Consequential Life Cycle Greenhouse Gas Study of Automotive Lightweighting with Advanced High Strength Steel (AHSS) and Aluminum

FINAL REPORT

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Automakers in the U.S. have used vehicle weight reduction ("lightweighting") as one of many strategies to comply with mandated federal fuel efficiency targets. This strategy often involves substituting one material for another; for instance, replacing mild steel with aluminum or replacing mild steel with advanced high strength steel (AHSS). This lightweighting process typically results in improved fuel efficiency and a corresponding reduction in greenhouse gas (GHG) emissions from the vehicle's use phase. However, such lightweighting doesn't necessarily result in an overall GHG savings, since the production phase emissions for some lightweighting materials can counteract the improvement in the tailpipe or use phase.

Aluminum is one of the materials that is often considered for lightweighting applications, and in North America, the Aluminum Association has projected a significant increase in the use of aluminum in vehicle body and closure panels.[1] The Steel Recycling Institute (SRI) and Steel Market Development Institute (SMDI), both business units of the American Iron and Steel Institute (AISI), conducted this study to assess the GHG emissions consequences of an increase in the use of aluminum equal to that projected by the Aluminum Association, and alternately, to assess the GHG emissions consequences of using AHSS instead of aluminum to lightweight the same vehicle fleet.

These consequences were assessed using a spreadsheet model (hereinafter referred to as the Model) developed by Dr. Roland Geyer, PhD, Associate Professor, Bren School of Environmental Science and Management, University of California at Santa Barbara. The report describing the model is titled *"Consequential Life Cycle Assessment (CLCA) of Replacing Steel with Aluminum in Vehicles: User Guide and Final Project Report",* dated February 26, 2016. The Model and referenced report were independently reviewed by a three-person panel. (See Appendix A for a copy of the report and review letter.)

The CLCA was conducted according to the requirements of ISO 14044:2006. Strictly speaking, this study is a consequential life cycle greenhouse gas emissions (assessed as global warming potentials, or GWP-100) assessment. However, for simplicity the acronym "CLCA" is used in this report. It is also important to keep in mind that ISO 14044 was written with attributional life cycle assessment (ALCA) in mind and therefore some interpretation may be necessary when it is applied to CLCA.

The goal of this study is to identify and quantify the main GHG emissions consequences of a significant increase in the use of aluminum for vehicle body and closure parts, and compare these consequences to the GHG emissions consequences of the use of AHSS for the same parts, as part of an overall vehicle fleet lightweighting strategy. The study considers light-duty vehicles produced in North America between 2015 and 2053.

Four sets of consequences are modeled in the study:

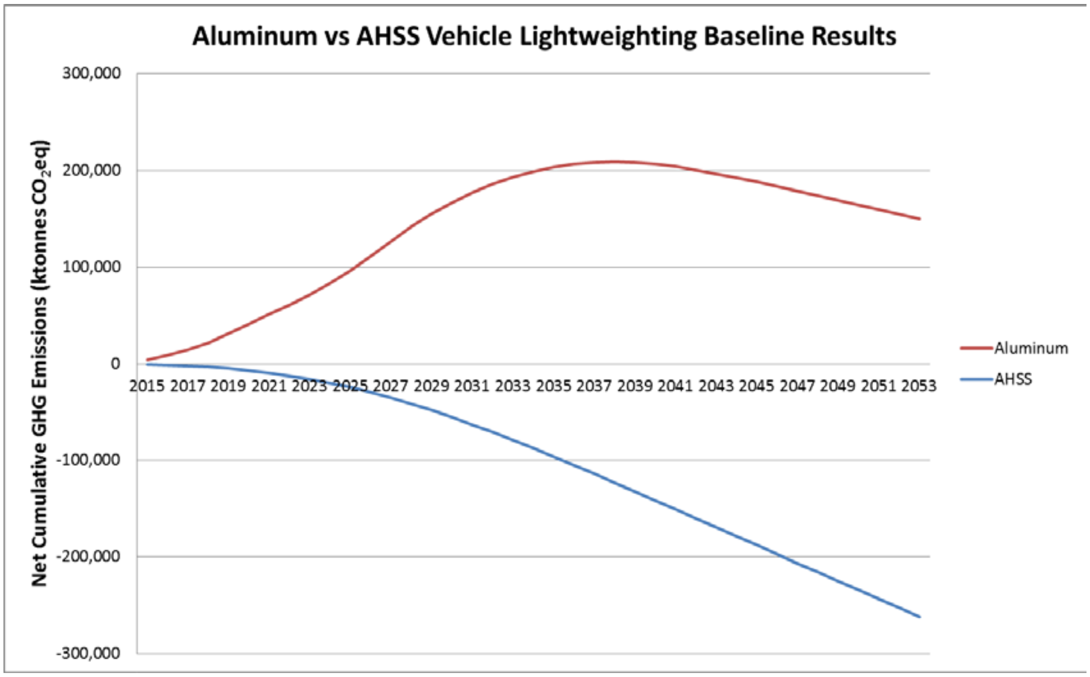
1) Changes in the production levels of the steel and aluminum used in the modeled body and closure parts, as well as secondary mass savings associated with these production level changes;
2) Changes in the fuel economy of the vehicles due to mass reduction;

[1] Ducker Worldwide. "Aluminum Content in North American Light Vehicles 2016 to 2028." Summary Report prepared for the Aluminum Association. July 2017. http://www.drivealuminum.org/research-resources/ducker2017/.

3) Changes in the generation and use of steel and aluminum scrap from material forming processes; and,
4) Changes in the generation and use of steel and aluminum scrap from vehicle end-of-life management.

In order to develop the data required for the intended comparison of an increase in the use of AHSS vs. aluminum, the Model's calculations are run separately for two different sets of assumptions. All basic input data is the same for both Model runs, except for the production levels of AHSS or aluminum.

The baseline results of the assessment can be seen in the following graph:



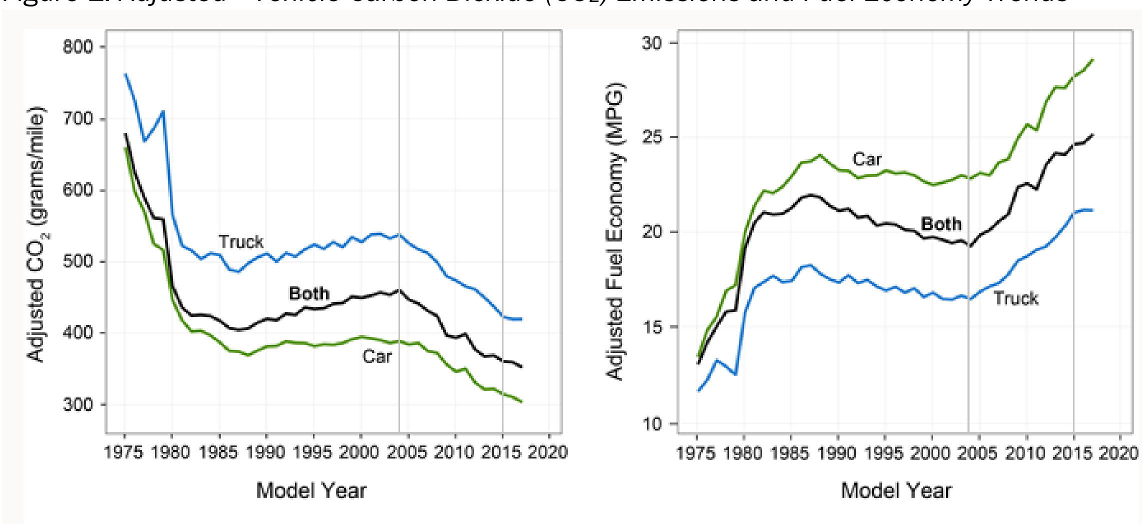
The graph shows the GHG consequences of the baseline comparison. In short, the projected increase in the use of aluminum for lightweighting of body and closure parts results in peak cumulative GHG emissions of approximately 209 million metric tons, while a similar increase in the use of AHSS results in an immediate and sustained decrease in overall GHG emissions. In this baseline case, at the time of the peak increase in emissions for the aluminum option (approximately Year 2038), the difference in GHG emissions between the two options is approximately 332 million metric tons. This net difference continues to grow throughout the study period until it reaches over 411 million metric tons in 2053. In other words, a significant increase in the use of aluminum for lightweighting of light-duty vehicles, as described in this report, results in an increase in overall GHG emissions of over 330 million tons in approximately 20 years time, when compared to similar lightweighting of the same vehicle fleet with AHSS.

