Alcoa

Comparative Life Cycle Assessment of Aluminum and Steel Truck Wheels

9/20/2012

PE INTERNATIONAL & Five Winds Strategic Consulting

Contact:	PE INTERNATIONAL, Inc.
Christoph Koffler, PhD	344 Boylston Street, 3rd Floor
Jonathan Provo	Boston, MA 02116, USA

Phone	+1 [617] 247-4477
Fax	+1 [617] 236-2033
Email	c.koffler@pe-international.com

Table of Contents

List of Figures

List of Tables

Acronyms

AP	Acidification Potential
EoL	End-of-Life
EP	Eutrophication Potential
GaBi	*Ganzheitliche Bilanzierung* (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
PED	Primary Energy Demand
POCP	Photochemical Ozone Creation Potential (Summer Smog)
VOC	Volatile Organic Compound

EXECUTIVE SUMMARY

Alcoa Inc., a major global manufacturer of aluminum products, desired a comparative environmental assessment of its forged aluminum truck wheels with steel truck wheels. In order to better understand the impacts arising from the production and use of its own forged aluminum truck wheels and to evaluate those impacts in comparison to steel truck wheels, PE INTERNATIONAL has conducted a 'cradle-to-grave' Life Cycle Assessment of these products. The resulting study is a comparative assessment intended for public disclosure and thus must adhere to ISO 14040/44 standards including submission to a Critical Review Panel.

The LCA was conducted based on a functional unit of "coupling truck tires to vehicle hubs" for an estimated wheel lifetime mileage of 1,000,000 miles under North American boundary conditions or 1,500,000 kilometers under European boundary conditions.[1] The functional unit is represented as a complete set of truck wheels—eighteen (18) for North America and twelve (12) for Europe—with sensitivity analysis performed around the potential need for additional truck wheels under warranty or failure conditions. Mass-restricted, volume-restricted, and average use case scenarios are evaluated and supplemented by a sensitivity analysis to capture the full breadth of potential operating conditions for a tractor-trailer truck.

Primary data for aluminum wheel production were obtained from five Alcoa facilities worldwide, while steel wheel production is based on conservative estimates derived from process expertise. PE provided upstream data for fuels, raw materials, and steel wheel manufacturing processes, including primary metals and chemicals.

Primary data for aluminum is based on 2009 data for North American aluminum production from the Aluminum Association and 2005 data for European aluminum production from the European Aluminum Association. Primary steel production is based on 2007 data from Worldsteel, and is assumed to be representative of the global production activity. At the time of this study, these data points represent the most recent industry-average information for these primary metals available.[2]

In End-of-Life, a novel approach to Value-Corrected Substitution was applied for the base case scenario, which uses the ratio of scrap to primary metal value as an indicator for the product-specific degree of quality loss based on four-year average price ratios.[3] To test the influence of different substitution

[1] Herbert and Fischer (2004): Load Program Development and Testing of Super Single Wheels in the Biaxial Wheel Test Rig and Numerical Pre-Design. SAE International 2004-01-2691.

[2] The 2009 Aluminum Association (AA) data on US primary ingot is part of the currently ongoing data update performed jointly by AA and PE INTERNATIONAL. The data was shared with Alcoa for this specific project under authorization by AA and is an update to the primary aluminum LCI developed in 2010 available at www.aluminum.org\lca

[3] Koffler (2011): Tackling the Downcycling Issue - A Revised Approach to Value-Corrected Substitution. ACLCA LCA XI conference. October 4-6, 2011, Chicago. Available at http://lcacenter.org/lcaxi/presentations/342.pdf.

factors, the two extreme scenarios of 0% (cut-off) and 100% (avoided burden) were also calculated as part of the study's sensitivity analyses.

Wheel life cycle environmental impacts were calculated for primary energy demand, acidification potential, eutrophication potential, global warming potential, ozone depletion potential, smog formation potential, human toxicity and eco-toxicity. All aluminum wheel impacts are shown as differences to the steel wheel baseline unless otherwise stated.

Impact results are dominated by the use phase savings and upstream primary metal production. Primary aluminum production carries a higher specific burden than steel production, giving the aluminum wheels a larger 'footprint' at the onset of the use phase. The lightweight aluminum wheels enable use phase environmental benefits when compared to steel wheels, either by allowing the vehicle to carry additional cargo (*mass-restricted case:* gross vehicle weight remains unchanged) or through improved fuel efficiency due to light-weighting (*volume-restricted case:* gross vehicle weight decreases). This results in break-even points for most studied impacts (exceptions being ozone depletion potential and primary energy demand in the US and smog potential in the EU) which are within the lifetime mileage of the wheels in both of these extreme scenarios. The impacts from the mass-restricted and volume-restricted use phases are then combined as a weighted average. A combination of 69% mass restricted and 31% volume restricted was utilized to approximate a 78% utilization rate, which is typical for a tractor-trailer truck according to the last US Census Bureau Vehicle Inventory Use Survey (VIUS) conducted in 2002.[4]

As a result, the aluminum wheel life cycle shows an improved environmental performance compared to steel wheels for most studied impacts in all three use phase scenarios if recycling credits are included. This outcome is generally consistent for both North American and European boundary conditions.

[4] United States Census Bureau, Vehicle Inventory and Use Survey (VIUS), 2002 Data Releases. Online at http://www.census.gov/svsd/www/vius/2002.html.

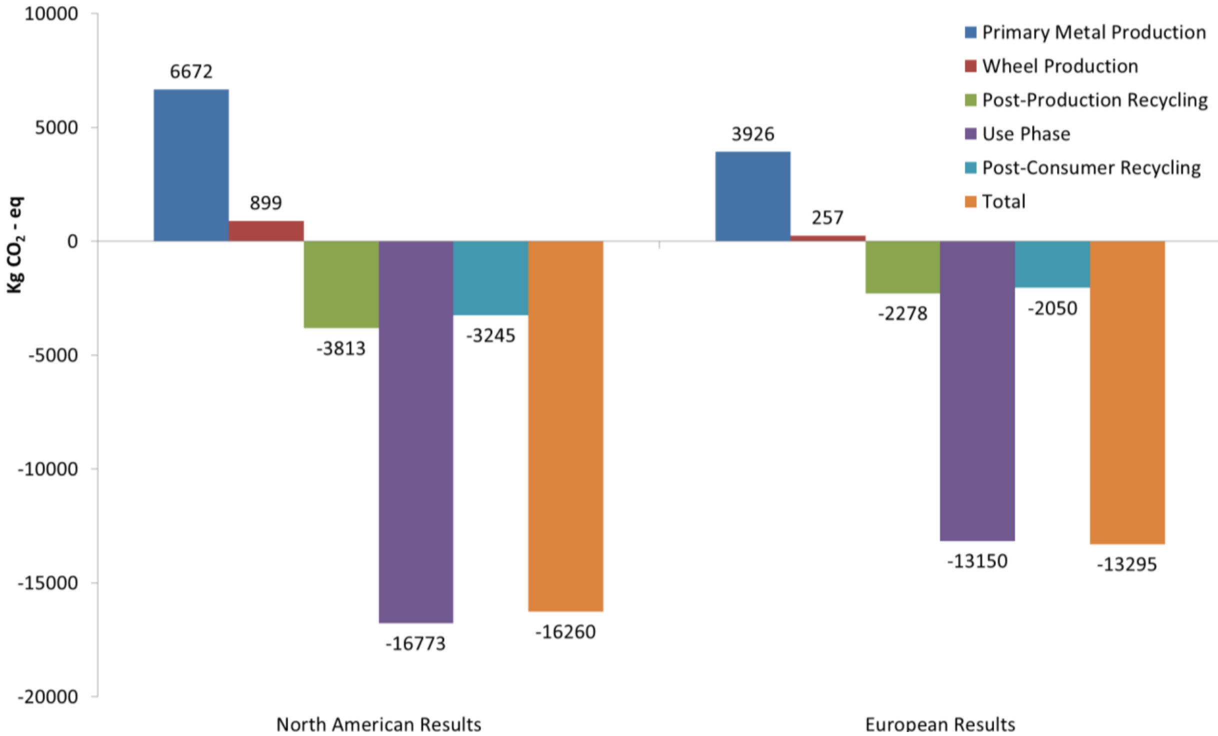

Figure 0-1: Alcoa Aluminum Truck Wheels vs. Steel Wheels (Average Use Case)

Figure 0-1 displays the full life cycle global warming potential for both European and North American boundary conditions **compared to steel wheels for the average use case** applying a Value-Corrected Substitution approach to End-of-Life allocation. Positive values indicate those life cycle phases where aluminum wheels have a higher global warming potential than steel wheels, and negative values indicate those with a lower global warming potential than steel wheels. Primary metal production and wheel production (the blue and red bars) are higher for aluminum wheels; however, use phase savings (16.8 t resp. 13.2t, represented by the purple bars above) lead to a net benefit for aluminum wheels over steel wheels. Recycling credit is given for post-production and post-consumer recovery of metal (green and light blue bars in Figure 0-1) which, as shown in the chart, further increase the net savings over the steel truck wheels (orange bars).

As can be seen, aluminum wheels allow for a **net cradle-to-grave reduction of 16.3 metric tons of CO_{2e} emissions** under North American boundary conditions. That means that substituting 18 conventional steel wheels by aluminum wheels with a weight advantage of 414 pounds[5] saves 16.3 tons of CO_{2e} over their total lifetime.

Under European boundary conditions, 13.3 tons of CO_{2e} savings over the steel wheel baseline are achieved over the total wheel life cycle. The truck model for Europe employs 12 wheels with a total weight advantage of 474 pounds (251 kg)[6], which is even higher than for the US scenario due to

[5] 810 lbs of aluminum vs. 1,224 lbs of steel
[6] 268 kg of aluminum vs. 483 kg of steel

different wheel geometries. The EU use phase savings in the average use case are nevertheless smaller than in the US since it is dominated by the mass-restricted results, which produce higher fuel savings per tkm for the US truck due to its lower fuel economy. However, the European scenario is not to be considered "worse" than the North American case as the total CO_{2e} savings per wheel in Europe (1.11 tons CO_{2e}) are actually greater than the savings per wheel in North America (0.93 tons CO_{2e}).

The CO_{2e} savings are tied to the Global Warming Potential of the product and include an aggregation of multiple greenhouse gases (carbon dioxide, methane, nitrous oxide, various volatile organic compounds, perfluorocarbons) into a carbon dioxide equivalency. To put this in perspective, the savings from switching *one truck* from steel wheels to forged aluminum wheels in the US average use case is *approximately* equal to the average annual carbon footprint of a four person household[7]. Again, this is just the savings from one truck. Global Warming Potential is only one of the various impact categories examined in this study. For a further explanation of Global Warming Potential and other impact categories, please see Chapter 4.

It can clearly be seen that the benefits of the fuel savings during the use phase significantly over-compensate the additional burden during the production of the wheels. If one was to calculate a **'Carbon Return-on-Investment'** (an analogy to a financial return on investment[8]) for the Aluminum truck wheels based on the results obtained in this study, it would amount to a notable **426 % for the US scenario** and **700 % for the EU scenario**. This result is arrived at by dividing the net carbon savings (use phase savings + end-of-life credit – manufacturing burden) by the manufacturing burden, or more explicitly (16.8+3.2-3.8)/3.8 = 426%.

This is further substantiated by the **break-even mileages of roughly 224,000 miles in the US scenario and about 225,000 km (140,000 miles) in the EU scenario**, which correspond to only 22 % and 15 % of the respective wheel lifetime mileages.

Other use case scenarios and End-of-Life treatments capture a spectrum of life cycle outcomes in the comparison of aluminum and steel truck wheels. The *cut-off approach* is a conservative End-of-Life scenario in which no credit is given for metal recycling; *avoided burden*, on the other hand, gives full credit for the substitution of primary metal at End-of-Life. The *volume-restricted scenario* takes a conservative approach to the use-phase, while the *mass-restricted scenario* is where aluminum truck wheels have the highest benefit over steel truck wheels.

A volume-restricted use case combined with an End-of-Life cut-off –the most conservative scenario– results in a net burden of 2.9 tons of carbon dioxide for the aluminum wheels when compared to steel wheels. The most favorable approach for aluminum truck wheels (the mass-restricted use case with avoided burden at End-of-Life) provides a lifetime savings of 18.9 tons of carbon dioxide for aluminum truck wheels over steel truck wheels.

[7] http://www.epa.gov/climatechange/emissions/ind_home.html
[8] Return on investment (%) = Net profit ($) / Investment ($) * 100 %

Based on the above results and taking into consideration the rather conservative assumption about wheel lifetime and the negligence of rotational inertia effects on fuel economy, the use of Alcoa forged aluminum wheels over steel wheels can be seen as an active and highly efficient investment into the reduction of greenhouse gas emissions in the commercial vehicle sector.

1 GOAL OF THE STUDY

Alcoa Inc., a major global manufacturer of aluminum products, sought to compare the environmental performance of aluminum truck wheels with their steel counterparts by conducting a full Life Cycle Assessment (LCA) according to the ISO 14040/14044 methodology. Specifically, they are interested in juxtaposing their own forged aluminum truck wheels and steel truck wheels from cradle-to-grave.

Alcoa has engaged PE INTERNATIONAL, Inc. to assess and compare the environmental impacts of aluminum and steel truck wheels. The analysis was performed conducting a cradle-to-grave, comparative life cycle assessment (LCA). The goals of this study are to:

1. Better understand the environmental performance of Alcoa's aluminum truck wheels;
2. Compare the environmental performance of Alcoa's aluminum truck wheels to functionally equivalent steel wheels
3. Identify the break-even mileage for each impact category considered

The intended audience of this study includes internal stakeholders at Alcoa such as product designers, marketing professionals, environmental and sustainability personnel, and senior management, as well as external stakeholders such as customers, NGOs, investors, and the general public. The intended applications will cover Alcoa business functions related to aluminum wheel design as performed by engineers and designers, as well as marketing of aluminum wheels as fulfilled by the marketing department to inform customers and other external parties.

The results of this study represent comparative assertions intended to be disclosed to the public. As such, this report will be critically reviewed by a Critical Review Panel as required by the ISO 14044 standard.

2 Scope of the Study

The following section describes the general scope of the project and the approach used to achieve the stated goals. This includes the identification of specific manufacturing technologies to be assessed, the supporting product systems, the system boundary of the study, allocation procedures, and cut-off criteria. Data sources are discussed in this section, but the actual life cycle modeling will be reported in detail in section 3.

2.1 Product Description

The Alcoa Aluminum wheel modeled is a 22.5”x8.25” (22.5”x9” and 22.5”x11.75” for EU) forged aluminum wheel with a standard finish that is covered by a five year warranty. The representative steel wheel to be compared is a 10 bolt tubeless, coated steel wheel. The steel wheel is also covered by a five year warranty which serves to further emphasize the justification of assuming an equal reference flow for both materials.[9]

Figure 2-1: Alcoa Aluminum Wheel

2.2 Functional Unit & reference flows

The functional unit determines the amount of Alcoa’s aluminum wheels to which all data will be related in the study. Since the study is to compare different wheels, the functional unit needs to express the common service provided by these products. The main function of a wheel is to couple the tire to the vehicle hub, enabling locomotion of the vehicle. To that end, aluminum and steel wheels are said to have functional equivalence.

The magnitude of the service is then described by the number of wheels per vehicle, which is

[9] Based on Accuride steel wheel P/N 50487 and on Hayes Lemmerz steel wheels P/N 10053TW and P/N 2920524TW (for the EU case)

- 18 for a US class 8 Semi-Trailer Truck (10 on tractor / 8 on trailer) using 8.25'' wide wheels,
- 12 for a European category N3 Large Goods Vehicle (6 on tractor, 6 on trailer) using six 9'' and six 11.75" wide wheels, [10] and
- 10 for a US class 8 Semi-Trailer Truck (6 on tractor / 4 on trailer) using Alcoa's new series of 14'' wide wheels.

The latter scenario will only be considered under US boundary conditions, as the wide base aluminum wheels are only applicable to the US market.

The *lifetime of the wheels* is based on the Fraunhofer Institute for Structural Durability and System Reliability (LBF) biaxial fatigue testing where it is mandated by all EU truck manufacturers that wheels be able to sustain load for an equivalent 1.5 million kilometers of testing.[11] Alcoa's aluminum wheels have achieved this requirement, and it is assumed that equivalent steel wheels do as well as they are also sold in the EU. The lifetime of the wheels is therefore set as 1,500,000 km (932,056 miles) for Europe and 1,000,000 miles for the US (value rounded up from the European number for simplicity). The desired *duration of the service* is also set to the same values resulting in the consideration of one set of wheels for each scenario as described above.

The expected lifetime mileage for both steel and aluminum wheels does not address edge cases, such as accidents that might catastrophically damage the wheels. This scenario will be addressed in sensitivity analysis. Information on wheel corrosion is insufficient for making conclusions on failure, but as this might represent another failure mode it is said to be addressed in the sensitivity analysis around replacing wheels.

In summary, the functional unit for this study is defined as:

Coupling truck tires to vehicle hubs over a total mileage of
1,000,000 miles (US) / 1,500,000 km (EU)

The resulting reference flows per scenario therefore are:

- **Scenario A1:** eighteen (18) 8.25'' wide aluminum wheels and eighteen (18) 8.25'' wide steel wheels for the US,
- **Scenario A2:** two (2) 8.25'' and (8) 14'' wide aluminum wheels and eighteen (18) 8.25'' wide steel wheels for the US, and
- **Scenario B:** six (6) 9'' and six (6) 11.75" aluminum wheels and six (6) 9'' and six (6) 11.75" steel wheels for the EU

[10] US: Federal Highway Administration Classification; EU: Directive 2001/116/EC
[11] Herbert and Fischer (2004): Load Program Development and Testing of Super Single Wheels in the Biaxial Wheel Test Rig and Numerical Pre-Design. SAE International 2004-01-2691.

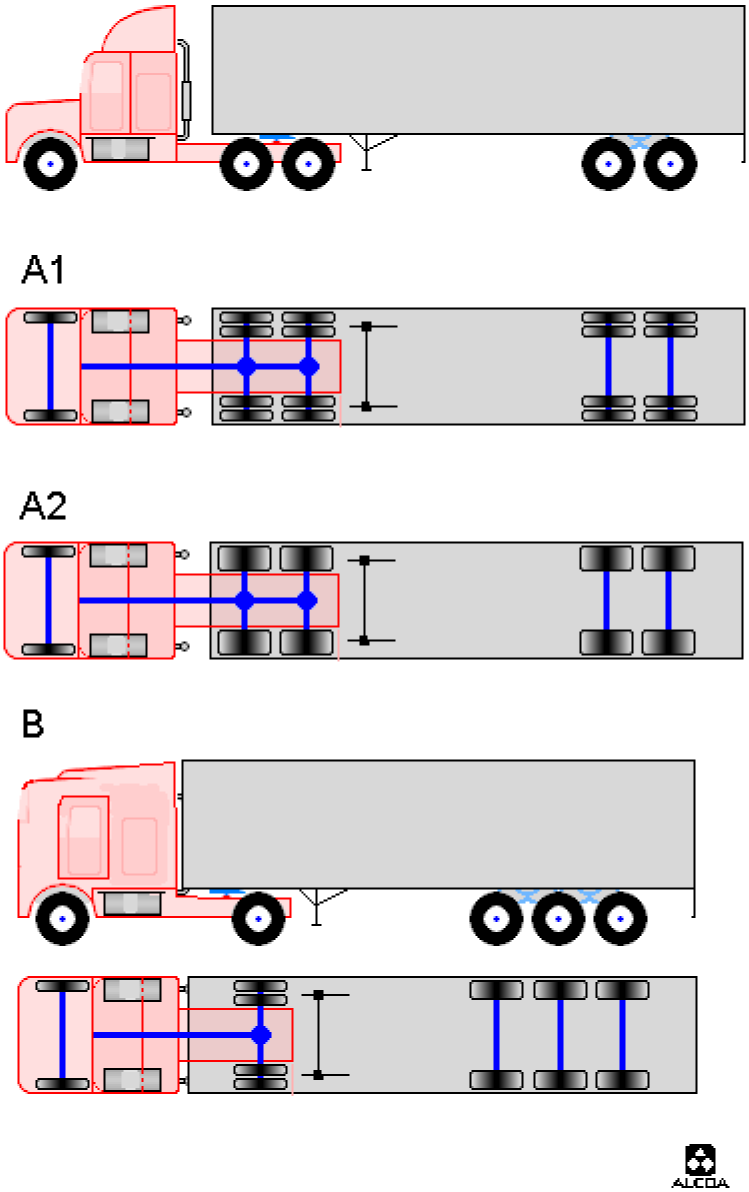

Figure 2-2. Truck and Trailer Schematics

The respective mass per reference flow can be taken from Table 2-1 below. It displays the different functional unit aspects and the calculation of the reference flows.

Table 2-1: Functional unit and reference flows calculation

	Aluminum		Steel	
Function	Couple truck tires to vehicle hubs			
Magnitude	A1: A2: B:	18 wheels 10 wheels 12 wheels	A1: A2: B:	18 wheels 18 wheels 12 wheels
Duration	1,000,000 miles (US) / 1.500.000 km (EU)			
Level of quality	22.5'' heavy-duty truck wheels			
Reference flows:	A1: A2: B:	810 lbs. 554 lbs. 268 kg	US: US: EU:	1,224 lbs.[12] 1,224 lbs. 483 kg[13]

2.3 System Boundaries

A cradle-to-grave system boundary was chosen because it provides the most complete and relevant perspective on the environmental impacts and prevents flawed conclusions being drawn that promote burden shifting between life cycle phases. For instance, it is known that the manufacturing burden per kg of primary aluminum is higher than that of steel. However, the higher payload capacity resulting from the lower weight of the aluminum wheels (mass-restricted cases) along with the fuel consumption benefit of a lower gross weight (volume restricted cases) can result in environmental break-even points during the use phase after which the potential additional manufacturing burdens is offset and the environmental load is actually lowered compared to the steel wheels. A generic system boundary schematic representing either product systems is shown in Figure 2-3, with a list of major components that are included and excluded in Table 2-2. Steel and aluminum wheels undergo recycling at End-of-Life to reclaim the metal. "Metal production" represents the manufacturing of the aluminum ingot and steel coil used to produce aluminum and steel wheels respectively. "Wheel production" represents the activities that take place within Alcoa and steel wheel manufacturing facilities. These activities are described in further detail in the technology coverage section.

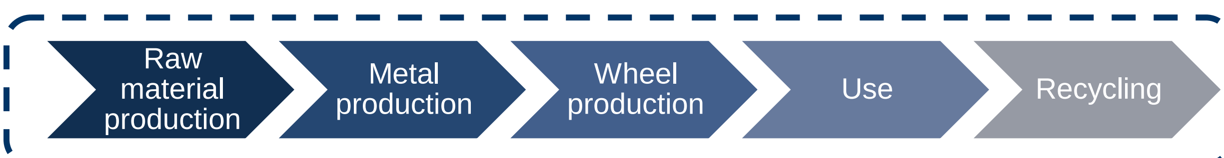

Figure 2-3: System boundaries

[12] Based on Accuride steel wheel P/N 50487
[13] Based on Hayes Lemmerz steel wheels P/N 10053TW and P/N 2920524TW

Table 2-2: Included and excluded components

Included	Excluded
✓ Raw material production ✓ Ingot production and wheel manufacturing ✓ Energy production ✓ Use phase scenarios ✓ End-of-Life	× Inbound and outbound transportation of production materials & products to market × Construction of capital equipment × Human labor and employee commute × Overhead (heating, lighting) of manufacturing facilities (if feasible)

As can be seen from Table 2-2, inbound and outbound transportation of materials and products is excluded by convention as it is not possible to collect that data on an equally high level of detail for the steel wheels without knowing the specific manufacturing sites involved. Since it is known that the use phase usually dominates the cradle-to-grave results of truck LCAs due to the extremely long mileages involved[14] and that the upstream burden of metal production is usually more important than its transports, this data gap is deemed negligible. It is further assumed that the full sets of wheels are recycled at End-of-Life.

2.3.1 Time Coverage

Annual data from 2010 have been collected for Aluminum wheel production from four Alcoa facilities; 2009 data were used for one facility. Background data (mainly raw materials, chemicals, fuels, and purchased electricity) are obtained from the GaBi 5 database which contains data with reference to the years 2002 – 2010 depending on the dataset. Steel production data is based upon datasets published by Worldsteel from 2007.

