Driving better material choices for automobiles

The impact of low CO$_2$ footprint aluminium on life cycle emissions

White Paper

March 2018
Executive Summary

Designing an Al-Intensive vehicle with half the BIW and all closures made of Al reduces weight and overall life cycle emissions by 12.6% for internal combustion engine vehicles (ICEVs), compared to a baseline steel ICEV, C-segment. The carbon payback occurs at 63,300 km due to the initial increase in material emissions, and further use-phase fuel economy improvements. Choosing low CO₂ Al in the AI-Int vehicle further reduces life cycle emissions by 17% compared to the baseline steel ICEV (C-segment), with a carbon payback occurring at just 8,400 km, an improvement of 54,900 km.

The reduction in carbon emissions of switching to low CO₂ AI-Intensive BIW and closures for battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are different than ICEVs due to increased material and manufacturing emissions impacts of the powertrains. Further, the carbon intensity of the electricity source is a particularly important topic with the electrification of vehicle fleets. Simply switching to low CO₂ Al for an already Al-Int BEV reduces its life cycle emissions by 6.2%, with ICEVs (4.7%) and PHEVs (5.5%).

Lightweighting passenger vehicles with low CO₂ Al is a Gigaton solution for global CO₂ emissions on all powertrains studied.

The goal of this study is to determine the most effective material substitute in lightweighting (LW) for steel in passenger vehicles by defining the differentiated life cycle CO₂ emissions impacts of BIW and closure materials in BEVs, PHEVs, and ICEVs for various vehicle segments - A, C, and E. Further, this study takes a life cycle analysis (LCA) perspective to determine the value low CO₂ Al brings in terms of a carbon payback to meet OEMs’ product life cycle CO₂ footprint goals. The reductions in global CO₂ emissions from choosing low CO₂ Al in passenger vehicles are significant - it will take 4 years of current light duty production levels to achieve a Gigaton (billion) CO₂ impact.

Not all aluminium is created equal. Global Al production carbon intensities range from 2 – 41 T CO₂ / T Al per smelter (full scope).

A literature review of 24 LCAs from industry and academic sources have concluded that the most effective way to reduce vehicle weight to meet national fuel economy targets is to reduce weight by designing AI-Intensive vehicles, as aluminium material substitution (AMS) demonstrates the most attractive carbon payback over the life cycle of the vehicle. Low CO₂ Al achieves a much quicker carbon payback to reduce the overall vehicle life cycle footprint.

LW has tangential impacts to the overall life cycle emissions of the vehicle. Regulators, engineers, and automotive executives must consider the carbon footprint of the substitutive LW materials in order to determine if their choice is truly improving the emissions performance of passenger vehicles throughout their lifetime. With this study, OEMs and regulators have the knowledge to holistically address the carbon emissions in the use-phase of their vehicles along with their supply chain, in order to truly address emissions for the life cycle of their vehicles.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AI</td>
<td>Aluminium</td>
</tr>
<tr>
<td>AHSS</td>
<td>Advanced High Strength Steel</td>
</tr>
<tr>
<td>AMS</td>
<td>Aluminium Material Substitution</td>
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<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
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<tr>
<td>BIW</td>
<td>Body-in-white</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>eq</td>
<td>Equivalent</td>
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<tr>
<td>EPD</td>
<td>Environmental Product Declaration</td>
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<td>EOL</td>
<td>End-of-life</td>
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<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
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<tr>
<td>ICEV</td>
<td>Internal Combustion Engine Vehicle</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Analysis</td>
</tr>
<tr>
<td>Low CO$_2$ Al</td>
<td>Low Carbon Aluminium</td>
</tr>
<tr>
<td>LW</td>
<td>Lightweighting</td>
</tr>
<tr>
<td>MWh</td>
<td>Megawatt hour</td>
</tr>
<tr>
<td>NEDC</td>
<td>New European Driving Cycle</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>T</td>
<td>Tonnes (metric)</td>
</tr>
<tr>
<td>TTW</td>
<td>Tank-to-wheel</td>
</tr>
<tr>
<td>UHSS</td>
<td>Ultra High Strength Steel</td>
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<td>WTW</td>
<td>Well-to-wheel</td>
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1. Study Scope

1.1 Lightweighting and Material Substitution

The passenger automobile market is changing faster than ever with digital innovation, vehicle electrification, and improved design. Automobile manufacturers are facing increased pressure by corporate average fuel economy (CAFE) targets (measured in km / liter) and greenhouse gas (GHG) standards (g CO₂eq / km) to reduce the mass of their vehicles, develop more efficient technologies, and incorporate alternative vehicles in their fleets. Many of these ambitious goals by 2025 are below 100 g CO₂eq / km.

The most cost effective way to meet these environmental and efficiency goals is to reduce vehicle weight, primarily through substituting a ‘baseline’ steel body-in-white (BIW), with lighter materials, without compromising safety or quality. The BIW is one of the primary contributors to the vehicle’s weight, approximately 25% for passenger vehicles. Aluminium, advanced high-strength steel (AHSS), magnesium, and carbon fiber are currently on top of the list to reduce BIW weight (Ducker Worldwide 2016).

