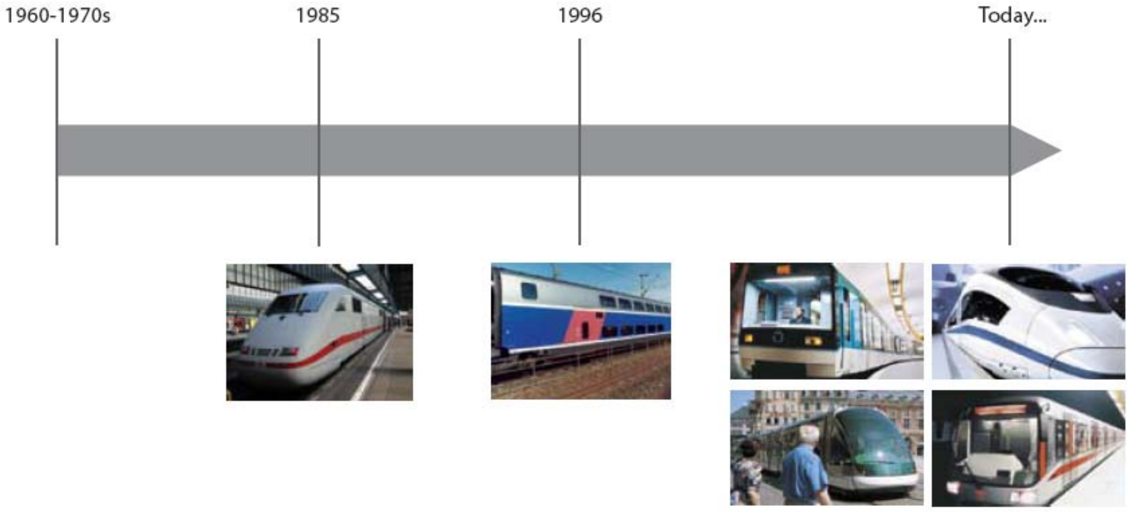


Figure 2.6: Historical evolution of aluminium use in trains

2.5 Marine transport

Aluminium was used for boat construction as far back as 1891 in the first steam launch by Escher Wyss, followed in 1894 by the first torpedo boat by Yarrow & Co. In 1895, the aluminium-skinned “Defender” won the America’s Cup. It was in the 1920s that aluminium marine applications started to expand in both the civil and military domains, due to new corrosion-resistant alloys becoming available. By 1960, aluminium was firmly established in all marine sectors around the globe. In 1962, the transatlantic liner “France” was built using 1 600 tonnes of aluminium for its superstructure. The first high-speed catamarans were produced in 1970.

Today, 1 000 high-speed passenger ships are in service, most of which have a structure and superstructure made of aluminium. Cruise ship superstructures continue to be made of aluminium, while over half of all yachts have aluminium hulls. These ships take full advantage of aluminium’s lightness and strength, as well as its other indispensable property for marine environments, in particular corrosion-resistance, significantly reducing maintenance costs.

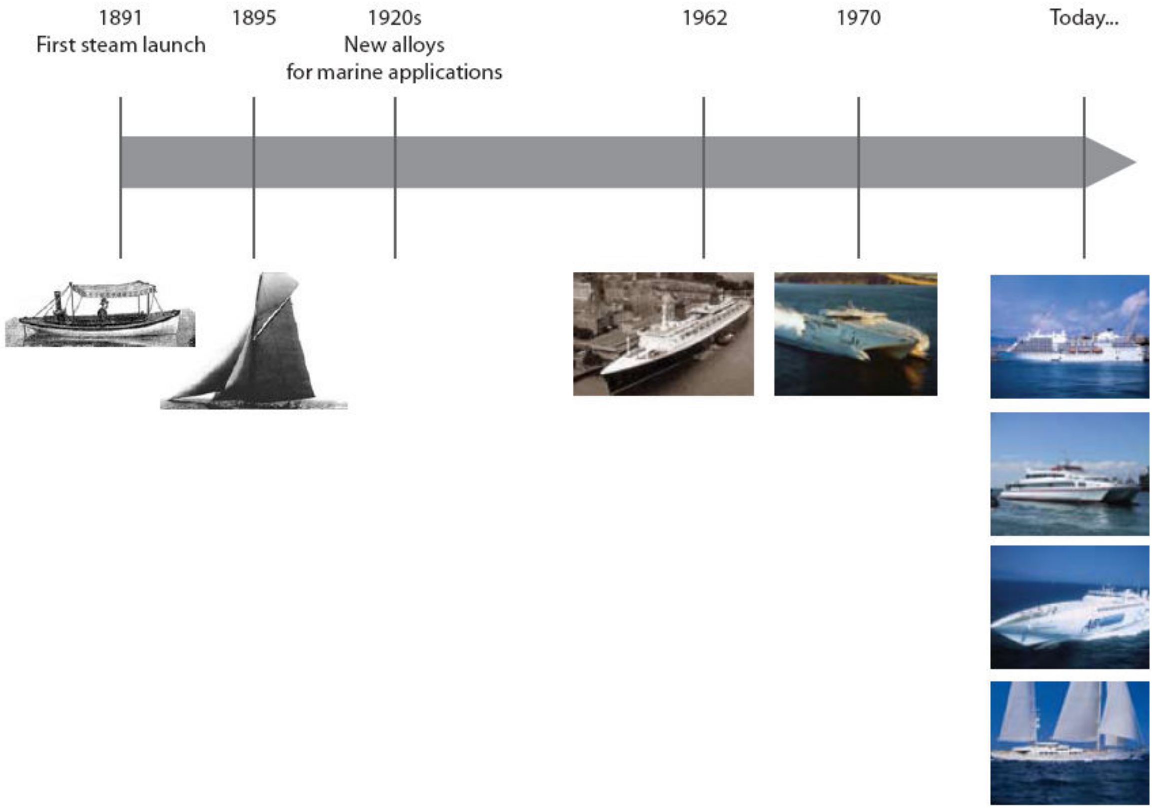


Figure 2.7: Historical evolution of aluminium use in ships (based on Alcan, 2004)

3 Energy and greenhouse gas savings during the use stage by light-weighting - quantitative results

3.1 The importance of the use stage within the life cycle of vehicles

Looking at a vehicle's life cycle, it is acknowledged that the use stage by far dominates energy consumption and correspondingly CO_2eq emissions, while production and end-of-life stage represent together usually less than 20% of its CO_2eq burden. Therefore measures to reduce the energy consumption during the full life cycle of a vehicle should primarily concentrate on the use stage.

Reducing the final energy demand (fuel or electricity used by the vehicle) means reducing the extraction of energy resources, i.e. a reduction of primary energy consumption. All analysed primary energy savings are independent of the technical realisation of the weight reduction (e.g. new materials or improved design).

3.2 Resistance factors

To determine the impact of mass reduction on energy usage and greenhouse gas emissions in the transport sector, quantitative studies have been undertaken by IFEU-Institute (see Helms et al (2003), Helms and Lambrecht (2004) and Helms and Lambrecht (2007)), which have analysed the potential energy savings (fuel or electricity consumption) during the use stage for different types of vehicles.

The energy consumption per road and rail vehicle km depends on four types of physical resistances which the vehicle has to overcome during its operation, see Figure 3.1. Rolling resistance, gradient resistance and acceleration resistance are proportional to the mass of the vehicle, whereas, for a given shape of the vehicle, the aerodynamic resistance does not depend on the mass; it is proportional to the square of the speed.

More details can be found in Annex A

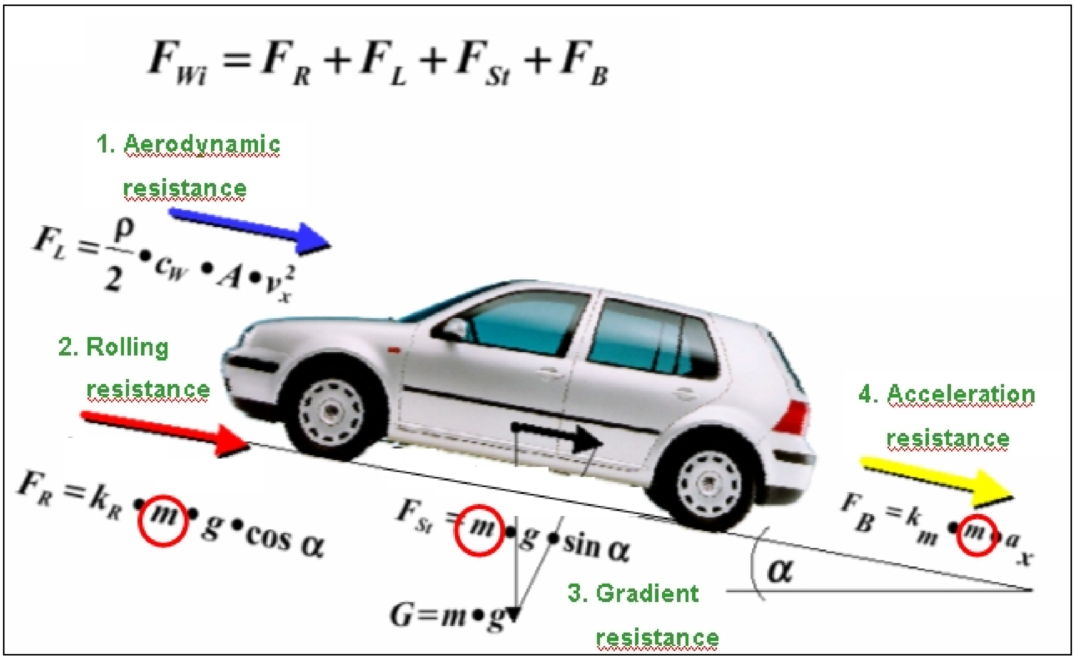


Figure 3.1: Influence of the mass of different parameters which control the fuel consumption of road and rail vehicles (Source: Volkswagen AG, 2002)

3.3 Road vehicles

Fuel and CO_2eq savings from different vehicle examples have been calculated based on data and methodology used in the IFEU studies. These are shown in Table 3.1. The transparent methodology used by IFEU allows for easy calculation of further vehicles. A weight reduction of 100 kg results in lifetime fuel savings between 300 to 800 litres for standard passenger cars but, it can be significantly higher for taxis and city buses.