These results are based on baseline data and inputs. This study includes numerous sensitivity scenarios which are described in Section 4.5.

1. BACKGROUND

Corporate Average Fuel Economy (CAFE) standards for U.S. vehicles were first established by Congress in 1975 to reduce fuel consumption by cars and light trucks. These standards are administered by the Department of Transportation's National Highway Traffic Safety Administration (NHTSA). NHTSA sets and enforces the standards, while the U.S. Environmental Protection Agency (U.S. EPA) calculates average fuel economy levels for vehicle manufacturers, and also sets related standards for greenhouse gas (GHG) emissions associated with fuel combustion. The effect of these standards on average vehicle carbon dioxide (CO_2) emissions and fuel economy in the U.S. is shown in Figure 1. From model year (MY) 2004 to MY 2016, CO_2 emissions have decreased by 102 g/mi, or 22%, and fuel economy has increased by 5.4 mpg, or 28%.[2]

Figure 1. Adjusted Vehicle Carbon Dioxide (CO_2) Emissions and Fuel Economy Trends*



[1]Adjusted CO_2 and fuel economy values reflect real world performance and are not comparable to automaker standards compliance levels. Adjusted CO_2 values are, on average, about 25% higher than the unadjusted, laboratory CO_2 values that form the starting point for GHG standards compliance, and adjusted fuel economy values are about 20% lower, on average, than unadjusted fuel economy values that form the starting point for CAFE standards compliance.

Source: U.S. EPA, 2018. [3]

* Adjusted CO_2 and fuel economy values reflect real world performance and are not comparable to automaker standards compliance levels. Adjusted CO_2 values are, on average about 25% higher than the unadjusted, laboratory CO_2 values that form the starting point for GHG standards compliance, and adjusted fuel economy values are about 20% lower, on average, than unadjusted fuel economy values that form the starting point for CAFÉ standards compliance.

These more recent improvements were achieved primarily through the development and implementation of new engine and transmission technologies, such as gasoline direct injection, turbocharging, continuously variable transmissions, and non-hybrid start/stop technology.[4] Regulatory targets are currently set to become even more stringent through MY 2025, causing automakers to look to additional solutions, such as reducing the mass of vehicles to decrease fuel consumption, commonly referred to as "lightweighting." On April 2, 2018, the U.S. EPA's Administrator announced the completion of the Midterm Evaluation

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[2] U.S. EPA, Light-Duty Vehicle CO_2 and Fuel Economy Trends website https://www.epa.gov/fuel-economy-trends/highlights-co2-and-fuel-economy-trends. Last accessed June 1, 2018.
[3] Ibid.
[4] U.S. EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2016" Report. November 2016. pg. 47.

process for cars and light trucks for model years 2022-2025, noting that the current standards should be revised.[5] It is currently unclear what this revision will entail.

A common lightweighting strategy is designing vehicles to use materials that enable the weight reduction of vehicle components and systems, while still maintaining functionality and performance. These materials may include advanced high-strength steels (AHSS), aluminum, carbon fiber composites, and magnesium. Each of these materials can contribute to vehicle mass reduction, thereby helping to improve fuel economy; however, each does so at different manufacturing cost levels and environmental impacts.

While the focus of federal regulations has been on the vehicle use phase (i.e., fuel economy), the complete GHG and energy profile of a vehicle is only evident by considering the entire life cycle. A vehicle's life cycle can be subdivided into three distinct parts (or phases): production (materials, auto parts, and vehicle assembly), use (driving and maintenance) and end-of-life (recycling and/or disposal). Because the use of lightweight materials may increase vehicle production emissions while improving use phase performance, a life cycle approach is necessary to assess trade-offs and ensure improvements in one phase are not causing larger impacts in another.

To evaluate these trade-offs, the Steel Recycling Institute (SRI) and Steel Market Development Institute (SMDI), both business units of the American Iron and Steel Institute (AISI), have taken a two-part approach. In November 2017, SRI and SMDI released an ISO critically reviewed study[6] of the greenhouse gas (GHG) emissions and energy consumption implications associated with lightweighting the body and closures of various MY 2016 vehicle types with aluminum and AHSS. This more common "attributional" life cycle study found that, even though the use phase currently dominates the life cycle results for most vehicle types, AHSS-intensive vehicles had lower or equivalent life cycle emissions than aluminum-intensive vehicles for every class of vehicles tested. The study demonstrated that a focus only on tailpipe emissions is likely to produce unintended consequences of higher total GHG emissions. Previously published studies, notably Das et al. 2014[7] and Bushi et al.[8], as well as the various automotive lightweighting life cycle assessment (LCA) studies assessed by Hottle et al. 2017[9], found the use of aluminum to have life cycle GHG advantages over steel and even AHSS, largely due to the use phase fuel consumption savings of aluminum over steel. The 2017 SRI/SMDI study reached a different conclusion largely due to differences in the approach to recycling allocation methods (holistic assessment of possible methods vs. the avoided burden end-of-life approach), accounting for imported primary aluminum, and recycled content assumptions and was subjected to a rigorous ISO 14044 review by a panel of four experts.

Since individual vehicle-to-vehicle comparisons, such as those in attributional life cycle assessments (ALCAs), may not fully assess the GHG emissions implications of a large-scale shift in the material composition of vehicles produced in North America, SRI and SMDI have also commissioned an alternate approach to assessing these larger scale consequences, termed "consequential" life cycle assessment (CLCA), which is the focus of this study.

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[5] U.S. EPA, News Release, "EPA Administrator Pruitt: GHG Emissions Standards for Cars and Light Trucks Should Be Revised." April 2, 2018. https://www.epa.gov/newsreleases/epa-administrator-pruitt-ghg-emissions-standards-cars-and-light-trucks-should-be.

[6] Steel Recycling Institute and Steel Market Development Institute. "Life Cycle Greenhouse Gas and Energy Study of Automotive Lightweighting." November 7, 2017. http://www.steelsustainability.org/automotive/auto-ghg/.

[7] Das, S., "Life Cycle Energy and Environmental Assessment of Aluminum-Intensive Vehicle Design," *SAE Int. J. Mater. Manf.* 7(3):588-595, 2014, https://doi.org/10.4271/2014-01-1004.

[8] Bushi, L., Skszek, T., and Wagner, D., "MMLV: Life Cycle Assessment," SAE Technical Paper 2015-01-1616, 2015, doi:10.4271/2015-01-1616.

[9] Hottle, T., Caffrey, C., McDonald, J., and Dodder, R. "Critical factors affecting life cycle assessments of material choice for vehicle mass reduction," *Transportation Research Part D* 56 (2017) 241–257. http://dx.doi.org/10.1016/j.trd.2017.08.010.

In the field of life cycle assessment (LCA), consequential LCA is a relatively new and emerging assessment method. For ALCA, a static or fixed inventory of inputs and outputs is determined for all processes in the life cycle of a product or service and scaled linearly to a functional unit.[10] ALCA typically utilizes global or national averages to model the involved unit processes. For CLCA, marginal or incremental inventories are used to assess the consequences of a change to the life cycle under study. In this study, CLCA is applied as an assessment of the physical and economic processes that are affected by a well-defined change to the studied product system, causing it to evolve over time from its initial state. Key consequential parameters are identified and defined and the sensitivity of the results to their variation is modeled.

[10] Koffler, C.; Geyer, R.; Volz, T. Life Cycle Inventory. In *Environmental Life Cycle Assessment: Measuring the environmental performance of products*; American Center for Life Cycle Assessment: Vashon Island, Washington, 2014; pp 46–57.

2. GOAL OF THE STUDY

SRI and SMDI conducted this study to assess the life cycle GHG emissions, assessed as 100-year global warming potentials (GWP-100), resulting from a projected large-scale shift of closure and body parts from primarily mild steel to aluminum in North American production of light duty vehicles, and compare these GHG implications, or consequences, to a similar shift from primarily mild steel to AHSS.