This is particularly important for BEVs due to the weight of additional battery capacity as a typical BEV weighs more than an ICEV of the same segment (Hottle 2017). For example, segment B vehicles on similar platforms such as the Chevrolet Sonic Hatchback (ICEV) and the Chevrolet Bolt (BEV) show a 300 kg difference after the addition of battery and motors, along with the subtraction of the engine and transmission.

Lighter vehicles require less powertrain demand, and thus operate with lower use-phase emissions. This ‘use-phase’, defined as the emissions from powering the vehicle over its usable life, attributes the majority of emissions of the life cycle – almost 80% for a typical ICEV, and can be varied for PHEVs and BEVs due to the carbon intensity of the electricity mix (Kim and...
Wallington 2013) (Seifert 2017). An important distinction is between the tank-to-wheel (TTW) and well-to-wheel (WTW) basis – for TTW, BEVs are immensely cleaner on a GWP basis due to the lack of tailpipe emissions, but their WTW emissions directly depend on the carbon footprint of their electricity source. The rest of the life cycle contributions are broken down into materials production, vehicle manufacturing, and end-of-life processing.

Previous studies have determined that LW initiatives typically necessitate the use of materials which have a higher carbon footprint than the historically baseline BIW metal, steel, due to higher production energy demands. The use of the alternative materials from substitution indicates there is a need to think holistically in order to not ‘shift’ the environmental burden to other sectors. As fuel efficiency regulations are implemented by 2025, most vehicles will see a significant reduction in the use-phase life cycle emissions and smaller increases in material production and manufacturing.

This is referred to as the ‘Gigaton solution’ - a drastic reduction of carbon emissions from the use of LW materials (Modaresi 2014).

Practical experience shows that for BIW components, 1 kg of Al replaces between 1.66 and 1.87 kg of steel, while in chassis could be 1 kg to 2 kg replacement (Stodolsky 1995). For a 10% mass reduction with powertrain resizing, the fuel consumption reductions for ICEVs & PHEVs were 7% and 6.3%, respectively (Kim and Wallington 2016). This incorporates direct and indirect downsizing, defined further in the study. A range of 19-31% weight reduction for an ICEV (270 to 460 kg) is possible with intensive use of aluminium, resulting in a fuel economy savings of 12-20% over steel (Cheah 2010). These ranges will be further refined by powertrain and car segment based on the literature review and developed model.

1.2 Life Cycle Assessment

Many design constraints and trade-offs such as cost, functionality, safety, and durability determine the material of choice (Hottle 2017). Automotive designers must be cognizant of these trade-offs to determine the amount of material which can be substituted per part, as the life cycle impacts for the entire vehicle will change if just one part is materially substituted.

Life cycle carbon accounting is a necessary method to prove the value of the low carbon footprint substitution material to automotive industry customers (such as metals transformers and semi-fabricators) and end-users (OEMs) with the ongoing innovation around LW. Although each automotive part is chosen from a select group of qualified suppliers, it is important that OEMs and regulators “move beyond single product LCAs and consider the entire vehicle fleet, its development over time, and connection to the material industries” (Modaresi 2014). Though many OEMs do not publicly disclose their incorporation of raw materials’ carbon footprint as a design aspect, there are initiatives by many to evaluate the emissions of their supply chains (Scope 3 emissions) to input into internal LCAs.

One goal of this study is to determine the most effective material substitute for steel by defining, through differentiated life cycle CO$_2$eq emissions impacts of material production in ICEVs, BEVs, and PHEVs for various vehicle segments. Further, the study determines the impact of using low CO$_2$ Al in the Al-Intensive vehicles through a part-by-part vehicle material component model, as not all Al is created with similar carbon footprints. For this study, an Al-Intensive vehicle is defined as having all closures and half the BIW made of Al, a composition that is much alike that of the Audi A8 2017. We use LCA methodology with the components:
(1) material extraction / pre-manufacturing (2) manufacturing, (3) use, and (4) end of life (EOL), in order to assess the full carbon dioxide equivalent (CO$_2$eq) implications of AMS.

This is part of RUSAL’s research into the benefits of using low CO$_2$ Al for the automotive sector. For this study, low CO$_2$ Al is defined as having a verified carbon footprint of < 4 T CO$_2$ / T Al, over three times better than the world average (13.4 T CO$_2$ / T Al), both smelter Scope 1 & 2 (IAI 2017). Primary aluminium producers commonly communicate CO$_2$ emissions in smelter Scope 1 & 2. As LCAs require full scope figures, this study used IAI averages for bauxite and alumina production CO$_2$ emissions in order to develop full scope primary aluminium CO$_2$ emissions. This added 2.4 T CO$_2$ / T Al from bauxite and alumina production to define low CO$_2$ Al as 6.4 T CO$_2$ / T Al, full scope. Explanation on the use of low CO$_2$ Al in the LCA model is defined further. The global primary steel and AHSS production carbon intensity average is 2.4 T CO$_2$ / T steel, full scope, with far less deviation from the average compared to Al (Lewis 2014) (Quader 2015).