Vehicles operating in urban areas, with frequent stops and accelerations generally lead to higher energy savings compared to vehicles on highways operating at steady speeds.

Table 3.1 also shows that a weight reduction of a car of 100 kg reduces the direct CO_2eq emissions by about 9 grams per km. This means that weight reduction can significantly contribute to the required reduction of the CO_2eq emissions of a car.

Vehicle type	Fuel type	Specific fuel savings per 100 kg weight savings	Specific direct greenhouse gas savings per 100 kg weight savings	Lifetime fuel savings per 100 kg weight savings	Lifetime greenhouse gas savings per 1 kg weight savings
		ml/km	g CO_2eq/km	(in litres)	kg CO_2eq
Small car, average use	Gasoline	3.6	8.4	720	20
Small car, mainly urban	Gasoline	5.5	12.9	829	23
Medium sized car, mainly long distances	Gasoline	2.8	6.6	844	24
Luxury car, mainly long distances	Gasoline	3.0	7.0	300	8
Medium sized car, Taxi	Gasoline	5.2	12.0	2 578	72
City bus, few stops	Diesel	1.5	3.9	1 485	44
City bus, many stops	Diesel	2.6	6.6	2 550	76
Long distance bus, high speed	Diesel	0.4	1.1	500	15
Long distance bus, medium speed	Diesel	1.0	2.5	1 167	35

Table 3.1: Use stage final energy and greenhouse gas (direct and indirect) savings per 100 kg weight reduction for road transport vehicle examples

3.4 Other transport

The methodology demonstrated in Figure 3.1 can also be applied to rail vehicles. The final energy savings during the use stage of trains in the form of electrical energy are shown in Table 3.2.

Vehicle type	Electricity consumption per 100 kg weight	Electricity savings per 100 kg weight savings	Lifetime distance	Lifetime electricity savings per 100 kg weight savings	Lifetime greenhouse gas savings per 1 kg weight savings
	MJ/100 km	MJ/100 km	km	kWh	kg CO_2eq
Subway/urban train – per wagon	2.5	2.00	3 000 000	167	71
Short distance train – per wagon	2.5	1.75	4 000 000	194	83
Normal passenger train - per wagon	1.0	0.40	8 000 000	89	38
High-speed passenger train - per wagon	1.0	0.32	15 000 000	133	57
Freight train - per wagon	0.8	0.40	8 000 000	89	38

Table 3.2: Use stage final electricity and greenhouse gas savings by weight savings of different types of train examples

In addition, the IFEU has analysed different types of freight-carrying, ocean-going vessels (container ships, general cargo vessels and tankers) and ocean-going ferries and high-speed ferries. For ships, fuel consumption is related to the displacement of the ship, which in turn is linked to the gross ship weight for a given ship, form and size. Table 3.3 shows the greenhouse gas savings by weight savings for different types of ship examples. The savings are especially high for high-speed ferries. But also for container ships, general cargo ships and sea freight containers the savings are most significant. Again, the transparent methodology allows for the calculation of further examples.

Type of ship	Fuel consumption per hour and per t weight	Specific fuel savings per hour and per t weight savings	Lifetime	% of lifetime under use	Lifetime fuel savings per t weight savings	Lifetime greenhouse gas savings per t weight savings
	kg Diesel	kg/h	Years	%	t/t	t CO2eq
Container ships	0.203	0.191	25	82%	34.4	123
Freight containers	0.203	0.191	13	41%	8.6	31
General cargo ships	0.106	0.099	25	82%	17.9	64
Tankers	0.046	0.023	25	82%	4.1	15
Passenger ferries	0.39	0.27	20	51%	327	87
High-speed passenger ferries	5.26	3.68	20	51%	24	1 171

Table 3.3: Use stage final energy and greenhouse gas (direct and indirect) savings by weight savings for different types of ship examples

3.5 Impact of light-weighting on a global scale

Besides an analysis on a per vehicle basis, the potential contribution of light-weighting to a reduction of the global transport energy consumption and greenhouse gas emission has also been estimated in the study of Helms and Lambrecht (2004).

In 2000, all modes of transport were responsible for greenhouse gas emissions (refers to CO2eq) of about 7 600 million tonnes. The studies concluded that about 660 million tonnes of greenhouse gas annually could be saved (see 3rd and 4th column in Figure 3.2), if all transport units (including road vehicles, trains and aircraft) were replaced by the same number of lightweight vehicles with the same functional properties, but built according to current design. Additional savings of about 220 million tonnes of greenhouse gas were made if these units would be built according to an improved design, which makes use of additional possibilities of light-weighting. Summing up both steps, a total potential of annual greenhouse gas savings of 870 million tonnes (see 5th and 6th column in Figure 3.2) has been calculated.

As shown in Figure 3.3, by far the highest savings potential lies in the weight savings of passenger vehicles.

However, it cannot be concluded from this study that the global greenhouse gas emissions of vehicles will decrease even if weight reduction takes place in the developed nations. As shown in Figure 1.2, the number of vehicles will grow dramatically in the next decades, especially in non-OECD countries.

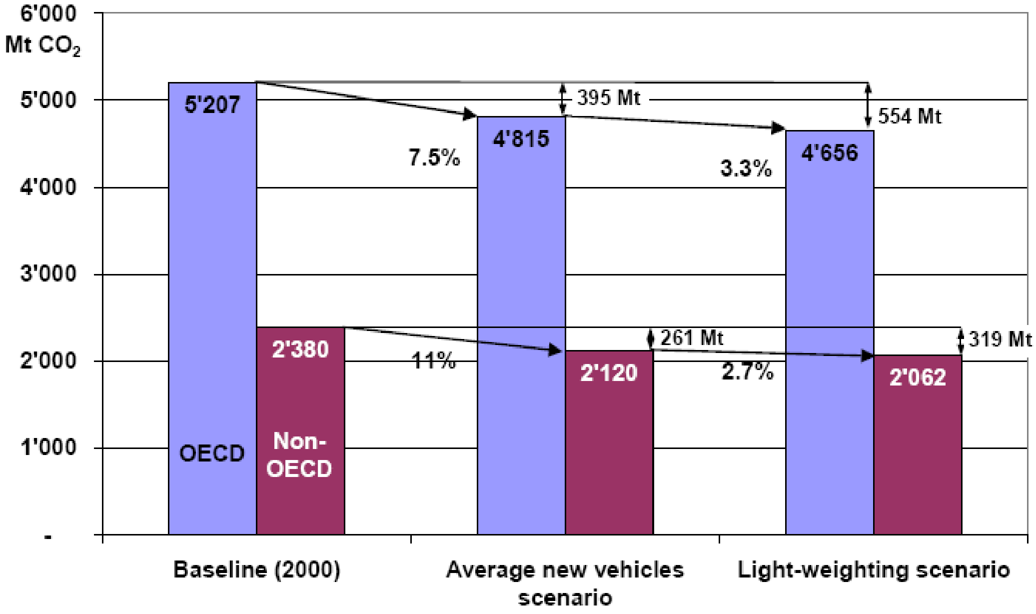


Figure 3.2: Potential of global annual greenhouse gas savings by light-weighting of vehicles

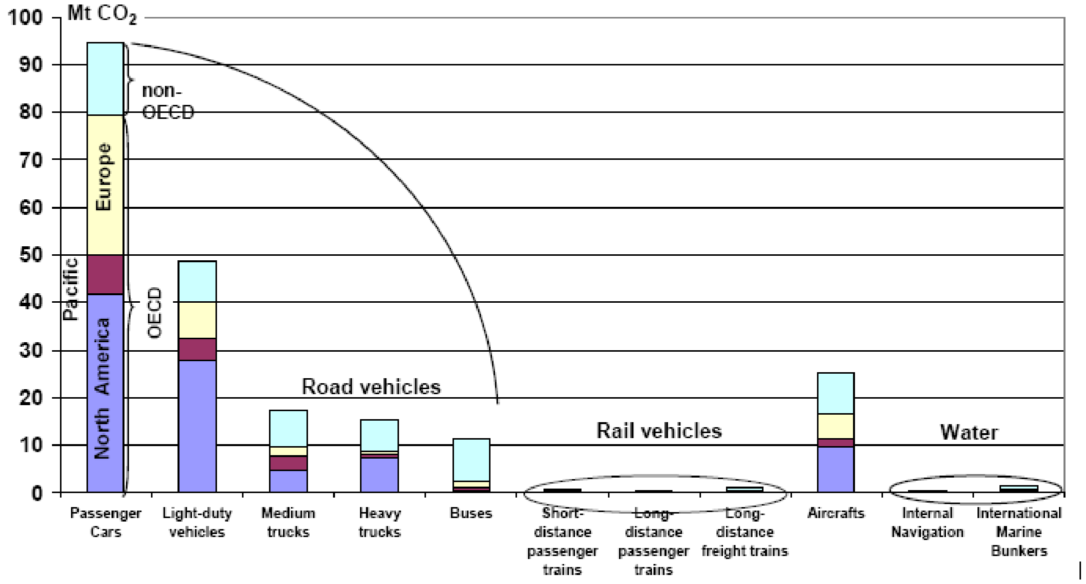


Figure 3.3: Influence of the different types of vehicles to the global annual potential of greenhouse gas savings

4 Energy and greenhouse gas savings by aluminium substituting heavier materials – qualitative information

4.1 The life cycle of aluminium products and components in transport

The aluminium economy is a material cycle economy. Indeed, for most aluminium products, aluminium is not actually consumed during a use stage, but only used. The life cycle of an aluminium product is not the traditional “cradle-to-grave” sequence, but rather a renewable “cradle-to-cradle”. Therefore, the "cradle-to-cradle" systems modelling, as shown in Figure 4.1, are appropriate. The production stage starts with the ingot (cradle), from which the vehicle component is produced, and the end-of life stage ends with the recycled ingot. Any material losses, mainly within the recycling processes, have to be substituted by primary material from ore. As long as the primary ingots and the recycled ingots have the same inherent properties, it makes no difference if the component is produced from primary or recycled material.