The intended application of the study is to develop comparative claims and assess trade-offs across different life cycle stages on the basis of life cycle GWP-100 (hereafter referred to as "GHG emissions" for convenience) for communication with internal and external stakeholders. As described in Section 5, the focus on a single impact is a limitation of the study. However, GHG emissions that cause climate change impacts are of high public and institutional interest, and is among the currently most pressing environmental issues relative to the production and operation of vehicles. Since the study assesses a single indicator, it is not intended to support "comparative assertions" as defined by ISO 14040, Section 3.6, [11] or claims of overall environmental superiority. Nevertheless, since it does compare the GHG emissions implications of two options, the study was subjected to a critical review by a panel of independent experts to demonstrate its conformance with ISO 14044 (see Appendix B). The target audience includes all internal and external stakeholders with an interest in understanding the GHG implications of large-scale automotive material substitution for reasons of vehicle mass reduction. Due to its sole focus on climate change impacts, the study does not investigate any potential trade-offs across different impact categories. Strictly speaking, this study is a consequential life cycle GWP-100 assessment; however, for simplicity the acronym CLCA will be used in the remainder of this report.

The CLCA model is highly parameterized and thus it is possible to conduct extensive sensitivity analyses by varying key input parameters. Section 4.5 of the report includes several of these sensitivity analyses.

This study has been conducted according to the requirements of the international standard ISO 14044:2006[12]. It is important to note that ISO 14044 was written with ALCA in mind, and therefore, some interpretation of these requirements is necessary when applied to CLCA.

[11] ISO 14040: Environmental management – Life cycle assessment – Principles and framework. Geneva: International Organization for Standardization. 2006.
[12] ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines. Geneva: International Organization for Standardization. 2006.

3. SCOPE OF THE STUDY

The following sections describe the project scope as defined to achieve the stated goals. This scope is reflected in the consequential life cycle assessment model (the Model) developed by Dr. Roland Geyer, PhD, Associate Professor, Bren School of Environmental Science and Management, University of California at Santa Barbara. The computational structure and methodology of the Model is described in the report titled "Consequential Life Cycle Assessment (CLCA) of Replacing Steel with Aluminum in Vehicles: User Guide and Final Project Report", dated February 26, 2016. The Model and referenced report were independently reviewed by a three-person panel. (See Appendix A for a copy of the report and review letter.) The independent review concludes that the model *"… conforms to the LCA requirements of ISO 14040:2006 and 14044: 2006 standards*."

3.1 Product System Description

The product system in this study is the fleet of North American light duty vehicles that would be lightweighted with aluminum (or alternatively, AHSS) to meet the aluminum industry's projected increase in aluminum use in body and closure applications in North American vehicles. The projected increase in the use of aluminum is based on a publicly-available study conducted by Ducker Worldwide and commissioned by the Aluminum Association.[13] For the AHSS scenario, the projected increase in the use of AHSS is based on lightweighting the same body and closure parts in the vehicle fleet modeled in the aluminum case. Since the weight reduction potential (i.e., Material Replacement Coefficient; see Section 4.1.2) for AHSS to mild steel is lower than for aluminum to mild steel, the overall weight of the vehicle fleet is higher and the fuel savings lower for the AHSS scenario versus aluminum.

3.2 Functional Unit

The functional unit of the study consists of the transportation services (total vehicle miles traveled) provided between 2015 and 2053 by all light duty vehicles produced in North America between 2015 and 2053. Only vehicles produced between 2015 and 2053 are considered, and vehicle use or end-of-life (EOL) management after 2053 is excluded. This definition of the functional unit means that not all included vehicles reach the end of their lives within the study period. However, all vehicles lightweighted during the aluminum industry's projected growth curve[14] are modeled to reach their EOL and are recycled during the study timeframe. The industry projection ends in 2028, so the aluminum content and production volumes are held constant from 2028 to 2053. This assumption creates a steady state annual emission profile by the end of the modelling period and improves the interpretation of the results (see Section 3.3 for additional details).

An alternative functional unit would be to stop considering vehicle production at a given year, but include vehicle use until all of the included vehicles reach end of life. However, this creates annual GHG emissions that are somewhat artificial and difficult to interpret, since vehicle production, use, and end-of-life goes on concurrently. Furthermore, the amount of aluminum use in vehicles, once implemented, is relatively fixed without significant vehicle redesign. Therefore, the functional unit definition described above was employed.

3.3 System Boundary

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[13] Ducker Worldwide. "Aluminum Content in North American Light Vehicles 2016 to 2028." Summary Report prepared for the Aluminum Association. July 2017. http://www.drivealuminum.org/research-resources/ducker2017/.

[14] Ibid.

The system boundary has been defined to capture the main GHG emissions changes caused by the material substitution described in the reference flow of the study, where the reference flow consists of two separate parts. The first part is a time series of annual North American light vehicle production in vehicles per year from 2015 to 2053. For each year the total production number is broken into eight different vehicle classes, including A/B, C, D, E, MPV (passenger vans), SUV (sport-utility vehicles), VAN (utility vans), and PUP (pick-up trucks), and five different power train types, including gasoline- and diesel-powered internal combustion vehicles (ICVs), standard and plug-in hybrid electric vehicles (HEVs), and pure battery electric vehicles (BEVs). Gasoline vehicles comprise the majority of the vehicle fleet, decreasing slightly from 90.3% to 81.3% during the study period. All other power train types make up the rest of the share, with the hybrid and electric power train vehicles growing modestly during the study period. The fleet model calculations and assumptions are detailed in the CLCA Model User Guide and Project Report found in Appendix A.

The second part of the reference flow is a time series of the annual amount of additional aluminum body and closure parts, or the additional amount of AHSS body and closure parts, used instead of mild steel body and closure parts in North American light vehicle production. The total amount is further converted into average amount per vehicle, as a function of power train type and vehicle class composition of each power train type.

Note that the input data in the aluminum case uses forecasts from a Ducker Worldwide study (as previously described) for the years 2015 to 2028 and aluminum production levels are then held constant between 2029 and 2053. The AHSS case is handled similarly. Keeping production of aluminum or AHSS level for another 25 years beyond 2028 results in several advantages from a modeling standpoint. First, it is a conservative modeling approach that allows for complete consideration of the use phase and EOL recycling savings associated with vehicles lightweighted during the industry projection timeframe. Second, it enables the model to calculate a cross-over time, i.e. the time at which use phase savings have completely made up for the GHG increase during vehicle production, and cumulative GHG emissions have reached zero.

The aim of this CLCA study is to account for all significant changes caused by the reference flow rather than to account for every significant part of a product or service life cycle, which is the typical objective of an ALCA. Four distinct consequences (changes) within and outside of the vehicle life cycles are modelled: 1) increases and/or decreases in the production of steel and aluminum used in the modeled body and closure parts as well as secondary mass savings, 2) fuel economy of the mass-reduced vehicles, 3) the generation and use of steel and aluminum scrap from material forming processes (prompt or manufacturing scrap), and 4) the generation and use of steel and aluminum scrap from vehicle end-of-life management. All life cycle stages or processes that do not experience significant GHG emission changes due to the material substitution are omitted. Examples are the production of tires, vehicle fluids, non-structural materials, as well as vehicle assembly.

3.4 Cut-off Criteria

The cut-off criterion of this study is to capture at least 95% of all GHG emission changes as described in Section 3.3 and caused by the studied increase in aluminum production for use in North American vehicles as a replacement of equivalent primarily mild steel closures and body parts. For the AHSS scenario, the studied replacement is AHSS closures and body parts for the same amount of primarily mild steel replaced in the aluminum option. In this context, "equivalent" is defined as meaning that the material substitution does not affect the technical specifications and safety rating of the vehicles.

4. LIFE CYCLE INVENTORY ANALYSIS

The scope of the study results in the following set of unit processes:

- Cradle-to-gate production of primary aluminum ingots and integrated (blast furnace / basic oxygen furnace, or BF/BOF) steel slabs used in vehicle production or displaced due to production and end-of-life scrap recycling;
- Scrap-to-gate production of secondary aluminum ingots and electric arc furnace (EAF) steel slabs used in vehicle production or from automotive production and end-of-life scrap;
- Gate-to-gate aluminum rolling, extrusion, and casting and steel rolling and casting;
- Cradle-to-gate gasoline, diesel, and electricity production; and,
- In-vehicle gasoline and diesel combustion.