A literature review of 24 LCAs from industry and academic sources was performed to gather a diverse set of opinions in a field typified with a variety of assumptions, methodologies, and data sources. In the literature, studies focusing on LW/AMS of ICEVs are much more common than those focused on PHEVs and BEVs. Even with commonly used standardization systems such as ISO-14040 and ISO-14044, it was necessary to discern relevant information for BIW weight reduction, lifetime driving distance, and emissions contributions for a level comparison.

The traceability and assurance of carbon footprint verification statements for low CO$_2$ Al smelters will unlock the potential for the Al entire value chain to be more knowledgeable about its life cycle carbon footprint. This will initiate vehicle sustainability communications such as environmental product declarations (EPDs) and product LCAs with the help of verified trustworthy data sources. A significant number of OEMs currently conduct LCAs for their vehicles, but not all are publicly available. LCAs from Audi and Toyota were reviewed due to the high data transparency in their studies compared to competitors.

As discussed in (Liu and Muller 2012),

“there is a growing need to critique the state and utility of low carbon aluminium applications in specific product systems to better inform industry and government policy-making. Low carbon aluminium is increasingly used to demonstrate the GHG emissions ‘payback’ or ‘avoidance’ resulting from its downstream applications.”

Although current marketing factors point out that LCAs and ‘green’ production methods have little impact on consumer preferences, as they are not willing to pay a visible premium for a ‘clean’ or recyclable car, there is a movement to certify low-carbon supply chains (Chanaron 2007). For example, BMW’s i3 is characterized by this marketing strategy: lowering the manufacturing footprint through powering their Leipzig production plant with 100% renewable energy, along with sourcing raw materials made exclusively with renewables (BMW). Acknowledging the impacts of LW with AMS, it is clear that lowering automotive life cycle emissions must be done from all aspects of LCAs to benefit both the product and OEM efforts towards sustainability.

1.3 Vehicle Weight Reduction and Market Dynamics

A ‘rule of thumb’ is that a 10% weight reduction results in a lifetime fuel consumption reduction of 3-7% without regenerative braking, and 1-5% with – but this tells only part of the vehicle life cycle emissions story (Kim and Wallington 2016). All OEMs are driven by fuel efficiency
Approximate Passenger Vehicle Mass Breakdown by System

An approximate passenger vehicle mass breakdown by system is provided in Figure 2. The major systems are contributed of various components: BIW – cross and side beams, roof, front-end, underbody, passenger compartment frame, and floor; Powertrain – engine, transmission, exhaust, fuel tank; Chassis – chassis, suspension, tries, wheels, steering, brakes; Interior – seats, instrument panel, trim, insulation, air bags; Closures – front and rear doors, hood, lift gate; Miscellaneous – lighting, windows, glazing, thermal, electrical (Mayyas 2012).

The typical vehicle BIW is made up of around 400-500 stamped metal component parts, which are joined together mainly through a spot welding (around 5,000 spot welds per vehicle) process, and then painted (Mayyas 2012). These components can be made of different metals in the same vehicles: different types of steel, aluminium and some small applications in magnesium and carbon fiber.

Steel is the most basic and cheapest option. Aluminium is often regarded as a better alternative, allowing 40% LW on average at a slightly higher cost. While aluminium tends to be widely used in upper segment vehicles, the advantages of LW are undeniable across all segments and powertrains.

Currently, many studies highlight how aluminium usage is a growing trend:

**Ducker forecasts a growth in the average aluminium content in European cars (150.6 kg in 2016) of 27.6 - 45.6 kg (18-30%) by 2025.**
Global growth is going to be driven mainly by the greater use of flat rolled product, as the closures are increasingly moving towards Al (Ducker Worldwide 2016). Specifically, the hood is often the first element of a car that moves from steel to aluminium, due to both low technical complexity and ideal effects on the center of mass (moved backwards and downwards).

1.4 Limitations of the Study

It must be noted that this study is focused on Global Warming Potential (GWP) of primary aluminium material substitution, and limited in that:

a. The impact of recycling on aluminium or steel life cycle emissions are not addressed

It is well known that there is approximately a 90% emissions reduction in secondary aluminium versus primary aluminium (Liu and Muller 2012), and an 80% reduction in secondary steel versus primary steel (Quader 2015). In the automotive sector, certain parts cannot use secondary aluminium and steel due to quality concerns or use of particular alloys. This means that some components need to be primary aluminium, for example most of the cylinder heads, while less critical ones such as the engine housing are entirely secondary aluminium.

This study uses the methodology of EOL accounting which takes into account the energy used in recycling the vehicle, not crediting aluminium or steel used in the future as a carbon emissions reduction. The purpose of this assumption was to isolate the impacts of the BIW to weight reduction, therefore removing the recyclability benefits of these metals and recovered scrap during processing as outside the scope of this study.

b. It solely focuses on the GWP (CO$_2$eq) aspect of LCAs

The other aspects such as Total Primary Energy (MJ) & Cumulative Energy Demand (MJ), along with the Acidification, Eutrophication, Photochemical Smog, Respiratory Effects, and Ozone Depletion Potentials were not analyzed.