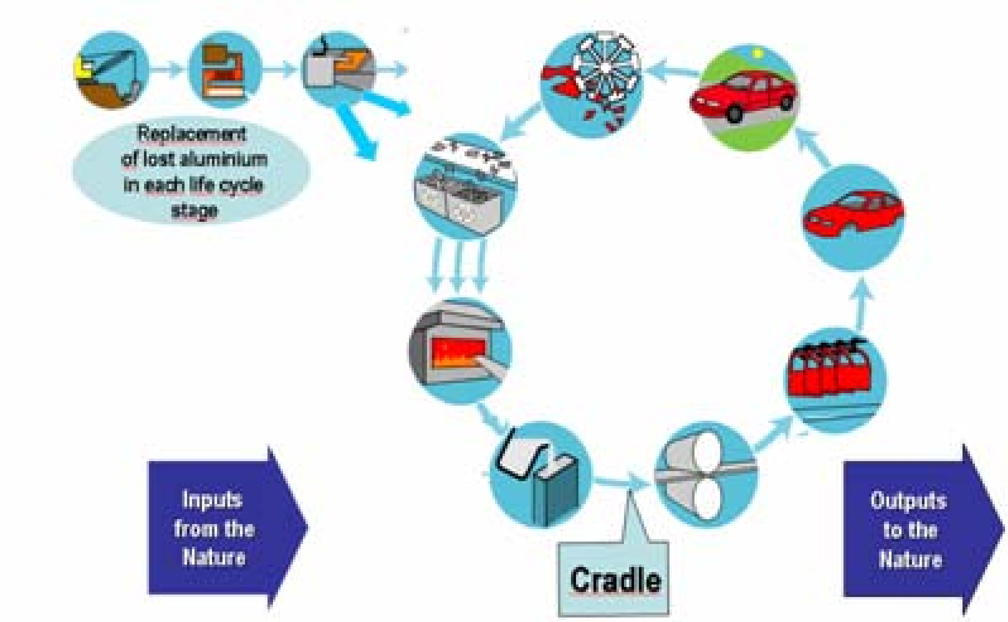


Figure 4.1: The life cycle of aluminium products and components in transport

4.2 Fabrication, manufacturing and use stage

The cradle of the life cycle is the ingot from which the different semi-finished products can be fabricated by rolling, extrusion, forging or foundry casting. Each of these processes (including the remelting of process scrap) has direct and indirect potential environmental impacts, which must be quantified.

The next stage of the life cycle is the manufacturing of finished components and includes forming operations, heat treatment, surface treatment, etc... These processes can be located at an aluminium plant, at plants of suppliers or directly at the car manufacturer. Again the direct and indirect potential environmental impacts of this life cycle stage have to be considered. The same procedure must be applied to the assembly and finishing of the vehicle.

As already stated, the use stage is the stage of the life cycle of vehicles, which has by far the highest environmental impacts. However, the environmental impacts of this stage can vary significantly, depending on the specific circumstances, such as driving cycle and lifetime driving distance, etc...

4.3 End-of-life operations

A number of efficient processes are used to recover aluminium scrap from vehicles. Figure 4.2 shows the process presently applied to recycle a typical passenger car. Some easy-to-dismantle aluminium parts are often removed during the initial dismantling of the vehicle. The car body, including the remaining aluminium, is fed to the shredder where it is smashed into pieces by a hammer mill. After separating the ferrous fraction using magnets and the removal of the light shredder residue by a cyclone, a mixture of plastics, rubber, glass, textiles, high grade steel and nonferrous metals is obtained. This mixed fraction is subjected to sink-float and eddy current separation and results in the extraction of aluminium scrap. Additional sorting processes to further increase the recycling rate and the quality of the recycled material are in use or under development.

Aluminium scrap recovered using the various separation procedures is today mainly processed into aluminium casting alloys. Typical applications for castings include engine blocks, cylinder heads and gearboxes. Due to the increased use of aluminium wrought alloys in car bodies, a growing volume of wrought alloy scrap is anticipated in the future. Hence, the separate collection of wrought alloys from cars might become economically viable in the coming decades.

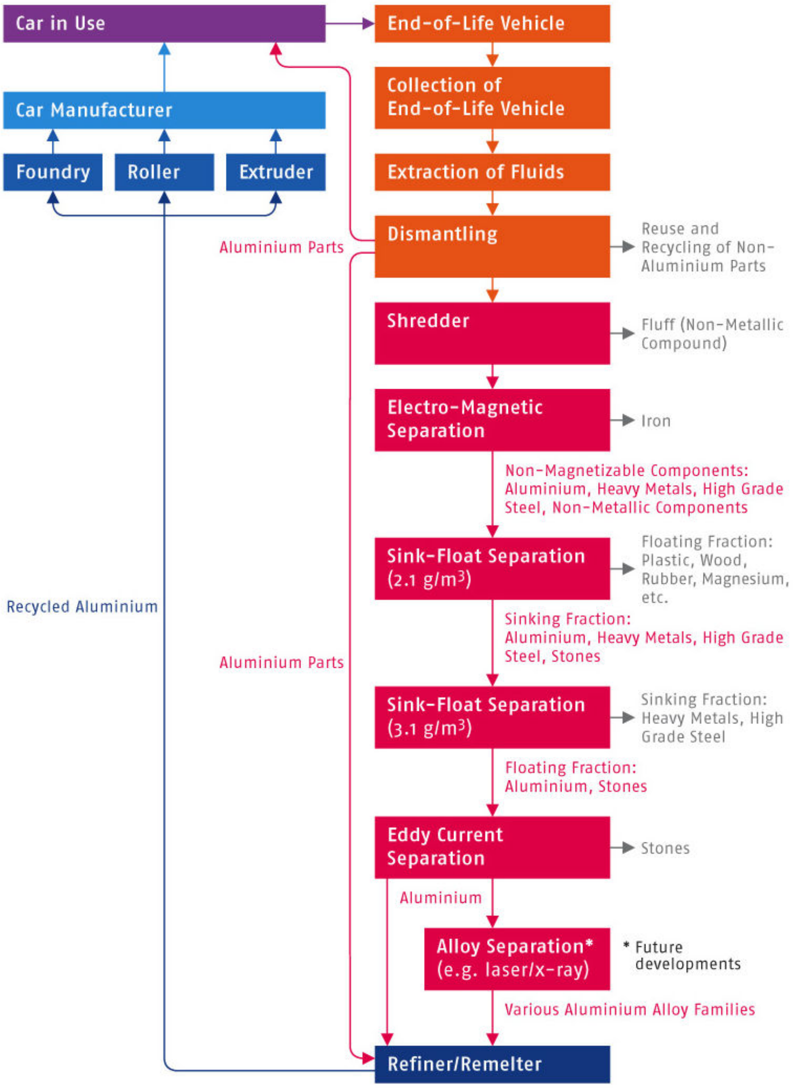


Figure 4.2: Modern end-of-life vehicle dismantling and aluminium recycling process

4.4 Substitution of lost material by primary aluminium

The cradle-to-cradle life cycle as described in chapter 4.1 assumes that the quantity of the recycled metal has the same mass and the same inherent properties as the material at the starting point. Aluminium lost during the life cycle, mainly during the end-of-life operations, has to be substituted by primary metal. In life cycle assessments, the environmental loads of the production of this primary metal have to be charged to the product under study.

The process chain of the production of primary aluminium consists of

- bauxite mining;
- refining of bauxite into aluminia (aluminium oxide trihydrate),
- smelting of alumina into aluminium by electrolysis.

Primary aluminium production facilities are located all over the world, often in areas where there are abundant supplies of inexpensive energy, such as hydro-electric power.

Sometimes, recycled aluminium may have different inherent properties and lower market value, compared with primary metal. In this case, in LCAs, this loss of market value has to be compensated by a "value correction".

Details about the treatment of aluminium in LCAs, with special regard to recycling issues, are found in Annex B.

4.5 Mass reduction capability of aluminium

The potential of aluminium as a mass reduction material becomes obvious when looking at the specific weight (2.7 grams per cubic centimetre), which is less than half of that of iron (7.6 g/cm3) and copper (8.5 g/cm3). Of course this is a simplistic view, since application-specific 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, as well as weight. Therefore, each component must be individually evaluated based on all its desired performance criteria.

But apart from the direct weight reduction by material substitution, there are additional possibilities for light-weighting. Aluminium-specific fabrication techniques, such as complex, multi-hollow extrusions or thin-walled, high-strength, vacuum die casting, enable new design solutions.

Furthermore, the reduction of the total vehicle weight also offers the potential for indirect weight savings. When Audi designed the model of the A8 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. Once Audi decided in favour of the aluminium alternative, they could also realise additional weight-saving measures, e. g. a smaller engine or a smaller fuel tank in order to fulfil the given requirements for the car (acceleration, mileage per tank filling).

Audi reported such "indirect" weight savings as 45 kg which is 23 % of the direct weight savings of 194 kg. This means that the 247 kg aluminium body-in-white effectively reduces the car weight by 239 kg.

It is nearly impossible to establish a proper value for the indirect weight saving potential in the various case studies. Therefore as an arbitrary measure, an extra mass reduction of 23 % of the direct mass savings will be added to total weight savings based on Audi's experience.

Furthermore it must be noted that the on-going developments in aluminium technology (new design concepts for optimised aluminium solutions, introduction of aluminium alloys with improved properties, better forming and joining technologies, etc.) may result in further weight reduction measures. Significant additional weight reduction potential is also envisaged by the application of advanced product forms such as tailored blanks (produced by different methods), roll formed profiles, etc...

4.6 Case studies

A car consists of many components and modules produced from various materials using different manufacturing processes, which undergo different types of end-of-life operations. This study tries to use a pragmatic approach to assess mass reduction by comparing specific examples of components meeting identical performance criteria:

- bumper beams
- front hoods
- motor blocks
- bodies-in-white
- metro/subway car body shells

The 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.

The quantitative determination of the environmental parameters does not only include the use stage of the component, but also considers material production, fabrication, manufacturing and end-of-life recycling. For this purpose, classical life cycle assessment (LCA) methodology is used to calculate primary energy (see Figure A1) and CO2eq savings.

5 Life Cycle Case studies

The energy savings and the resulting CO2 emissions reductions have been calculated for some case studies. The name of the vehicle manufacturer and the vehicle type has been eliminated.