4.1 Data Collection and Sources

For many input parameters, initial values are sourced from the SRI/SMDI ALCA study titled "Life Cycle Greenhouse Gas and Energy Study of Automotive Lightweighting" dated November 7, 2017. These key input values and their justification are described below in Sections 4.1.1 to 4.1.6. Several of these inputs vary over the study time period and are indicated as such. All other inputs are described in the CLCA Model User Guide and Project Report (see Appendix A). The SRI/SMDI 2017 ALCA study was subjected to a comprehensive independent peer review by a panel of four subject matter experts. The review concluded in part: "*After an exhaustive three rounds of review of comments and responses by the panel members and the AISI, based on the goals set forth to review this study, the review panel concludes that the study conforms to ISO 14044:2006 as a comprehensive study that may be disclosed to the public*."

Input data values for this study are based partly on a survey of relevant literature sources to assess the validity of these inputs and their appropriateness for use in representing North American conditions over the study time period. Data is primarily sourced from high quality and reputable secondary sources, such as material associations and published literature. This section describes the specifics for key data sources and parameter inputs. Several input parameters are tested in sensitivity analyses to assess their influence on the baseline results over time (see Section 4.5).

4.1.1 Material Inputs

Steel and aluminum comprise the majority of a vehicle's bill of materials. Furthermore, the replacement of steel with aluminum or AHSS in vehicle body and closures is modeled to only affect the production levels of those two materials in this study. There is sufficient capacity in North America to supply automotive steels for North American vehicle production and the use of imported steel in automotive applications is very limited based on information from North American steel industry experts. However, there is no North American steel slab or finishing data currently available. As shown in Table 1, the steel input data used in this study is based on the latest LCI data published by the World Steel Association and represents global average production, which includes North American sites, between 2006 and 2009. The global LCI data was benchmarked against aggregated cradle-to-steel mill gate North American LCI datasets for hot-dip galvanized (2.16 kg CO_2eq/kg) and hot rolled coil (2.00 kg CO_2eq/kg). These datasets are comprised of a blend of BF/BOF and EAF steel production and are comparable to the global average values used in this study. The World Steel

Association (worldsteel) released new global average LCI datasets in September 2017. These datasets are aggregated on a cradle-to-gate basis and the unit process data necessary for the modeling in this study has not been released. However, the LCI data used in the CLCA Model was benchmarked against the new worldsteel data for hot-dip galvanized (2.7 kg CO_2eq/kg) and hot rolled coil (2.22 kg CO_2eq/kg). These datasets are comprised of a blend of BF/BOF and EAF steel production and are comparable to the global average values used in this study. Furthermore, updated North American average LCI datasets are currently in-progress, but not yet available.

Table 1. Cradle-to-gate GHG Intensity (GWP-100, IPCC AR5) for Steel and Aluminum Inputs

Material	GHG Intensity (kg CO_2eq/kg)	Source
Steel, BF/BOF slab	1.87	World Steel Association (WSA), 2010; representing global average production between 2006-2009.
Steel, EAF slab	0.40	
Mild steel finishing, flat	0.485	
Mild steel finishing, long	0.29	
AHSS finishing, flat	0.534	Calculated assuming a 10% increase over mild steel finishing.
AHSS finishing, long	0.319	
Aluminum, primary ingot – North American	8.937	GaBi dataset: "RNA: Primary Aluminum Ingot AA, primary production, consumption mix"; reference year 2011.
Aluminum, primary ingot – imported	16.5	GaBi dataset: "GLO: Aluminum ingot mix, International Aluminium Institute (IAI)", reference year 2010.
Aluminum, secondary ingot	0.68	GaBi dataset: "RNA: Secondary Aluminum Ingot AA, production mix, at producer"; reference year 2010.
Aluminum finishing, rolling	0.5	GaBi dataset: "EU-27: Aluminium sheet ts <p-agg>"
Aluminum finishing, extrusion	0.73	GaBi dataset: "EU-27: Aluminium extrusion profile ts <p-agg>"

Note: GaBi datasets are from the thinkstep GaBi Professional Database Service Pack 30, released July 2016. http://www.gabi-software.com/international/databases/.

AHSS represents a broad spectrum of steel grades ranging from slightly higher strength grades to significantly higher strength grades. While AHSS does not require a significantly greater degree of processing versus other sheet steel products, specific LCI data does not exist for AHSS products. To account for this uncertainty, the GHG intensity of the finishing processes for mild steel have been increased by 10% for the base case, as noted in Table 1 above.

The model separately accounts for primary and secondary material production (in the aluminum case) and EAF vs. integrated production (in the mild steel and AHSS cases), as well as finishing processes, such as rolling, extruding, casting, and galvanizing. The aluminum share of secondary production increases over time based on the amount of prompt scrap and end-of-life scrap available for recycling back into automotive sheet via a closed-loop recycling approximation (see Section 4.3). The share of flat steel produced by the EAF route is 6% for the base case; however, the use of EAF-produced sheet in automotive applications is increasing, so this value was tested in the sensitivity analyses (see Section 4.5).

Aluminum primary ingot GHG intensity values (shown in Table 2 above) are based on the most recent North American average production mix data collected by the Aluminum Association and global average production data collected by the International Aluminium Institute. The CLCA model uses import shares for primary aluminum of 22% in 2015 and 34% in 2016, which represent the actual shares based on import, export, and production data from the Aluminium Association of Canada[15], U.S. Geological Survey[16], and the Canadian International Merchandise Trade Database, part of Statistics Canada[17]. The import share (where "import share" refers to imports into North America, and does not include imports from Canada into the United States or vice versa) is modeled to increase at a rate of 3.6% per year based on the increasing demand for aluminum in North American vehicles as projected by the Ducker study commissioned by the Aluminum Association.

The CLCA model also includes a downward trend in imported primary aluminum GHG intensity (reduction of 0.9% per year until 2029) to reflect expected improvements in aluminum production processes and electricity grid mixes from a Hao, et al., 2015 study[18].

Using global average data to model imported primary aluminum ingots is a conservative approach because it includes production from regions with relatively low GHG intensity, such as North America, whereas the regions most likely to export primary aluminum to North America have coal and natural gas-fueled production.[19] The global average also includes primary aluminum production in China. While at the time of data collection, most primary aluminum produced in China was consumed within the country, China has become a significant exporter of primary aluminum over the last several years.[20] In fact, according to Aluminum Association data, China now produces more than half of the world's primary aluminum and U.S. imports of semi-fabricated aluminum products from China grew 183% between 2012 through 2015 before leveling off in 2016.[21] The majority of the Chinese imports to the U.S. are comprised of sheet and plate products.

Furthermore, according to the Aluminum Association's energy production accounting methods, 75% of North American primary ingots are produced using electricity generated by hydropower.[22] This accounting is embedded in the GHG intensity of North American produced primary aluminum shown in Table 1. The validity of this assumption is not well documented, but was maintained in the base case modeling for this study as a conservative assumption. Secondary ingot data represents North American average production in 2010 based on data collected by the Aluminum Association.

4.1.2 Material Replacement Coefficients

The material replacement coefficients (MRCs) indicate the ratio of substituting one material for another. For example, the MRC for advanced high strength steel (AHSS) is 0.75 lb AHSS/lb mild steel.[23] This means, by switching from mild steel to AHSS in a given application, 25% less steel by weight is needed. The MRCs used in this study are shown in Table 2.