These aspects are outside the scope of this paper due to the fact that vehicles are regulated in GWP, and any reduction due to LW and carbon footprint of raw materials, are more easily compared on the same scale. For more complete information on primary aluminium life cycle aspects, consult (IAI 2017). Next we address the worldwide aluminium production scenario.

2. Aluminium Industry Emissions Footprint

Global aluminium production uses ~3.5% of global electricity production, and accounts for approximately 1% of global CO$_2$ emissions (Cullen and Allwood 2013). The aluminium industry resource for emissions data is the International Aluminium Institute (IAI), which provides energy intensity and carbon emissions data for each aluminium-producing country.
As seen in Figure 4, global aluminium smelting energy intensity has been gradually decreasing over the past 10 years of data, decreasing from 15.3 MWh / T Al in 2010 to 14.2 MWh / T Al in 2015 (IAI 2017) - energy efficiency at the smelter being a innovation major focus for producers.

Due to the lack of global transparency and accurate data of bauxite and alumina production, primary aluminium producers commonly communicate the carbon footprint of primary aluminium based on smelter Scope 1 & 2. To allocate for this difference in the LCA model, we use a definition that low CO$_2$ Al is < 4 T CO$_2$ / T Al, smelter Scope 1 & 2 with the addition of the IAI world average data for bauxite and alumina (adding 2.4 T CO$_2$ / T Al), thus making the full scope number for this study 6.4 T CO$_2$ / T Al.

It is inferred that low CO$_2$ Al is produced with hydropower - 27% of worldwide production with a minimal amount being produced with nuclear and other renewable energies.

Smelter Scope 1 & 2 covers the process emissions (Scope 1) and emissions from energy or heat consumed at the plant (Scope 2). Scope 3 is defined as emissions from raw materials and products used, in this case bauxite mining, transport, alumina refining, caustic soda, etc. (Liu and Muller 2012). Full scope (Scope 1 + 2 + 3) emissions are typically called mine-to-casthouse and are estimated in this study based on IAI data after internal analysis.

To this effect, data from 2015 points to the smelter Scope 1 & 2 global average being 13.4 T CO$_2$ / T Al, and full scope being 15.8 T CO$_2$ / T Al (IAI 2017) (Liu and Muller 2012). Full scope emissions are broken up accordingly below, demonstrating that the majority of emissions (78%) occur at the smelter (process emissions, electricity carbon footprint, PFCs, anode production, and ingot casting). The disparate carbon footprints related to primary aluminium production range from 2 – 41 T CO$_2$ / T Al globally per smelter, full scope (Liu and Muller 2012). Over half (35.7 million Tons, MT) of global capacity is based in China, where 90% of primary aluminium production is coal powered. The other 27.3 MT is distributed among the other regions as shown in Figure 6 (CRU 2017).
The data presents a holistic overview of the energy sources used in the aluminium industry. RUSAL’s smelting capacity is almost entirely in Russia, with one smelter operating in Sweden. The dominating energy source for RUSAL’s production is hydro-power (> 90% as of 2016), with goals to be at 95% by 2025.

As data on each smelter’s emissions data is confidential, we rely on averages provided by IAI of emissions per electricity type, shown below from internal analysis based on (IAI 2017) data. It is interesting to note from Figure 8 that hydro-powered smelters have dramatically lower emissions than coal based smelters – ranging from 2.4 to 16.4 T CO$_2$ / T Al.
3. LCA Literature Review

3.1 Methods

The life cycle components of vehicles are comprised of: (1) material production, (2) manufacturing, (3) use, and (4) end of life – EOL, as shown in Figure 9. There are several industry models which are typically used for life cycle analysis – in the literature review, two of the most prominent used in European-focused sources in this study is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model and the Ecoinvent 3.3 model, along with the US Life Cycle Inventory. The different LCA methodologies present a need to calibrate the results with a standardized set of assumptions.

Many studies focusing on ICEVs tend to focus on a WTW analysis, which just cover the use-phase (versus a full LCA with material production, manufacturing, and EOL). For this analysis, fuel production and vehicle operation were considered as ‘use phase’. This number varies for PHEVs and BEVs due to the carbon intensity of the electricity source.

![Life Cycle Assessment](image)

*Figure 9. WTW and LCA methodologies.*

The 24 LCA studies reviewed had differing assumptions and methods attributing their respective findings. For this study, each source’s data was standardized with a unified methodology to deliver a comprehensive review of life cycle emissions different powertrains, varied by car segment. This standardized LCA data could then be used to study the implications of AMS.

Automotive fuel economy standards are typically measured in g CO$_2$ eq / km, but often studies report g CO$_2$ eq / kg vehicle or T CO$_2$ eq over the life of the vehicle. The distance driven over the course of the vehicle life was assumed to be 230,000 km, an average between the EU (180,000 km) and US (280,000 km) numbers and close to the average discussed in (Hottle 2017). The T CO$_2$ eq life cycle values were then scaled to the contributions per category. All of the LCA studies reviewed used the full scope primary aluminium production world average at the time of data collection, typically between 10-14 T CO$_2$ / T Al depending on the study year.