For all case studies an end-of-life vehicle-processing rate of 95% was used for aluminium and steel. For all car component case studies indirect, or secondary, mass savings of 23% were factored in based on Audi’s experience with the A8 (except where noted). The actual indirect weight saving potential depends of course on the manufacturer's strategy, but is mainly determined by the realised overall vehicle weight reduction. The introduction of a single aluminium component (e.g. a bumper beam or a hood) offers little or no potential for indirect weight savings whereas significant weight reductions (e.g. an all-aluminium body structure) enable much higher indirect weight savings of the order of 50% or more

The IAI transport model for each case study can be ordered from the International Aluminium Institute (iai@world-aluminium.org)

5.1 Bumper beam of a compact car

The vehicle in Case 1 has a mass of 1 000 kg and a gasoline consumption of 6 litre per 100 km. The car manufacturer has studied an aluminium version and a steel version with identical crash energy absorption characteristics and specified the following masses from which the effective savings were calculated:

Case 1

- Mass of Al component: 3.9 kg
- Mass of mild steel component: 7.0 kg
- Mass difference: 3.1 kg

The vehicles in Case 2 have similar weight (1 100 to 1 200 kg) and similar diesel consumption of about 6 litres per 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:

Case 2

- 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

The resulting primary energy and greenhouse gas savings per kg of aluminium as a function of the lifetime distance are shown in Table 5.1. Results show, after a lifetime driving distance of 200 000 km, savings of about 210 (Case 1) and190 (Case 2) MJ per kg of aluminium in primary energy and approximately 16 (Case 1) and 15 (Case 2) CO_2eq per kg of aluminium in greenhouse gas.

	Case 1		Case 2	
Life time driving distance (km)	CO_2eq savings (kg CO2eq/kg Al)	Primary energy savings (MJ/kg Al)	CO_2eq savings (kg CO2eq/kg Al)	Primary energy savings (MJ/kg Al)
0	0	-15	0	-15
100 000	8	96	7	87
200 000	16	210	15	190
300 000	24	320	22	290

Table 5.1: Influence of lifetime driving distance on greenhouse gas and primary energy savings per kg of aluminium in the bumper of a compact car.

While the introduction of a single bumper beam offers little or no opportunity for indirect weight savings, the authors understand that the majority of automotive aluminium applications do not occur in isolation and therefore have included the following calculations to show the potential of indirect weight savings these bumper beams offer as part of an aluminium-intense structural system.

Case 1A

- Mass of Al component: 3.9 kg
- Mass of mild steel component: 7.0 kg
- Mass difference: 3.1 kg
- Indirect mass savings: 23 % of 3.1 kg = 0.71 kg
- Effective weight savings: 3.8 kg

Case 2A

- 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
- Indirect mass savings: 23 % of 2.6 kg = 0.6 kg
- Effective weight savings: 3.2 kg

The resulting primary energy and greenhouse gas savings per kg of aluminium as a function of the lifetime distance, including indirect weight savings, are shown in Table 5.1A. Results show, after a lifetime driving distance of 200 000 km, savings of about 260 (Case 1A) and 240 (Case 2A) MJ per kg of aluminium in primary energy and approximately 20 (Case 1A) and 19 (Case 2A) CO_2eq per kg of aluminium in greenhouse gas.

	Case 1A		Case 2A	
Life time driving distance (km)	CO_2eq savings (kg CO2eq/kg Al)	Primary energy savings (MJ/kg Al)	CO_2eq savings (kg CO2eq/kg Al)	Primary energy savings (MJ/kg Al)
0	0	-12	1	-12
100 000	10	120	9	110
200 000	20	260	19	240
300 000	30	400	28	370

Table 5.1A: Influence of lifetime driving distance on greenhouse gas and primary energy savings per kg of aluminium in the bumper of a compact car including indirect weight savings.

It is worth noting that this crash management comparison is valid not only with mild steel, but also with high-strength steel. In both comparisons, the aluminium bumper beam achieved significant energy and emissions advantages. Future developments should increase the weight savings using aluminium. With the same crash management requirements as case 2, 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.

5.2 Front hood of a large family car

Aluminium closure panels have offer significant weight savings. As an example, the front hood of a USA manufactured family car has been calculated. This large car has a mass of 2 041 kg with gasoline consumption of 11.2 litre per 100 km. The car manufacturer has studied the following masses from which the effective savings were calculated:

Case 5.2

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

The resulting primary energy and greenhouse gas savings per kg of aluminium as a function of the lifetime distances are shown in Table 5.2. Results for this large family car show, after a lifetime driving distance of 200 000 km, savings of approximately 170 MJ per kg of aluminium in primary energy and about 13 CO_2eq per kg of aluminium in greenhouse gas.

Here again, this study shows aluminium’s ability to reduce mass is not significantly diminished when compared to high-strength steels in closure panel applications.

Life time driving distance (km)	CO_2eq savings (kg CO2eq/kg Al)	Primary energy savings (MJ/kg Al)
0	0	-20
100 000	6	74
200 000	13	170
300 000	20	260

Table 5.2: Influence of lifetime driving distance on greenhouse gas and primary energy savings per kg of aluminium in the front hood of a large family car

As with the bumper studies, the authors also decided to include calculations showing the power of indirect weight savings for this application.

Case 5.2A

- Mass of Al component: 10.1 kg
- Mass of high strength steel component: 17.5 kg
- Mass difference: 7.4 kg
- Indirect mass savings: 23 % of 7.4 kg = 1.7 kg
- Effective weight savings: 9.1 kg

The resulting primary energy and greenhouse gas savings per kg of aluminium as a function of the lifetime distances are shown in Table 5.2A. Results for this large family car show that after a lifetime driving distance of 200 000 km, savings of approximately 210 MJ per kg of aluminium in primary energy and about 16 CO_2eq per kg of aluminium in greenhouse gas.

Life time driving distance (km)	CO_2eq savings (kg CO2eq/kg Al)	Primary energy savings (MJ/kg Al)
0	-1	-17
100 000	8	98
200 000	16	210
300 000	25	330

Table 5.2A: Influence of lifetime driving distance on greenhouse gas and primary energy savings per kg of aluminium in the front hood of a large family car including indirect weight savings

5.3 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 litres per 100 km. The car manufacturer has studied an aluminium version and a steel 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

The resulting primary energy and greenhouse gas savings per kg of aluminium as a function of the lifetime distance are shown in Table 5.3. Results for this compact car show, after a lifetime driving distance of 200 000 km, savings of approximately 280 MJ per kg of aluminium in primary energy and about 20 CO_2eq per kg of aluminium in greenhouse gas.

Life time driving distance (km)	CO_2eq savings (kg CO2eq/kg Al)	Primary energy savings (MJ/kg Al)
0	-2	-24
100 000	9	130
200 000	20	280
300 000	31	440

Table 5.3: Influence of lifetime driving distance on greenhouse gas and primary energy savings per kg of aluminium in the motor block of a compact car

5.4 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 litre per 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 primary energy and greenhouse gas savings per kg of aluminium as a function of the lifetime distances are shown in Table 5.4. Results for this luxury car show, after a lifetime driving distance of 200 000 km, savings of approximately 190 MJ per kg of aluminium in primary energy and about 15 CO_2eq per kg of aluminium in greenhouse gas.

Life time driving distance (km)	CO_2eq savings (kg CO2eq/kg Al)	Primary energy savings (MJ/kg Al)
0	-1	-21
100 000	7	84
200 000	15	190
300 000	22	290

Table 5.4: Influence of lifetime driving distance on greenhouse gas and primary energy savings per kg of aluminium in the body-in-white of a luxury car

5.5 Aluminium body of a metro/subway car

This metro/subway car has a mass of 28 000 kg and an electricity consumption of 700 MJ per 100 km. The manufacturer has studied the following masses from which the effective savings were calculated:

- Mass of Al component: 6 000 kg
- Mass of steel component: 8 000 kg
- Mass difference: 2 000 kg
- Indirect mass savings: 12 % of 2 000 kg = 240 kg
- Effective weight savings: 2 240 kg

The resulting primary energy and greenhouse gas savings per kg of aluminium as a function of the lifetime distances are shown in Table 5.5. Results for this metro/subway car show, after a lifetime driving distance of 3 000 000 km, savings of approximately 500 (European grid) and 700 (USA grid) MJ per kg of aluminium in primary energy savings and about 26 (European grid) and 51 (USA grid) CO_2eq per kg of aluminium in greenhouse gas.

	Generic European grid		Generic USA grid	
Life time driving distance (km)	CO_2eq savings (kg CO2eq/kg Al)	Primary energy savings (MJ/kg Al)	CO_2eq savings (kg CO2eq/kg Al)	Primary energy savings (MJ/kg Al)
0	-1	-25	-1	-25
1 500 000	13	200	25	300
3 000 000	26	500	51	700
4 500 000	39	700	76	1 000

Table 5.5: Influence of lifetime driving distance on greenhouse gas and primary energy savings per kg of aluminium in the aluminium body of a subway car

5.6 Total global avoided greenhouse gas emissions and primary energy savings for automotive aluminium

In chapter 5.1 to 5.4 the approximated savings for specific component case studies calculated. These were then put into context with the average component mass contained in a passenger car.

In 2006, new vehicles (passenger cars and light trucks) produced contained between 110 and 145 kg of aluminium per car and light truck (see Table 2.1). The achieved weight savings will lead to avoided global life cycle CO_2eq emissions of roughly 140 million tonnes and to primary energy savings equivalent to about 55 billion litres of crude oil.