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[15] Aluminum Association of Canada. "Canadian Primary Aluminium Production", October 2017. Available at: http://aluminum.org/sites/default/files/CanadaPrimaryProduction092017.pdf.
[16] U.S. Geological Survey. "2015 Minerals Yearbook: Aluminum" and "2017 Mineral Commodity Summary: Aluminum". Available at: https://minerals.usgs.gov/minerals/pubs/commodity/aluminum/.
[17] Statistics Canada, Canadian International Merchandise Trade Database. "Merchandise imports and exports between "Canada" and "World", by Harmonized System section, customs basis, September 2017". Available at: http://www5.statcan.gc.ca/cimt-cicm/home-accueil?lang=eng.
[18] Hao H., Geng Y., and Hang W. "GHG emissions from primary aluminum production in China: Regional disparity and policy implications," *Applied Energy*, 2015. Published online: http://dx.doi.org/10.1016/j.apenergy.2015.05.056.
[19] Accenture, LLC. "North American Primary Aluminum Smelter Study," prepared for the American Iron and Steel Institute. December 7, 2015.
[20] Aluminum Association. "Getting Trade Right – Addressing Chinese Overcapacity." Available at: http://www.aluminum.org/getting-trade-right. Accessed October 2017.
[21] Ibid.
[22] Aluminum Association. "The Environmental Footprint of Semi-Finished Aluminum Products in North America: A Life Cycle Assessment Report." December 2013.
[23] WorldAutoSteel. UltraLight Steel Auto Body – Advanced Vehicle Concepts (ULSAB-AVC) Programme. www.ulsab.org.

Table 2. Material Replacement Coefficients for Steel and Aluminum.

Material	MRC	Unit	Source
AHSS replacing mild steel	0.75	lb AHSS/ lb mild steel	WorldAutoSteel ULSAB-AVC[24]
AHSS replacing average steel	0.805	lb AHSS/lb average steel	Calculated based on the average of the AHSS MRCs (0.75 – 0.86) found in the SRI 2017[25] ALCA study.
Aluminum replacing mild steel	0.67	lb aluminum/ lb mild steel	A2Mac1 Automotive Benchmarking, 2017[26]; average of vehicle types.
Aluminum replacing average steel	0.782	lb aluminum/ lb average steel	Calculated based on the AHSS and aluminum mild steel MRCs using a 50% share of aluminum replacing mild steel and 50% AHSS.

The aluminum to mild steel MRC is based on actual body structure and closure lightweighting from a mass benchmarking study using the A2Mac1 tear-down database.[27] The study entailed a detailed analysis of approximately 250 vehicles representing MY 2011-2015. The MRC for replacing mild steel with aluminum represents average nominal designs. In this CLCA, an MRC for replacing aluminum with average steel was used as the base case. As newer vehicle models are developed, aluminum would need to replace lighter advanced steels in addition to mild steel and in increasingly more mass efficient vehicle designs. In the A2Mac1 study, mass efficient designs lightweighted with aluminum achieved significantly less mass savings, i.e., MRCs increased to 0.78-0.79.

A recent paper by Hottle, et al., 2017[28] assessed several published automotive LCA studies, which include aluminum to mild steel MRCs in the range of 0.46 – 0.74. Three of the five non-SMDI studies with specific MRCs are on the high end of the range, including Dubreuil 2012 (0.74), Marretta 2012 (0.65), and Stasinopoulos 2012 (0.70). There are only two studies with lower MRCs, specifically Raugei 2015 (0.5) and Baroth 2012 (0.46). Furthermore, a paper by Kelly, et al., 2015[29] presents a wide range of MRC values for "Steel to Wrought Al" with most between 0.48 – 0.72 for body or general part applications. There are outliers of 0.29 and 0.99. Specific part or component-level MRCs are generally not applicable to this study, as they would be applied across all components and systems for every vehicle type in the fleet we are modeling. The aluminum to mild steel MRC used in the study (0.67) is considered reasonable and was tested in a sensitivity analysis (see Section 4.5).

For AHSS, the selected baseline MRC is based on steel industry applied research through the WorldAutoSteel ULSAB-AVC Programme and experience in vehicle designs as described in

[24] Ibid.

[25] Steel Recycling Institute and Steel Market Development Institute. "Life Cycle Greenhouse Gas and Energy Study of Automotive Lightweighting." November 7, 2017. http://www.steelsustainability.org/automotive/auto-ghg/.

[26] A2Mac1 Automotive Benchmarking. Malen, D.; Nagaraj, B.; and Singher, B. "Automotive Mass Benchmarking." February 2017.

[27] Ibid.

[28] Hottle, T., Caffrey, C., McDonald, J., and Dodder, R. "Critical factors affecting life cycle assessments of material choice for vehicle mass reduction," Transportation Research Part D 56 (2017) 241–257. http://dx.doi.org/10.1016/j.trd.2017.08.010.

[29] Kelly, J.C., Sullivan, J.L., Burnham, A, and Elgowainy, A. "Impacts of Vehicle Weight Reduction via Material Substitution on Life-Cycle Greenhouse Gas Emissions," *Environ. Sci. Technol*. 2015, 49, 12535−12542. DOI: 10.1021/acs.est.5b03192.

the SRI 2017 ALCA study[30]. The A2Mac1 database used to derive the aluminum MRCs does not distinguish between different steel types, such as AHSS and mild steels; therefore, it could not be used to discern a specific MRC for AHSS. The base case AHSS MRC is the average of the range of MRC values presented in that study (0.75 – 0.86) and reflects the fact that, like aluminum, it is anticipated that newer grades of AHSS will be replacing both mild steel and earlier grades of AHSS during the study period.

The MRC values for both aluminum and AHSS are assessed in a sensitivity analysis described in Section 4.5.

4.1.3 Secondary Mass Savings

Secondary mass savings (SMS) or secondary mass change indicates additional vehicle mass that can be saved, for example in braking and suspension systems, as a result of the reduction in mass due to primary lightweighting. This secondary savings, like primary mass reduction, must fulfill performance and function requirements. SMS is typically expressed as a percentage of primary weight savings. The primary mass reduction in this study occurs in the body structure and closures. As a result, additional mass savings would come from other systems, such as the chassis and braking systems. The composition of secondary savings modeled in the base case is shown in Table 3.

Table 3. Composition of Secondary Mass Savings

Material	Secondary savings (%)
Flat products	40%
Long products	30%
Castings	30%
Total	100%

The most commonly used SMS in literature surveys of previous studies[31,32] is 50%; however, this value is typically applied at the individual component-level and is generally lacking justification beyond industry rules of thumb and expert opinion. In a 2013 study by Malen et al.,[33] the estimated mass influence coefficients using analytical and regression methods is 0.342 and 0.406 ± 0.052 (34.2% and 40.6 ± 5.2%), respectively. These represent the sum of various subsystem lightweighting potentials. A 2012 study by Alonzo, et al,[34] found the mean theoretical SMS potential is 0.95 kg for every kg of primary mass savings; however, when realistic manufacturing and design limitations were implemented, the SMS potential decreased to a mean of 0.12 kg/kg. The base cases in this study use a SMS of 20% to conservatively reflect realistic limitations on current vehicle design. This value is assessed in a sensitivity analysis in Section 4.5.

4.1.4 Lifetime Driving Distance

The lifetime driving distance parameter refers to the total number of miles a vehicle can be expected to be driven during its useful lifetime. A 2006 study by the National Highway Traffic Safety Administration (NHTSA) reports lifetime mileage for passenger cars to be 152,137

[30] Steel Recycling Institute and Steel Market Development Institute. "Life Cycle Greenhouse Gas and Energy Study of Automotive Lightweighting." November 7, 2017. http://www.steelsustainability.org/automotive/auto-ghg/.
[31] Malen, D.; Gobbels, R; and Wohlecker, R. "Secondary Mass Changes in Vehicle Design Estimation and Application." Prepared for WorldAutoSteel. January 2013.
[32] Alonso, E.; Lee, T.M.; Bjelkengren, C.; Roth, R.; and R. Kirchain. "Evaluating the Potential for Secondary Mass Savings in Vehicle Lightweighting." *Environmental Science & Technology*. 2012, 46, 2893−2901.
[33] Malen, D.; Gobbels, R; and Wohlecker, R., 2013. Ibid.
[34] Alonso E.; Lee, T.M.; Bjelkengren, C.; Roth, R.; and R. Kirchain, 2012. Ibid.

miles and light-duty trucks to be 179,954 miles.[35] The Oak Ridge National Laboratory Transportation Data Book[36] and the GREET 2 (2016) vehicle life cycle model [37] use 150,000 miles for passenger vehicles and 180,000 miles for light-duty trucks. The base case scenarios in this study use 251,500 km (approximately 156,000 miles), based on an approximately 21% share of light-duty trucks and utility vans in the modeled vehicle fleet at an average of 180,000 miles and a 79% share of passenger cars at 150,000 miles. This parameter is also assessed by a sensitivity analysis in Section 4.5.