Studies that focused primarily on one powertrain type were compared to those analyzing an array of data on car segments, powertrains, and differing geographical driving cycles and electricity mixes. Literature that is non-LCA was used to provide necessary information to analyze the research question in the context of AMS. Most studies were in peer-reviewed journals or national laboratory/institute reports, with all but four studies published after 2010. Steel was always the baseline metal, with various materials being used as substitutes, predominantly aluminium, AHSS, and magnesium.

The 24 studies analyzed covering LW & LCA for ICEVs, PHEVs, and/or BEVs are listed in Table 1.
### 3.2 BIW Analysis

After standardization of driving distances to 230,000 km, GHG reporting and other LCA methodologies, life cycle stage contributions were produced from average CO₂eq emissions between segments A - F, as demonstrated in Figure 10 and Figure 11 for ICEVs and BEVs, respectively. These average contributions include data from passenger vehicles of all classes. PHEVs demonstrated a similar breakdown to ICEVs, but due to their larger battery, have slightly lower material production emissions (14%), higher manufacturing emissions (9%), lower use-phase emissions (73%), and similar EOL emissions (4%) – with total life cycle emissions of 46.3 T CO₂eq (147 g / km use-phase).

Note that the BEV use-phase emissions are based on the average European electricity mix in 2015, with a carbon intensity of 0.521 T CO₂ / MWh. This is based on a mix of 29% renewables, 28% nuclear, 25% coal, 16% natural gas, 2% oil (Ellingsten 2016).

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**Table 1. Selected LCAs for vehicle mass reduction.**

<table>
<thead>
<tr>
<th>First Author</th>
<th>Year</th>
<th>Publication</th>
<th>Country / Affiliation</th>
<th>ICEV</th>
<th>PHEV</th>
<th>BEV</th>
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<td>Audi</td>
<td>2016</td>
<td>Self-published</td>
<td>Germany / Self</td>
<td>x</td>
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<td>Chanaron, L</td>
<td>2007</td>
<td>Int. Journal of Product Lifecycle Mgmt.</td>
<td>France / University</td>
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<td>Cheah, L</td>
<td>2010</td>
<td>PhD Dissertation (MFT)</td>
<td>USA / University</td>
<td>x x</td>
<td></td>
<td></td>
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<tr>
<td>Das, S.</td>
<td>2014</td>
<td>EAI International Journal</td>
<td>USA / Nat. Lab.</td>
<td>x</td>
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<tr>
<td>Harakotu, et al.</td>
<td>2012</td>
<td>Journal of Industrial Ecology</td>
<td>Norway / University</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Heims, et al.</td>
<td>2010</td>
<td>Int. Symp. Transport and Air Pollution</td>
<td>Germany / Institute</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Hettle, et al.</td>
<td>2017</td>
<td>Transportation Research</td>
<td>USA / Nat. Lab.</td>
<td>x x</td>
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<tr>
<td>Kim, H.J., et al.</td>
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<tr>
<td>Kim &amp; Wallington</td>
<td>2016</td>
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<td>USA / Ford</td>
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<td>Ungureanu, et al.</td>
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<td>Austria / Institute</td>
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<td>China / University</td>
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**Average Contribution to Life Cycle Emissions (% of total) - all segments ICEVs across all reviewed studies**

Average 60.9 T CO₂eq life cycle (244 g / km use-phase)

- Use Phase: 16%
- Materials Production: 4%
- Manufacturing: 78%
- EOL: 3%

**Average Contribution to Life Cycle Emissions (% of total) - all segments BEVs across all reviewed studies assuming European electricity mix 2015**

Average 44.8 T CO₂eq life cycle (97 g / km use-phase)

- Use Phase: 12%
- Materials + Vehicle Production: 4%
- Battery Production: 24%
- EOL: 60%

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It can be seen that materials and vehicle production, along with battery production, play a much larger role in a BEV’s life cycle contributions compared to ICEVs. Although it was difficult to parse out manufacturing from the materials and vehicle production section of BEVs, it is known that OEMs are strongly focusing on LW to improve the range of their BEVs. This should lead to a split incentive as OEMs are regulated on fuel efficiency and carbon emissions on a g CO₂eq/km basis – they can LW ICEVs to directly improve emissions and range, but LW a BEV does not always directly improve emissions. In some countries’ regulation, BEV emissions...
are counted as 0 g CO₂eq/ km, not incorporating the grid carbon intensity. In this case, LW does not improve further the vehicle efficiency and only has a positive effect on the vehicle range. Under such regulation, the positive impact of LW on emissions does not exist anymore.

Many studies evaluated or provided data in order to calculate breakeven driving distances (carbon paybacks) of LW and AMS, with a general depiction of using higher energy intensive materials (aluminium, AHSS, carbon fiber, etc.) to achieve lower use-phase emissions shown in Figure 12. The green arrow represents the net savings of GHG over the vehicle life cycle.