	North America		Europe		Japan		Rest of the World		World	
	2002	2006	2002	2006	2002	2006	2002	2006	2002	2006
Vehicles produced (million units)*	16	15	19	20	10	11	10	19	56	65
Avoided greenhouse gas emissions (kg CO_2eq/car)	2 350	2 730	1 860	2 200	1 980	2 170	1 610	1 790	1 980	2 200
Primary energy savings (litres of crude oil/car)	900	1 050	710	840	760	830	620	690	760	850
Total avoided greenhouse gas emissions (million tonnes CO_2eq)	39	42	36	45	19	23	17	34	110	140
Total primary energy savings (billion litres of crude oil)	15	16	14	17	7	9	7	13	42	55

Table 5.6: Avoided life cycle greenhouse gas emissions and primary energy (measured in equivalent litres of crude oil) savings for passenger cars – (excluded indirect weight savings for closures and bumpers)
*Includes passenger cars and light commercial vehicles (International Organization of Motor Vehicles Manufacturers, 2007)

6 Vehicle safety

An important point concerning a vehicles sustainability is its crash performance. Today's vehicles have to fulfil different crash test requirements (e.g. EuroNCAP, IIHS etc.). Two of the most important vehicle crash tests are the front and the side impact. The front crash load path starts at the bumper and proceeds via the longitudinal beams to the centre area of the vehicle. At a side impact the load path starts at the doorsill and the B pillar and proceeds via the crossbeams in the floor and the roof area to the other side of the vehicle. So, in these two examples very different body components are a part of the load paths. This shows the complexity of the crash design for vehicle body structures.

In the development of the body structure, it is most important to find a suitable compromise between stiffness, crash performance and further body requirements (e.g. package, etc.). Aluminium is well suited to solve these often conflicting goals with maximum performance and the lowest possible mass. The mass-specific energy absorption capacity of aluminium is twice that of mild steel and compares also favourably to the newly developed high strength steel grades. But car safety is not only a question of the applied material, even more important is the design and assembly concept.

To increase the chances of survival in an accident, vehicles include a stiff and stable passenger cell to ensure survival space and surrounding deformation zones where the crash energy can be absorbed to a maximum amount. The high rigidity of an aluminium structure compared to a steel design is the result of the higher material thickness (aluminium components are generally about 50% thicker) and in particular the possibility to use closed multi-hole extrusions and high quality die castings of sophisticated design (which also allows the elimination of joints). Depending on the available package space, it is therefore still possible to improve the rigidity of the entire structure while maintaining a weight reduction of up to 40 – 50 %. The same principles also apply to pedestrian protection where properly designed aluminium front end structures and hoods help to prevent injuries and reduce the fatality risk.

The crash worthiness and crash compatibility of a typical SUV with other vehicles has been examined in a recent study which was carried out by Dynamic Research, Inc. (DRI, 2004) for the Aluminum Association (USA). For the first part of the study, DRI cut the weight of the SUV by 20 %, but kept its size. Next, the size of the SUV was increased by about 12 cm, keeping the weight the same. 500 virtual collisions of the SUV were simulated with various crash situations. Eighty-five crashes were single vehicle crashes, including rollovers and collisions with fixed objects, such as poles. The remaining 415 simulations were two vehicle crashes. A combination of passenger car and SUV as well as SUV and SUV crashes was used.

The initial 500 tests were run on a baseline steel SUV. The exact same 500 tests were then conducted on an aluminium SUV that had been designed to incorporate the operations of a light SUV. Finally, the same tests were again run on a slightly longer SUV, but without necessarily changing the material. Therefore the effect of weight and size on the two models was isolated.

The crash dummy was belted-in and sensors were placed in numerous locations to understand exactly how injury would occur. In every different simulation, DRI observed the impact to both drivers in the two-car crashes or the SUV driver alone in the single vehicle crashes.

When analysing the crash data and safety data, DRI used equivalent life units, in which lower numbers indicate the increased safety of passengers.

Results as Equivalent Life Units				
		Baseline steel SUV	Light aluminium SUV	Longer SUV (same weight as steel SUV)
SUV driver	Rollover (25)	0.36	0.45	0.11
	Hit fixed object (60)	0.41	0.22	0.08
	SUV-Car (250)	0.16	0.29	0.13
	SUV-SUV (164)	2.20	3.83	2.42
	Subtotal (499)	3.13	4.79	2.74
Other driver	SUV-Car	2.52	1.26	1.86
	SUV-SUV	2.35	0.74	1.31
	Subtotal	4.87	2.00	3.17
	Total	8.00	6.79 (-15%)	5.91 (-26%)

Table 6.1: Equivalent life units for a baseline steel, an light aluminium and a long SUV version

As predicted, in the baseline set of accidents (see Table 6.1), the other driver suffered more injuries. When the vehicle was light-weighted, but size remained the same, the result was 15 % fewer injuries. In the scenario of the light SUV, it is important to note that the additional design changes that could be pursued by automakers to mediate impact were not taken into account, nor was the nature of the other cars on the road. When the weight of a vehicle remains the same but the size increases, there is an even greater reduction in injury rate. Safety improves over the bottom line vehicle by 26 %. Of even greater importance is that the drivers of both vehicles in the accident see an improvement in safety.

This study supports the conclusion that varying both the weight and the size of a vehicle provides societal benefits in terms of reducing energy, injury and making roads a safer place. Aluminium is a readily available material that can help automakers produce optimised cars and trucks that consumers demand, without adding weight and without compromising fuel economy or safety. If the weight is taken out of a vehicle and size remains the same, there is less energy to absorb, while the vehicle structure is still in place to absorb the resulting energy. Further, in a vehicle-to-vehicle crash, lighter cars and trucks are much less damaging to the other vehicle, particularly the traditional passenger car. If the crush zone is increased, even by a few inches, it can have a very significant and positive safety benefit to all in every crash situation. It is in this scenario that aluminium has the most to offer for increasing both safety and environmental performance.

Furthermore, the biggest road users, trucks can also be designed to further reduce casualties in the case of crash with passenger cars. In Europe, the first step in that process was the introduction of front under run protections (FUPs) and rear under run protections (RUPs) solving the issue of the bumper height compatibility. The second step, that some truck manufacturers already made, is installing energy absorbing FUPs (eaFUPs), where aluminium can be used. In case of crash with a car, the truck eaFUP will absorb crash energy in addition to the one absorbed by the car itself, increasing significantly the safety performance.

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Annex A - Further information on light-weighting and key environmental performance indicators

A1 Primary energy by energy source and greenhouse gas emissions as an environmental performance indicator

This study will focus on the environmental aspects of the light-weighting of transport which are related to the savings of fuel and electricity.

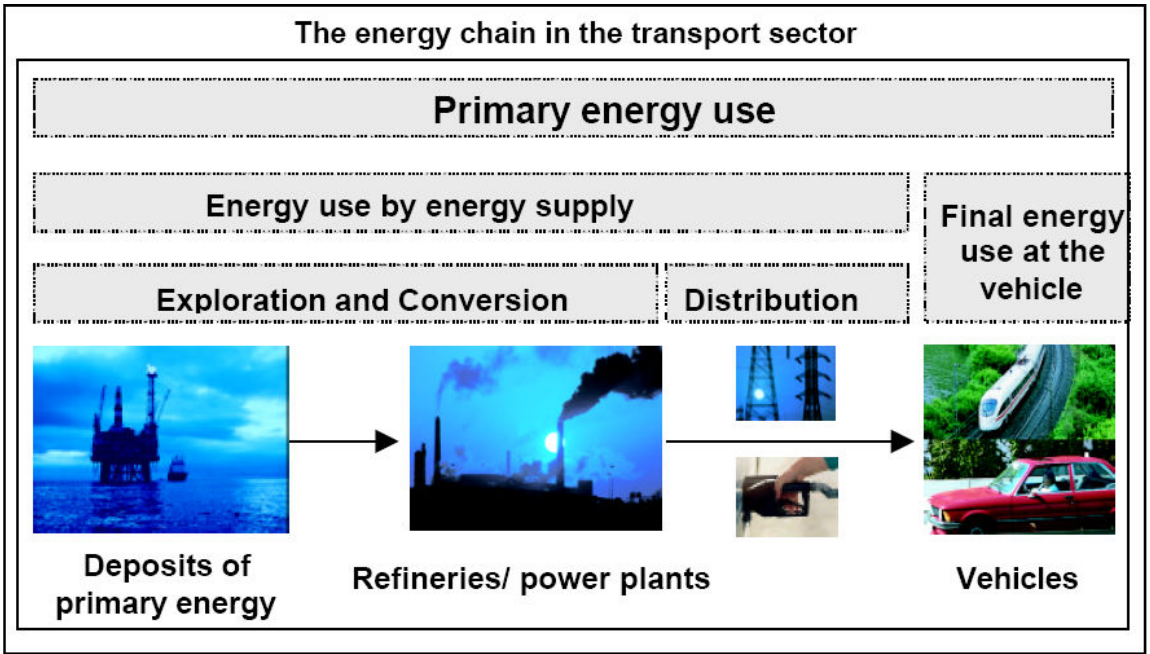
As a first step, "final energy" savings for the vehicle user are calculated, based on specific assumptions. Such final energy figures are technically very important, as they can be easily used for cost calculations. Since final energy has completely different environmental impact whether produced from hydro power, oil, gas, coal or uranium it is necessary to have a closer look at the elementary flows (e.g. the inputs directly from nature, and outputs directly to nature) of all processes of the energy supply chain are considered, including:

- extraction of energy carriers (coal, oil, natural gas, uranium) from the soil
- transport of the energy carriers to the energy conversion plants (power stations, refineries);
- conversion of the energy carriers into usable energy (electricity, fuels, etc.)
- transport of the transformed energy to the user.

Further energy is consumed and greenhouse gases are emitted with each step of the energy supply chain.

From each of these energy supply processes it is calculated how many energy resources (crude oil, natural gas, coal and uranium) have to be extracted, and their lower combustion energies and inherent energies, respectively, have to be added up. The result is a figure of environmental relevance, termed "*primary energy*".

A reduction of the final energy consumption thus also reduces the energy consumption and emissions of the upstream processes. In case of energy savings, primary energy savings (over the entire energy chain) are thus even higher than the final energy savings (at the vehicle).



Source: [IFEU 2002b] IFEU 2003

Figure A1: Energy chain in the transport sector

In order to calculate greenhouse gas emissions, all emissions of the different energy supply processes have to be added to the emissions which are generated by fuel combustion in the vehicle. From these emissions, mainly CO_2, the greenhouse gas potential is calculated in CO_2equivalents, based on internationally agreed assumptions.

Other impact categories and parameters of environmental relevance, as used in life cycle assessments, are not considered here.

A2 Final energy savings by light-weighting of road and rail vehicles

The studies by Helms et al (2003), Helms and Lambrecht (2004) and Helms and Lambrecht (2007) showed that 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 three first resistance factors are proportional with 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.