2.3.2 Geographical Coverage

The geographical coverage for wheel production is global. Data have been obtained for Alcoa's plants in the United States, Mexico, Japan and Hungary. Use phase coverage includes both US and European boundary conditions.

2.3.3 Technology Coverage

Primary data for current Alcoa aluminum wheel production processes have been collected from all relevant facilities. For the steel wheels, best available secondary data on representative production processes have been employed based on interviews with professionals from the steel wheel industry. Both systems have been modeled to ensure to the best of the authors' abilities that any differences between the products are based on technology rather than on varying degrees of completeness of the inventories.

[14] Marques et al (2008). Life Cycle Thinking in the Brazilian Automotive Industry. SAE Paper 2008-36-0324.

2.4 SCENARIO DESCRIPTIONS

2.4.1 USE PHASE SCENARIOS

The use phase was modeled to represent both US and European boundary conditions. It takes into account the increase of maximum allowable payload due to the decrease in wheel weight, and calculates the decrease in GHG emissions over the lifetime mileage based on three scenarios:

Mass-restricted transport: The utilization rate of the truck is held constant at 100% for both the aluminum and the steel wheel configuration. The resulting increase in maximum payload leads to a decrease of environmental burden per mass of cargo.

Volume-restricted transport: The absolute freight weight is held constant at 30% of the steel wheel truck's maximum payload capacity.[15] The resulting reduction of the gross vehicle weight improves the fuel economy of the truck.

Average use case: The average utilization rate of a class 8b truck is 78% according to the 2002 VIUS study.[16] Based on the above values, this corresponds to a combination of roughly 69% mass-restricted and 31% volume-restricted transports.

The average use case is calculated as a weighted average of the volume- and mass-restricted results to arrive at a 78% utilization rate rather than directly modeling the latter since it represents a volume-restricted use case and would therefore completely disregard any mass-restricted cases. Instead, the simplified approach taken here assumes a linear relationship between utilization rate and burden-per-tkm for all utilization rates between 30% and 100%.

This calculation may overestimate the share of mass-restricted transports in the field for class 8b trucks *in general*. However, it is deemed representative for the study at hand as Alcoa markets the payload benefit of aluminum wheels explicitly for mass-restricted applications. This represents a significant portion of their business as the additional payload delivers an immediate economic benefit to the fleet operators for these applications; though in either the mass or volume-restricted application, Alcoa wheels provide valuable benefits to the end user such as visual appeal, natural corrosion resistance and durability, higher resale value, fuel savings, extended tire life, and other benefits.

---

[15] EcoTransit (2011). Ecological Transport Information Tool for Worldwide Transports – Methodology and Data Update. Accessible online at http://www.ecotransit.org/download/ecotransit_background_report.pdf

[16] Average utilization rate for class 8b tractor trailers with a GVWR > 60,001 lbs according to US federal 2002 Vehicle Inventory and Use Survey (VIUS). Accessible online at http://www.census.gov/svsd/www/vius/2002.html

2.4.2 End-of-Life Scenarios

The base scenario applies a novel approach to Value-Corrected Substitution (VCS 2.0) to account for the depreciation of metal quality as it is recycled into further product systems.[17] This value-corrected substitution approach employs the market value of recyclable scraps relative to primary material to determine the product-specific degree of quality loss and the appropriate End-of-Life credit, i.e., the allocation factor for splitting the burden of primary material production between its first application (here: truck wheels) and the (many times unknown) subsequent application of the secondary material in an open-loop recycling situation.

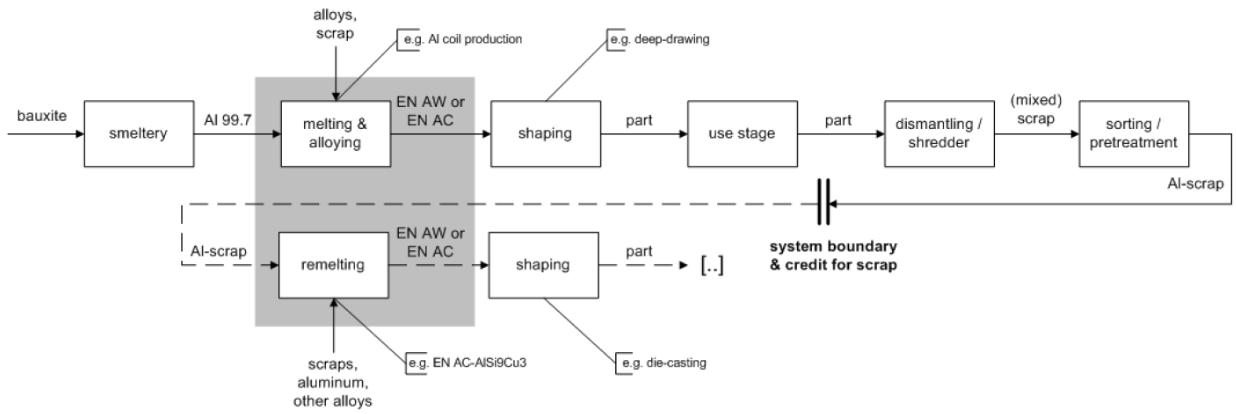

Figure 2-4: Value-Corrected Substitution system boundary [Koffler & Pflieger 201x]

This means that the system boundary needs to be drawn before the EoL wheels enter the remelting step or are mixed with any other scraps to (a) preserve full causality between material application and quality loss and to (b) avoid the bias introduced by the industry-average, scrap-unspecific addition of primary ingot and/or additional alloying elements as represented by the remelting inventories available from the respective metal associations (Figure 2-4).

Partial credit for the substitution of primary material is given to the incumbent product system using the ratio of the market values of scrap truck wheels and the primary material they are made from. This approach more accurately accounts for any product-specific quality losses ("change in inherent properties") of the material over the product life cycle. The VCS approach does not explicitly consider losses that occur during the recycling of the wheels as these losses are considered to be implicitly accounted for in the market price of the scrap.

To test the sensitivity of the EoL allocation procedure, the conventional avoided burden approach without any value-correction is considered as an alternative scenario that accounts for the generation of

[17] Koffler and Pflieger (201x): Tackling the Downcycling Issue – A Revised Approach to Value-Corrected Substitution in Life Cycle Assessment of Aluminum (VCS 2.0). Currently under review at the Journal of Industrial Ecology.

secondary materials from scrap wheels and grants full credit to the incumbent product system.[18,19] The third End-of-Life scenario modeled is the cut-off approach, where no credit is given to the incumbent system for aluminum or steel. These three scenarios thereby cover the full spectrum of possible End-of-Life allocation procedures (no/partial/full substitution).

Note that the majority of the metals industry has endorsed the avoided burden approach in 2007 as method of choice to address the End-of-Life allocation issue.[20] Nevertheless, the cut-off approach is included in this study for reasons of completeness and defensibility. The results will be discussed appropriately in the interpretation phase, but shall not be construed as an endorsement of this approach by Alcoa or the aluminum industry in general.

Recycling of post-production scrap is modeled using the avoided burden approach throughout all scenarios. The justification for this decision lies within the use of only a single alloy in the production of the wheels, which makes for a 'clean' scrap that can easily be recycled in a closed loop without any relevant quality losses.

2.5 Selection of LCIA Methodology and Types of Impacts

The following life cycle impact assessment (LCIA) categories are included in this study:

- Global Warming Potential (GWP100)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Ozone Depletion Potential (ODP)
- Smog Potential (POCP)

The TRACI 2.0 characterization model was selected as it is currently the only impact assessment methodology framework which incorporates US average conditions to establish characterization factors, while the CML LCIA framework was chosen for European boundary conditions.[21,22,23]

Global Warming Potential and Non-Renewable Primary Energy Demand were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be one of the most pressing environmental issues of our times.

[18] Atherton J (2007). Declaration by the Metals Industry on Recycling Principles. International Journal of Life Cycle Assessment 12(1), 69-70.
[19] Frischknecht R (2010). LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. International Journal of Life Cycle Assessment, DOI 10.1007/s11367-010-0201-6.
[20] Atherton et al (2007): Declaration by the Metals Industry on Recycling Principles. Int J LCA 12 (1) 59 – 60
[21] http://cml.leiden.edu/software/data-cmlia.html
[22] Bare J (2011): TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. Clean Technology Environmental Policy, 13:5, 687–696
[23] An operational guide to the ISO-standards (Guinée *et al.*) Centre for Milieukunde (CML), Leiden 2001

Eutrophication, Acidification, and Photochemical Ozone Creation Potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burden of regulated emissions such as NO_x, SO_2, VOC, and others commonly associated with road transport.

Ozone depletion potential was chosen because of its high political relevance, which eventually led to the worldwide ban of ozone-depleting substances. Impact category details are shown in Appendix A.

An assessment of Human and Ecotoxicity using the USEtox characterization model was also included in the report. The precision of the current USEtox characterization factors is within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity.[24] This is a substantial improvement over previously available toxicity characterization models, but still significantly higher than for the impacts noted above.

Therefore, the USEtox characterization factors were used within this study to identify key contributors within product lifecycles which influence that product's toxicity potential. The life cycle results would indicate which materials show up as 'substances of high concern', but shall not be used to make any comparative assertions.

It shall be noted that the above impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emitted molecules would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so.

Impact categories have been selected to capture a complete picture of the environmental effects of the life cycle of aluminum wheels. Land, water and air pollution as well as toxicity are all covered by these impact categories.

It is important to note that LCIA results are relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

2.5.1 Optional Life Cycle Impact Assessment Steps

Additional, optional life cycle impact assessment (LCIA) steps include normalization, grouping, and weighting. As this is a comparative LCA intended to be disclosed to the public, no grouping or weighting is employed. Normalization is used to discern the product systems' contributions to the reference geographies' annual environmental load per impact category.

[24] Rosenbaum et al. (2008). "USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment." The International Journal of Life Cycle Assessment. Volume 13, Number 7, 532-546, DOI: 10.1007/s11367-008-0038-4. Available: http://www.springerlink.com/content/8217520256r12w36/

2.6 Sources of Data

Alcoa provided primary data for aluminum wheel production from five facilities: two in the United States (Cleveland and Barberton), one in Mexico, one in Hungary, and one in Japan. Annual (2009 or 2010) average data was collected in the following categories for the production, packaging, and distribution of aluminum wheels:

- Fuel and energy use
- Use of raw materials
- Products and co-products
- Emissions to air, water, and soil
- Wastes

The facilities participating in this study perform different steps of the aluminum wheel production to varying degrees of completion. Some facilities perform both forging and finishing, while other facilities perform either forging or finishing. Alcoa utilizes a global flow path to deliver the goods to market in the regions they are demanded. These five facilities together represent the total global production of Alcoa's aluminum truck wheel production.

Data on steel wheel production was deduced from technology descriptions provided by an expert engineer with over ten years of experience in the steel wheel steel wheel manufacturing industry as well as literature review. The model was generated by PE International.

PE supplied secondary data for ancillary materials, fuels, and purchased energy. Inbound and outbound transportation distances were excluded from the study, given the lack of knowledge regarding steel wheel transportation values.

2.6.1 Cut-Off Criteria

The cut-off criteria for including or excluding materials, energy and emissions data of the study are as follows:

- Mass – If a flow is less than 2% of the cumulative mass of the model it may be excluded, providing its environmental relevance is not a concern.

- Energy – If a flow is less than 2% of the cumulative energy of the model it may be excluded, providing its environmental relevance is not a concern.

- Environmental relevance – If a flow meets the above criteria for exclusion, yet is thought to potentially have a significant environmental impact, it will be included. Material flows which leave the system (emissions) and whose environmental impact is greater than 2% of the whole impact of an impact category that has been considered in the assessment must be covered. This judgment was made based on experience and documented as necessary.

The sum of the excluded material flows must not exceed 5% of mass, energy or environmental relevance. These criteria were applied to mill operations, specifically for chemical consumption.

2.6.2 Data Quality

Data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., if there are any unreported emissions), consistency (degree of uniformity of the methodology applied on a study serving as a data source) and representativeness (geographical, time period, technology). To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent, background LCA information from the GaBi 2011 databases were used. This background information from the GaBi LCI database is widely distributed and used with the GaBi 5 Software. GaBi datasets have been used in LCA models worldwide for several years in industrial and scientific applications for many critically reviewed studies. As part of the quality control process, PE compares these datasets with values from industry and science. In this particular case, aluminum wheels were compared with other aluminum products and found to render reasonable results in terms of orders of magnitude.

Precision and completeness

- **Precision:** Primary data was based on measured and/or calculated data. The facility data was collected on the basis of yearly averages, which accounts for any seasonal variations in, e.g., energy demand or production volume. The data precision in terms of accuracy is therefore deemed to be high for all measured and calculated data, and considered a conservative worst-case estimate for permitted data since actual emissions are assumed to be lower than what is permitted.

- **Completeness:** All relevant process steps within the system boundary were considered. While building the model, PE conducted cross-checks concerning the precision and completeness of mass and energy flows. The provided primary data for aluminum wheel manufacturing was benchmarked with other models available to PE.

Consistency and reproducibility

- **Consistency:** To ensure consistency, only primary data of the same level of detail and time interval (i.e., one calendar year) were used. Background data was sourced from the same version of the GaBi database. Particular attention was given to the fact that the steel wheel production is based on secondary data. The use of primary data for one product system and secondary data for another product system is recognized as inconsistent, which may limit comparability of life cycle impacts between these product systems depending on the contribution of wheel manufacturing to the overall results. The goal was to attempt to ensure that differences between technologies are not based on differences in data sources or data availability.

- **Reproducibility:** The reproducibility of the study results is warranted by the information provided in this report. Due to confidentiality of data values, however, some of the data tables will be removed before publication of the report and will therefore limit the reproducibility.

Representativeness

- **Time related coverage:** Primary data is based on Alcoa's annual operations from either 2009 or 2010, depending on facility, consistent with the goal and scope of this analysis. Steel wheel data is based on industry expertise and literature review.

- **Geographical coverage:** The geographical coverage for this study is North American and European. As such, data was sourced from facilities located in the United States, Mexico, Hungary and Japan. Multiple sites were selected to best capture a production weighted average for aluminum wheel manufacturing in each region (US and EU). Since the environmental performance will likely vary from facility to facility, this approach is appropriate for the goals of the study.

- **Technological coverage:** Technological representativeness is high for Aluminum wheel production since it will be based on primary manufacturing data from all involved manufacturing facilities worldwide. For the steel wheel, best available secondary data was used to adequately represent the predominant production technology in use today. Product parameters such as weight, size, etc. have been derived from published technical and commercial documentation from a major steel wheel OEM.[25,26]

Uncertainty

There are two types of uncertainty: data uncertainty and model uncertainty. Model uncertainty is addressed through extensive sensitivity analysis. Regarding data uncertainty, quantification of uncertainty in the primary data is currently not feasible in a reliable and consistent manner due to the lack of primary data on measurement uncertainty.

2.6.3 Exceptions

There are no exceptions to the stated scope of this study.

2.7 Allocation

A process, sub-system, or system may produce co-products in excess of the necessary reference flow or intermediate product. Such co-products leave the system to be used in other systems, yet should carry a portion of the burden of their production system. To allocate burden in a meaningful way between co-products, several procedures are possible (e.g., allocation by mass, market value, heating value, etc.).

[25] Based on Accuride steel wheel P/N 50487

[26] Based on Hayes Lemmerz steel wheels P/N 10053TW and P/N 2920524TW

Whenever allocation is necessary, the method chosen will be based upon the nature and purpose of the process in need of allocation.

Materials and energy needed during manufacturing are modeled using the allocation rule most suitable for the respective product. Upstream data (energy and materials) were allocated as follows:

- For all refinery products, allocation by mass and net calorific value is applied. The manufacturing route of every refinery product is modeled and so the effort of the production of these products is calculated specifically. Two allocation rules are applied: 1. the raw material (crude oil) consumption of the respective stages, which is necessary for the production of a product or an intermediate product, is allocated by energy (mass of the product * calorific value of the product); and 2. the energy consumption (thermal energy, steam, electricity) of a process, e.g. atmospheric distillation, being required by a product or an intermediate product, are charged on the product according to the share of the throughput of the stage (mass allocation).
- Materials and chemicals needed during manufacturing are modeled using the allocation rule most suitable for the respective product. For further information on a specific product see http://documentation.gabi-software.com/.

2.8 Software and Database

The LCA model was created using the GaBi 5 Software system for life cycle engineering, developed by PE INTERNATIONAL AG. The GaBi 2011 database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

2.9 Interpretation

The interpretation of results will be conducted following the steps provided in the ISO standard. Significant issues are identified based on life cycle inventory and life cycle impact assessment results, and results from completeness, sensitivity, and consistency checks will be presented and discussed. Conclusions are then presented along with study limitations and recommendations.

The sensitivity analyses include End-of-Life treatments, fuel savings from light weighting, the mix of mass vs. volume constrained transport in the average case use phase, and wheel replacement from premature failure. These allow for a broader perspective around key assumptions that have been identified as highly relevant to the outcomes of the study.

2.10 Limitations

This study compares the environmental performance of aluminum and steel truck wheels and it is recognized that the scope and conduct of this work denotes certain limitations. The study is based on Alcoa aluminum truck wheels, and thus does not apply to other aluminum wheels or wheels for other vehicle classes. This work is further limited by the boundaries of the study and only applies to trucks operating within the US or EU.

2.11 TYPE AND FORMAT OF THE REPORT

The study report at hand will serve as the background documentation for critical review as well as a third-party report according to ISO 14044, section 5.2. It will be made available to the general public in Portable Document Format (.pdf) through Alcoa's website.

2.12 CRITICAL REVIEW

A critical review by a panel of interested parties was conducted as part of this study. The critical review panel members are:

- Prof. Matthias Finkbeiner, TU Berlin – Chair
- Prof. Greg Keoleian, University of Michigan
- Dr. Scott Kaufman, PeerAspect

Individual members of the review panel were not engaged or contracted as official representatives of their organizations and acted as independent expert reviewers.

The review has been performed according to section 6.3 of ISO 14040 and ISO 14044. The review is supposed to cover the potential use of the study for comparative assertions intended to be disclosed to the public. The Critical Review Panel report can be found in the appendix.

3 LIFE CYCLE INVENTORY (LCI) ANALYSIS

3.1 DATA COLLECTION

3.1.1 DATA COLLECTION & QUALITY ASSESSMENT PROCEDURE

All primary data were collected using customized data collection templates, which were sent out by email to the respective data providers at the participating facilities. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, and benchmarking. If gaps, outliers, or other inconsistencies occurred, PE International engaged with the data provider to resolve any open issues.

3.1.2 FUELS AND ENERGY – BACKGROUND DATA

Fuel consumption from the facilities relating to internal operations and transport will be reported by Alcoa. These fuels include natural gas and diesel for thermal energy. PE will supply upstream data for the fuels from the GaBi 2011 database.[27] Electricity used in the primary aluminum smelting process is indicative of the smelting power grid mix in the respective regions of production. These grid models are assembled by the Aluminum Association and the European Aluminum Association and are based upon data from industry members. Energy datasets from PE used in all models other than primary aluminum production are shown in Table 3-1.

Table 3-1: Fuel and energy datasets used in model

Energy Dataset Name	Reference Region	Reference Year	Primary Source
Fuels			
Diesel	US / EU-27	2008	GaBi DB 2011
Thermal Energy from Natural Gas	US / EU-27/ JP	2008	GaBi DB 2011
Electricity			
Power grid mix	US / HU / MX / JP	2008	GaBi DB 2011

3.1.3 RAW AND PROCESS MATERIALS – BACKGROUND DATA

Data for upstream raw materials and transportation to the facilities were also obtained from the GaBi 2011 database. Table 3-2 contains a list of raw material datasets used in inventory modeling.

Inventory data for Aluminum ingot manufacturing will be based on industry averages obtained from the US Aluminum Association (AA) and the European Aluminum Association (EAA). AA data was based on the ongoing update of the currently available 2007 data as available in GaBi DB 2011 and at

[27] For more information, see www.documentation.gabi-software.com

www.aluminum.org\lca. The use of this unpublished data was possible through direct authorization granted by the Aluminum Association.

Steel data is taken from Worldsteel with a global reference as US specific production data was not available at the time of the study.

Table 3-2: Raw material datasets used in model

Raw Material Dataset Name	Reference Region	Reference Year	Primary Source
Primary Metals			
Aluminum Ingot (Aluminum Association)	NA	2009	AA
Aluminum Ingot (European Aluminum Association)	RER	2005	EAA
Steel, pickled, hot rolled coil	GLO	2007	Worldsteel
Ancillary Materials			
Tap Water	RER	2010	GaBi DB 2011
Compressed Air 10 bar (low power consumption)	GLO	2008	GaBi DB 2011
Lubricant	GLO	2010	GaBi DB 2011
Pretreatment Chemicals (Degreasing, phosphating)	DE	2010	GaBi DB 2011
Treatment Chemicals (by mass % from MSDS)			GaBi DB 2011
Iron	US	2009	GaBi DB 2011
Chlorine	RER	2010	GaBi DB 2011
Aluminum hydroxide mix	RER	2008	GaBi DB 2011
Joint Sealing Tape; butyl	DE	2010	GaBi DB 2011
Cotton – Fabric	US	2010	GaBi DB 2011
Sodium Hydroxide Mix (50%)	DE	2010	GaBi DB 2011
Nitric Acid (60%)	US	2010	GaBi DB 2011

3.1.4 Transportation

As stated in chapter 2.3, inbound and outbound transportation of raw materials and products were excluded for reasons of data availability and consistency.

3.1.5 Emissions to Air, Water and Soil

All emissions captured in official reporting for the manufacturing phase by suppliers are taken into account in the study. All gate-to-gate emissions data were obtained from the suppliers. In only one case, CO_2 emissions from natural gas burning were calculated based on stoichiometric conversion of CH_4 to CO_2.[28] Those emissions are only for the combustion of the fuel on-site, consequently there is no double-counting with any upstream greenhouse gas emissions (production of fuel or combustion of fuel to produce electricity for the grid mix). The energy supply emissions are provided by the GaBi 2011 database.

[28] This calculation double-counts the carbon that is reported to be released as methane or carbon monoxide from combustion. The resulting over-estimation of the facility's GWP is marginal and therefore negligible.

Data for all upstream materials, electricity, and energy carriers were obtained from the GaBi 2011 database as well. The emissions (CO_2, etc.) due to the use of electricity are accounted for with the use of the database processes.

Tailpipe emissions associated with the use phase were calculated using US and EU truck datasets from the GaBi 2011 database.

3.2 Alcoa Aluminum Wheels

3.2.1 Overview of Life Cycle

The cradle-to-grave life cycle of aluminum truck wheels is comprised of five distinct phases: raw material production, aluminum ingot production, wheel production, use and recycling. Aluminum is mined and processed from raw bauxite ore into ingots, which are sent to Alcoa facilities where they serve as the raw material for wheel forging. Aluminum is the only raw material in the product, all other materials involved in manufacturing are ancillary. The wheels are then sold to customers who attach the them to trucks and trailers. Forged wheels are used in other transportation vehicles such as buses, passenger cars, light trucks, and RVs, however this study is only an investigation into the use phase associated with large commercial trucks. The use phase of aluminum truck wheels can last for varying amounts of time depending on individual usage patterns, but have been demonstrated to last at least 1.5 million kilometers (or roughly 1,000,000 miles) under test conditions. Experience indicates that the lifetime can be much longer than this, and manufacturing defects, which will typically present themselves in the first 5 years of wheel use, are extremely scarce based on warranty data provided by Alcoa. Once the wheels are deemed no longer usable, they are recycled to reclaim the aluminum for use as a secondary raw material.

3.2.2 Description of Process Flow

The cradle-to-grave life cycle descriptions and data are provided below for the North American boundary conditions. European input/output data and other relevant information can be found in appendix B.