4.1.5 Fuel Reduction Values and Power Train Resizing

Fuel reduction values (FRVs) represent the amount of energy that is saved for a given amount of mass savings and are expressed in units of liters/(100km*100kg). In this study, FRVs are used to calculate the use phase GHG emissions savings from lightweighting. They were derived from the Dr. Don Malen (University of Michigan) & Dr. Roland Geyer (University of California, Santa Barbara) Power Train Model for different vehicle classes and power train types with and without resizing.[38] FRVs for HEVs were derived from engine map simulations conducted in 2010-2011 by Forschungsgesellschaft Kraftfahrwesen mbH Aachen (fka) [39], an automotive engineering and strategic consulting firm. The Malen & Geyer Power Train model was developed independently, and the model and supporting documentation will be published separately.

FRVs with power train resizing assume a fully optimized engine design matched to the new lightweighted vehicle, which is not typically demonstrated in practice. Automakers have a fixed number of engine and transmission combinations available to incorporate into their vehicle designs. Therefore, entire power train systems or power train components are often used in several vehicle models and many vehicle models are offered with more than one power train option. Since this study is of average vehicle types and considering the practical limitations of power train resizing, an approximation of 25% power train resizing was selected for the base case scenarios in this study. This calculation adds 25% of the difference in the FRVs with and without power train resizing to the FRV without resizing for each vehicle type to approximate the benefits of power train resizing realized by an average vehicle. While an arbitrary value, it is most likely that the benefit of power train resizing is closer to 0% than 50% or 100%.

The amount of power train resizing was assessed in a sensitivity analysis as described in Section 4.5.

4.1.6 Recycling Rates

Recycling rates are modeled separately for each material and for prompt and end-of-life scrap in the Model. Values used in this study are shown in Table 4. These values remain constant over time due to lack of information to support an alternative assumption; however,

[35] National Highway Traffic Safety Administration. "Vehicle Survivability and Travel Mileage Schedules". DOT HS 809 953 Technical Report. January 2006.
[36] Davis, S.; Williams, S.; Boundy, R. Oak Ridge National Laboratory, Center for Transportation Analysis, Energy and Transportation Services Division. *Transportation Energy Data Book*, Edition 35, ORNL-6992. October 2016. pp. 3-17 and 3-18.
[37] Argonne National Laboratory. Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) 2 Vehicle Life Cycle Model, 2016 Update, Revision 1. January 2017. Available at: https://greet.es.anl.gov/index.php.
[38] Geyer, Roland. "Life Cycle Energy and Greenhouse Gas (GHG) Assessments of Automotive Material Substitution: User Guide for Version 5 of the UCSB Automotive Energy and GHG Model." University of California at Santa Barbara, CA, on behalf of WorldAutoSteel. March 2017.
[39] FKA simulations in 2010-2011 based on their 2007 report "Determination of Weight Elasticity of Fuel Economy for Conventional ICE Vehicles, Hybrid Vehicles and Fuel Cell Vehicles," Report 55510, Forschungsgesellschaft Kraftfahrwesen (FKA), Aachen, Germany

the amount of material recycled over time changes as a function of aluminum and steel production and vehicles reaching their end-of-life during the study period.

Table 4. Recycling Rates for Aluminum and Steel

	Prompt Scrap Recycling Rate		End-of-life Scrap	
	Steel	**Aluminum**	**Steel**	**Aluminum**
Collection Rate	99%	99%	97%	97%
Shredder Rate	-	-	98%	90%

4.2 CLCA Model Calculation Procedures

All of the calculation procedures used in the Model are detailed in the report *"Consequential Life Cycle Assessment (CLCA) of Replacing Steel with Aluminum in Vehicles: User Guide and Final Project Report",* dated February 26, 2016, which can be found in Appendix A.

4.3 Allocation

Consequential LCA does not require allocation procedures since all significant changes in process activities are included through system expansion. In this study, system expansion is required when the changes in scrap inputs to metal production and scrap outputs from material forming and vehicle end-of-life management are recycled in an open loop. As a conservative assumption, aluminum was modeled as being recycled in a closed loop process, which was tested as a sensitivity case (see Section 4.5). For steel scrap, open loop recycling was assumed for the scope of this study, which is specific to the automotive sector. On a more general scale, steel scrap recycling can be approximated as a closed loop system; however, in practice, it is readily recycled from one product system or sector to another based on where scrap is demanded. This is considered a conservative approach as the use of closed loop recycling for aluminum provides the lowest cumulative GHG results as can be seen in the sensitivity analysis results (see Section 5.2). The Model system expansion equations are detailed in Section 4 (Appendix A: Consequential system expansion) of the Model report, which is included with this report as Appendix A.

4.4 Data Validation and Data Quality Assessment

Data quality was assessed for the inventory data used as inputs to the model. Specific discussion of key input parameters is included in Sections 4.1.1-4.1.6. Validation was performed through benchmarking against published literature sources and by sensitivity analyses (see Section 4.5).

ISO 14044 includes a set of data quality requirements to address time-related, geographical, and technology coverage; data precision, completeness, and representativeness; consistency, reproducibility, sources, and uncertainty. These criteria are described below in the context of this study.

4.4.1 Time-related Coverage

This criterion addresses the age and timeframe of data. This study utilizes the most current secondary data available from reputable sources, such as industry associations and the GaBi professional database, which is subjected to a rigorous quality assurance process, is widely distributed, and has been used globally in many critically reviewed and published LCA studies. Most data inputs are less than 5 years old. The steel input data is approximately 10 years old. New global steel LCI data was released in September 2017, but is available only for an aggregated cradle-to-gate scope. As described in Section 4.1.1, the LCI data used in this study was benchmarked against the new global average data and was found to be reasonably comparable. New North American steel LCI data is currently being collected; however, this data was not yet available at the time of this study. The aluminum input data is 6-7 years old.

Reasonable assumptions have been made about whether input data will vary over the project time horizon or remain relatively constant. Projecting future processes is a necessary part of this and many consequential LCAs. To address inherent uncertainty, a sensitivity analysis has been conducted (see Section 4.5).

4.4.2 Geographical Coverage

This criterion addresses the geography from which data was collected for unit processes to satisfy the goal of the study. The study focuses on North American production of average MY 2016 vehicles. The driving cycle used to model the use phase driving conditions is the U.S. combined cycle. Electricity and fuel inputs represent U.S. average production, which is appropriate for a fleet-level study of average vehicles. Aluminum inputs represent the percentage split of North American and imported primary aluminum and all North American-produced secondary ingot. The share of imports changes over time as described in Section 4.1.1. Global average data was used to model steel inputs due to the aggregated nature of North American average production LCIs for steel. However, the global average data was benchmarked against the North American average data and was found to be a good approximation.

4.4.3 Technology Coverage

This criterion addresses the technology mix represented in the data. For material inputs, the amount of primary and secondary material is modeled separately to reflect the different technologies used in those production routes. For aluminum, the model assumes an increase in secondary content over the study period as a result of an increase in both prompt and end-of-life aluminum scrap becoming available for recycling back into automotive sheet. For steel production, the split of integrated and EAF production for automotive applications is independent of the availability of automotive scrap since steel is readily recycled from one product system or sector into another without loss of quality. Use phase fuel and electricity inputs are representative of average U.S. production technologies.

4.4.4 Precision

The precision of the data is a measure of the variability in the values for each data input (e.g. variance). Data precision is addressed in this study through the use of individual parameter sensitivity analyses.

4.4.5 Completeness

Completeness addresses the percentage of flow that is measured or estimated. As described in Section 3.4, the cut-off criterion of this study is to capture at least 95% of all GHG emission changes caused by the studied replacement of primarily mild steel closures and body parts with equivalent aluminum closures and body parts, or equivalent AHSS closures and body parts. The recycling stage is based on the amount of material recovered and recycled during auto part manufacturing (i.e., stamping and forming) and at vehicle end-of-life. Overall data completeness is also judged to be high in the context of this study as data is derived from reputable secondary sources, such as industry associations and the GaBi professional database.

4.4.6 Representativeness

Data representativeness entails a qualitative assessment of the degree to which the dataset reflects the true population of interest. In reference to the discussion in Sections 4.4.1 to 4.4.3, the time, geographic, and technology coverage of the data used in this study is considered representative for the assessment of North American light-duty vehicle production.