In this study, the final energy savings per 100 kg weight savings and 100 km driving distance are therefore calculated using equation (1).

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

S = Final energy savings (litres of fuel or kWh of electricity)

M = Mass of the vehicle (kg)

E = Energy consumption of the vehicle for 100km (litres/100km or kWh/100 km)

W = Portion of the aerodynamic resistance to the total resistance of the vehicle for an average driving cycle (%)

EXAMPLE: A car has a mass of M=1000 kg and an average gasoline consumption of E=6 litres per 100 km. If the aerodynamic resistance were negligible, then a 10 % mass reduction (by 100 kg) would lead to 10 % fuel savings, i.e. 0,6 litres per 100 kg and 100 km. Under realistic conditions, a W = 40 % contribution of the aerodynamic resistance to the total resistance can be assumed. This means that the savings will be in reality 60 % of 0,6 litres, i.e. 0,36 litres per 100 kg and 100 km.

Equation (1) can be applied for any individual car and driving cycle, if the basic data are known. Table A1 shows typical examples. The lifetime gasoline savings may lie between 300 and 3000 litres. The same applies for Diesel cars, where the savings in litres are about 30 % smaller.

Vehicle type	Weight	Average gasoline consumption	Gasoline consumption per 100 kg weight	Percent age air friction	Gasoline savings per 100 kg weight savings	Lifetime performance	Lifetime gasoline savings per 100 kg weight savings
	t	l/100 km	l/100 km	%	l/100 km	km	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

Table A1: Final energy savings by weight savings for different passenger car examples

The transparent methodology allows for the easy calculation of further vehicle examples. The results, however, are highly dependent on the percentage of air resistance on the total resistance. This percentage varies by vehicle, driving situation (e.g. city or highway) and driving behaviour (e.g. sportive or eco-driving). As regards different vehicle types, the air resistance in the New European Driving Cycle (NEDC) varies between 23% for luxury cars and almost 45% for sub-compact cars.

Figures A2, A3 and Table A2 demonstrate the influence of air resistance on the fuel consumption of different types of cars and driving conditions. As the underlying study has not taken the influence of the gradient resistance into account, the percentage of the air resistance is in reality smaller. If the gradient resistance is on the total fuel consumption is assumed to be 10 %, the relevant percentages given in Fig A2 and A3 and Table A2 must be reduced by 10 %.

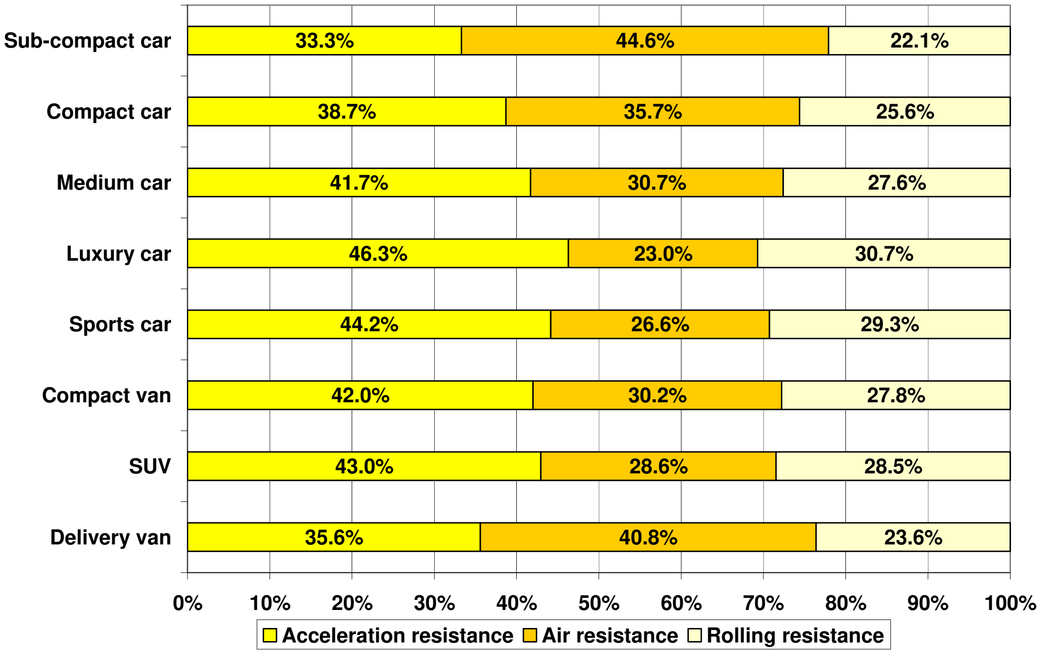


Figure A2: Share of resistance factors on total resistance in NEDC (Arning et al. (2007))

In respect to different driving situations, here represented by standard test cycles, the share of aerodynamic resistance varies between 10% in the urban part of the NEDC and almost 50% in the US HWFET (Arning et al. (2007)). At a steady speed of 120 km/h, air resistance has been found to be responsible for about 75% of the total fuel consumption (Friedrich (2002)).

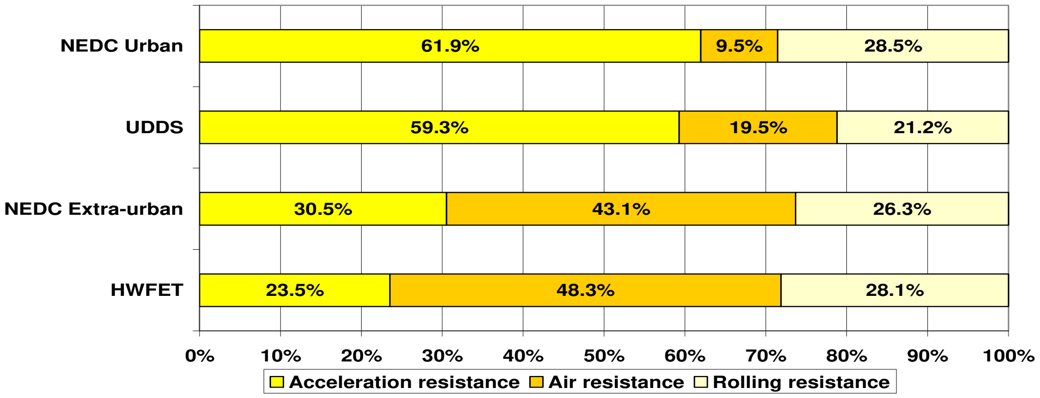


Figure A3: Share of resistance factors on total resistance in different test cylces (Arning et al. (2007))

Test cycle	Average speed	Maximum speed
New European Driving Cycle (NEDC)	32.5 km/h	120 km/h
NEDC extra urban	62.7 km/h	120 km/ h
NEDC urban	18.8 km/h	50 km/h
US Urban Dynamometer Drving Schedule (UDDS)	34.1 km/h	91.2 km/h
US Highway Fuel Economy Test Driving Cycle (HWFET)	74.3 km/h	96.4 km/h

Table A2: Speed profile of different standard driving cycles

The final energy savings during use of buses (in litres diesel), calculated according to formula (1) are shown in Table A3. It is shown that the Diesel savings per 100 kg weight savings of such vehicles are much lower than for cars, but the lifetime diesel savings per 100 kg weight savings are often higher because of the higher lifetime distance. For trucks and trailers, equation (1) and the resulting Table A4 is only valid for volume limited cargo. If a truck is used for heavy goods, the payload is restricted by the maximum permitted mass of the truck, e.g. 40 tonnes. In this case, any kg of weight savings of the truck leads to the same amount of additional payload. Depending how often the truck drives with limited maximum payload, the diesel savings during use can be significantly higher than shown in Table A4.

Vehicle type	Weight	Average gasoline consumption	Gasoline consumption per 100 kg weight	Percent age air friction	Gasoline savings per 100 kg weight savings	Lifetime performance	Lifetime gasoline savings per 100 kg weight savings
	t	l/100 km	l/100 km	%	l/100 km	km	l
City bus, few stops	15.0	40.5	0.27	45%	0.15	1 000 000	1 485
City bus, many stops	15.0	45.0	0.30	15%	0.26	1 000 000	2 550
Long distance bus, high speed	18.0	30.0	0.17	75%	0.04	1 200 000	500
Long distance bus, medium speed	18.0	35.0	0.19	50%	0.10	1 200 000	1 167

Table A3: Final energy savings by weight savings for different bus examples

Vehicle type	Weight at full load	Average diesel consumption at full load	Diesel consumption per 100 kg weight	Percentage air friction	Diesel savings per 100 kg weight savings	Lifetime performance	Lifetime Diesel savings per 100 kg weight savings
	t	l/100 km	l/100 km	%	l/100 km	km	l
Truck/trailer, long distance, medium speed	40	59	0.15	50%	0.074	1 200 000	889
Truck/trailer, long distance, high speed	27	35	0.13	70%	0.039	1 200 000	467
Truck/trailer, long distance, medium speed	27	40	0.15	50%	0.074	1 200 000	889
Light-duty vehicle, average use	3.5	12	0.34	50%	0.171	375 000	643
Light-duty vehicle, urban commercial use	3.5	13.5	0.39	25%	0.289	450 000	1302
Light truck, average use	7.5	18	0.24	50%	0.120	300 000	360
Light truck, urban commercial use	7.5	20	0.27	25%	0.200	570 000	1140

Table A4: Final energy savings by weight savings for different volume limited truck examples

The considerations leading to equation (1) can also be applied to rail vehicles. The final energy savings during the use stage of trains in form of electrical energy (in MJ) are shown in Table A5.

Vehicle type	Electricity consumption per 100 kg weight	Percentage air friction	Electricity savings per 100 kg weight savings	Lifetime performance	Lifetime electricity savings per 100 kg weight savings	
	MJ/100 km	%	MJ/100 km	km	MJ	kWh
Subway/urban train -per wagon	2.5	20%	2.00	3 000 000	60 000	16 667
Short distace train -per wagon	2.50	30%	1.75	4 000 000	70 000	19 444
Normal passenger train -per wagon	1.00	60%	0.40	8 000 000	32 000	8 889
High-speed passenger train -per wagon	1.00	70%	0.30	15 000 000	45 000	12 500
Freight train -per wagon	0.80	50%	0.40	8 000 000	32 000	8 889

Table A5: Final electricity savings by weight savings for different train examples

A3 Primary energy and greenhouse gas savings of vehicles by light-weighting

Based on the final energy (fuel and electricity) savings during the use stage primary energy savings and greenhouse gas savings caused by weight savings of 100 kg have been calculated (see Table A6 to A10).