3.2.2.1 Manufacturing

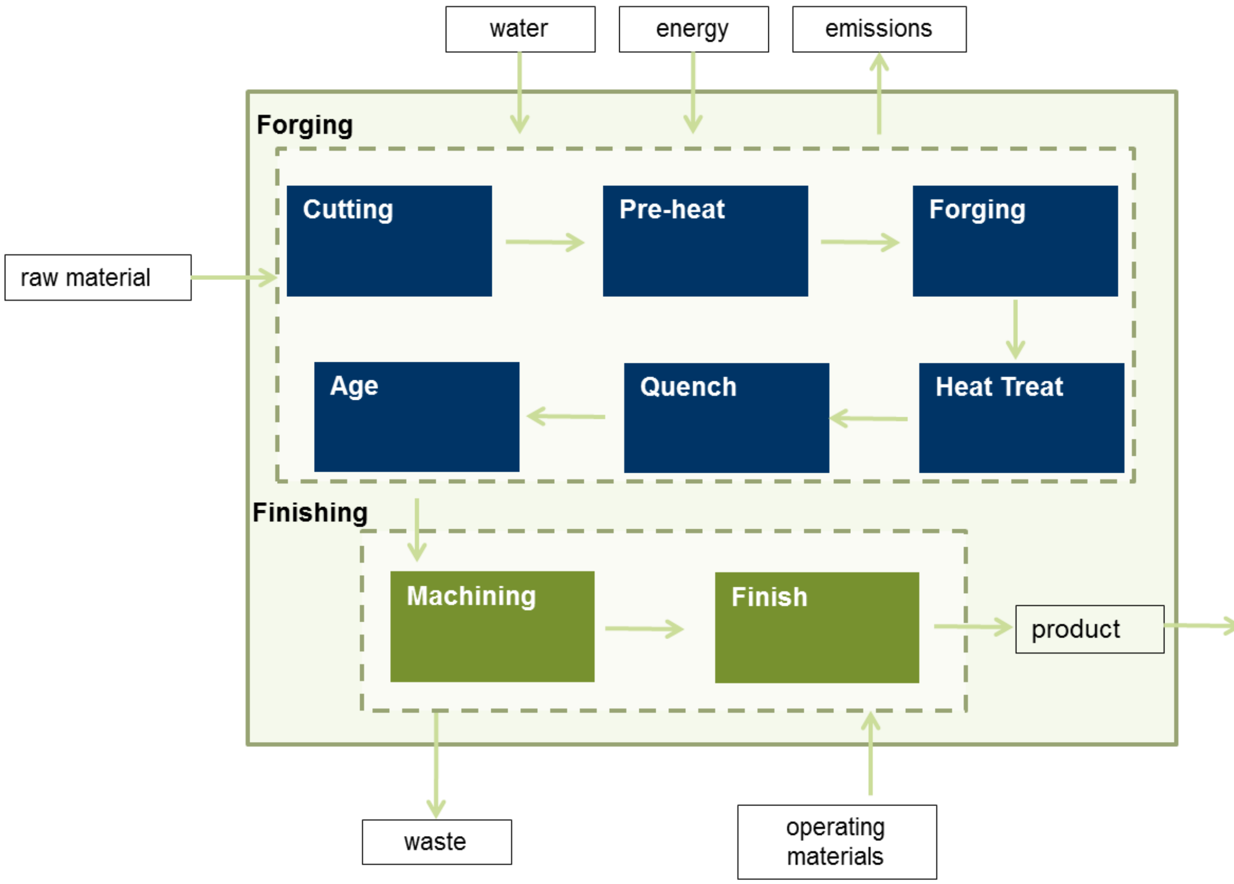

Figure 3-1. Aluminum Wheel Production Flow Diagram

Aluminum wheel manufacturing is comprised of two major production steps—labeled forging and finishing—that can take place at the same or different facilities within Alcoa.

3.2.2.1.1 Forging

When the 100% primary aluminum ingot arrives at the manufacturing facility, it is first cut into smaller units for forging. The aluminum block is then heated before it passes through a multi-step forging process. During this forging process, a series of presses apply different features to the forge to achieve the desired wheel shape. The final three forging steps—heat treatment, quenching, and aging—confer the requisite material properties to the wheel.

Table 3-3: Forging data for North American Aluminum Wheel Production

[redacted]

Confidential

Table 3-3 displays major inputs and outputs from the forging of a full set of eighteen aluminum truck wheels for the US market. Scrap losses account for ~8% of the aluminum input, with the majority of aluminum leaving as the forged wheel and some residual scrap lost with lubricant. Any remaining scrap is contained in the waste output and is landfilled. The thermal energy demand of the forging steps results in high natural gas consumption, while the water needed for cooling and processing drives the water consumption. Nearly 100% of the aluminum scrap enters into closed loop recycling, with trace quantities going to waste. The corresponding table for the EU scenario can be found in Annex B.

3.2.2.1.2 Finishing

The finishing process begins with removal of all the excess aluminum from the wheel in a machining step where a large portion of aluminum is removed and sent to scrap recycling. The final stages of machining involve drilling holes in the wheel for the valve and fixing elements of the wheel. The last manufacturing step is the polishing of the wheel to give the desired look and surface condition before it is sent out.

Table 3-4 displays the major inputs and outputs of the aluminum wheel finishing process for the US market. The extensive processing and machining needed to refine the wheel into its final dimensions and quality results in high electricity consumption. Nearly 100% of the aluminum scrap enters into closed loop recycling, with trace quantities going to waste.

Table 3-4: Finishing Data for North American Wheel Production

[redacted]

Confidential

Since no data regarding transportation or packaging information is available for the steel truck wheels being compared in this study, transportation and packaging data are excluded from the gate-to-gate manufacturing of aluminum wheels. The corresponding table for the EU scenario can be found in Annex B.

3.2.2.2 Use

During the use phase, the wheel fulfills its purpose of coupling the tire to the hub and enabling locomotion of the truck. The use of aluminum wheels reduces the gross weight of the unburdened truck. This weight savings can be leveraged either by transporting additional cargo or by lowering fuel consumption. The operation of the truck results in emissions related to the burning of diesel. Carbon dioxide and sulfur dioxide emissions are calculated stoichiometrically, while other emissions (e.g. nitrogen oxides, particles to air, etc.) are based on the US EPA MOVES model for truck emissions.

To model the use phase activity associated with the truck wheel life cycle in the volume-restricted scenarios, the truck processes as available in the GaBi DB 2011 were modified to account for the reduced weight. The parameter of 0.0000344 mpg per pound of gross weight was taken from a study by Volvo Truck.[29] This value was compared against other studies investigating the effects of light weighting on the fuel economy of trucks.[30] [31] The value calculated from the Volvo study is between the values from the other studies as is seen in Table 3-5. The other studies derived their light-weighting parameters from simulation, whereas the Volvo parameter is based on certification measurements, lending a higher

[29] Volvo Truck Corporation. (2003, 11 20). Emission from Volvo's trucks (standard diesel fuel). 20640/03-017.
[30] NESCCAF. (October 2009). Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 emissions.
[31] IFEU. (January 2003) Energy Savings by light-weighting.

degree of credibility. The light-weighting parameters are based on specific drive cycles, and may not reflect alternate use conditions. A sensitivity analysis of this parameter has been performed to address its importance in the outcome of this study. Full details of the sensitivity analysis are found in section 5.3.2.

Table 3-5. Light Weighting Parameter Values

Source	MPG per lb cargo
Volvo (2003)[29]	**0.0000344**
IFEU (2003)[31]	0.0000451
NESCCAF (2009)[30]	0.0000333

For the mass-restricted scenario, the overall vehicle weight remains the same whether the truck is equipped with aluminum or steel wheels; however, in the case where aluminum wheels are used, additional cargo can be transported. Thus, the overall burden is the same, but the transportation performance (as measured on a per-ton-kilometers basis) is improved when aluminum wheels are applied.

3.2.2.3 End-of-Life

As described in chapters 2.3 and 2.4.2, the End-of-Life of the aluminum wheel assumes 100% recycling of the wheels for use in other applications where secondary aluminum is suitable for the function of that product system. To account for any quality loss due to pollution with foreign materials of the aluminum alloy, a value correction is applied. While there is a separate scrap class for Scrap Aluminum Auto Wheels (Figure 3-2), it was determined that this scrap grade is not appropriate for the forged aluminum truck wheels under study as it represents cast aluminum auto wheels that are made from different kinds of aluminum alloys. As the Alcoa truck wheels are made from an AA 6061 wrought alloy and are usually traded as a mono-material scrap, their scrap value is significantly higher. Based on actual price information provided by scrap companies, the scrap class Scrap Low Copper Aluminum scrap class was chosen, resulting in a substitution factor of 93 %. The corresponding chart for the EU scenario can be found in Annex B.

It should be noted that the price ratios presented in the figure below are based on a four year average of historical price data (2007-2010). Although price ratios remained remarkably stable over this time period, the lifetime of the wheels will extend beyond 10 or more years into the future. Therefore, it is possible that the substitution factors will have changed significantly by the time the wheels are recycled.

For this reason, an avoided burden End-of-Life scenario, where the secondary aluminum generated through wheel recycling is considered to replace primary aluminum in a 1:1 ratio, and a cut-off approach, giving no benefit to the secondary aluminum generated through wheel recycling, will also be evaluated.

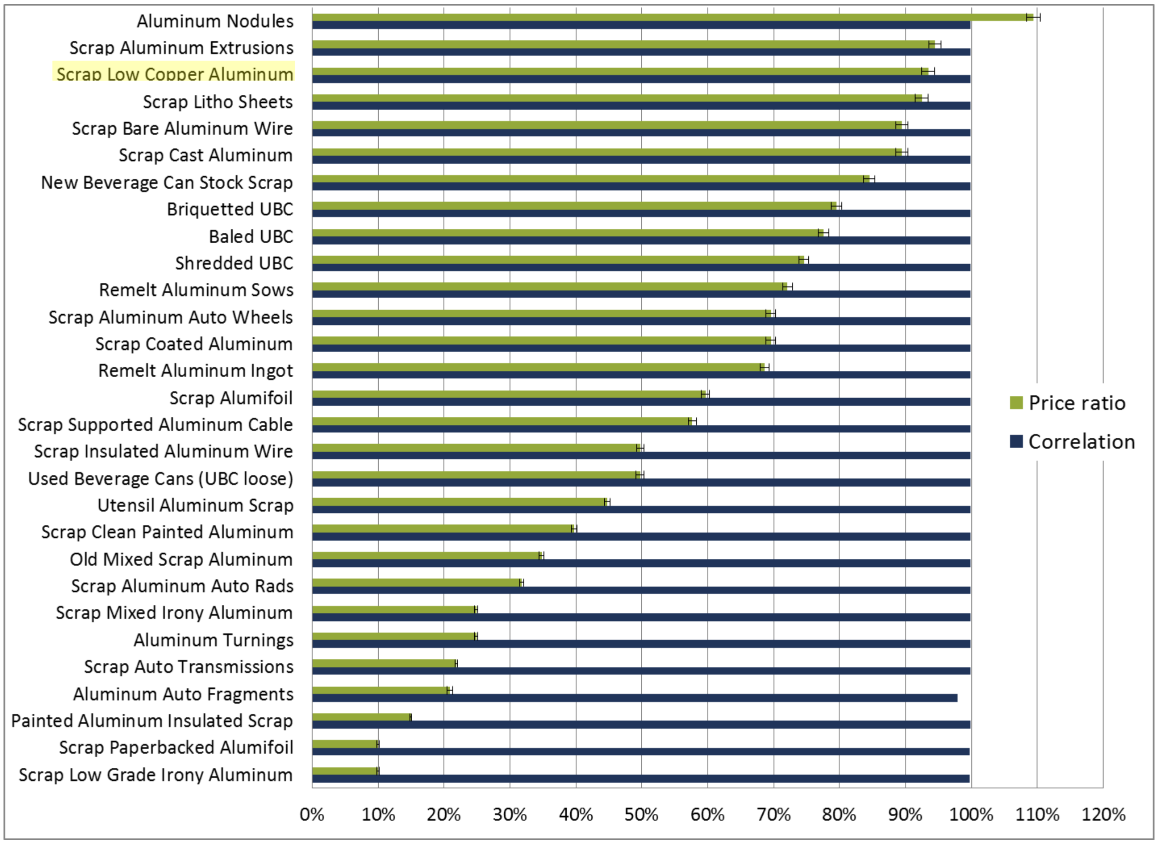

Figure 3-2: US aluminum scrap classes' correlation and average ratio with primary ingot price 2007-2010

3.3 Steel Truck Wheels

3.3.1 Overview of Life Cycle

The same phases that comprise the aluminum wheel life cycle also comprise the cradle-to-grave steel wheel life cycle. The incoming metal takes the form of a hot-rolled steel sheet that is manipulated into the shape of the wheel. The wheel is comprised of two pieces, the disc and the rim, which are welded together to form the final wheel assembly. Steel wheel life expectancy and quality are assumed to be no different than aluminum in respect to functionality. End-of-Life treatment also entails recovery of the metal for further use.

3.3.2 DESCRIPTION OF PROCESS FLOW

3.3.2.1 Manufacturing

Steel wheel production is comprised of three key steps: wheel disc fabrication, wheel rim fabrication, and wheel assembly. Production details describing these three processes are based on industry expertise and literature and are provided below.

- **Disc Fabrication**
  - Use hot rolled coil of pickled steel as the starting material
  - Straighten the steel coil and stamp out a round blank
  - Place blank in a flow forming machine to achieve the specified shape and thickness of the disc
  - The disc then passes through a succession of eccentric presses where the stud holes and center holes are punched
  - The vent holes are cut and deburred and the disc flange is punched flat
  - The final disc fabrication stage involves machining the final dimensions of the center hole and outer diameter on a CNC lathe
- **Rim Fabrication**
  - Use hot rolled coil of pickled steel as the starting material
  - Straighten the steel coil and cut to the appropriate length
  - The longitudinal edges of the coil are deburred and rounded off to prevent tire beads from being damaged in the final product
  - The strip is sent into a hoop machine that forms it into a ring
  - The ends of the strip are crimped and welded together
  - The weld is deburred
  - The rim is shaped to create conical profiles on both open sides
  - Next, the rim is given its final contours by rollers
  - The rim then undergoes a calibration stage
  - Finally, the valve hole is cut in the rim and chamfered to prevent damage to the valve

- **Wheel Assembly**
  - Press fit the disc into the rim
  - A weld securely joins the disc and rim into the final unit
  - The wheel flange is then punched flat to correct any distortion that may have been caused by the welding
  - The wheel assembly is sent to an expanding station to achieve final dimensions
  - Final machining is conducted for the pilot hole and attachment face
  - For quality control, uniformity data is taken and a leak test is performed on the final product
  - Finally, the wheel is coated to protect the metal

This qualitative process description served as the basis for the inventory modeling of steel wheel production. It is based on the expertise of an engineer who spent 10 years working in the steel wheel industry. It is recognized that this approach has limitations; however, the salient impacts come from the use phase, which dominate any errors from manufacturing assumptions.

Transportation and packaging information are not available for steel wheel production and so have been excluded in the gate-to-gate manufacturing of the steel truck wheels. Steel Wheel production data for a complete set (18) of truck wheels can be found below in Table 3-6.

Table 3-6: Steel Wheel Production Data

Type	Flow	Magnitude	Unit	DQI*
Inputs				
	Steel Coil	779	kg	estimated
	Lubricant	6.9	kg	estimated
	Electricity	318.3	MJ	estimated
	Natural Gas	1.66	kg	estimated
	Water	278.9	Liters	estimated
	Air	56.3	m^3	estimated
	Clear Coat	1.36	kg	estimated
	Steel Wire	4.54	kg	estimated
Outputs				
	Steel Wheel	555.2	kg	estimated
	Steel Scrap	224	kg	estimated
	Waste Water	278.9	Liters	estimated

*Data Quality Indicator: measured/calculated/estimated

3.3.2.2 Use

The use phase of steel truck wheels is considered as the baseline case against which the aluminum truck wheels are evaluated. The truck datasets from the GaBi 5 database are employed and considered for an operation of 1 million miles in the US scenarios and 1.5 million km in the EU.

3.3.2.3 End-of-Life

The End-of-Life treatment for steel wheels applies value-corrected substitution to maintain congruity with the aluminum wheel End-of-Life. The market value of Scrap Steel Wheel Rims is 34 % that of primary steel, so a 34 % primary metal credit is given at the End-of-Life (Figure 3-3). The corresponding chart for the EU scenario can be found in Annex B.

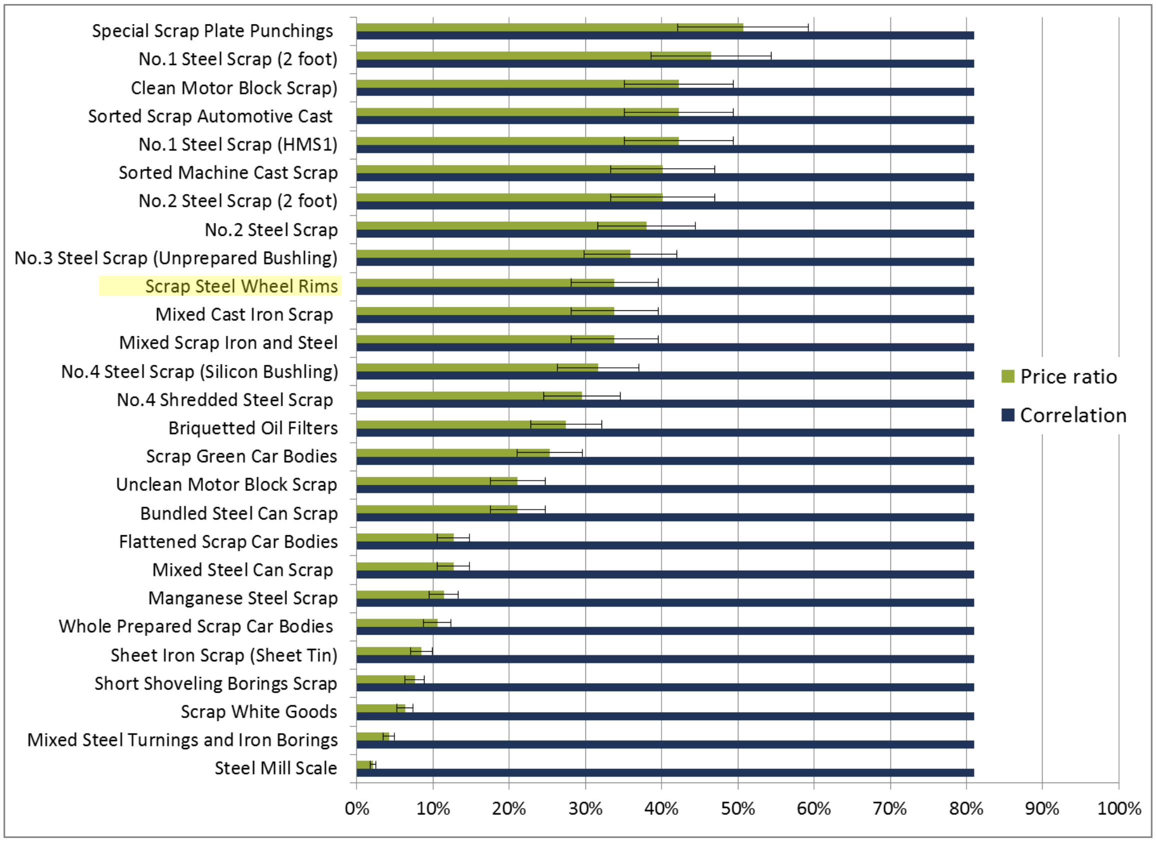

Figure 3-3: US steel scrap classes' correlation and average ratio with primary steel billet price 2007-2010

Additionally, an avoided burden End-of-Life scenario will be evaluated where the secondary steel generated through wheel recycling is considered to replace primary steel in a 1:1 ratio. A cut-off approach will also be evaluated as a conservative End-of-Life scenario, giving no benefit to the secondary steel generated through wheel recycling.

3.4 LIFE CYCLE INVENTORY ANALYSIS RESULTS

ISO 14044 defines the Life Cycle Inventory Analysis Result as the "outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment". As the complete inventory comprises hundreds of flows, the below table only displays a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results. Table 3-7 below presents LCI results for the different life cycle phases with the steel wheel baseline and shows the positive or negative difference when compared to the aluminum wheel case. The volume-restricted use case is captured in the LCI results because it is an actual case, rather than an average.

As can be seen in Table 3-7, certain emissions in the aluminum wheel inventory are higher than for steel wheels (e.g., PAH to soil, heavy metals to water, PM and SO_2 to air, etc.). Many of these arise from upstream metal production. The life cycle impact assessment (next chapter) elucidates where these emissions affect the overall environmental profile.

Table 3-7: LCI results of aluminum wheels shown as difference to steel wheel results

Type	Flow	Metal		Production		Prod-Recycling		Use Phase		EOL Recycling		Total	
		St	Al	St	Al	St	Al	St	Al	St	Al	St	Al
Resources	Crude oil	3.9	+439.656	10.5	+12.9	4.74	-225.06	--	-2163.2	2.05	-113.45	21.19	-2049.18
	Hard coal	617.925	+764.924	14.6	+98	-199.13	-477.13	--	-41.678	-184.5	-382.05	248.86	-37.9559
	Natural gas	13.3219	+528.859	5.54	+206	14.4407	-269.5	--	-181.9	-2.0358	-171.74	31.27	+111.652
Emissions to air	CO_2	1556.69	+5813.31	61.6	+794	-378.95	-3294	--	-5873.1	-412.57	-2056.4	826.8	-4615.94
	CH_4	4.22155	+7.19736	0.121	+2.2	-1.1545	-4.3473	--	-8.1001	-1.182	-2.4875	2.0058	-5.54006
	N_2O	0.00581	+0.11567	0.001	+0.032	-0.0014	-0.0577	--	-0.0277	-0.016	-0.0248	-0.0102	+0.037447
	NO_x	1.85785	+11.0306	0.103	+1.16	-0.3644	-5.8177	--	-3.4388	-0.6319	-3.8396	0.9644	-0.90402
	SO_2	1.97901	+21.8571	0.2	+1.89	-0.4813	-11.067	--	-4.4488	-0.748	-6.4582	0.9499	+1.769036
	NMVOC	0.22689	+1.32545	0.019	+0.228	-0.0291	-0.726	--	-1.9709	-0.0518	-0.4378	0.1646	-1.58135
	CO	21.0558	-18.09	0.042	+0.589	-6.0846	+4.62977	--	-1.8238	-6.5439	+5.49177	8.4692	-9.20263
	PM_{10}	0.05147	-0.003	0	0	-0.0138	-0.0096	--	0	-0.0261	+0.02387	0.0116	+0.011361
	$PM_{2.5}$	0.04658	+0.56365	0.003	+0.056	-0.0023	-0.2992	--	-0.0458	-0.0404	-0.1606	0.0072	+0.114229
	Heavy metals	0.00877	+0.00607	0	+0.003	0.00011	-0.0075	--	-0.0022	-0.0014	-0.0029	0.0075	-0.00388
Emissions to water	NH_3	2.50E-06	+0.0006	0	+0.001	-3.00E-06	-0.0003	--	-0.0005	-1.00E-06	-0.0003	0.0001	+0.000782
	NO_3^-	0	+0.16838	0.002	+0.339	0.23736	-0.3199	--	-1.0525	-0.011	-0.057	0.2287	-0.92226
	PO_4^{3-}	4.70E-05	+0.00148	0	+0.002	4.70E-05	-0.0008	--	-0.0259	-2.00E-05	-0.0005	0.0001	-0.02343
	Heavy metals	0.01514	+0.5203	0.01	+0.334	0.01929	-0.2727	--	-0.0451	-0.0281	-0.0374	0.0162	+0.499283
Emissions to soil	PAH	6.20E-08	-6.00E-08	0	0	-4.00E-08	+3.60E-08	--	-8.00E-10	-5.00E-08	+4.50E-08	-2.00E-08	+2.18E-08
	Heavy metals	0.00042	+0.01409	0	0	0.00029	-0.0066	--	-2.00E-06	-4.00E-05	-0.0003	0.0007	+0.00722

4 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

It shall be reiterated at this point that the reported impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emitted molecules would (a) in fact follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. LCIA results are relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

All results are given for the average use scenario. All results are presented here for the North American case. Results for the EU case can be found in Annex B.