4.4.7 Consistency

Consistency entails a qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis. The data used in this study for material inputs represents a consistent scope and was collected from consistent sources, including industry associations and the GaBi database.

4.4.8 Reproducibility

This criterion entails a qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study. The use of the CLCA Model, along with the use of documented sources for input values, would allow any practitioner to replicate the base case results and sensitivities presented in this study.

4.4.9 Sources of Data

This data quality criterion simply requires an assessment of data sources in the context of data quality. The input data for this study is sourced from reputable secondary data sources, such as industry associations and the GaBi professional database. These sources are described in detail in Section 4.1.1 to 4.1.6.

4.4.10 Uncertainty

This criterion simply requires an assessment of data uncertainty. Data uncertainty is addressed in this study through the use of individual parameter sensitivity analyses.

4.5 Sensitivity Analysis

Sensitivity analysis is typically included in life cycle studies to determine the influence of key assumptions, methods, and input data on study results. A sensitivity analysis compares the base case results with results obtained using variations on key parameters or assumptions. In the absence of published literature, these variations are often quantified by adjusting data by a specified range, such as ±15%.

Individual sensitivity tests were conducted by varying single parameters in the base case scenario to assess the influence of key parameter assumptions on the results. The scenarios included in this study are listed below. Results of these assessments are presented in Section 5.2.

- S1: Aluminum Material Replacement Coefficient Varied from 0.5 – 0.8 lb Alum./lb Mild Steel and AHSS MRC Varied from 0.75 – 0.86 lb AHSS/lb Average Steel.
- S2: AHSS Greenhouse Gas Intensity Increased by 25%.
- S3: Open loop, closed loop prompt scrap, and closed loop prompt and EOL scrap scenarios considered for both aluminum and AHSS.
- S4: Secondary Mass Savings varied from 0% to 50%% for both aluminum and AHSS.
- S5: Percentage of power train resizing varied from 0% to 50% for both aluminum and AHSS.
- S6: Growth rate of imported primary aluminum varied from 0% to 6%.
- S7: Flat steel stamping yield varied from 50% to 60%.
- S8: Aluminum sheet stamping yield varied from 50% to 55%.
- S9: Imported primary aluminum GHG intensity varied ±25% from baseline.
- S10: Mean vehicle lifetime varied from 10 years to 16 years.
- S11: Vehicle Lifetime Driving Distance Varied from 200,000 km (Approx. 124,000 Miles) to 300,000 km (Approx. 186,000 Miles).

5. LIFE CYCLE IMPACT ASSESSMENT (LCIA) RESULTS

The CLCA Model calculates cumulative GHG emissions from all life cycle phases over the period from 2015 to 2053 for the considered scenario. These GHG emissions are assessed as global warming potentials measured on a 100-year time horizon (GWP-100), in kg carbon dioxide equivalents (CO_2eq) using GWP characterization factors from the International Panel on Climate Change (IPCC) 5th Assessment Report[40]. These methods are the most up-to-date with high international acceptance. While this is a limitation of the study, GWP-100 has high environmental relevance specific to assessing climate change impacts, which is of high public and institutional interest, and is among the currently most pressing environmental issues, especially relative to the production and operation of vehicles. The focus on GHG emissions is consistent with the majority of automotive LCA studies published in literature.[41] Furthermore, the use of a custom-built Excel model for this study was not conducive to assessing other LCIA indicators simultaneously.

This section contains the results of studied scenarios for GWP-100 on the basis of the chosen functional unit. The reported results represent impact potentials and should be interpreted as approximations of environmental impacts that could occur if the emissions followed the underlying impact pathway. LCIA results are therefore relative expressions only and do not predict impacts on category endpoints (or actual impacts), the exceeding of thresholds, safety margins, or risks.

5.1 Base Case Results

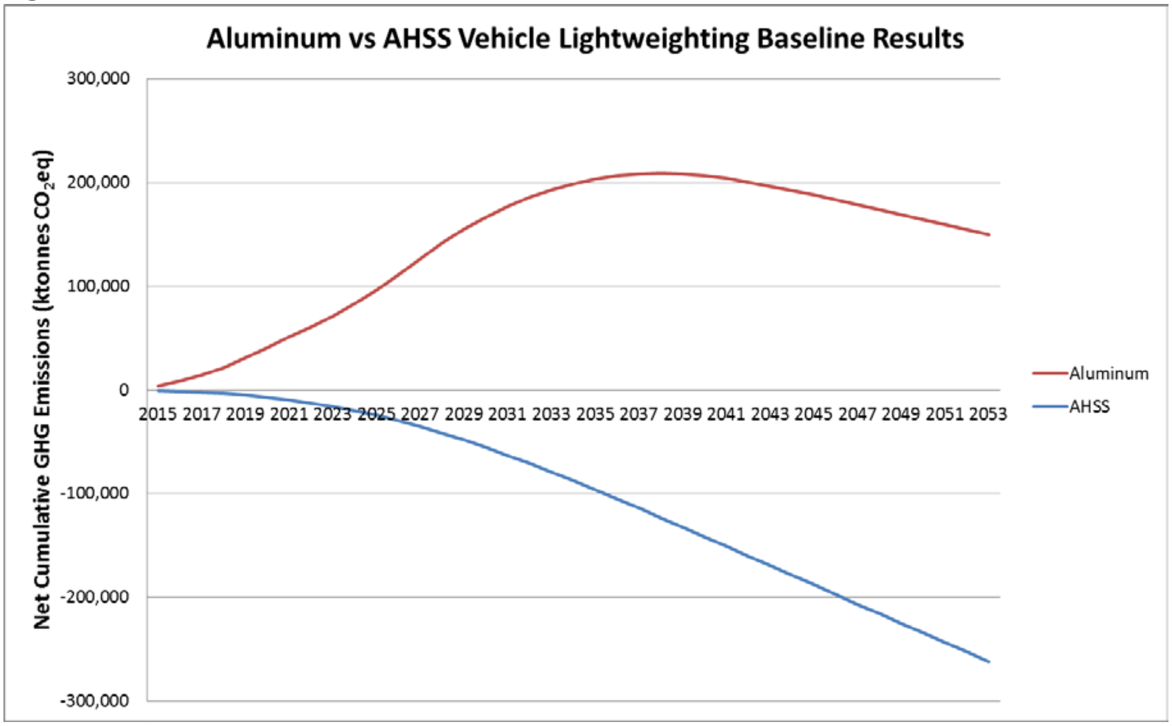
This section presents the results of the base case scenarios comparing an increase in the use of aluminum versus a similar increase in the use of AHSS for lightweighting of vehicles. Results are presented in graphical format, along with a value for peak net emissions and a “breakeven year” for the aluminum option.

As shown in Figure 2, the peak cumulative emissions for the baseline aluminum option are 209 million metric tons CO_2eq, occurring at about the year 2038, and the “breakeven year”, where cumulative GHG emissions return to zero, is calculated as 2084. The AHSS option results in cumulative GHG emissions savings of over 123 million metric tons in 2038, increasing to over 261 million metric tons CO_2eq by 2053. (See accompanying Model files for the base case detailed results.)

[40] International Panel on Climate Change (IPCC). 5th Assessment Report (AR5). “Climate Change 2013: The Physical Science Basis.” 2013.