Vehicle type	Weight	Average gasoline consumption	Percent-age air friction	Lifetime performance	Lifetime primary energy savings by 1 kg weight savings	Lifetime greenhouse gas savings by 1 kg weight savings
	t	l/100 km	%	km	MJ	kgCO2eq
Small car, average use	1.0	6.0	40%	200 000	280	20.2
Small car, mainly urban	1.0	8.5	35%	150 000	323	23.3
Medium sized car, mainly long distances	1.6	9.0	50%	300 000	328	23.7
Luxury car, mainly long distances	2.0	12.0	50%	100 000	117	8.4
Medium sized car, Taxi	1.6	11.0	25%	500 000	1 004	72.5
City bus, few stops	15	40.5	45%	1 000 000	610	44.3
City bus, many stops	15	45	15%	1 000 000	1 048	76.0
Long distance bus, high speed	18	30	75%	1 200 000	205	14.9
Long distance bus, medium speed	18	35	50%	1 200 000	479	34.8
Truck/trailer, long distance, medium speed	40	59	50%	1 200 000	548	39.7
Truck/trailer, long distance, high speed	27	35	70%	1 200 000	415	30.1
Truck/trailer, long distance, medium speed	27	40	50%	1 200 000	438	31.8
Light-duty vehicle, average use	3.5	12	50%	375 000	264	19.2
Light-duty vehicle, urban commercial use	3.5	13.5	25%	450 000	535	38.8
Light truck, average use	7.5	18	50%	300 000	148	10.7
Light truck, urban commercial use	7.5	20	25%	570 000	468	34.0

Table A6: Primary energy and greenhouse gas savings for different road vehicle examples

Vehicle type	Electricity consumption per 100 kg weight	Percentage air friction	Lifetime performance	Lifetime primary energy savings by 1 kg weight savings	Lifetime greenhouse gas savings by 1 kg weight savings
	MJ/100 km	%	km	MJ	kgCO2eq
Subway/urban train -per wagon	2.5	20%	3 000 000	1304	71.2
Short distace train -per wagon	2.5	30%	4 000 000	1522	83.1
Normal passenger train -per wagon	1.0	60%	8 000 000	696	38.0
High-speed passenger train -per wagon	1.0	70%	15 000 000	978	53.4
Freight train -per wagon	0.8	50%	8 000 000	696	38.0

Table A7: Primary energy and greenhouse gas savings for different rail vehicle examples

	Unit	Container ships	General cargo ships	Tankers	Container
Dead weight	t	20 000	20 000	100 000	20 000
Ship weight	t	5 000	5 000	25 000	5 000
Total weight	t	25 000	25 000	125 000	25 000
Motor performance	HP	16 961	8 806	19 170	16 961
Fractional load	%	80%	80%	80%	80%
Fuel consumption	t/ h	5.1	2.6	5.7	5.1
Fuel consumption per hour and per t weight	kg Diesel	0.203	0.106	0.046	0.203
Hours per day	h/ d	24	24	24	24
Operation days per year	d/ a	300	300	300	150
% under use	%	82%	82%	82%	41%
Hrs per year	h/ a	7 200	7 200	7 200	3 600
Years in operation	a	25	25	25	13
Lifetime operation hours	h	180 000	180 000	180 000	45 000
Lifetime fuel consumption	t	91 4492	474 796	1 033 595	228 623
Lifetime fuel consumption per tonne of total weight	t/t	36.6	19.0	8.3	9.1
Lifetime energy consumption	GJ	39 286 571	20 397 237	44 403 252	9 821 643
Lifetime energy consumption per t of total weight	GJ/t	1571	816	355	393
% energy savings by 10 % gross weight reduction	%	7%	7%	7%	7%
% use at full load	%	80%	80%	50%	80%

	Unit	Container ships	General cargo ships	Tankers	Container
% use with ballast	%	0%	0%	50%	0%
% other use	%	20%	20%	0%	20%
Fuel savings per % gross weight savings	%	94%	94%	50%	94%
Lifetime fuel savings per tonne weight savings	t/t	34.4	17.9	4.1	8.6
Lifetime final energy savings per tonne of weight savings	GJ/t	1 477	767	178	369
Lifetime primary energy savings per tonne weight savings	GJ/t	1 698	882	204	424
Lifetime CO2eq savings	t CO2/t	123.2	64.0	14.8	30.8

Table A8: Primary energy and greenhouse gas savings of cargo ships, tankers and containers

	Unit	High speed passenger ferry
Total weight, steel version	tonnes	2 030
Total weight, aluminium version	tonnes	1 425
weight saving	tonnes	605
Running time	hours/year	4 440
% under use	%	51%
Years in operation	years	20
Hours in operation	hours	88 800
Annual final energy consumption, steel version	GJ/year	2 074 425
Lifetime final energy consumption, steel version	GJ	41 488 500
Annual final energy consumption, aluminium version	GJ/year	1 649 760
Lifetime final energy consumption, aluminium version	GJ	32 995 200
Lifetime final energy savings Al vs steel	GJ	8 493 300
Lifetime final energy savings per tonne weight saving	GJ/t	14 039
Lifetime fuel savings per tonne weight saving	t/t	327
Fuel savings per hour and per tonne weight saving	kg Diesel	3.7
% energy savings by 10 % gross weight reduction	%	70%
Fuel consumption per hour and tonne	kg Diesel	5.3
Lifetime primary energy savings per tonne weight saving	GJ/t	16 136
Lifetime greenhouse gas savings per tonne weight savings	tonnesCO2eq/t	1 171

Table A9: Primary energy and greenhouse gas savings of a high speed passenger ferries

	Unit	Passenger ferry
Total weight	Tonnes	2 000
Motor performance	Horsepower	2 415
Fuel consumption	t/h	0.70
Years in operation	Years	20
Hours in operation	Hours	88 800
% under use	%	51%
Lifetime fuel savings per tonne weight saving	t/t	24.2
Fuel savings per hour and per tonne weight saving	kg Diesel	0.27
% energy savings by 10 % gross weight reduction	%	7%
Fuel consumption per hour and tonne		0.39
Lifetime final energy savings	GJ/t	1 040
Lifetime primary energy savings	GJ/t	1 200
Lifetime greenhouse gas savings per tonne weight savings	tonnesCO2eq/t	87

Table A10: Primary energy and greenhouse gas savings of passenger ferries

Annex B - Aluminium recycling in Life Cycle Assessment

B1 Introduction

Within the concept of sustainable development, the closing of the material loops plays an essential role. Therefore, the recycling of used products and scrap associated with product systems are of crucial importance. The European aluminium industry puts a lot of effort into continuously enhancing the recycling of used aluminium products and scrap including the reduction of the environmental impacts associated with recycling processes. This document may assist LCA practitioners, experts and users to adequately reflect today's reality for aluminium recycling and how to model this in LCAs.

Numerous factors affect the results of an LCA study of a specific product. Not only the material it is made of, the various production processes involved and the use phase but also its end-of-life treatment. The ISO 14040 and ISO 14044 standards aim at defining the rules and the methodologies for considering and integrating properly all these phases of a product life time but some necessary flexibilities are left to practitioners, especially in relation to allocation methods and system boundary definition. Regarding the end of life treatment of a product, different scenarios like re-use, recycling, incineration, or land filling can be envisaged. This document aims at a more detailed analysis how to consider recycling within an LCA study where aluminium is involved and how to credit the recycling benefits to the product system under consideration.

The metallic structure distinguishes metals from other materials, as this structure is not affected by melting processes, which are at the heart of the recycling operations. That is why metals and their alloys can maintain their inherent properties after scrap melting and are in principle indefinitely recyclable into new products.

In practice, recycled aluminium alloys generally substitute primary aluminium alloys for new aluminium products. The system expansion and substitution method, which follows the guidance given in ISO 14044, aims at considering this ability of aluminium in LCA studies.

B2 Aluminium recycling today

In order to assess the aspects associated with aluminium recycling in an LCA study, the following issues should be considered:

a) The quantity and quality of the new scrap from the fabrication of semi-finished products, components or final products. This scrap typically arises, e.g. during the production of semis, fabrication processes of parts or components from semi-finished aluminium products (sheet, foil, extrusions, etc.) or through machining operations.

b) The available quantity and quality of old scrap, e.g. end-of-life aluminium scrap. This is generally determined by the efficiency of the collection and sorting prior to the scrap melting itself.

c) The efficiency of the scrap melting process and its corollary, the quantity of aluminium lost in the recycling process. To assess this quantity accurately, it is necessary to define the end of life treatment of the product under consideration as well as the recycling operations in detail, based on realistic scenarios, because it depends of a number of factors such as scrap type or melting process. Except for a few high volume types of scrap, recycling is commonly not product-specific, i.e. process scrap and scrap from different end-of-life products are often mixed in the recycling process stream input with the intention of producing an alloy according to a specification. A careful check of the particular aluminium product situation is always recommended.

These various elements are necessary to evaluate the complete efficiency and the environmental consequences of the recycling process.