4.1 NORMALIZED NET IMPACT ASSESSMENT RESULTS

Alcoa's aluminum wheel LCIA results are provided here normalized to the statistical annual environmental burden for North-America. Specifically, the results are normalized for TRACI 2.0 to convey which indicator results have a higher contribution to the average US impact levels in the aluminum wheel life cycle. Furthermore, each life cycle phase for aluminum wheels is quantified as the difference to the steel truck wheels reference.

The normalized results do not reveal the actual share of the production systems in the geographical reference area since the life cycle approach will tolerate a certain share of the emissions released outside of that area. Since the majority of the absolute burden occurs during the use phase (not shown in Figure 4-1), this bias is rather low.

Life cycle phases in Figure 4-1 having positive values (primary metal production and wheel production) have a higher burden than the corresponding phase for steel wheels, while phases with negative values (use phase, post-production and post-consumer recycling) have a lower burden compared to the steel wheel life cycle phases representing an environmental benefit related to the use of aluminum wheels. As the chart shows, global warming potential, acidification potential, and smog potential are quantitatively the most notable impact category results with regard to the average emission situation in the US. Eutrophication potential and primary energy demand represent less substantial impact category results, and ozone depletion potential is so minimal as to not even be visible on the chart.

Of the impact categories considered, the most attention will be given to global warming potential, which will be discussed in further detail throughout the results section. For EU Normalized results see Annex B.

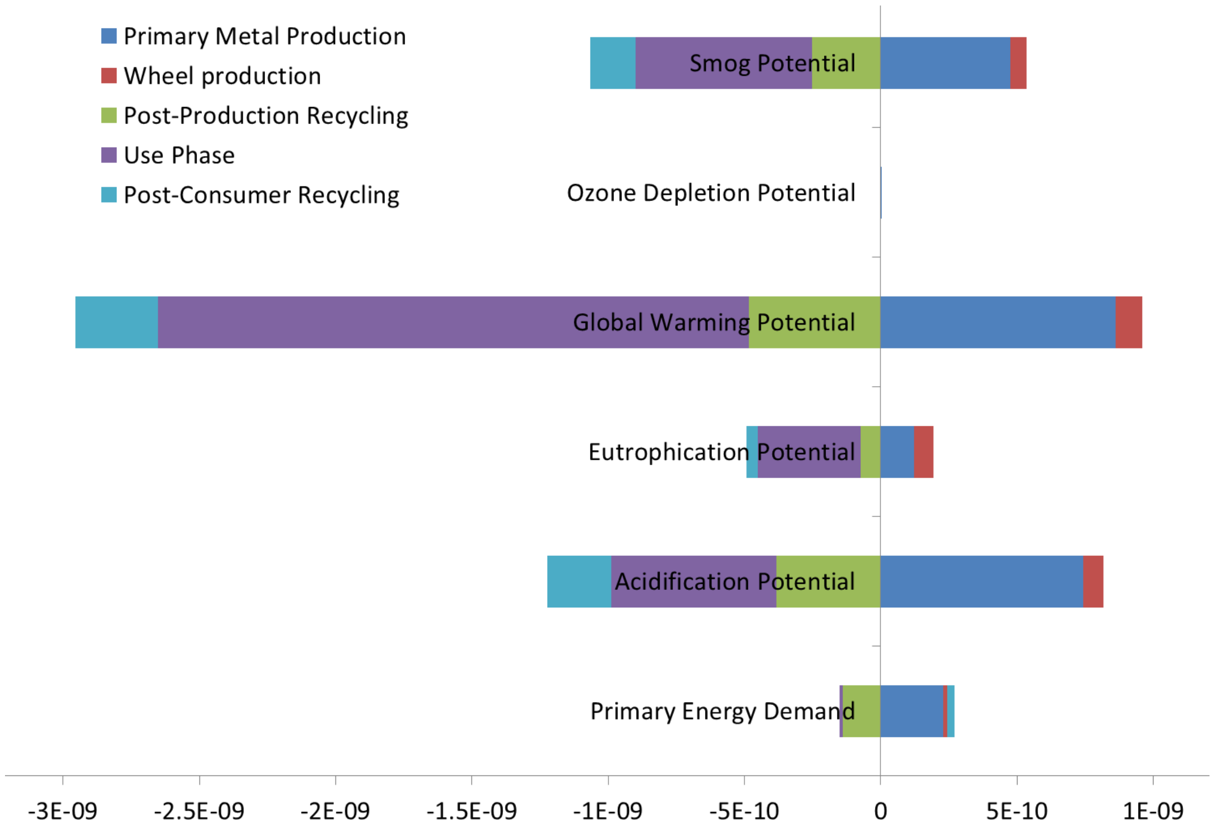

Figure 4-1: TRACI 2.0 Normalized Impact Results as difference to the steel wheel reference (US base case)

4.2 Detailed Impact Assessment results

4.2.1 Full life Cycle

The aluminum wheel complete life cycle results for North American are presented in Figure 4-2: as the percentage distributions of the differences between the aluminum wheels results and the steel wheel results. Environmental savings from use phase (average scenario), post-consumer and post-production recycling are shown as negative values to capture the environmental benefit aluminum wheels provide during these life cycle stages. Aluminum production and wheel manufacturing have a higher burden for aluminum wheels than steel wheels and thus have positive values in the chart.

For smog potential, global warming potential, eutrophication potential and acidification potential, aluminum wheels provide a net benefit to the environment over their complete life cycle when compared with steel wheels. For primary energy demand and ozone depletion potential, the upstream metal production drives these quantities to have a higher environmental burden than steel wheels.

Recall from the normalized life cycle results in Figure 4-1 that ozone depletion potential, and to a lesser extent, eutrophication potential and primary energy demand have relatively small contributions when considered in the context of the total North American burden.

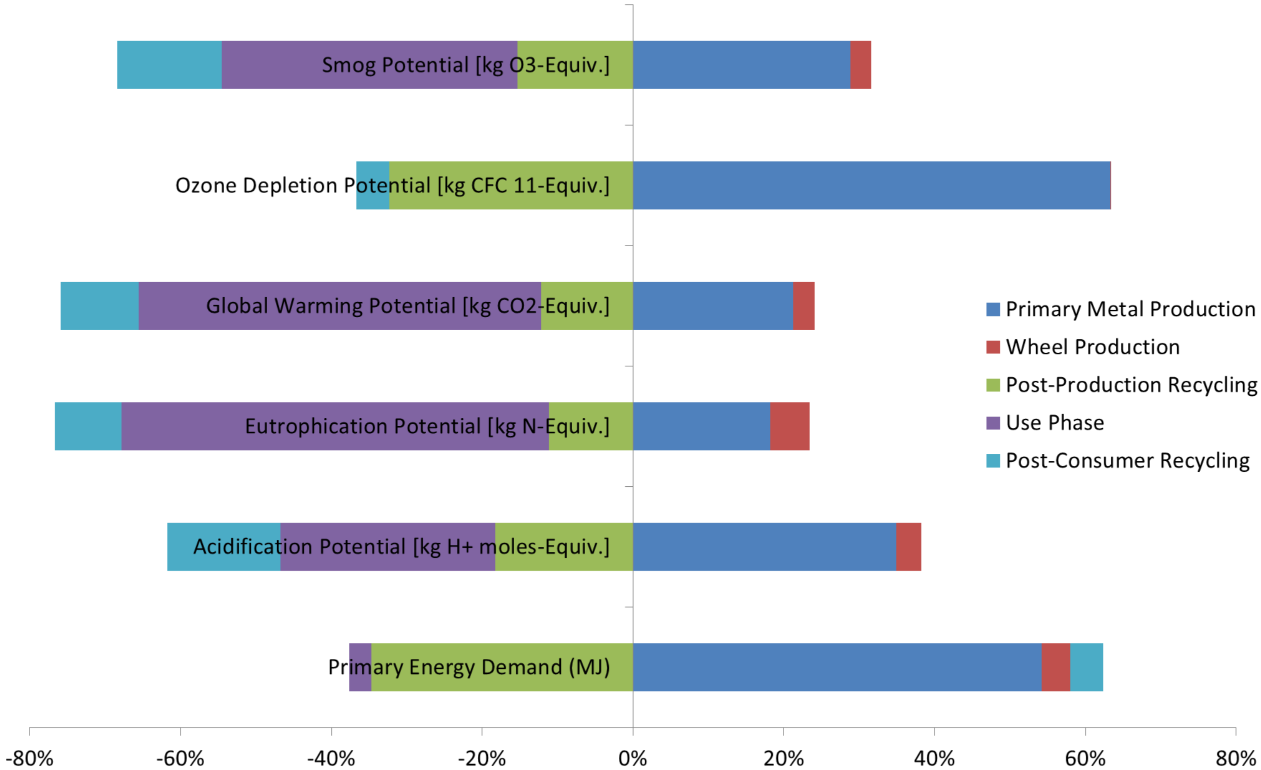

Figure 4-2: North American Aluminum Wheels Life Cycle Results

4.2.1.1 *Global Warming Potential (GWP)*

The global warming potential for aluminum wheels is driven chiefly by use phase savings. Use phase savings in Figure 4-2: are calculated for the average use scenario. Break even charts for all use phase scenarios are presented below in the use phase results. Besides the use phase, primary metal production is a major source of global warming impacts, and along with wheel manufacturing, has a net positive impact over the steel wheel counterparts.

Global warming potential is driven by direct carbon dioxide emissions from burning fossil fuels to meet the energy demand for manufacturing aluminum. Also, the fuel savings in the use phase decrease the amount of diesel burned by the truck equipped with aluminum wheels and directly reduce the carbon dioxide released.

4.2.1.2 *Smog potential*

Smog potential for aluminum wheel production has a net savings when normalized to steel wheel life cycle impacts, with most of the savings arising from the use phase. Use phase smog emissions arising from aluminum production have a positive impact, and are largely the result of nitrogen oxides released to air from fossil fuel burning. Reduction in nitrogen oxides during the use phase account for the smog potential benefit in the use phase.

4.2.1.3 Acidification Potential (AP)

The acidification potential for aluminum wheels life cycle are driven by sulfur dioxide and nitrogen oxides released to air during fossil fuel burning. The use phase benefit in acidification potential comes from the reduced diesel consumption of the truck, limiting the total amount of nitrogen oxides and sulfur dioxide emitted.

4.2.1.4 Eutrophication Potential (EP)

Eutrophication potential is driven by nitrates released to water along with nitrogen oxides released to air, both coming from fossile fuel burning. Primary aluminum production and wheel production drive positive eutrophication values, while some of this burden is recovered during the recyling of aluminum post production and at the End-of-Life. As with other impacts, use phase savings relative to the steel wheeled truck arise from limiting fuel consumption.

4.2.1.5 Ozone Depletion Potential (ODP)

Ozone depletion potential is driven by the release of R-11 (trichlorofluoromethane) during the upstream production of aluminum ingot. R-11 is a chlorofluorocarbon used as a refrigerant and has the highest ozone depletion potential of any refrigerant, so even small quantities can drive ODP. Across the aluminum wheel life cycle, no impacts arise from the use or manufacturing phases, and some environmental credit is given for the recycling of aluminum.

4.2.1.6 Primary Energy Demand (PED)

Primary energy demand is driven by upstream aluminum ingot production. This is driven by fuel consumption in mining, heat generation in alumina refining, and the high energy consumption in the electrolysis phase of producing aluminum from alumina. Normalization to steel wheels demonstrates savings in PED during the End-of-Life recycling, as well as slight savings during the use phase related to the reduction in diesel demand.

4.2.1.7 USEtox

Although not displayed in the life cycle results, USEtox is used to evaluate human toxicity and eco toxicity in the life cycle of aluminum wheels to scan for “substances of high concern”. The biggest contributors to eco toxicity are polycyclic aromatic hydrocarbons (PAH) such as anthracene and other simple aromatic compounds such as phenol and benzene. These pose a significant risk mostly owing to their bio accumulative nature. These chemicals arise from diesel use during the use phase and are released to water. Similarly, the use of coal to provide primary energy to the upstream aluminum production releases other PAH compounds (chiefly benzo{a}pyrene) that contribute to ecotoxicity.

Human health toxicity for the aluminum wheel life cycle is driven by hexane and formaldehyde released to air during diesel burning in the use phase. Upstream aluminum production also releases formaldehyde indirectly through the burning of fossil fuels needed to supply the energy for aluminum refining.

Since the majority of chemicals identified as potential eco and human health toxins result from the use phase, the use of aluminum wheels actually helps to limit the consumption of diesel and reduce these emissions when compared to steel wheels.

4.2.2 MANUFACTURING

The cradle-to-gate global warming potential of aluminum wheel production is displayed in Figure 4-3. The area and shading of each block corresponds to the relative impact of each step of aluminum wheel production. Upstream aluminum ingot production accounts for 81% of the carbon footprint. Auxiliaries are materials that are used in the production process but are not part of the final wheel (e.g., lubricants, water, etc.). Note that the 5.2 tons of CO2e in manufacturing include the credit for post-consumer recycling. This scrap material in recycled 100% in a closed loop within the process.

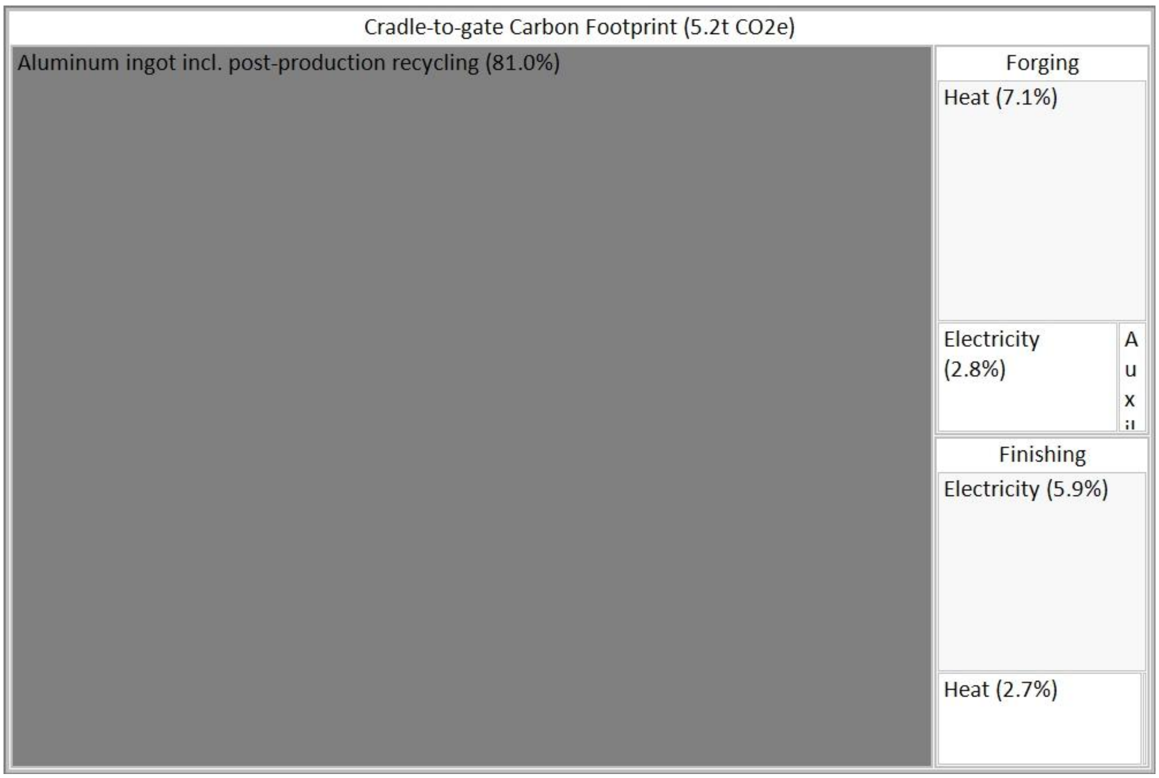

Figure 4-3. Cradle-to-gate Global Warming Potential of Aluminum Wheel Production

Manufacturing accounts for the remaining 19% of the carbon footprint and is explained in greater detail below in the gate-to-gate manufacturing impacts displayed in Figure 4-4. Of the gate-to-gate processes, forging accounts for 54% of the total gate-to-gate burden and wheel finishing represents the remaining 46%. From all facilities, thermal energy from natural gas consumption ('heat' on the chart) accounts for 51.6% of the carbon footprint and electricity consumption is responsible for 45.9%, and auxiliaries approximately 2.5%.

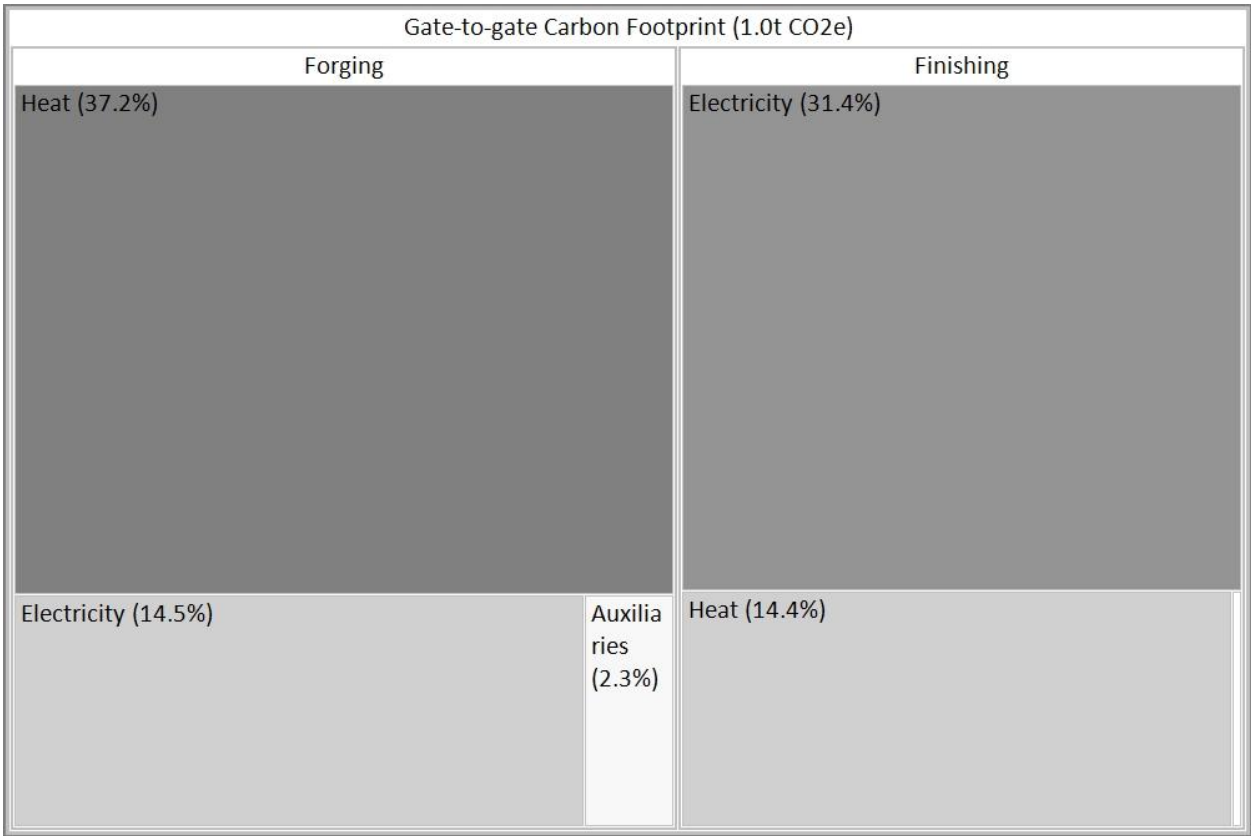

Figure 4-4. Gate-to-Gate Global Warming Potential of Aluminum Wheel Manufacturing

4.2.3 USE

Three different use-phase scenarios (mass-restricted, volume-restricted, and average) were calculated for North American and European boundary conditions. The results for European boundary conditions can be found in Annex B. Each scenario is depicted as a break-even chart along with a table of use phase statistics for trucks equipped with aluminum or steel wheels.

4.2.3.1 Mass-Restricted Scenario

In the mass restricted scenario, the gross vehicle weight remains the same whether the truck is equipped with aluminum or steel wheels; however, in the case where aluminum wheels are used, additional cargo can be transported. Table 4-1 contains parameters relevant to the mass-restricted use phase. As indicated in the table, the overall diesel consumption is the same, but the transportation performance (as measured by ton-kilometers) is improved when aluminum wheels are applied. Thus, the emissions per ton kilometer are improved when a truck is equipped with lighter weight aluminum wheels.

Table 4-1. US Mass-Restricted Scenario Relevant Quantities

	Truck with Alcoa Wheels	Truck with Steel Wheels
Payload (lbs)	**45,414**	**45,000**
Utilization rate	100%	100%
Gross Weight (lbs)	80,000	80,000
Distance (mi)	1,000,000	1,000,000
Fuel Economy (mpg)	5.7	5.7
Diesel Consumed (gal)	173,290	173,290
Use Phase CO_{2e} (kg)	1,990,332	1,990,332
Total t*km	**33,151,592**	**32,849,446**
kg CO_{2e} / t*km	**0.0600**	**0.0606**

Figure 4-5 depicts the lifetime performance of a truck with Alcoa aluminum wheels relative to the baseline scenario of a truck with steel wheels. At the end of manufacturing (the 0 ton kilometer point on the chart), the aluminum wheels have a higher global warming potential than steel wheels. This is due to the higher burden associated with aluminum production. Once the use phase begins, the environmental benefit of aluminum truck wheels is realized, and the initial difference in GWP (approximately 3.8 tons of CO_{2e}) gradually decreases across the lifetime of the wheel.

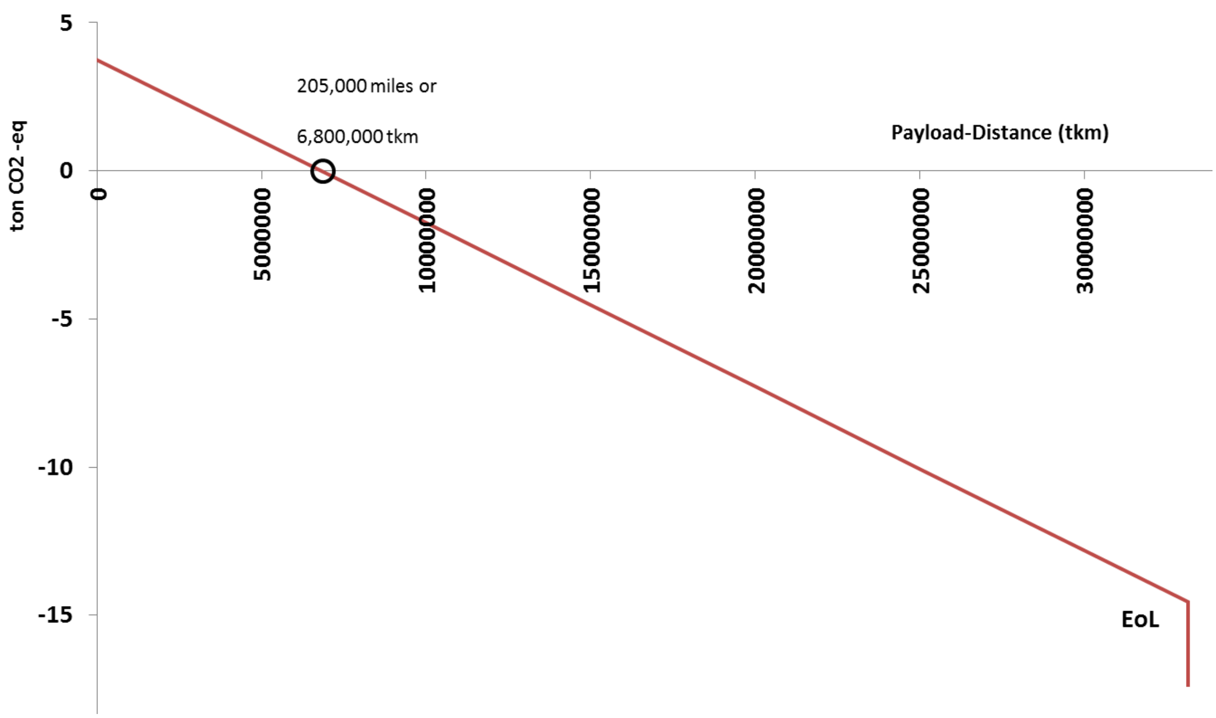

Figure 4-5. US Mass-Restricted Break Even Chart

The GWP break-even point for Alcoa aluminum wheels occurs around 6.8 million ton kilometers (or at 20.5% of the vehicle's lifetime or 205,000 miles). After this point, aluminum wheels provide a net benefit in environmental performance through the remainder of the use phase and End-of-Life. Use phase savings total 18.3 tons of carbon dioxide. After one million miles of use, the steel and aluminum wheels are recycled. The recycling credit for aluminum is greater than that of steel, giving additional benefit in the End-of-Life treatment.