To begin, in (Kim and Wallington 2013), a comprehensive literature review of 43 LW-focused automobile LCA studies with a similar scope to this paper in its standardization methodologies, found that all reviewed studies indicated that using aluminium, AHSS, and carbon fiber to replace conventional steel decreases vehicle life cycle energy use and GHG emissions.

Further, a clear pattern from the reviewed 24 LCA studies showed that out of all the BIW material substitutes for steel, the aluminium’s carbon footprint contribution to a vehicle’s material production emissions has the highest life cycle sensitivity in terms of LW payback. In other words, due to aluminium’s high energy production demand (correlating with higher CO₂eq emissions) and significant LW potential, reducing aluminium’s production emissions can have the highest potential to reduce overall vehicle life cycle emissions among all substitutive materials. Even though magnesium and carbon fiber are lighter than aluminium, their energy (and emissions) intensive production does not offer attractive carbon paybacks compared to aluminium (Das 2014) (Kim and Wallington 2013) (Lewis 2014) (Mayyas 2012) (Modaresi 2014) (Poulikidou 2015) (Ungureanu 2007) (Wang 2013).

In summary, the above studies all found that replacing a steel BIW with an Al-Intensive BIW has the highest potential to decrease vehicle life cycle emissions, of all LW materials.

These studies compared various LW BIWs to a baseline steel BIW, assuming a world average aluminium carbon intensity (varies by study year). Figure 13 provides an example ICEV life cycle with AHSS vs. Al-Int BIWs from (Mayyas 2012). Although the AHSS BIW has much lower material production emissions compared to world average primary aluminium, the initial material production emissions pay back (similar to Figure 12) during the use-phase and recycling components, with a total 3.1% improvement.
The attractive carbon payback of Al-Intensive vehicles would be further improved with low CO₂ footprint primary aluminium, as the material extraction and production emissions would be below 6.4 T CO₂ / T Al, compared to the 12 T CO₂ / T Al world average presented in (Mayyas 2012). This will be analyzed in detail further in section 5 - Advantages of Low Carbon Aluminium.

It must be stated that due to aluminium’s high recyclability emissions savings versus steel, there are significant life cycle impacts upon crediting the recycled aluminium (EOL phase), as it would avoid future use of primary aluminium. Exemplified in (Mayyas 2012) is the EOL crediting methodology, but this is not addressed in this study’s model to keep a conservative perspective on EOL recycling as discussed in the limitations of this study in section 1.4.

### 3.3 Powertrain Analysis

This study aims to parse out the life cycle emissions between various powertrains – ICEVs, PHEVs, and BEVs. The life cycles of Hybrids, Fuel Cell Vehicles, and Compressed Natural Gas (CNG) vehicles were not considered in this study. There was not enough literature for a complete LCA literature review of Fuel Cell Vehicles and CNG vehicles. Hybrids presented life cycle footprints and contributions between ICEVs and PHEVs, and due to this study’s focus on electricity mix carbon intensities, PHEVs were chosen.

BEVs are considered to have higher material production and manufacturing emissions than ICEVs and PHEVs due to intensive and larger battery production. Many studies ‘baked’ these two LCA components together, but it is considered that BEVs have 2-3 times of the absolute material production and manufacturing emissions than ICEVs (Tagliaferri 2016).

If BEVs are entirely powered by renewable sources during their use, it is intuitive that almost their entire footprint will be from material production and manufacturing emissions.

Factories such as BMW’s i3 manufacturing facility in Leipzig are going renewable, further lowering the manufacturing (and assembly) footprint of their vehicles (BMW). With energy mixes that are not dominated by coal, BEVs already have lower life cycle emissions than ICEVs, and will continue to improve with ‘greener’ material production.

The current carbon intensity of European and US mixes (2015 data) conclude that PHEVs often have only slightly higher life cycle emissions with BEVs of the same class, even with life cycle contributions similar to ICEVs - characterized by 70-80% of emissions coming from the use-phase (Ellingsten 2016) (Hawkins 2012) (Helms 2010) (Lewis 2014) (Samaras and Meisterling 2008) (van Vliet 2010). Further, as BEVs increase in size, the ‘size and range effect’ shows that the larger battery production emissions and use-phase energy requirements dramatically increase the life cycle GWP, by 70% between BEVs of segments A and F (Ellingsten 2016).

The carbon paybacks between BEVs and ICEVs show a similar pattern as the ‘size and range effect’ due to higher battery production impacts of similar segment vehicles - with paybacks between 44,000 km (segment F) and 70,000 km (segment A) respectively. BEVs were found to have a 20-27% lower life cycle emissions than ICEVs for C-segment vehicles (Ellingsten 2016) (Hawkins 2012). In summary, BEV life cycle emissions are highly sensitive to battery size.