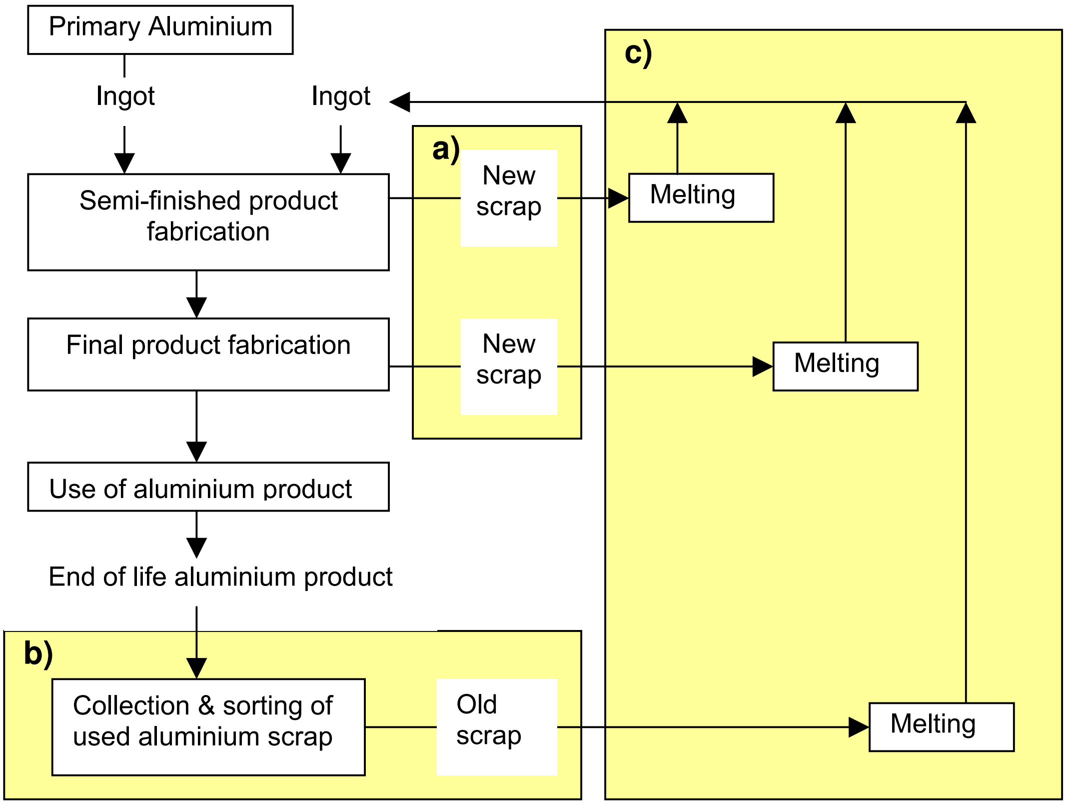


Figure B1: Recycling process, new and old scrap substitute primary aluminium

The output of scrap melting is a recycled aluminium alloy ingot. This material can be used interchangeably with ingots produced from primary aluminium. In other words it substitutes primary aluminium.

Those aspects are relevant when bringing aluminium products into an LCA context.

B3 System expansion and substitution method

An LCA deals with product systems which model the full life cycle of a product, including raw material acquisition, fabrication, transportation, use, recycling/disposal and the operations of energy supply, ancillary material supply, transports, etc. Thus recycling is part of any LCA. It is often a complex issue which requires specific considerations.

An easy case is if one product with a short lifetime is recycled into the same product, such as an aluminium can. However, in reality this is often the exception. Therefore modelling approaches have to be applied, which reflect or come close to the reality.

The aluminium economy is a cycle economy. Therefore, a life cycle of an aluminium product is not "cradle-to-grave", but rather "cradle-to-cradle". This means that the life cycle of an aluminium product usually ends when the recycled aluminium is rendered in a form usable for a new aluminium product

e. g. an ingot used to fabricate and manufacture new aluminium products, see also Figure 4.1.

According to ISO 14044 allocation procedures for recycling can be addressed as follows:

- *a closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems, where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.*

Because of their metallic nature, aluminium and its alloys have – contrary to solid organic materials or refractories – the ability to maintain their inherent metallic properties during recycling. As a consequence, the system expansion and substitution method is applicable to the LCA of aluminium products. Thus, ISO 14044 standard recommends to expand the system under study to include the end-of-life recycling, resulting in substitution of primary material by recycled material.

Example 1: System expansion and substitution method for recycling

100 kg of aluminium is required for a product system

90 kg of recycled aluminium ingots (with the same inherent metallic properties as primary aluminium) are obtained after collection and sorting of the end-of life product and scrap melting.

→ 90 kg of recycled aluminium ingots substitute 90 kg of primary aluminium ingots.

Thus, the environmental burdens of the production of only the lost aluminium, i.e. 10 kg of metal, have to be charged to the product system under study, together with the burdens of the recycling operations.

B4 Recycled aluminium as input

ISO 14044 requires that allocation procedures have to be uniformly applied to similar inputs and outputs of the system under consideration. The rules on how to treat incoming recycled aluminium have to correspond with the methods for treating recycled metal leaving the system.

The maintained inherent metallic properties also mean that the system expansion and substitution method can be applied here. Therefore, there is no need to consider the incoming portion of recycled aluminium, since only the metal loss during the complete life cycle of the product must be taken into account.

Example 2: System expansion and substitution method & recycled metal as input

100 kg of aluminium is required for a product system. It may consist of 40 kg of primary aluminium and 60 kg of recycled aluminium with the same inherent properties as the primary aluminium.

80 kg of recycled aluminium ingots result from recycling, including scrap melting.

→ 20 kg of aluminium is littered or landfilled.

The environmental burdens of the production only of the lost aluminium, i.e. 20 kg of primary metal, have to be charged to the product system under study, together with the burdens of the recycling operations. These environmental burdens are valid whatever the input of the recycled metal.

B5 Long lifetime products

Aluminium products often have extended life times because of their high corrosion resistance, e.g. in mass transportation systems or buildings. Such products may not be mistreated in LCA studies by omitting recycling credits as described in Section 3 above.

Any uncertainty about recycling rates and recycling techniques for long-life aluminium products is not sufficient to refuse recycling credits. It rather has to be dealt with by applying different recycling scenarios in the form of sensitivity analyses, which must include the state-of-the art recycling technique for the product under study and the expected recycling situation in the future.

B6 Market value analysis

operations can lead to a change of the inherent properties of the recycled material compared to primary (virgin) material. In this case an allocation procedure may be appropriate and can be addressed according to ISO 14044 as follows:

- *an open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.*

If inherent properties are changed, the standard ISO 14044 (subclause 4.3.4.3.4), recommends to use primarily physical properties or secondly economic value as basis for allocation procedure. In practice, only the second allocation procedure which compares the market value of the recycled material with that of the primary material, is applicable for aluminium. If the market value analysis shows that the market value of the material obtained from recycling end-of-life products is the same as the market value of primary material, then the system expansion and substitution method can be applied, effectively treating the product system as a closed loop system.

The so-called “value corrected system expansion and substitution method” is applied if the market value analysis shows a difference between the market value of the primary material and the market value of the corresponding recycled material obtained at the end-of-life. This method assumes that the substitution ability is reflected by the ratio between the market prices of the recycled and primary material. As an example, if the market price of the recycled material is 90% of the market price of the primary material, 1 kg of recycled material will substitute only 0,9 kg of primary material.

If the value-corrected system expansion and substitution method is applied for recycled material at the output side, then the value of the incoming recycled material has to be considered, as well, in order to ensure methodological consistency. Example 3 illustrates the calculation method.

Example 3: Value-corrected system expansion and substitution method

100 kg of material is required for a product system.

90 kg of recycled material with 90 % of the value of primary material result from recycling, including scrap melting. 10 kg of material is lost, e.g. littered or land-filled.

The **net material loss** is calculated as **Mass of input material** minus **value-corrected mass of output material**

- Mass of input material: 100 kg

- Value-corrected mass of output material: 90 kg x 0.9 = 81 kg.

- Net material loss is 100kg - 81 kg = 19 kg.

The environmental burdens of the production of the lost material, i.e. 19 kg of primary material, have to be charged to the product system under study, together with the burdens of the recycling operations.

NB: This example only considers value-correction on the output side. If the input material has a lower value than pure primary material, a value-correction needs to be applied on the input side as well.

The market value analysis can be applied for any specific situation, as the recycled material which leaves the product system is usually traded on the market.

In comparative LCA studies, the result is often highly dependent on the treatment of recycling of the different materials. For such studies, a market value analysis allows to clarify the question to what extent the system expansion and substitution method can be applied.

B7 Recycled metal content: the inappropriate method

“Recycled content” is a phrase with a certain ecological appeal. What, however, does “recycled content” actually mean in the context of the aluminium market?

If all aluminium applications were grouped together, the average global recycled content (excluding internal scrap) would stand at around 35% overall. But, in reality, recycled content varies substantially from one product to another. With the continued growth of the aluminium market and the fact that most aluminium products have a fairly long lifetime it is not possible to achieve high recycled content in all new aluminium products, simply because the available quantity of end-of-life aluminium falls considerably short of total demand.

Furthermore, recycled aluminium is used where it is deemed most efficient in economic and ecological terms. Directing the scrap flow towards designated products, in order to obtain high-recycled content in those products, would inevitably mean lower recycled content in other products. It would also result in inefficiency in the global optimisation of the scrap market, as well as wasting transportation energy. Calls to increase recycled content in specific categories of aluminium products make no ecological sense at all.

As an example, if an external region buys large quantities of aluminium scrap in Europe or North America, the recycled content of their own aluminium products increases and the recycled content of the aluminium products in other regions decreases. Thus it would be clearly misleading to conclude from this fact that the aluminium products of this specific region have become "greener"!

The above example shows that the "recycled metal content” approach is not appropriate for decision making.

B8 Key positions

1. The high value of aluminium scrap is a key incentive and major economic impetus for recycling. In practice, recycled aluminium alloys substitute primary aluminium alloys for new aluminium products. The system expansion and substitution method is adequate to reflect this.
2. If in comparative LCA studies there is any doubt for one of the materials that the recycled material does not have the same inherent properties as the primary material, then it should be clarified by a market value analysis whether it is necessary to apply a value correction or not.
3. From an LCA point of view the “recycled content” approach does not refer to end-of-life recycling and thus not to the life cycle of an aluminium product. From an environmental point of view, the demand for an increase in the amount of recycled material in some aluminium products does not make sense because of the limited available quantity for recycling. Thus this approach is not appropriate and cannot be justified by environmental considerations.
4. In practice, aluminium is not consumed but rather used. Therefore, the life cycle of an aluminium product is usually not "cradle-to-grave", but rather "cradle-to-cradle". This means that the life cycle of an aluminium product usually ends, when the recycled aluminium is rendered in a form usable for a new aluminium product e.g. as an ingot which is used to fabricate new aluminium products. In this context, the system expansion and substitution methodology appears

the most adapted method to integrate in LCA studies the recycling of aluminium products.