Upon completion of the use phase, aluminum wheels have saved approximately 14.5 tons of CO_2 compared to steel wheels. Inclusion of recycling credit brings the life cycle benefit of aluminum wheels over steel wheels to a negative 17.8 tons of CO_{2e}.

4.2.3.2 Volume-Restricted Scenario

In the volume-restricted scenario, the cargo weight is held constant for both the aluminum and steel wheeled trucks at 30% of the steel wheel truck's payload capacity. The overall transportation performance remains the same; however, the gross vehicle weight is lower where aluminum wheels are used, resulting in an improvement in fuel economy. Table 4-2 contains parameters relevant to the volume-restricted use phase. As with the mass-restricted case, the global warming potential per ton kilometer is lower for the truck with Alcoa aluminum wheels.

Table 4-2. US Volume-Restricted Scenario Relevant Quantities

	Truck with Alcoa Wheels	Truck with Steel Wheels
Payload (lbs)	13,500	13,500
Utilization rate	29.74%	30.00%
Gross Weight (lbs)	**48,086**	**48,500**
Distance (mi)	1,000,000	1,000,000
Fuel Economy (mpg)	**6.81***	**6.8**
Diesel Consumed (gal)	**145,165**	**145,689**
Use Phase CO_{2e} (kg)	**1,668,924**	**1,673,558**
Total t*km	9,854,818	9,854,818
kg CO_{2e} / t*km	**0.1694**	**0.1698**

* (6.8 + 414*0.0000344) = 6.8142416 using the factor from Table 3-5

Figure 4-6 depicts the lifetime performance of a truck with Alcoa aluminum wheels relative to the baseline scenario of a truck with steel wheels. At the end of manufacturing (the 0 ton kilometer point on the chart), the aluminum wheels have a higher global warming potential than steel wheels. This is due to the higher burden associated with aluminum production. Once the use phase begins, the environmental benefit of aluminum truck wheels is realized, and the initial difference in GWP (approximately 3.8 tons of CO_2) gradually decreases across the lifetime of the wheel.

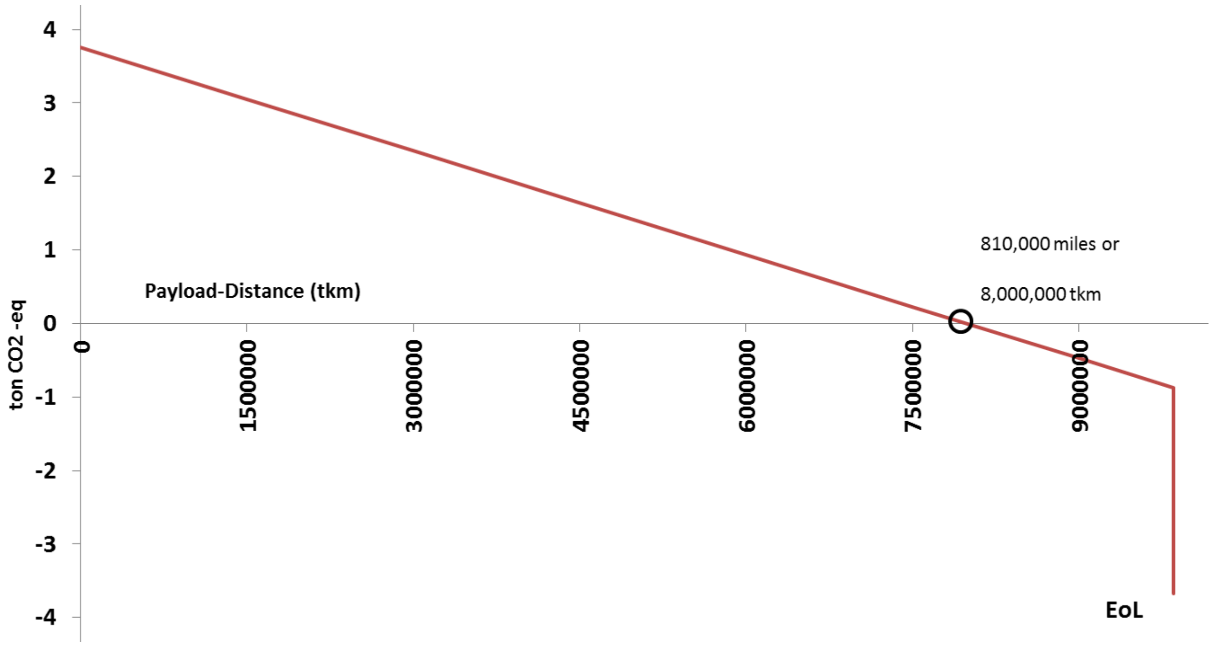

Figure 4-6. US Volume-Restricted Break Even Chart

The GWP break-even point for Alcoa aluminum wheels occurs around 8 million ton kilometers (or at 81% of the vehicle's lifetime or at 810,000 miles). After this point, aluminum wheels provide a benefit in environmental performance through the remainder of the use phase and End-of-Life. Use phase savings total 4.6 tons of carbon dioxide. After one million miles of use, the steel and aluminum wheels are recycled. The recycling credit for aluminum is greater than for steel, giving additional benefit in the End-of-Life treatment.

Upon completion of the use phase, aluminum wheels have saved approximately 0.9 tons of CO_2 when compared to steel wheels. Inclusion of recycling credit increases this savings to 4.1 tons of CO_2.

4.2.3.3 Average Use

In the average use scenario, an average utilization rate of 78% (according to the 2002 VIUS study) is constructed based on a 69% weighting of the mass-restricted case and a 31% weighting of the volume-restricted case. This calculation represents an approximation as—in real life—any utilization rate is possible and the 78 % average for class 8 trucks in the field does not constitute itself as a mix between just two extremes considered in this study as there are also transports that are not limited at all. Nevertheless, since the two extremes are based on essentially different calculation procedures, the artificial weighting of these two scenarios was the only feasible way to approximate the average use case for the purpose of this study. For a discussion of its representativeness, please refer to chapter 2.4.1.

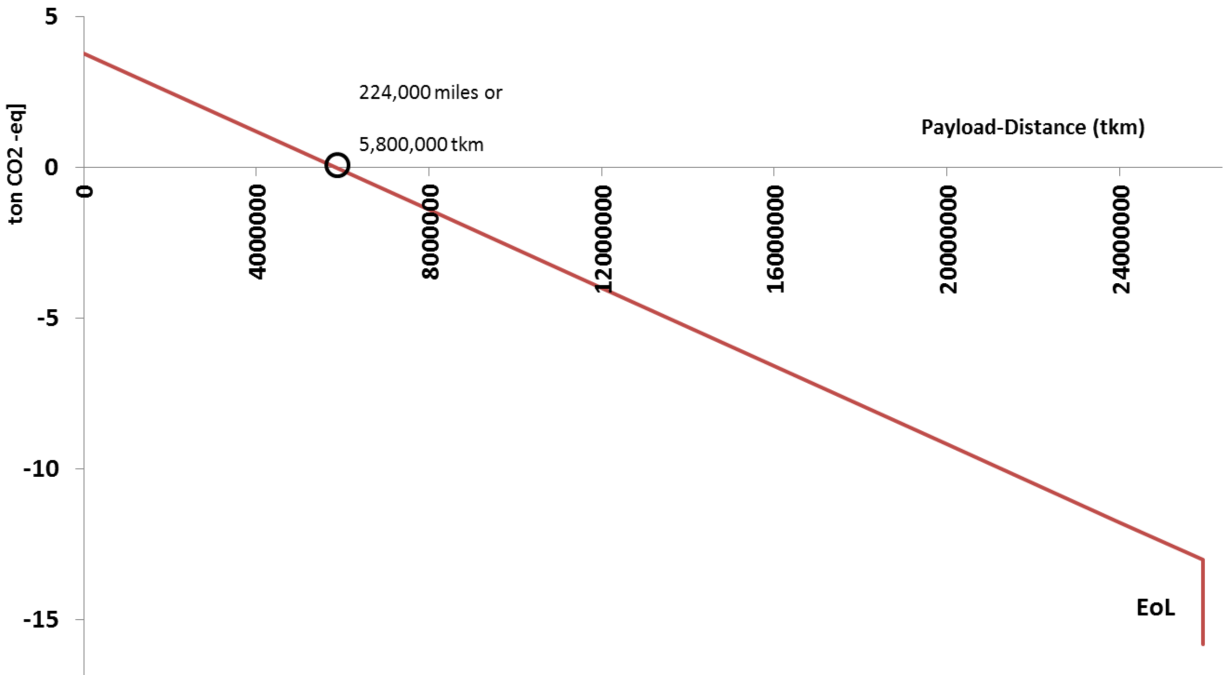

Figure 4-7. US Average Use Break-Even Chart

As with the mass-restricted and volume-restricted cases, the global warming potential per ton kilometer is lower for the truck with aluminum wheels. Figure 4-7 depicts the lifetime performance of a truck with Alcoa aluminum wheels relative to the baseline scenario of a truck with steel wheels. At the end of manufacturing (the 0 ton kilometer point on the chart), the aluminum wheels have a higher global warming potential than steel wheels. This is due to the higher burden associated with aluminum production. Once the use phase begins, the environmental benefit of aluminum truck wheels is realized, and the initial difference in GWP (approximately 3.8 tons of CO_2) gradually decreases across the lifetime of the wheel.

The GWP break-even point for Alcoa aluminum wheels occurs around 5.8 million ton-kilometers. It seems odd at first sight that the average use case results in the lowest break-even point in terms of t*km. The issue is the different lifetime payload distances for the two underlying scenarios. Also, by comparing on a ton-kilometer basis, the significantly higher lifetime ton-kilometers of the mass-restricted scenario dilute the volume-restricted scenario when an average is calculated. The break-even percentage of 22.4 % of the lifetime distance (or 224.000 miles) is nevertheless located between the two extreme scenarios. After this point, aluminum wheels provide a net benefit in environmental performance through the remainder of the use phase and End-of-Life, when compared with steel wheels. Over the course of the use phase, 16.8 tons of carbon dioxide are avoided. After one million miles of use, the steel and aluminum wheels are recycled. The recycling credit for aluminum is greater than that of steel, giving additional benefit at the End-of-Life.

Upon completion of the use phase, aluminum wheels have saved approximately 13 tons of CO_2 when compared to steel wheels. Inclusion of recycling credit increases this savings to 16.3 tons of CO_2.

4.2.4 END-OF-LIFE

The End-of-Life route for aluminum wheels entails recycling the wheels so that the aluminum can be recovered and used in further product systems. The credit for aluminum recycling in the results shown above is based on a value-corrected approach, where the market value of aluminum wheel scrap relative to virgin metal is applied. Scrap aluminum truck wheels have a value of 93% that of primary aluminum (compared to just 34 % for Scrap Steel Wheel Rims). This results in an absolute credit of 3.2 tons of carbon dioxide for the recycling of 367 kg of aluminum wheels.

5 INTERPRETATION

The goals of this study were to better understand the cradle-to-grave environmental profile of Alcoa's forged aluminum truck wheels and compare their performance to that of steel truck wheels. The model developed for this analysis was presented in section 3 with key results discussed in section 4 and additional scenarios covered in the appendices. The following section summarizes and interprets the results of this LCA study.

5.1 IDENTIFICATION OF RELEVANT FINDINGS

The comparison of Alcoa aluminum truck wheels with steel truck wheels suggest certain environmental advantages of using lighter weight forged aluminum wheels. The use of forged aluminum wheels allows for an increase in total payload capacity for mass-restricted transports and can reduce fuel consumption in volume-restricted transports. Upstream aluminum production renders the cradle-to-gate burden of aluminum wheels to be higher than for steel wheels, but the benefits achieved during the use phase allow for eventual break-even points and significant net environmental benefits.

The volume-restricted scenario shows the lowest use phase benefits due to the only marginal reduction of the vehicle gross weight, and achieves a break-even point after 810,000 miles of operation. In turn, the mass-restricted case allows for the greatest environmental benefits, reaching its break-even after 205,000 miles and realizing a total 16.8 tons of CO_{2e} savings over the full wheel life cycle. In the average use case, the break-even point occurs at approximately 224,000 miles, with total CO_{2e} savings of 15.3 tons over the wheel lifetime.

The mass saved due to light-weighting is the basis for the savings both in the volume-restricted (realized in fuel reduction) and mass-restricted (realized in additional cargo capacity) use cases. These weight savings are based on current Alcoa wheel production of high volume wheels in the US and EU juxtaposed with functionally equivalent steel wheels. The lifetime mileage is also decisive in the outcome of the volume restricted use case as the environmental break-even point of 810,000 miles in the base scenario is nearer the end of the assumed use phase.

5.2 DATA QUALITY ASSESSMENT

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied on a study serving as a data source) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data from Alcoa in combination with consistent background LCA information from the GaBi LCI database were used. The LCI data sets from the GaBi LCI database are widely distributed and used with the GaBi 5 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

The impacts from manufacturing steel wheels are believed to be conservatively low as the manufacturing is based on industry expertise and not directly derived from primary data collection. This is because generic GaBi inventories (e.g., stamping and bending, deburring, etc.) are used without further assumptions around energy consumption, which are likely to be higher for a wheel specific production system. The cradle-to-gate comparison probably represents a 'worse-case' situation for the aluminum wheels in a cradle to gate comparison. Still, use-phase savings dictate the outcomes of this study. The weight savings achieved by using aluminum wheels could vary depending on the type of steel wheels, but this variation is considered minute based upon a review of the weights of various steel wheels of the same size as the aluminum wheels modeled. Fuel economy savings achieved by weight limiting could vary depending on how gross weight affects fuel consumption, but this is influenced by a number of variables. The potential variation of fuel consumption savings is investigated in section 5.3.2, Sensitivity Analysis.

5.2.1 Precision and completeness

- **Precision:** As the relevant foreground data is primary data or modeled based on primary information sources of the owner of the technology, we believe that under the circumstance, no better precision is reachable within this project, and that improved precision would not affect the overall outcomes. Seasonal variations / variations across different manufacturers were balanced out by using yearly averages / weighted averages.

- **Completeness:** Each unit process was checked for mass balance and completeness of the emission inventory. No data was knowingly omitted.

5.2.2 Consistency and reproducibility

- **Consistency:** To ensure consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases. It is understood that comparing primary data for aluminum wheel production with secondary data used to describe steel wheel production is inconsistent. To the best of our ability, we attempted to address this by using favorable assumptions for steel wheel production and avoid an aluminum bias. Allocation and other methodological choices were made consistently throughout the model.

- **Reproducibility:** Reproducibility is warranted as much as possible through the disclosure of input-output data, dataset choices, and modeling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modeling approaches.

5.2.3 Representativeness

- **Temporal:** All primary data were collected for the year 2010 (and 2009 for one forging facility). All secondary data, including steel data, comes from the GaBi 5 2011 databases and are representative of the years 2006-2010. As the study intended to compare the product systems for the reference year 2010, temporal representativeness is warranted.

- **Geographical:** All primary and secondary data were collected specific to the countries / regions under study. Where country / region specific data were unavailable, proxy data were used. Geographical representativeness is considered to be high.

- **Technological:** All primary and secondary data were modeled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable (i.e., regarding steel wheel production), proxy data were used. Technological representativeness is considered to be high for aluminum wheels, and sufficient for steel wheels considering the conservative estimates used to model steel wheels.

5.3 Completeness, Sensitivity, and Consistency

This section addresses aspects of the study related to completeness, sensitivity of model parameters and consistency with regard to treatment of information.

5.3.1 Completeness

All relevant process steps for each product system were considered and modeled to represent each specific situation. The process chain is considered sufficiently complete with regard to the goal and scope of this study. The cut-off criteria applied to this study were met, with care taken during data collection to achieve a complete LCI. The cut-off criteria were applied in the exclusion of some minor waste flows (collectively <1% of mass).

5.3.2 Sensitivity Analyses

5.3.2.1 End-of-Life Treatment

Value-corrected substitution is the baseline End-of-Life case for the results provided in section 4. Alternative End-of-Life approaches are considered here. The conventional avoided burden approach is one case, where aluminum is given full credit for the secondary aluminum generated, assuming it replaces primary aluminum without any “changes to the inherent properties” in further product systems.[32] This results in a credit of 3.8 tons of carbon dioxide to the aluminum wheel life cycle, or an additional 0.6 tons of CO_{2e} over the baseline case, increasing the savings across all use phase scenarios considered.

Additionally, the cut-off approach is also evaluated for End-of-Life, in which the system boundary is drawn at the point of waste generation. Life cycle impact results for global warming would be decreased by 7 tons CO_2 (3.2 tons from EoL cut-off and 3.8 tons from post production cut-off). The carbon savings are provided for each of the use phase scenarios above before End-of-Life credit is applied and range from 0.9 tons CO_2 for volume restricted to 14.5 tons CO_2 for mass restricted. Post-production cut-off pushes the volume-restricted scenario into a net positive burden of 2.9 tons of CO_2 over the steel case;

[32] Note that the value-correction factor of 93 % used in the base scenarios in essence also corresponds to a scenario with no significant quality loss as a 7 % higher credit would be partially or fully offset by the additional burden of re-metling and casting the scrap depending on the impact category.

however, the mass-restricted scenario still has a total savings of 10.7 tons of CO_2, and the average case maintains a savings of 9.2 tons of CO_2. The cut-off scenario applied to post-production recycling would shift the break even points (or remove altogether in the volume-restricted case) to later in the use phase. The life cycle global warming potential for all End-of-Life scenarios applied to each use phase are given in Table 5-1.

Table 5-1. End-of-Life Scenario Evaluation

EoL Scenario	Average Case Savings (t CO_2)	Mass-Restricted Savings (t CO_2)	Volume Restricted Savings (t CO_2)
Value-Corrected Substitution	**16.3**	**17.8**	**4.1**
Avoided Burden	16.9	18.4	4.7
Cut-off	9.2	10.7	-2.9

Even with the most conservative End-of-Life treatment (the cut-off approach), Alcoa aluminum wheels still provide an environmental benefit to global warming for the average and mass-restricted use scenarios. Consideration of other factors that may affect the overall profile for aluminum wheels are presented in further sensitivity analysis below.

5.3.2.2 Fuel Reduction Value

Figure 5-1 portrays the results from sensitivity analysis of the parameter that connects the vehicle weight to fuel economy for the average and volume-restricted use scenarios. The parameter in question is used natively in the GaBi 5 truck dataset to calculate the fuel economy. The parameter only influences the volume-restricted and average use scenarios, as the mass-restricted scenario has no benefit from light weighting, but instead from the ability to carry additional cargo. These results indicate that the light-weighting parameter has an impact on the carbon savings in the volume-restricted scenario. A zero value for this parameter (adjustment by -100 %) yields no use phase savings relative to the steel wheels, while doubling the value provides an additional 60 % increase in use phase GWP savings.

A ~75 % reduction of the parameter would reduce the GWP savings by ~100 % and the aluminum wheels would no longer have a life-time environmental benefit over the steel wheels in the volume-restricted scenario. However, even a 50 % decrease in the parameter value reduces GWP savings by roughly 45 % still providing a cradle-to-grave environmental benefit for the aluminum wheels. It should be noted that this parameter does not affect the mass-restricted results, which are based on the vehicle performance as measured by ton-kilometers.

For the average use case, adjustments in the parameter have little to no effect on the overall outcome, since mass-restricted savings dominate the average case. Even without savings from light weighting (a 100% reduction in the parameter) the average use case only experiences a 9% reduction in GWP savings.

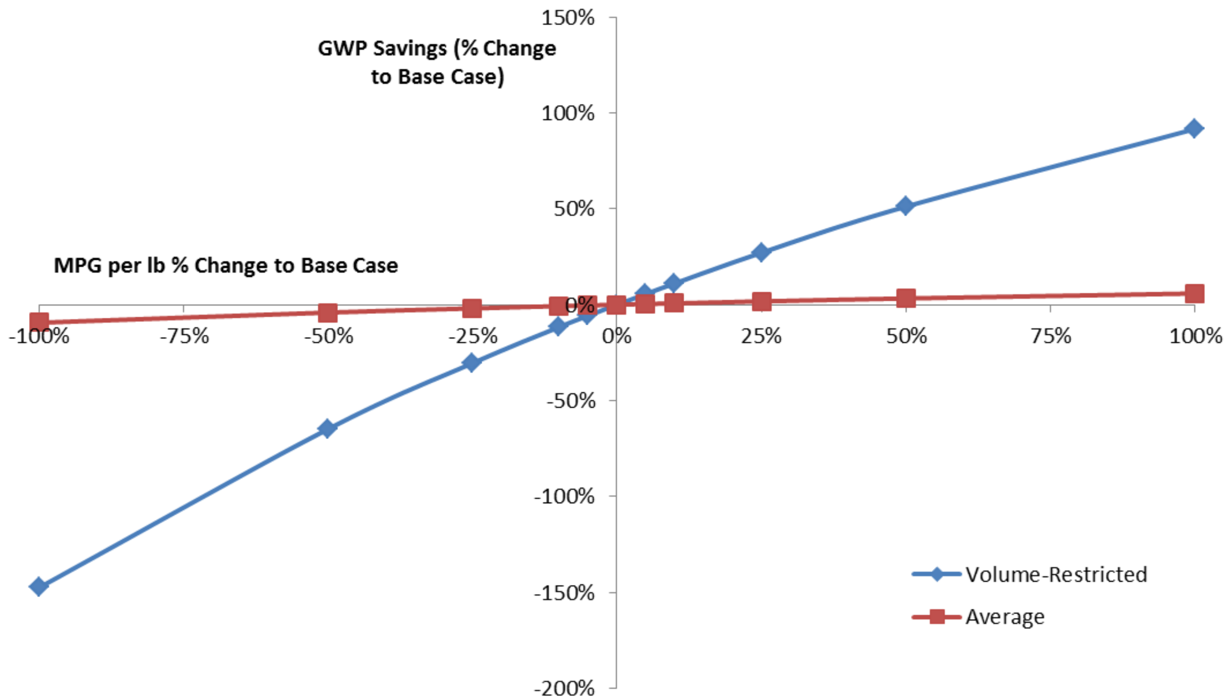

Figure 5-1. Use phase GWP savings as influenced by light-weighting

Furthermore, certain aspects of light weighting the wheels are not taken into account. Most notably, fuel economy savings related to a having a *lower rotational inertia* during acceleration and breaking have not been considered for this study. These savings could be non-negligible as the rotated mass is multiplied by the square of the distance *r* to the rotational center in order to calculate the rotational energy,[33] and could therefore significantly increase the total savings over a 1 million mile vehicle lifetime. Under these circumstances, the results in this report can be viewed as conservative estimates of the actual possible fuel savings.

5.3.2.3 Premature Failure and Replacement

Figure 5-2 portrays the effect of replacing truck wheels over the lifetime of the truck on the break-even point. Each wheel replaced represents an additional net increase of 28 kg of carbon dioxide on the total aluminum wheel life cycle burden when also replacing a steel wheel at the same time. This includes the End-of-Life recycling for both the wheel replaced, and the replacement wheel. For the average and mass-restricted cases, replacing the full 18 wheels across a one million mile lifetime still allows for an environmental benefit for aluminum wheels over steel wheels.