Further, the carbon-intensity of the electricity mix dramatically impacts these paybacks. For example, (Orsi 2015) shows that BEVs & PHEVs in China have higher use-phase (g CO₂eq / km) emissions than HEVs and are very close to the footprint of CNG vehicles, due to the coal-heavy grid (72%). This is a surprising finding considering that 22% of China’s grid is renewable (EIA).
After the LCA literature review, a market analysis was done on three car segments – A, C, and E – to model the primary and secondary aluminium content of an Al-Intensive vehicle over various powertrains. One of the limitations of this study is lack of sensitivity analysis on primary vs. secondary steel material production emissions impacts - this is an area to explore for future research. The steel vehicle data was based on findings from the standardized literature review. Actual vehicle specifications and data were gathered for the three segments on the VW Polo 2017, Skoda Kodiak 2016, and the Audi A8 2017, respectively. The specifications were then modified in order to obtain standardized vehicles - each car model has a unique breakdown of body materials that makes it impossible to draw meaningful comparisons.

Therefore, for this study it was considered that an Al-Intensive vehicle has all closures and half of the BIW made of aluminium, a composition that is much alike that of the Audi A8 2017 (original 1,995 kg, already Al-Intensive); the VW Polo 2017 (original 1,033 kg, 16% lighter with Al-Int) and the Skoda Kodiak 2016 (original 1,527 kg, 15% lighter with Al-Int) were then modeled to reflect the Al-intensive part-by-part composition breakdown, shown in Table 2. The model uses a replacement ratio of 1 kg Al to 1.4 kg steel.

Further, although the vehicles are all ICEVs, their BIW and powertrain material compositions were then modelled to reflect BEVs and PHEVs with a detailed part-by-part configuration of aluminium and steel components. With the detailed material composition data, the model was able to characterize the life cycle GWP impact of substituting ‘world average’ carbon intensity aluminium (15.8 T CO₂ / T Al) for full scope low CO₂ aluminium (6.4 T CO₂ / T Al). While it would have been possible to consider actual vehicles for each powertrain type, their design and material composition would have been different and therefore it would not have been possible to compare them accurately one to one. Modelling BEVs and PHEVs based on actual vehicle component representations of specific segments allows the exclusion of other variables in order to isolate the powertrain differences.

The contributions of primary aluminium to the vehicle’s life cycle GWP were then evaluated with data from the standardized literature review. The theoretical life cycle emissions impacts of an Al-Intensive vehicle between powertrains and segments was calculated, modelled on real data. Our model demonstrates that an Al-Int vehicle will have 12.6% lower life cycle emissions than a baseline steel ICEV (C-segment), a conservative figure in light of the findings from the literature review, shown in Figure 14. The carbon payback occurs at 63,300 km (Figure 15).
Comparing BEVs of various power mixes (European, coal-heavy, and wind-heavy) in Figure 16 shows that compared to the PHEV, the wind-powered BEV achieves a payback of 86,600 km. If it is powered by the European-mix, it achieves a payback at 144,800 km.

It is interesting to note that while the current carbon intensity of the European grid positions a BEV to be 11.2% better on a life cycle GWP perspective than a PHEV, the payback period compared to the Al-Int vehicle is shorter for a PHEV (63,900 km) than with a BEV European-mix (108,700 km) due to the PHEVs lower material and manufacturing emissions.
From a fuel regulation standards perspective (g CO₂eq / km), the impacts of the electricity mix carbon intensity and of substitutive materials can be seen in Figure 17. It is shown that a coal powered BEV would be 18% worse than the baseline steel ICEV, confirming the China findings from (Orsi 2015). Note that for BEVs, battery production is included in the manufacturing component in many studies. The use-phase values were scaled from the T CO₂eq life cycle.

A wind-powered BEV’s use-phase drops to 36% of total emissions, leaving materials and manufacturing (inc. battery) as the majority of environmental impact (60% of total).

The carbon paybacks to an Al-Intensive vehicle (and Baseline steel) is as follows:

BEV wind - 79,200 km (75,300 km)
BEV European – 108,700 km (94,700 km)
PHEV – 63,900 km (63,600 km)
5. Advantages of Low Carbon Aluminium

Figure 18 demonstrates the opportunity for a low carbon footprint primary aluminium to benefit Al-Intensive vehicles by powertrain. Using low CO$_2$ Al (6.4 T CO$_2$/T Al) vs. world average (15.8 T CO$_2$/T Al) full scope can significantly impact the life cycle emissions of Al-Intensive vehicles from 4.7 to 6.2% depending on the powertrain.

For the C-segment ICEV (4.7%) decrease, this accounts for a 2.6 T CO$_2$ difference over the life time of the vehicle reflected in the primary aluminium contribution reduction. Using this vehicle’s use-phase emissions (193 g CO$_2$eq / km), this would equate to approximately **13,500 km** ‘not driven’ during the lifetime.

This truly is a ‘Gigaton solution’ (Modaresi 2014) – that it will take slightly over 4 years of current light duty vehicle production levels to reach a one billion Ton CO$_2$ impact. For reference, that equates to 385 million passenger cars going Al-intensive with low CO$_2$ aluminium. There were ~90 million light duty vehicles produced in 2016 alone (IHS 2015).

For BEVs, this reduction can be even more dramatic (6.2%) as raw materials emissions make up a larger part of the life cycle picture, especially if powered by renewables.