[33]

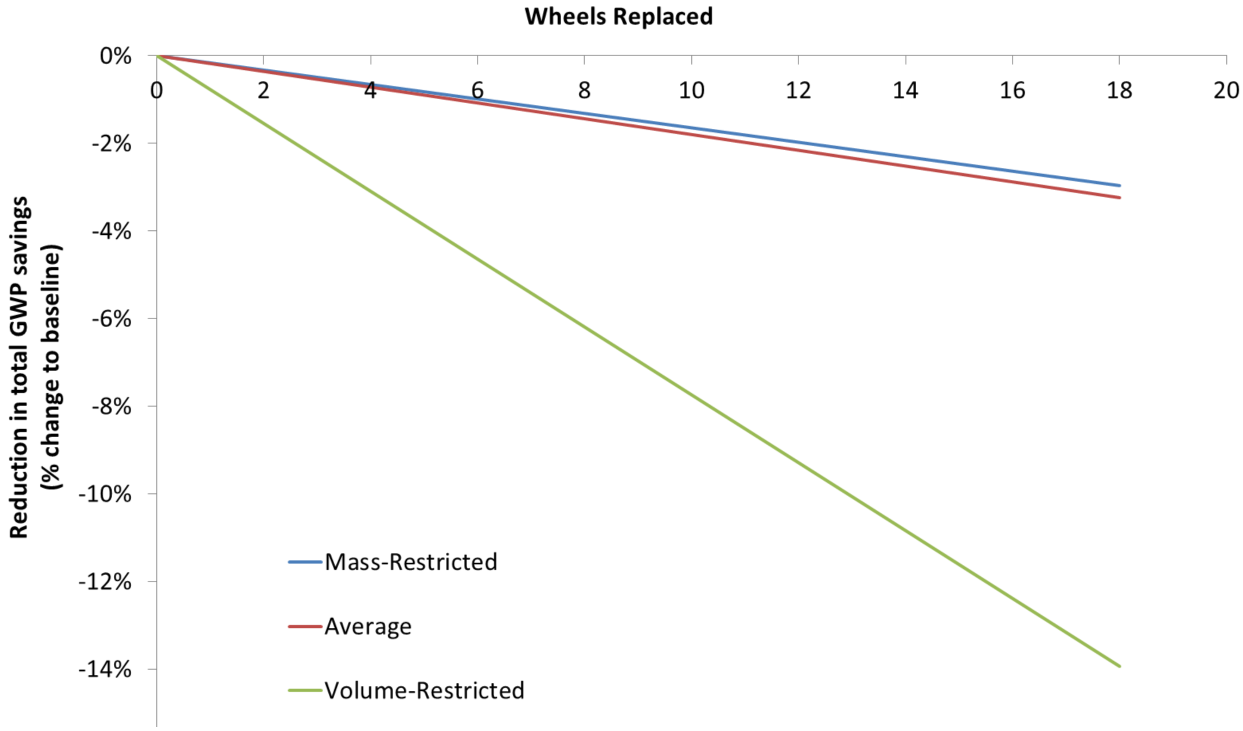

Figure 5-2: Number of Wheels Replaced vs. Baseline Carbon Savings

Even replacing a full set of 18 wheels, the mass-restricted case saves a net 16.8 tons of carbon dioxide and the average case saves a net 15.3 tons of carbon when compared with steel wheels. From Figure 5-2, the mass-restricted use phase has a 3% reduction in net carbon savings, while the average case has a 3.2% reduction when replacing the full set of aluminum wheels. In the volume restricted case, carbon savings are reduced by 14% when the full set of wheels is replaced.

In the volume-restricted scenario, an environmental break-even point is still achieved during the use phase after the full set of 18 wheels are replaced. After replacing a full set of wheels, the volume-restricted scenario still saves a net 3.2 tons of carbon.

Certainly, the application of an End-of-Life cut-off approach, would change these outcomes. Replacing a full set of aluminum wheels with a cut-off approach would cause a net environmental burden in the volume restricted case and would reduce the overall savings in the mass-restricted and average cases.

5.3.2.4 Average Use Case Mass and Volume-Restricted Weighting Share

The share of mass and volume restricted transport used to calculate the average use case was found to be an important parameter to the results of the study. Sensitivity analysis was then conducted to help better understand how this weighting changes the overall savings experienced by the truck equipped with aluminum wheels. The results of this analysis are displayed in Figure 5-3. The steep mass-restricted bias that is evident in the chart results from the truck performance (i.e. ton kilometers of transport) quantity used to calculate the savings. Specifically, the mass-restricted scenario provides a much greater performance than the volume restricted scenario, effectively diluting the impact of the volume restricted scenario.

The current mass-restricted/volume-restricted share is 69/31 and allows for 16.3 tons of carbon dioxide savings. When a 50/50 share is applied, the savings drop to 14.8 tons of carbon dioxide, and even a volume-restricted favored weighting of 25/75 allows for 11.5 tons of carbon dioxide savings.

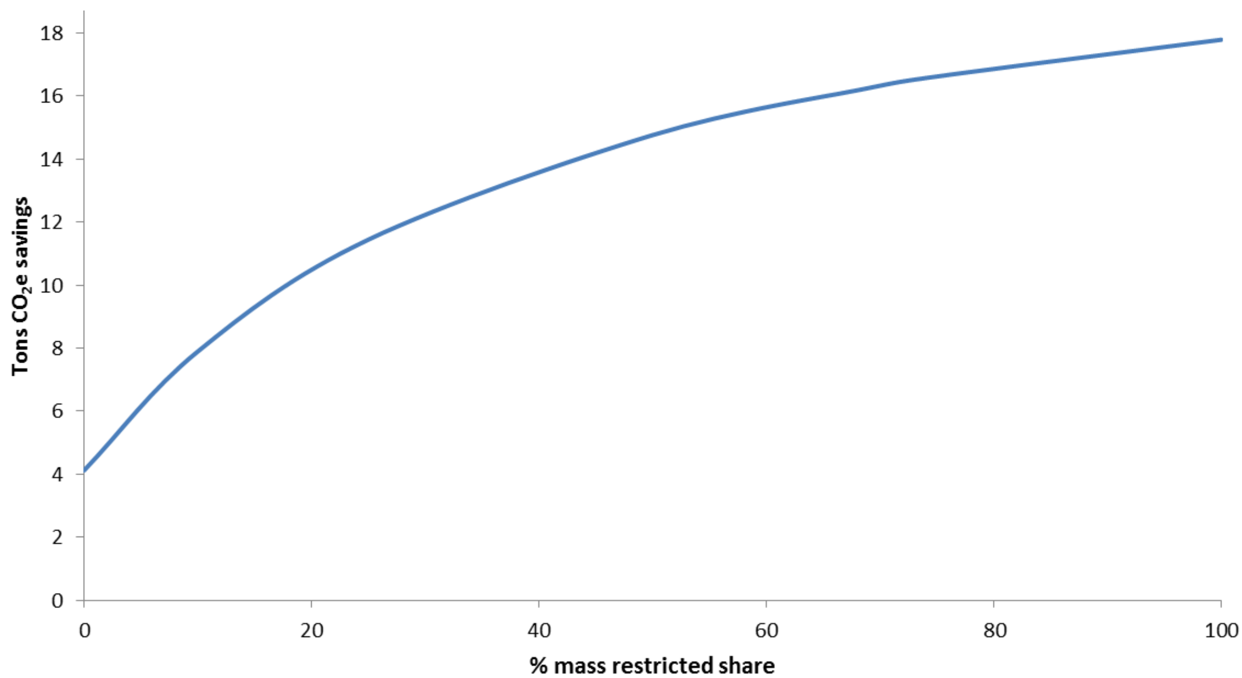

Figure 5-3. Average Use Phase GWP savings as a function of the mass-restricted share

5.3.3 Consistency

All assumption, methods, and data were found to be consistent with the study's goal and scope. Differences in background data quality were minimized by using LCI data from the GaBi 5 2011 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.4 Conclusions, Limitations, and Recommendations

This analysis represents a cradle-to-grave comparative life cycle assessment of aluminum and steel truck wheels. Work has been done to ensure the completeness of the study, to analyze the sensitivity of key aspects, and to check that the consistency in data and results is in line with the Goal & Scope of the study.

5.4.1 Carbon Return-on-Investment

To help describe the aluminum wheel life cycle benefits, the environmental savings can be thought of as a "Carbon Return-on-Investment." This describes the initial environmental "investment" of the aluminum wheel manufacturing that helps realize environmental "returns" during the remainder of the life cycle.

The initial investment can be thought of as the aluminum wheel manufacturing burden less the steel wheel manufacturing burden. The Carbon Return-on-Investment can then be calculated using the formula

CRoI = (net use savings + net EoL savings - net manufacturing burden) / (net manufacturing burden)

The below conclusions contain the resulting CRoI values for the different scenarios.

5.4.2 Conclusions

The following conclusions can be drawn from this study regarding aluminum wheels under the average use case (unless otherwise stated):

- Aluminum wheel cradle-to-gate production carries a total burden of 5.2 tons of CO_2-equivalents for a set of 18 wheels, which equals in increase in GWP of 3.8 tons compared to steel wheel production. In order to achieve a Carbon Return-on-Investment, the aluminum wheels have to overcome this 3.8 ton deficit over their lifetime.
- In the mass-restricted use case, aluminum wheels save approximately 16.8 tons of CO_{2e} over their entire lifetime when compared to steel wheels. Use phase savings total 18.3 tons of CO_{2e} and realize a break-even point around 205,000 miles. EoL recycling adds another net benefit of 3.2 tons of CO_{2e}. The mass-restricted scenario allows for the greatest environmental savings for aluminum wheels. The *Carbon Return-on-Investment* is (18.3+3.2-3.8)/3.8 or 466%.
- In the volume-restricted phase, aluminum wheels have saved approximately 4.1 tons of CO_{2e} over their entire lifetime when compared to steel wheels. Use phase savings total 4.6 tons of CO_{2e} and realize a break-even point around 810,000 miles. EoL recycling again adds another net benefit of 3.2 tons of CO_{2e}. The *Carbon Return-on-Investment* is (4.6+3.2-3.8)/3.8 or 105%.
- In the average use phase, aluminum wheels have saved approximately 15.3 tons of CO_{2e} over their entire lifetime when compared to steel wheels. Use phase savings total 16.8 tons of CO_{2e} and realize a break-even point around 224,000 miles. EoL recycling again adds another net benefit of 3.2 tons of CO_{2e}. The *Carbon Return-on-Investment* is (16.8+3.2-3.8)/3.8 or 426%.
- Most other impact categories considered show the same tendency: replacing steel truck wheels with aluminum truck wheels leads to overall net improvements in the environmental profile. This does not hold true for ODP and primary energy demand, or for smog potential in the EU case.
- Sensitivity analysis shows that replacing a full set of 18 aluminum truck wheels does not affect the life cycle environmental advantage of over steel truck wheels. This does not hold true when an End-of-Life cut-off approach is applied to the volume-restricted use case.
- Assuming no fuel savings from light-weighting does not significantly reduce the life cycle savings of the average use case. The above conclusions are therefore deemed sufficiently robust.

- The other impact categories considered (smog potential, acidification potential, eutrophication potential, and primary energy demand) all enjoy use phase savings (not the case for ozone depletion potential, or for smog potential in the EU) when compared to the steel wheel baseline.
    - The reduction of nitrogen oxides released to air during the use phase drives savings in smog potential, acidification potential and eutrophication potential.
- Overall EU environmental profiles and outcomes are similar to the North American case. Savings for each of the EU use phase scenarios are provided below:
    - Mass-restricted complete life cycle savings amount to 14.4 tons of CO_2.
    - Volume-restricted complete life cycle savings amount to 5.1 tons of CO_2.
    - Average case complete life cycle savings amount to 13.3 tons of CO_2.
- The North American wide wheels application provides considerable environmental savings through additional reduction in wheel weight by replacing traditional twin wheels with a single aluminum wide wheel. Savings for each of the wide wheels use phase scenarios are provided below:
    - Mass-restricted complete life cycle savings amount to 30.7 tons of CO_2.
    - Volume-restricted complete life cycle savings amount to 9.6 tons of CO_2.
    - Average case complete life cycle savings amount to 28.6 tons of CO_2.

5.4.3 Limitations & Assumptions

The following limitations have been identified for this study:

- Transportation of raw materials is not considered for the manufacturing phase of this comparative life cycle assessment of aluminum wheels. This was done because steel wheel transportation data was not available. While it is unlikely to dramatically change the results of this study, inclusion of transportation data may influence the aluminum truck lifetime savings (i.e., if the transportation distance of aluminum ingot was dramatically higher than for steel wheels). Due to the lower mass of raw material required for the aluminum wheel, the assumption is that even longer distances would not offset the weight advantage of aluminum in terms of transportation impacts.
- Packaging information was also excluded from this study, again because no such information was available for steel wheel production. While packaging is assumed to be similar for both steel and aluminum truck wheels, the different circumstances are not known and so could not be evaluated in this study. Due to the commonly low masses and low specific impacts of packaging materials like plastics and wood, this data gap is deemed negligible.
- Fuel-economy savings derived from a reduction in rotational inertia of the aluminum wheel relative to the steel wheel are not considered in this study. Inclusion of this analysis is likely to increase the environmental benefit of aluminum wheels.
- For steel wheel production, best estimates regarding losses, quantities and processes used in steel wheel manufacturing were employed. Conservative assumptions are used, so it is believed

that more accurate steel wheel manufacturing data would only extend the environmental benefit of aluminum wheels.

- Aluminum wheels enjoy better overall outcomes by applying value corrected substitution. While it is believed that this approach is appropriate, implementing a cut-off treatment shifts the outcome for the volume-restricted use case and lessens the benefit in the average and mass-restricted cases.

5.4.4 Recommendations

The outcomes of this analysis demonstrate favorable environmental results for most impact assessment categories and use phase scenarios for Alcoa aluminum wheels over their steel wheel counterparts – situations where this is not true have been addressed above. Given the mass-restricted scenario, the benefit of carrying additional payload is measurable and very concrete. With regard to savings from light-weighting (i.e., the volume-restricted case), it is advised that further research be conducted on the fuel economy benefits of implementing lighter weight aluminum wheels, especially any potential added benefits from the effect of a lighter wheel on rotational moment of inertia. Since one of the important considerations in this study is the longevity of wheels, it is further recommended that Alcoa gain a better understanding of the average lifetime of its truck wheels by collecting empirical data on wheel lifetime.

Appendix A. Impact Categories

Table 5-2. North American Impact Categories

Impact Category / Indicator	Description	Unit	Reference
Energy Use / Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) or energy demand from renewable resources (e.g. hydropower, wind energy, solar, etc.).	MJ	An operational guide to the ISO-standards (Guinée *et al.*) Centre for Milieukunde (CML), Leiden 2001.
Climate Change	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	Bare, TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. Clean Techn Environ Policy, Springer, 2011.
Smog Creation Potential	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops	kg O_3 equivalent	Bare, TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. Clean Techn Environ Policy, Springer, 2011.
Acidification / Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg mol H^+ equivalent	Bare, TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. Clean Techn Environ Policy, Springer, 2011.
Water Pollution / Eutrophication Potential	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In addition, high nutrient concentrations may also render surface waters unacceptable as a source of drinking	kg N equivalent	Bare, TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. Clean Techn Environ Policy, Springer, 2011.

Impact Category / Indicator	Description	Unit	Reference
	water. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.		
Toxicity	USEtox calculates characterization factors for human toxicity and freshwater ecotoxicity. As demonstrated Assessing the toxicological effects of a chemical emitted into the environment implies a cause–effect chain that links emissions to impacts through three steps: environmental fate, exposure and effects. The systematic framework for toxic impacts modeling based on matrix algebra was developed within the OMNIITOX project.		Rosenbaum et al.: USEtox—the UNEP-SETAC toxicity model: recommended characterization factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment, IJLCA, Springer, 2008.

Table 5-3. European Impact Categories.

Impact Category / Indicator	Description	Unit	Reference
Energy Use / Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) or energy demand from renewable resources (e.g. hydropower, solar, etc.).	MJ	An operational guide to the ISO-standards (Guinée *et al.*) Centre for Milieukunde (CML), Leiden 2001.
Climate Change	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	An operational guide to the ISO-standards (Guinée *et al.*) Centre for Milieukunde (CML), Leiden 2001.
Smog Creation Potential	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may damage crops.	kg Ethene equivalent	An operational guide to the ISO-standards (Guinée *et al.*) Centre for Milieukunde (CML), Leiden 2001.
Acidification / Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	An operational guide to the ISO-standards (Guinée *et al.*) Centre for Milieukunde (CML), Leiden 2001.
Water Pollution / Eutrophication Potential	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In addition, high nutrient concentrations may also render surface waters unacceptable as a source of drinking water. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg Phosphate equivalent	An operational guide to the ISO-standards (Guinée *et al.*) Centre for Milieukunde (CML), Leiden 2001.

Appendix B. European Results

The following tables depict the input and output data for aluminum wheel manufacturing in Europe.

Table 5-4: Forging Data for European Wheel Production

[redacted]

Confidential

Table 5-5: Finishing Data for European Wheel Production

[redacted]

Confidential

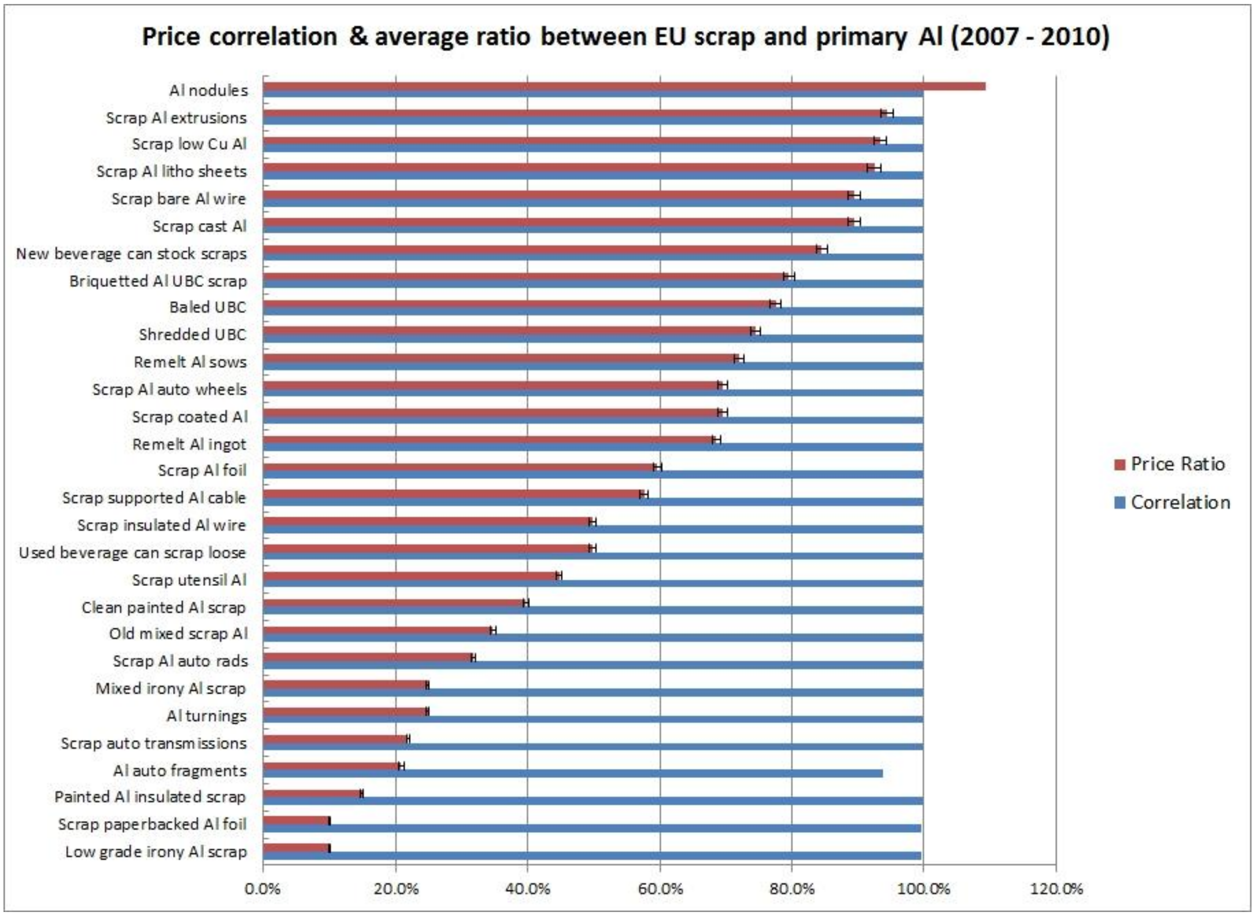

Figure 5-4. EU aluminum scrap classes' correlation and average ratio with primary ingot price 2007-2010

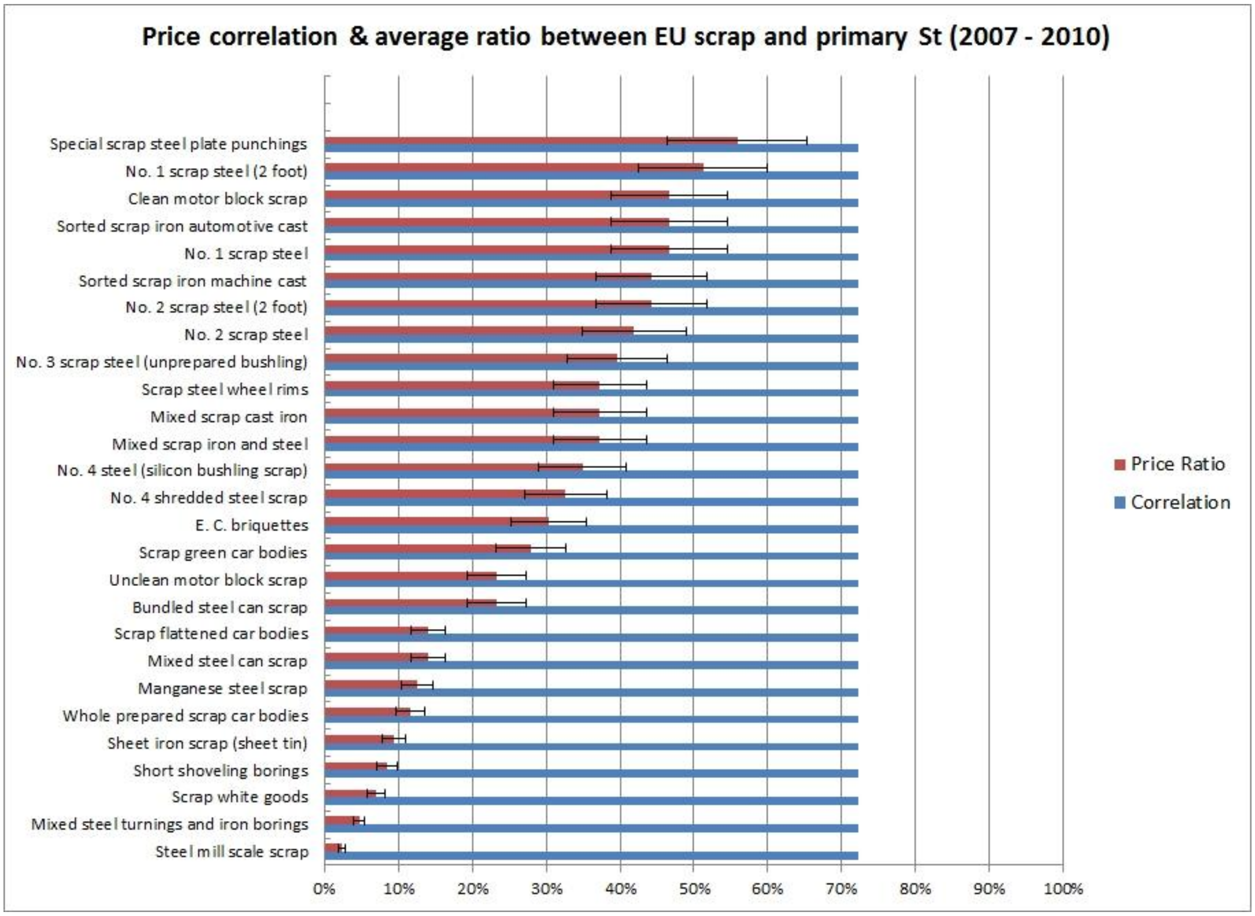

Figure 5-5. EU steel scrap classes' correlation and average ratio with primary steel billet price 2007-2010

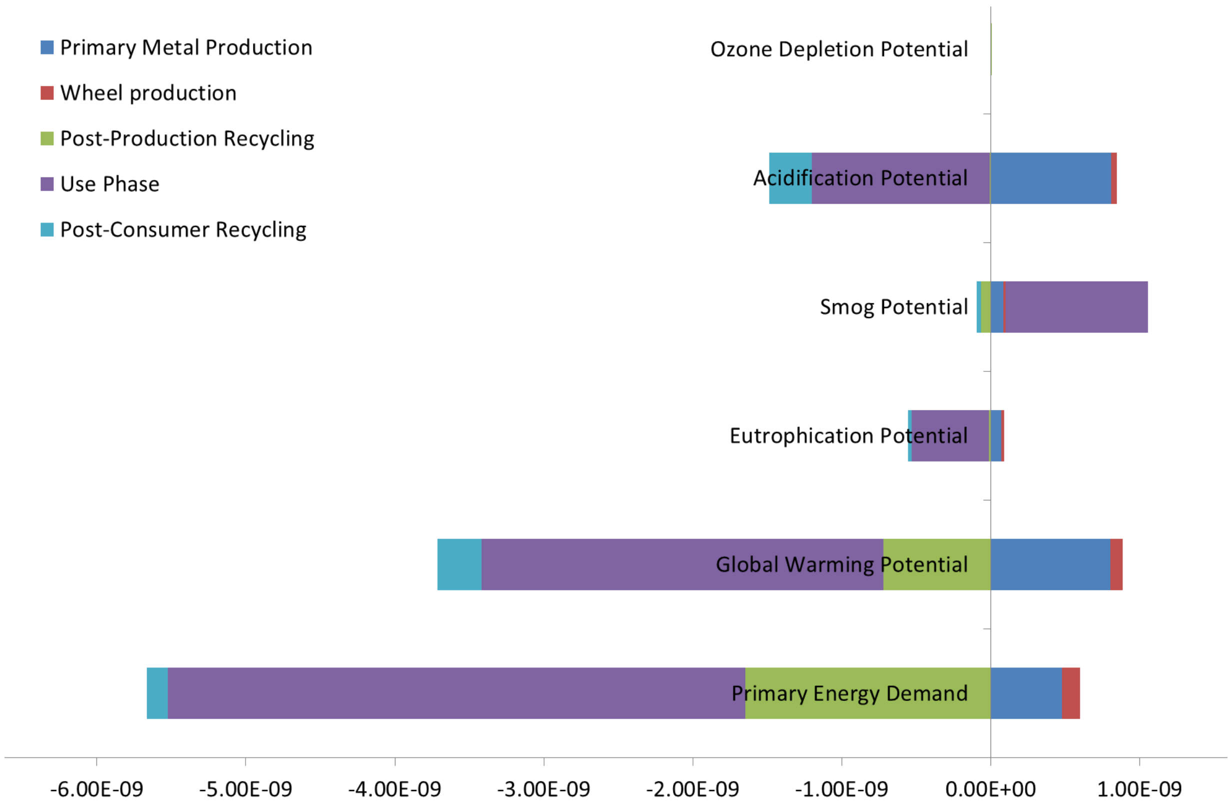

Figure 5-6. European Union CML Normalized Impact Results

Alcoa's aluminum wheel LCIA results are provided here normalized to the statistical annual environmental burden of the European Union. Each life cycle phase for aluminum wheels is presented as the difference to the steel truck wheels reference.

Life cycle phases in Figure 5-6 having positive values (namely primary metal production and wheel production) have a higher burden than the corresponding phase for steel wheels, while phases with negative values (use phase, post-production and post-consumer recycling) have a lower burden compared to the steel wheel life cycle phases –representing an environmental credit related to the use of aluminum wheels. As the chart shows, global warming potential, primary energy demand, and to a lesser extent, acidification potential are the most notable impact categories. Eutrophication potential and smog potential represent less substantial impacts, and ozone depletion potential is so minimal as to not even be visible on the chart.

Of the impact categories considered, the most attention will be given to global warming potential, which will be discussed in further detail throughout the results section.

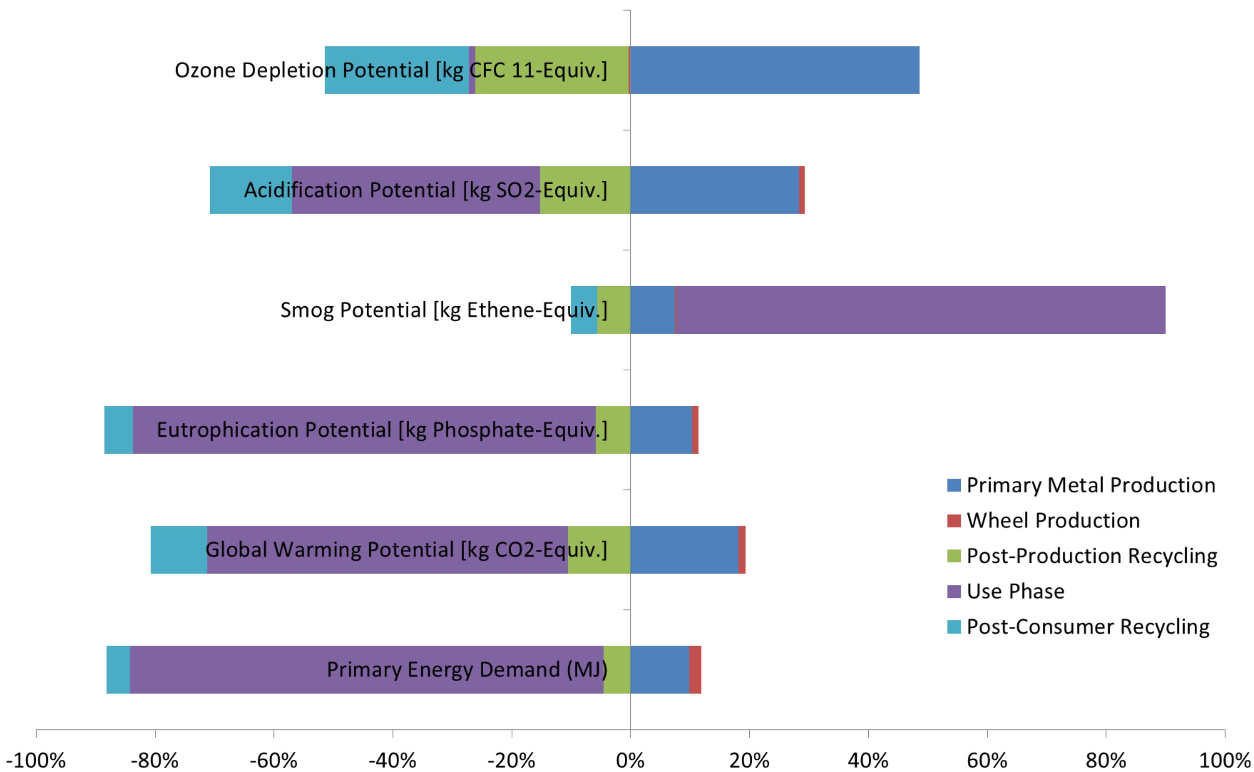

Figure 5-7. European Aluminum Wheel Life Cycle Results

The aluminum wheel complete life cycle results for Europe are presented in Figure 5-7. The values have been normalized to the steel wheel baseline, environmental savings from use phase (average scenario), post-consumer and post-production recycling are shown as negative values to capture the environmental benefit steel wheels provide during these life cycle stages. Aluminum production and wheel manufacturing have a higher burden for aluminum wheels than steel wheels and thus have positive values on the chart.

For global warming potential, primary energy demand, eutrophication potential and acidification potential, aluminum wheels provide a net benefit to the environment over their complete life cycle when compared with steel wheels. Ozone depletion potential net impacts are roughly zero and smog potential has a net positive impact.

Recall from the normalized life cycle results in Figure 5-6 that ozone depletion potential, and to a lesser extent, eutrophication potential and smog potential have relatively small impacts when considered in the context of the total European burden.

5.4.4.1 Global Warming Potential (GWP)

The global warming potential for aluminum wheels is driven chiefly by use phase savings. Use phase savings in Figure 5-7 are calculated for the average use scenario. Break even charts for all use phase scenarios are presented below in the use phase results. Besides the use phase, primary metal production is a major source of global warming impacts, and along with wheel manufacturing, has a net positive impact over the steel wheel counterparts.

Global warming potential is driven by direct carbon dioxide emissions from burning fossil fuels to meet the energy demand for manufacturing aluminum. Also, the fuel savings in the use phase decrease the amount of diesel burned by the truck equipped with aluminum wheels and directly reduce the carbon dioxide released.

5.4.4.2 Smog Potential

Smog potential for aluminum wheel production has a net savings when normalized to steel wheel life cycle impacts, with most of the savings arising from the use phase. Use phase smog emissions arising from aluminum production have a positive impact, and are largely the result of nitrogen oxides released to air from fossil fuel burning. The use phase ends up with a positive impact despite demonstrating savings in all other impact categories. This occurs because nitric oxide emitted by the truck actually counteracts smog, and since use phase emissions are reduced, less nitric oxide is emitted.

5.4.4.3 Acidification Potential (AP)

The acidification potentail for aluminm wheels life cycle are driven by sulfur dioxide and nitrogen oxides released to air during fossil fuel burning. The use phase benefit in acidification potential comes from the reduced diesel consumption of the truck, limiting the total amount of nitrogen oxides and sulfur dioxide emitted.

5.4.4.4 Eutrophication Potential (EP)

Eutrophication potential is driven by nitrates released to water along with nitrogen oxides released to air, both coming from fossile fuel burning. Primary aluminum production and wheel production drive positive eutrophication values, while some of this burden is recovered during the recyling of aluminum post production and at the End-of-Life. As with other impacts, use phase savings relative to the steel wheeled truck arise from limiting fuel consumption.

5.4.4.5 Ozone Depletion Potential (ODP)

Ozone depletion potential is driven by the release of R-11 (trichlorofluoromethane) during the upstream production of aluminum ingot. R-11 is a chlorofluorocarbon used as a refrigerant and has the highest ozone depletion potential of any refrigerant, so even small quantities can drive ODP. Across the aluminum wheel life cycle, no impacts arise from the use or manufacturing phases, and some environmental credit is given for the recycling of aluminum.

5.4.4.6 Primary Energy Demand (PED)

Primary energy demand is driven by upstream aluminum ingot production. This is because of the processing of bauxite to extract aluminum. Across the aluminum wheel life cycle, normalization to steel wheels demonstrates savings in PED during the End-of-Life recycling, as well as slight savings during the use phase related to the reduction in diesel demand.

5.4.5 MANUFACTURING

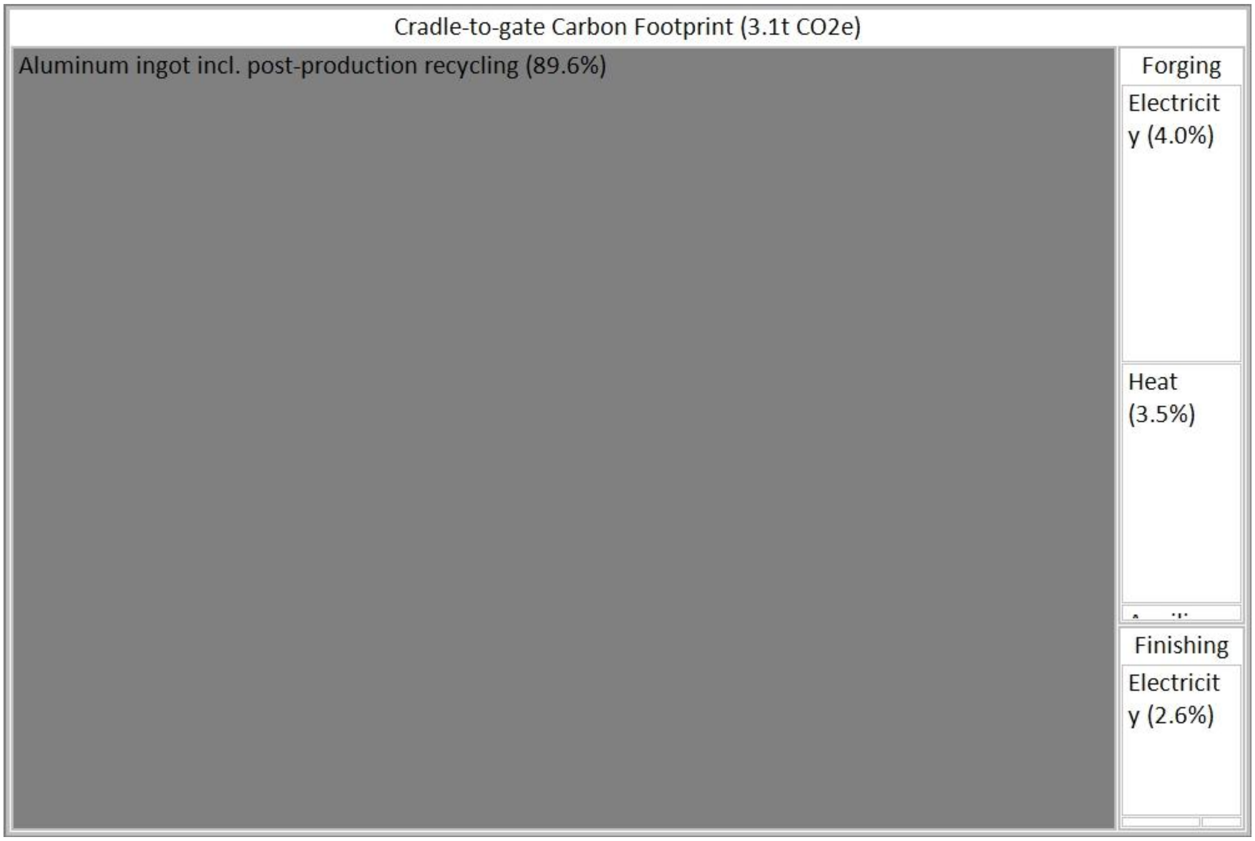

Figure 5-8. Cradle-to-Gate European Aluminum Wheel Production

The cradle-to-gate global warming potential of aluminum wheel production is displayed in Figure 5-8. The block areas and shading correspond to the relative impacts for each facet of aluminum wheel production. Upstream aluminum ingot production accounts for 89.6% of the carbon footprint, with only 10.4% of global warming attributed to the wheel manufacturing.

Manufacturing accounts for the remaining 10% of the carbon footprint and is given in further detail below in the gate-to-gate manufacturing impacts displayed in Figure 5-9. Wheel forging accounts for 73.8% of the total gate-to-gate burden, while finishing represents 26.2%. From all facilities, thermal energy from natural gas consumption (‘heat’ on the chart) accounts for 34% of the carbon footprint and electricity consumption is responsible for 62.9%, and auxiliaries 3.1%.

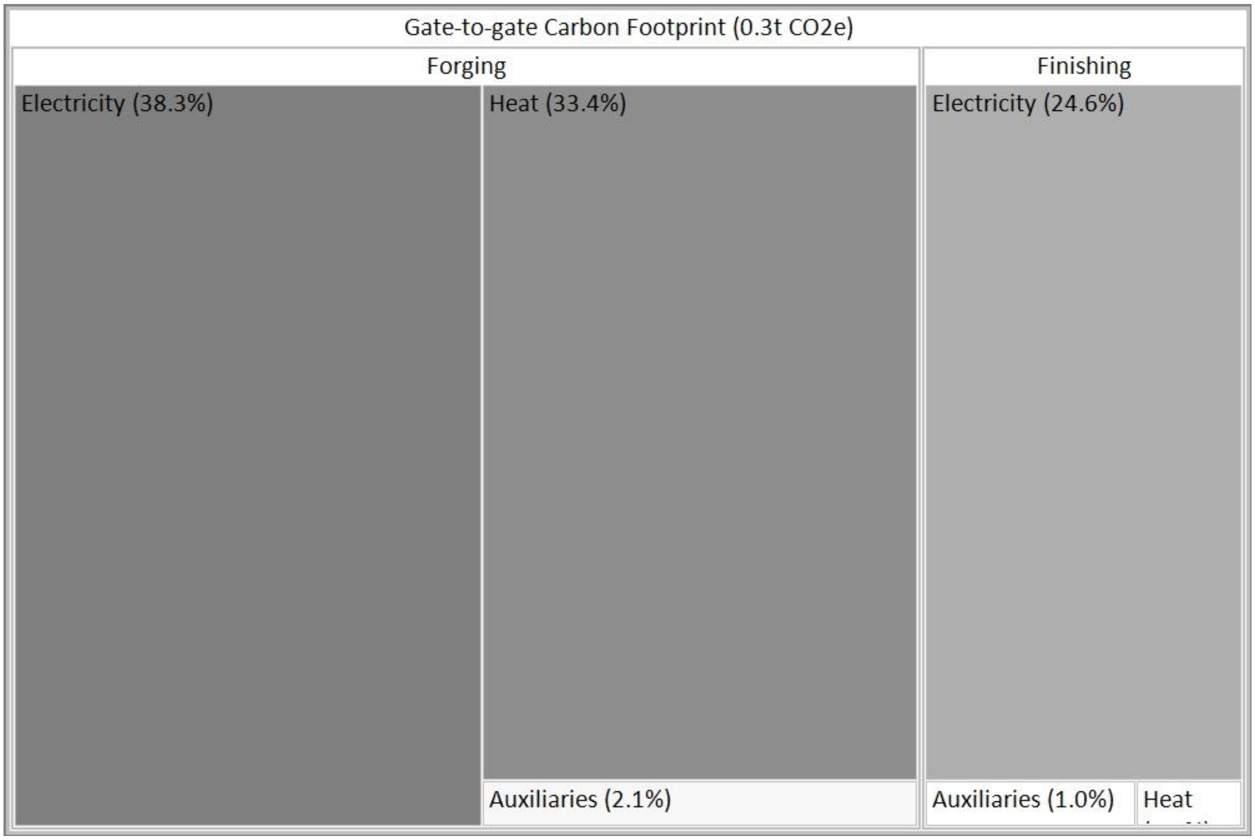

Figure 5-9. Gate-to-Gate Manufacturing of European Aluminum Wheels

5.4.6 Use Phase

5.4.6.1 Mass-Restricted Scenario

In the mass restricted scenario, the gross vehicle weight remains the same whether the truck is equipped with aluminum or steel wheels; however, in the case where aluminum wheels are used, additional cargo can be transported. Table 5-6 contains parameters relevant to the mass-restricted use phase. As indicated in the table, the overall burden is the same, but the transportation performance (as measured by ton-kilometers) is improved with aluminum. Therefore, the emissions per ton kilometer are lower when a truck is equipped with lighter weight aluminum wheels.

Table 5-6. EU Mass-Restricted Scenario Relevant Quantities

	Truck with Alcoa Wheels	Truck with Steel Wheels
Payload (kg)	**22.215**	**22.000**
Utilization rate	100%	100%
Gross Weight (kg)	29.000	29.000
Distance (km)	1.500.000	1.500.000
Fuel Economy (l/100 km)	33,2	33,2
Diesel Consumed (liters)	498.229	498.229
Use Phase CO2 (kg)	1.463.182	1.463.182
Total t*km	**33.322.500**	**33.000.000**
kg CO2 / t*km	**0,0439**	**0,0443**

Figure 5-10 depicts the lifetime performance of a truck with Alcoa aluminum wheels normalized to the baseline scenario of a truck with steel wheels. At the end of manufacturing (the 0 ton kilometer point on the chart) the aluminum wheels have a higher global warming potential than steel wheels. This is driven primarily by the higher burden associated with aluminum production. At use phase onset, the lower per ton-kilometer emissions of the aluminum wheel truck allow for a gradual improvement relative to steel wheel truck.

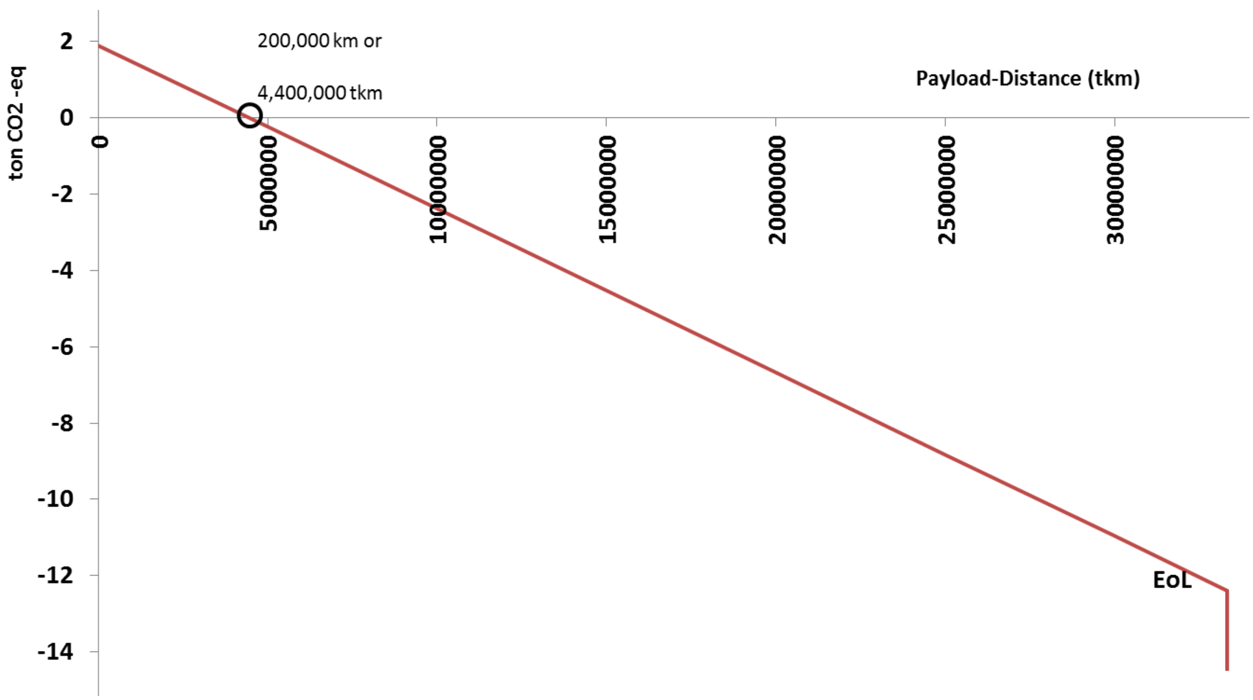

Figure 5-10. EU Mass-Restricted Case Break-Even Chart

The GWP break-even point for Alcoa aluminum wheels occurs around 4.4 million ton kilometers (or at 13.3% of the vehicle's lifetime or 200,000 kilometers). After this point, aluminum wheels provide a benefit in environmental performance through the remainder of the use phase totaling 14.3 tons of carbon dioxide equivalent. After the use phase lifetime of 1.5 million kilometers, the wheels are recycled. The value-corrected credit for aluminum recycling is greater than that of steel, giving additional benefit in the End-of-Life treatment.

Upon completion of the use phase, aluminum wheels have saved approximately 12.4 tons of CO_2 when compared to steel wheels. Inclusion of recycling credit increases this savings to 14.4 tons of CO_2.

5.4.6.2 Volume-Restricted Scenario

In the volume-restricted scenario, the same cargo mass is transported by the truck, but the light-weighting of the wheels improves fuel economy. Table 5-7 contains parameters relevant to the volume-restricted use phase.

Table 5-7. EU Volume-Restricted Scenario Relevant Quantities

	Truck with Alcoa Wheels	Truck with Steel Wheels
Payload (kg)	6.600	6.600
Utilization rate	29,71%	30,00%
Gross Weight (kg)	**13,600**	**13,385**
Distance (km)	1.500.000	1.500.000
Fuel Economy (l/100 km)	**24,72**	**24,85**
Diesel Consumed (liters)	**370.865**	**372.807**
Use Phase CO2 (kg)	**1.090.633**	**1.095.571**
Total t*km	9.900.000	9.900.000
kg CO2 / t*km	**0,110**	**0,111**

Figure 5-11 depicts the lifetime performance of a truck with Alcoa aluminum wheels normalized to the baseline scenario of a truck with steel wheels. The GWP break-even point for Alcoa aluminum wheels occurs around 3.8 million ton kilometers (or at 38.5% of the vehicle’s lifetime or 580,000 kilometers). After this point, aluminum wheels provide a benefit in environmental performance. Aluminum wheels allow for a total use phase savings of 4.9 tons of carbon dioxide equivalents. At the End-of-Life, the additional aluminum recycling credit can be seen by the vertical line at the final 9.9 million ton-kilometer point.