Note that secondary aluminium contribution is not shown on the graph, with a value < 0.2 T CO$_2$ over the lifetime for each vehicle segment due to the EOL accounting method used.
The C-segment low CO₂ Al-Int ICEV can have a 17% lower carbon footprint through its life cycle (10.3 T CO₂) versus the baseline steel vehicle, as shown in Figure 19. The carbon payback for the slightly higher material production emissions (0.4 T CO₂) is just 8,400 km, a significant improvement to the worldwide average Al-Int vehicle payback vs. baseline steel of 63,300 km, a difference in carbon payback of 54,900 km.

In order to reach a payback of 0 km (equal material production emissions for a functional unit of steel vs. lighter aluminium) the primary aluminium material production emissions would need to be below 3.4 T CO₂ / T Al, full scope. This assumes this study’s material replacement ratio and full scope production footprints for both materials.

The data presented shows an opportunity for OEMs to choose the most effective LW material possible - a low CO₂ Al-Intensive vehicle - on any powertrain. This is necessary to avoid ‘shifting’ the environmental burden to other sectors by replacing the historically baseline steel BIW with materials that are more than just lighter, but lower carbon footprint on a life cycle GWP basis.
6. Conclusion

This study has presented a lightweighting (LW) and aluminium material substitution (AMS) vehicle model based on an in-depth life cycle analysis (LCA) literature review which will guide car manufacturers to incorporate raw material carbon footprints in vehicle production. It is clear that a low CO$_2$ Al-Intensive vehicle demonstrates the most attractive carbon payback over the life cycle for every vehicle segment and powertrains studied.

The future of passenger vehicles on any powertrain necessitates rapid improvements in fuel efficiencies and use-phase emissions (g CO$_2$eq / km) to meet the aggressive national targets across many industrialized nations. Future environmental and efficiency standards relating to vehicle emissions should also discern the raw material production carbon footprints – what matters is the overall life cycle carbon footprint of the vehicle in terms of T CO$_2$eq, not simply the use-phase as currently regulated.

As ICEVs become lighter and more fuel efficient, the share of BEVs and PHEVs grows, and renewable electricity production increases - the overall life cycle footprint of passenger vehicles will dramatically decrease and the CO$_2$ emissions embedded in raw materials will become more prominent in proportion.

The results shown here conclude that (compared to baseline steel BIW C-segment):

a. **The use of aluminium in BIWs and closures (Al-Intensive) reduces life cycle emissions by 12.6% (7.8 T CO$_2$) for ICEVs – the carbon payback occurring at 63,300 km.**

b. **Low CO$_2$ Al produced with hydropower further reduces raw material emissions with a total savings of 17% (10.3 T CO$_2$) for ICEVs – the carbon payback is dramatically reduced to just 8,400 km.**

c. **BEVs are more sensitive to the carbon footprint of their raw materials compared to ICEVs. Low CO$_2$ Al further reduces the carbon payback of a European energy mix BEV by 16,900 km.**

d. **Lightweighting with low CO$_2$ Al is a Gigaton CO$_2$ reduction solution – 4.7%, 5.5%, 6.2% decreases in life cycle emissions compared to an Al-Intensive vehicle on all powertrains (ICEV, PHEV, BEV).**

Life cycle analyses play an important role in guiding car manufacturers to develop the fleet of the future. With this knowledge, car manufacturers and regulators will be able to address the need for initiating regulations which take into account the carbon emissions of raw materials in passenger vehicles.

Consequently, the use raw materials with higher carbon footprints could lead to suboptimal life cycle improvements in vehicles, even with use-phase improvements gained through LW.

Low CO$_2$ aluminium presents the most attractive life cycle CO$_2$ savings of any vehicle BIW or closure raw material, amplifying the benefits of lightweighting with aluminium.
References

List of 24 LCA studies used for literature review and model


Supplementary References


About the author

Ivalin (Evan) Petkov holds an MS in Civil and Environmental Engineering - Atmosphere / Energy from Stanford University. He has published papers on renewable energy forecasts with the Solutions Project, cellulosic bio-fuel chemistry, and wastewater treatment energy efficiency.

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About RUSAL

RUSAL is a leading, global aluminium producer. The company’s main products are primary aluminium, aluminium alloys, foil and alumina. RUSAL is a completely vertically integrated aluminium company with assets right through the production process – from bauxite and nepheline ore mines to aluminium smelters and foil mills. RUSAL has a unique position in the aluminium industry as it produces over 90% of its entire aluminium output with renewable hydropower, which makes RUSAL the largest producer of hydro-powered aluminium worldwide.

In a carbon-constrained world, low CO₂ aluminium from RUSAL, known as ALLOW, enables our customers to contribute to their climate change strategy. ALLOW aluminium is made from renewable hydropower and it enables our customers to deliver products with a lower CO₂ footprint to make a positive impact for society.

RUSAL supports global action to prevent climate change and stop global warming. We are firmly convinced that, as an industry leader, we are responsible for shifting commodity paradigms and supporting our customers and partners transition to a low carbon future.

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