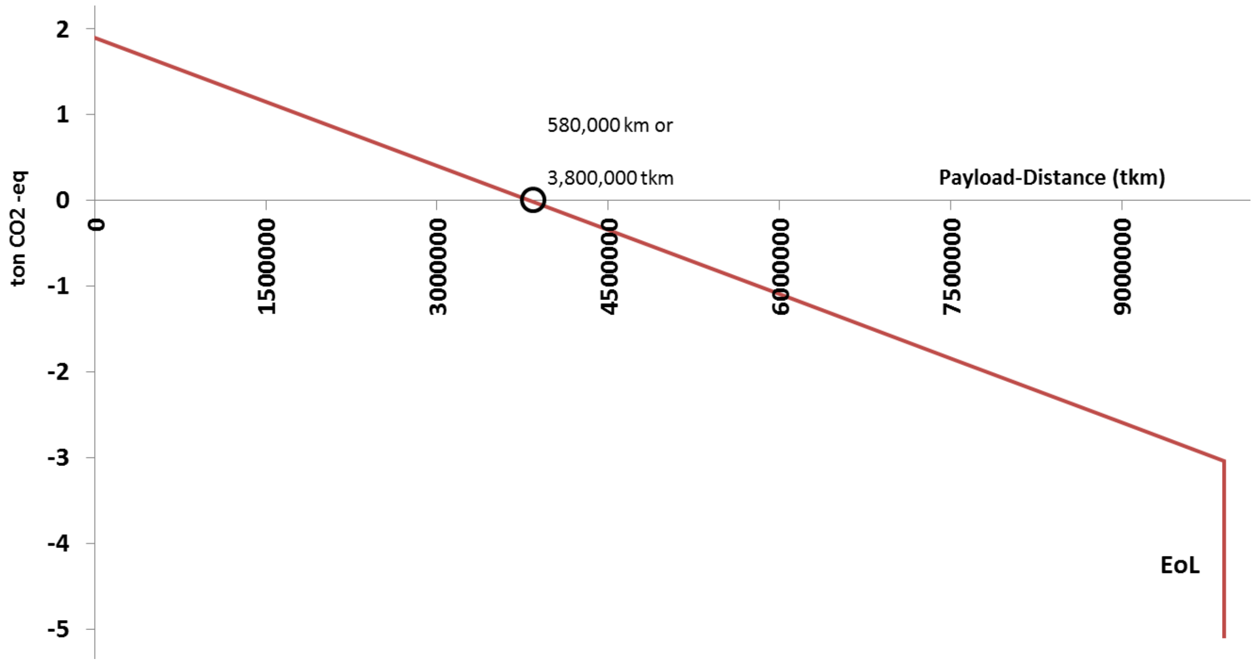

Figure 5-11. EU Volume-Restricted Case Break-Even Chart

Upon completion of the use phase, aluminum wheels have saved approximately 3 tons of CO_2 when compared to steel wheels. Inclusion of recycling credit increases this savings to 5.1 tons of CO_2.

5.4.6.3 Average Use

In the average use scenario, a utilization rate of 78% is assessed based on a 69% weighting of the mass-restricted case and a 31% weighting of the volume-restricted case. As with the mass-restricted and volume-restricted cases, the global warming potential per ton kilometer is lower for the truck with aluminum wheels.

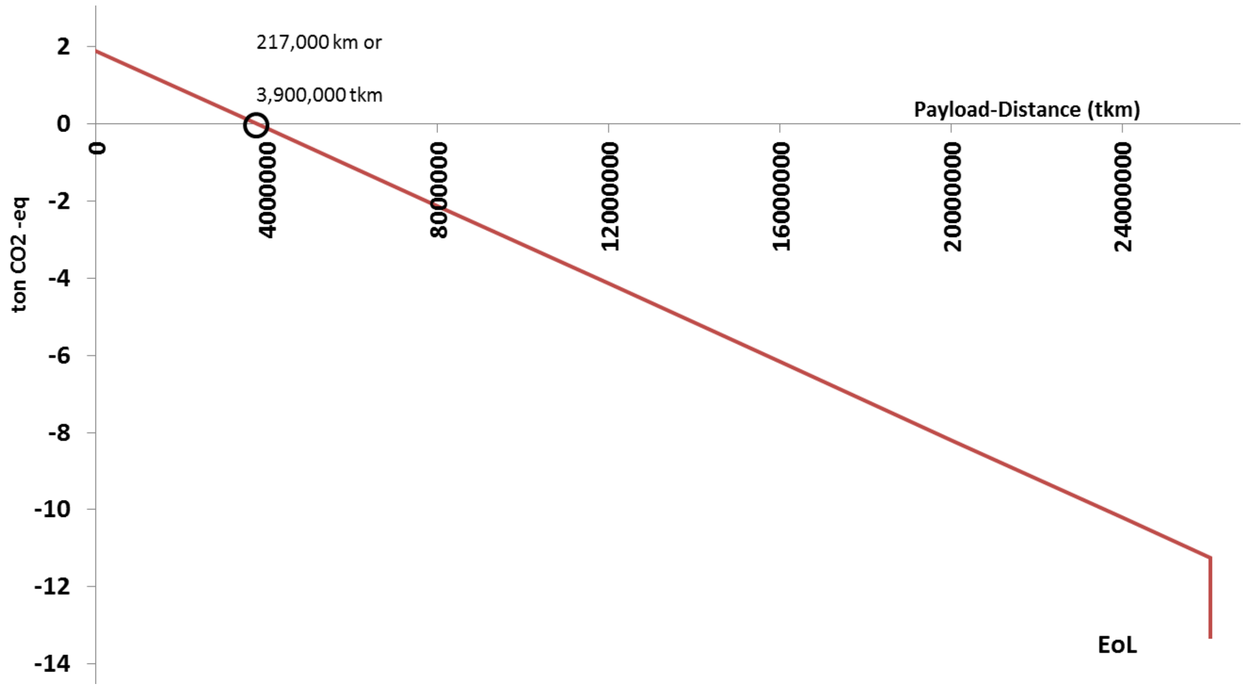

Figure 5-12. EU Average Use Break-Even Chart

Figure 5-12 depicts the lifetime average use performance of a truck with Alcoa aluminum wheels relative to the baseline scenario of a truck with steel wheels. The GWP break-even point for Alcoa aluminum wheels occurs around 3.9 million ton kilometers (or at 14.5% of the vehicle's lifetime or 217,000 kilometers). Use phase savings total 13.2 tons of carbon dioxide equivalents. After 1.5 million kilometers of operation, the wheels are recycled. The value-corrected credit for aluminum recycling is greater than that of steel, giving additional benefit in the End-of-Life treatment.

Upon completion of the use phase, aluminum wheels have saved approximately 11.2 tons of CO_2 when compared to steel wheels. Inclusion of recycling credit increases this savings to 13.3 tons of CO_2.

Appendix C. Wide Wheel Scenario

As an additional scenario, Alcoa's aluminum wide wheels are evaluated against the steel wheel baseline scenario. Wide wheels replace the traditional two-wheel configuration on US tractor trailer trucks and allow for substantial weight savings when substituting for steel wheels.

5.4.6.4 Mass-Restricted Scenario

In the wide wheels scenario, the mass-restricted benefit of carrying additional cargo is magnified by further reducing the wheel mass. Table 5-8 contains parameters relevant to the wide wheels mass-restricted use phase. The overall burden is the same for steel and aluminum wheels but the transportation performance (as measured by ton-kilometers) is improved when aluminum wheels are applied.

Table 5-8. US Wide Wheels Mass-Restricted Scenario Relevant Quantities

	Truck with Alcoa Wheels	Truck with Steel Wheels
Payload (lbs)	**45,670**	**45,000**
Utilization rate	100%	100%
Gross Weight (lbs)	60,000	60,000
Distance (mi)	1,000,000	1,000,000
Fuel Economy (mpg)	5.7	5.7
Diesel Consumed (gal)	173,290	173,290
Use Phase CO_2 (kg)	1,990,332	1,990,332
Total t*km	**33,338,527**	**32,849,446**
kg CO2 / t*km	**0.0597**	**0.0606**

Figure 5-13 is the wide wheels, mass restricted break even chart. The manufacturing burden for wide wheel production is lower than it is for standard Alcoa aluminum wheels, facilitating an earlier break-even point. The GWP break-even point is approximately 2.4 million ton kilometers (or at 7.2% of the vehicle's lifetime or 72,000 miles). Use phase savings total 29.6 tons of carbon dioxide equivalents. After one million miles of use, the steel and aluminum wheels are recycled. The recycling credit for aluminum is greater than that of steel, represented by the vertical drop at the End-of-Life.

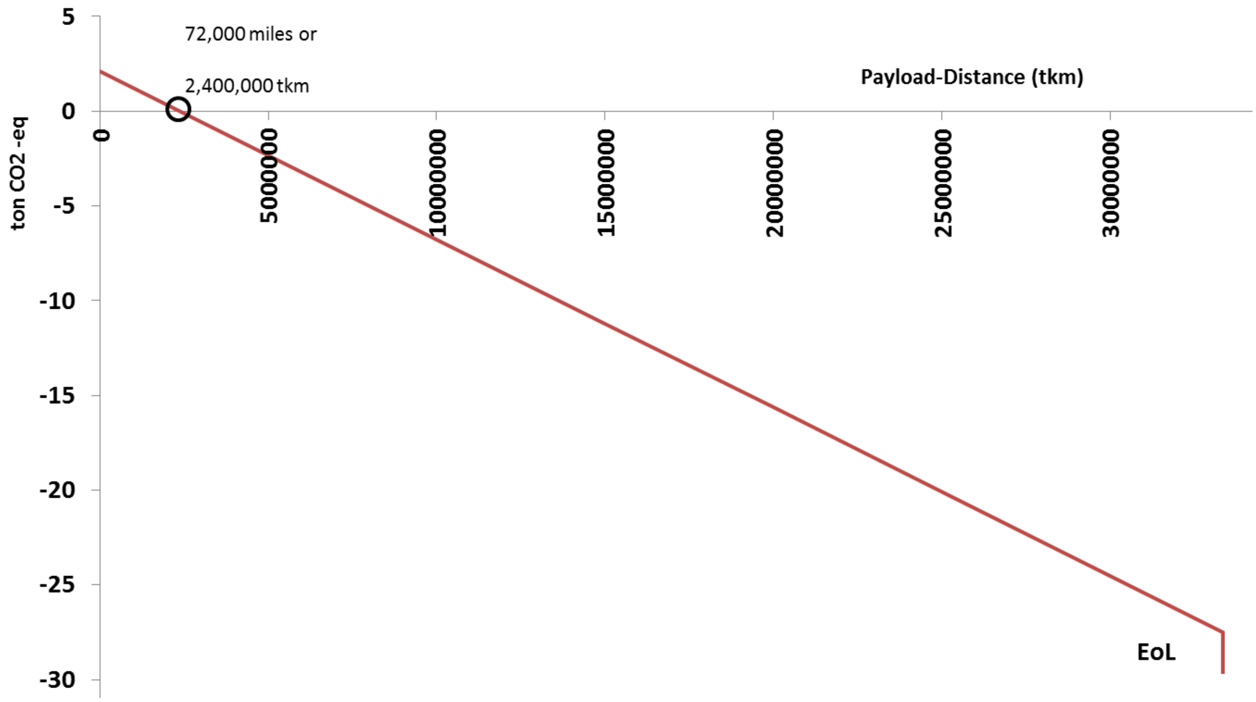

Figure 5-13. US Wide Wheels Mass-Restricted Case Break-Even Chart

Upon completion of the use phase, aluminum wheels have saved approximately 27.5 tons of CO_2 when compared to steel wheels. Recycling credit brings the relative impact to a negative 30.7 tons of CO_2.

5.4.6.5 Volume-Restricted Scenario

In the wide wheels scenario, the volume-restricted improvement in fuel economy is magnified by a further reduction in wheel mass. Table 5-9 contains parameters relevant to the wide wheels volume-restricted use phase. Total ton-kilometers of performance is the same for aluminum wide wheels and steel wheels, but the reduction in gross weight leads to a lower fuel consumption and reduced emissions.

Table 5-9. US Wide Wheels Volume-Restricted Scenario Relevant Quantities

	Truck with Alcoa Wheels	Truck with Steel Wheels
Payload (lbs)	13,500	13,500
Utilization rate	29.56%	30.00%
Gross Weight (lbs)	**27,830**	**28,500**
Distance (mi)	1,000,000	1,000,000
Fuel Economy (mpg)	**6.84**	**6.8**
Diesel Consumed (gal)	**144,815**	**145,689**
Use Phase CO2 (kg)	**1,665,105**	**1,673,558**
Total t*km	9,854,818	9,854,818
kg CO2 / t*km	**0.169**	**0.170**

Figure 5-14 shows the GWP break-even point for wide wheels volume-restricted use at approximately 2.5 million ton kilometers (or at 25% of the vehicle's lifetime or 250,000 miles). Use phase savings total 8.5 tons of carbon dioxide equivalents. After one million miles of use, the wheels are recycled, with a greater recycling credit for aluminum, represented by the vertical drop at the End-of-Life.

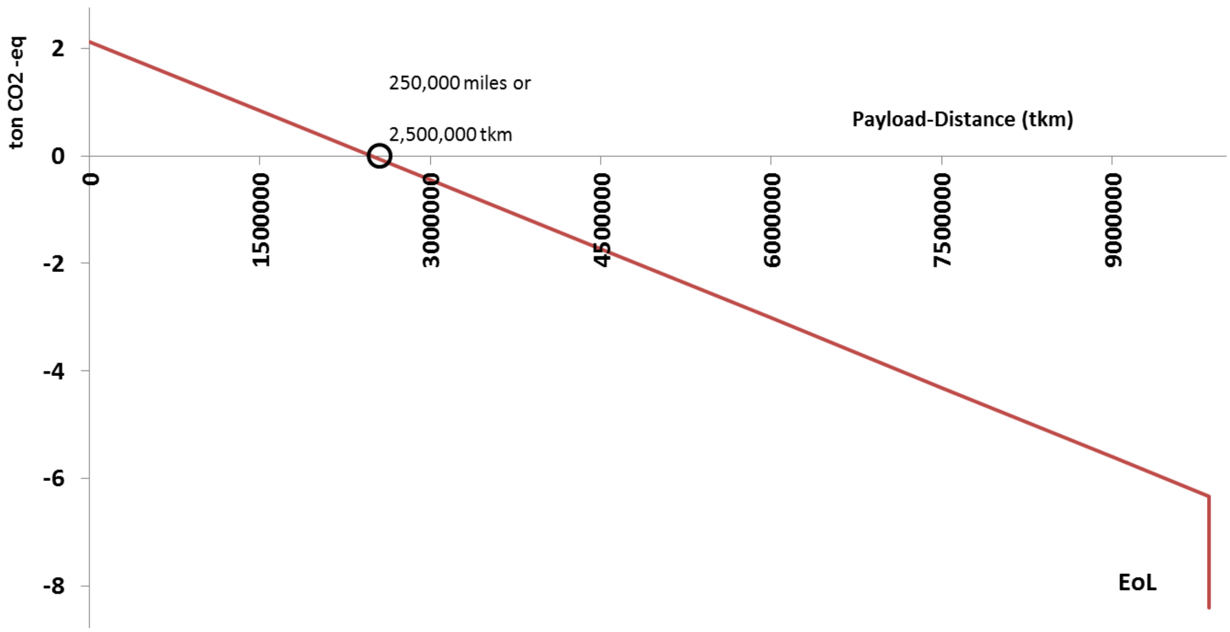

Figure 5-14. US Wide Wheels Volume Restricted Break-Even Chart

Upon completion of the use phase, aluminum wheels have saved approximately 6.3 tons of CO_2 when compared to steel wheels. Recycling credit brings the relative impact to a negative 9.6 tons of CO_2.

5.4.6.6 Average Use

In the average use scenario, a utilization rate of 78% is assessed based on a 69% weighting of the mass-restricted case and a 31% weighting of the volume-restricted case. As with the mass-restricted and volume-restricted cases, the global warming potential per ton kilometer is lower for the truck with aluminum wheels.

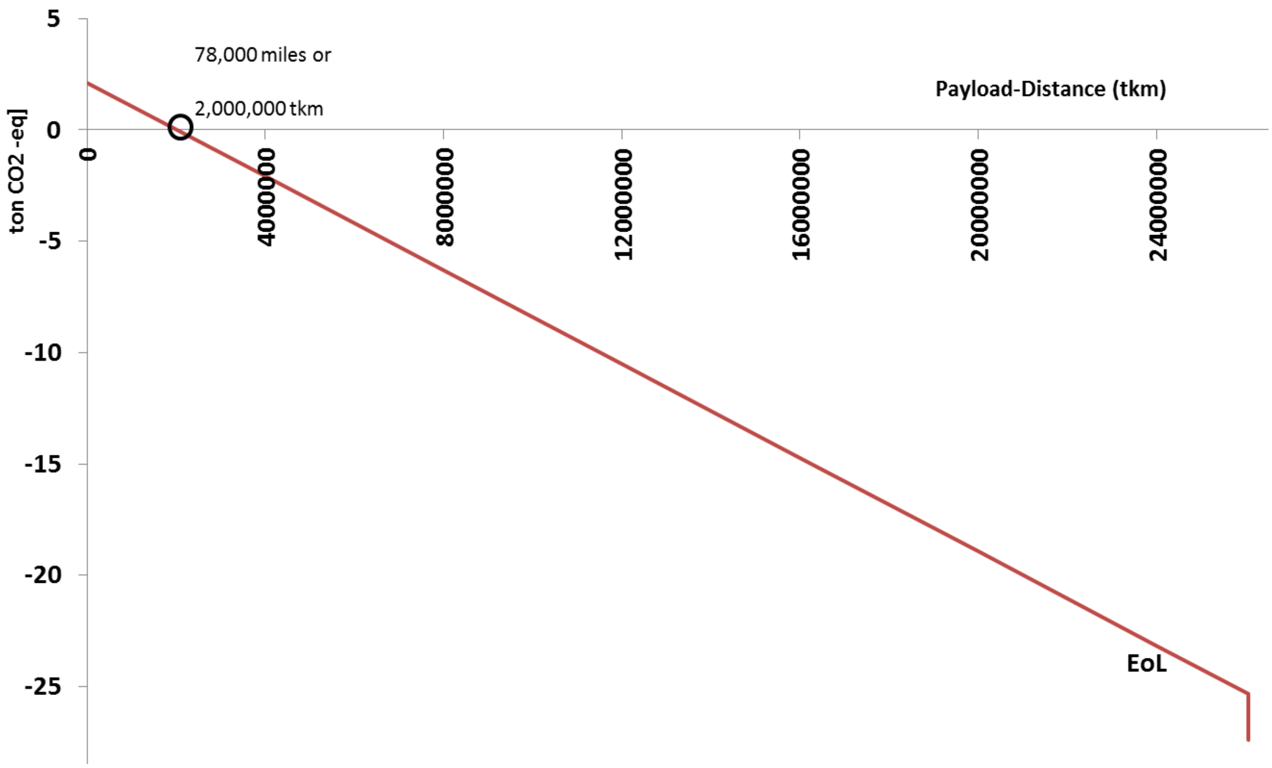

Figure 5-15. US Wide Wheels Average Use Break-Even Chart

Figure 5-15 depicts the lifetime average use performance of a truck with Alcoa aluminum wide wheels relative to the baseline scenario of a truck with steel wheels. The GWP break-even point for Alcoa aluminum wheels occurs around 2 million ton kilometers (or at 7.8% of the vehicle's lifetime or 78,000 miles). Use phase savings total 27.4 tons of carbon dioxide equivalents.

Upon completion of the use phase, aluminum wheels have saved approximately 25.3 tons of CO_2 when compared to steel wheels. Inclusion of recycling credit increases this savings to 28.6 tons of CO_2.

REVIEW STATEMENT

Critical Review of the study

COMPARATIVE LIFE CYCLE ASSESSMENT OF ALUMINUM AND STEEL TRUCK WHEELS

Commissioned by: Alcoa

Review Panel:

Prof. Matthias Finkbeiner, TU Berlin – Chair
Dr. Scott Kaufman, PeerAspect
Prof. Greg Keoleian, University of Michigan

Individual members of the review panel were not engaged or contracted as official representatives of their organizations and acted as independent expert reviewers.

Reference ISO 14040 (2006): Environmental Management - Life Cycle Assessment - Principles and Framework
ISO 14044 (2006): Environmental Management - Life Cycle Assessment – Requirements and Guidelines

The Scope of the Critical Review

The review panel had the task to assess whether

- the methods used to carry out the LCA are consistent with the international standards ISO 14040 and ISO 14044
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

The review was performed according to paragraph 6.3 of ISO 14044, because the study is intended to be used for comparative assertions intended to be disclosed to the public.

This review statement is only valid for this specific report received on 17th September 2012.
The analysis of individual datasets and the review of the LCA software models used to calculate the results are outside the scope of this review.

The review process

The review process was coordinated between PE INTERNATIONAL (PE) as consultant for Alcoa and the chair of the review panel. Initially, the review process was discussed and agreed in October 2011. The review panel was selected and confirmed on 14th November 2011. The review process was started with the provision of the first draft of the goal and scope definition on 27th January 2012. The critical review panel evaluated the draft and provided 44 comments of general, technical and editorial nature by 10th February 2012. A call to discuss the comments on this document was held on 22nd February 2012.
As next step, PE provided the draft final report on 17th May 2012. The critical review panel evaluated the draft and provided 97 comments of general, technical and editorial nature by 2nd June 2012. A phone conference between the review panel, PE and Alcoa was held on 11th June 2012 to establish a common understanding on several comments. PE and Alcoa revised the report accordingly and another call was held on 17th July between PE, Alcoa and the chair of the review panel to address some final remaining issues.
The second draft report was delivered to the panel on 27th August 2012. Overall, the feedback provided by the critical review team was adopted in the finalisation of the study. All critical issues and the majority of recommendations of the critical review panel were addressed in a proper manner. A final set of 8 comments was delivered on 15th September 2012. The review panel checked the implementation of the comments and agreed to the final report.
The critical review panel acknowledges the unrestricted access to all requested information as well as the open and constructive dialogue during the critical review process.

General evaluation

This comparative LCA study is performed on the current level of state of the art. Due to the use of primary data, the data quality is considered to be high for the aluminum wheels and adequate for the steel wheels, because they had to be modeled with secondary data.
The defined scope for this LCA study was found to be overall appropriate to achieve the stated goals. The results of the comparison of the different material concepts obviously depend on the choices made in the scope, particularly with regard to the functional unit respectively reference flows,

the use phase modelling and the allocation of benefits and burdens in the end of life phase.
The results of the study are mainly presented for a baseline scenario which includes assumptions for an average use case and a new value corrected substitution approach for end of life credits. Because the validity of this baseline scenario could not be determined due to lack of statistical data and new methods are applied, it is a key feature of the study that various assumptions were addressed by sensitivity analyses of critical data and methodological choices. This included also a worst case scenario for the Al wheel based on a volume restricted use case and no credits for end of life recycling. These sensitivity analyses allow a good understanding of the robustness of the results. It is also acknowledged that the focus on the carbon footprint of the wheels was complemented by results of a comprehensive set of other impact categories.

Conclusion

The study has been carried out in compliance with ISO 14040 and ISO 14044. The critical review panel found the overall quality of the methodology and its execution to be adequate for the purposes of the study. The study is reported in an adequate and comprehensive manner including a transparent documentation of its limitations in scope.

Matthias Finkbeiner	Scott Kaufman	Greg Keoleian

20th September 2012

GLOSSARY (ISO 14040/44:2006)

ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework, International Organization for Standardization (ISO), Geneva.

Allocation

Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems

Functional Unit

Quantified performance of a product system for use as a reference unit

Close loop & open loop

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.

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.

Cradle to grave

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the End-of-Life.

Cradle to gate

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of the production process ("gate of the factory"). It may also include transportation until use phase.

Life cycle

A unit operations view of consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. This includes all materials and energy input as well as waste generated to air, land and water.

Life Cycle Assessment - LCA

Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle

Life Cycle Inventory - LCI

Phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life Cycle Impact assessment - LCIA

Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life Cycle Interpretation

Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.