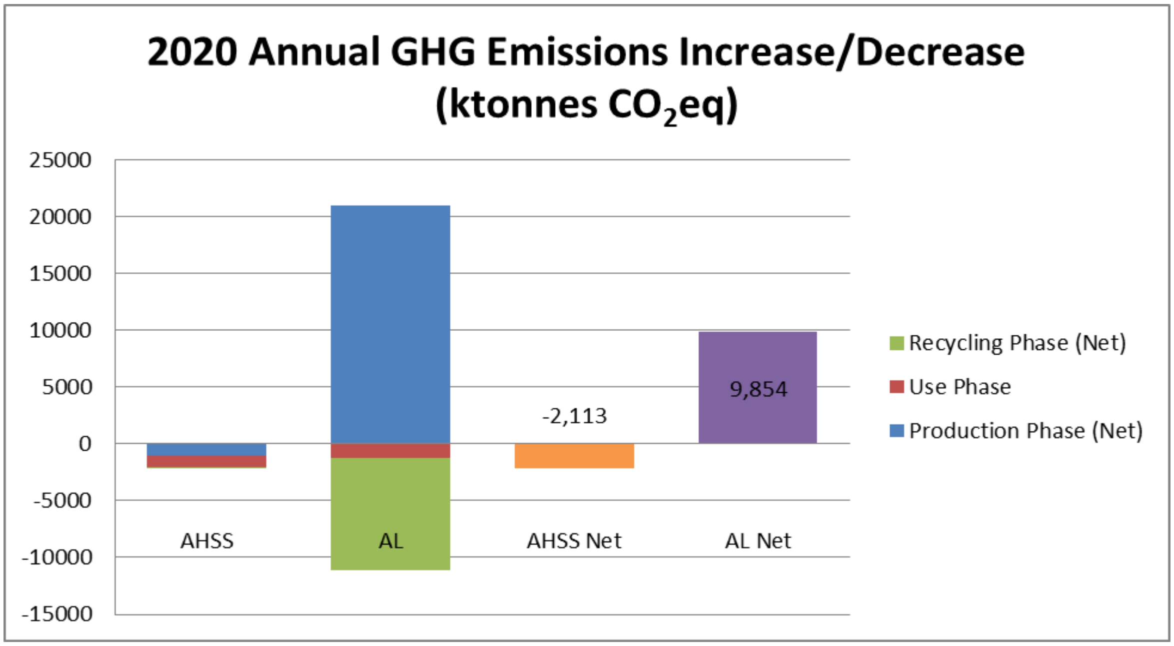
[41] Hottle, T., Caffrey, C., McDonald, J., and Dodder, R. “Critical factors affecting life cycle assessments of material choice for vehicle mass reduction,” *Transportation Research Part D* 56 (2017) 241–257. http://dx.doi.org/10.1016/j.trd.2017.08.010.

Figure 2. Base Case Results for Aluminum and AHSS Options

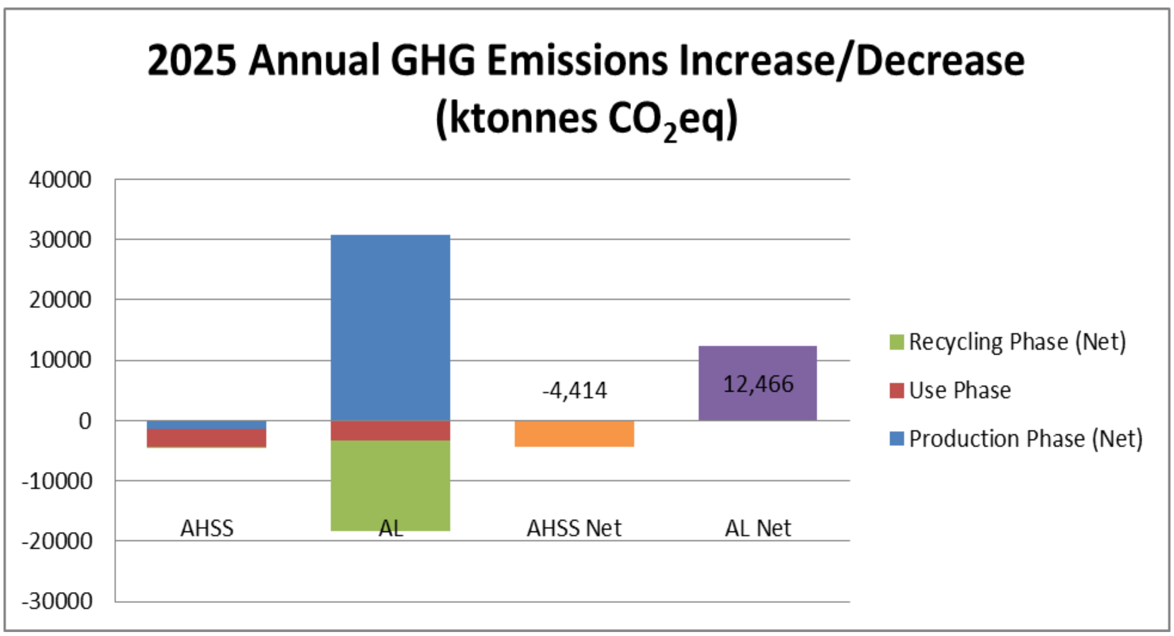


As supplemental information to the baseline results shown above in Figure 2, the following figures show the annual difference in emissions, both net and by life cycle phase, for the AHSS and Aluminum lightweighting scenarios at 5 different points in time. Since the AHSS lightweighting scenario is modeled as an open-loop system, the values for each phase and the net result are taken directly from the model's results. The Aluminum lightweighting scenario is modeled as a closed-loop system, so the model does not separately report a recycling credit. Instead, the significant credits assigned to aluminum recycling are implicitly included in the model's avoided burden calculations. However, by combining the material manufacturing footprint from the Aluminum open-loop sensitivity (which models 98% primary aluminum use) with the use phase footprint (which is identical in both closed and open loop cases) and the final emissions from the baseline closed-loop scenario, the aluminum recycling credit was calculated for use in these graphs.

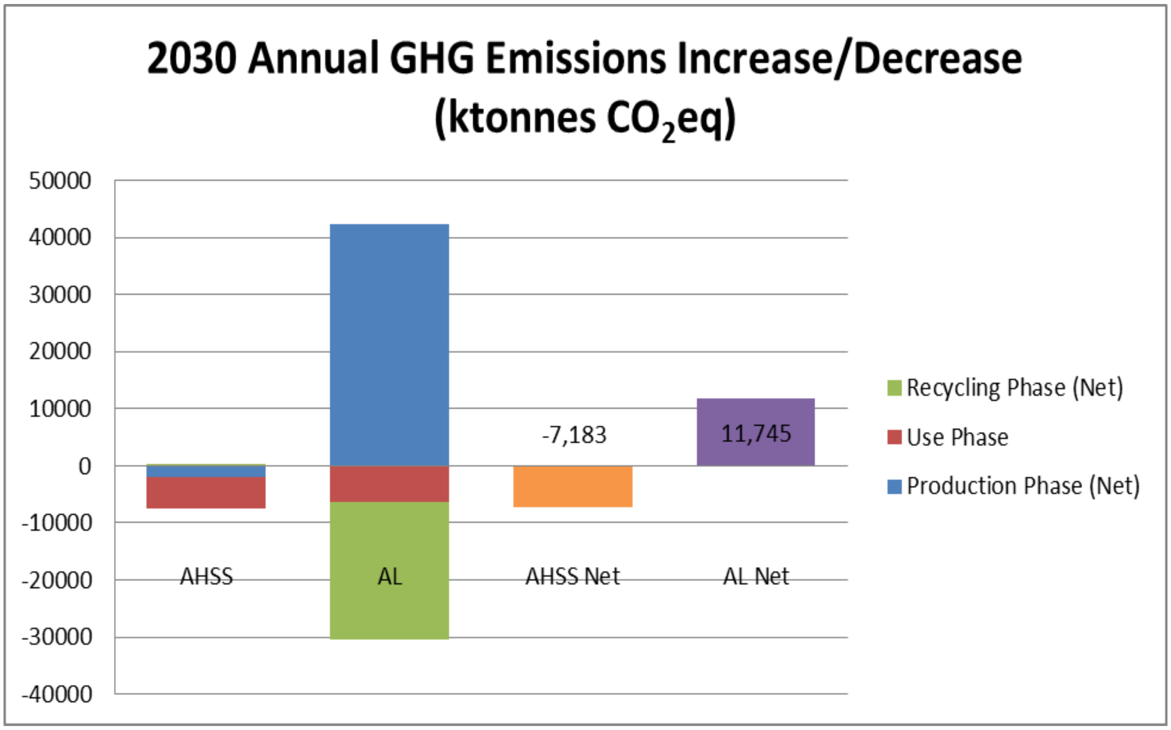
These results show that for the AHSS lightweighting scenario, both the manufacturing and use phase annual footprints are negative, resulting in a negative net footprint which grows every year. By contrast, in the Aluminum lightweighting scenario the production emissions are extremely high every year, and at no point are there greater annual emissions reductions than in the AHSS scenario.



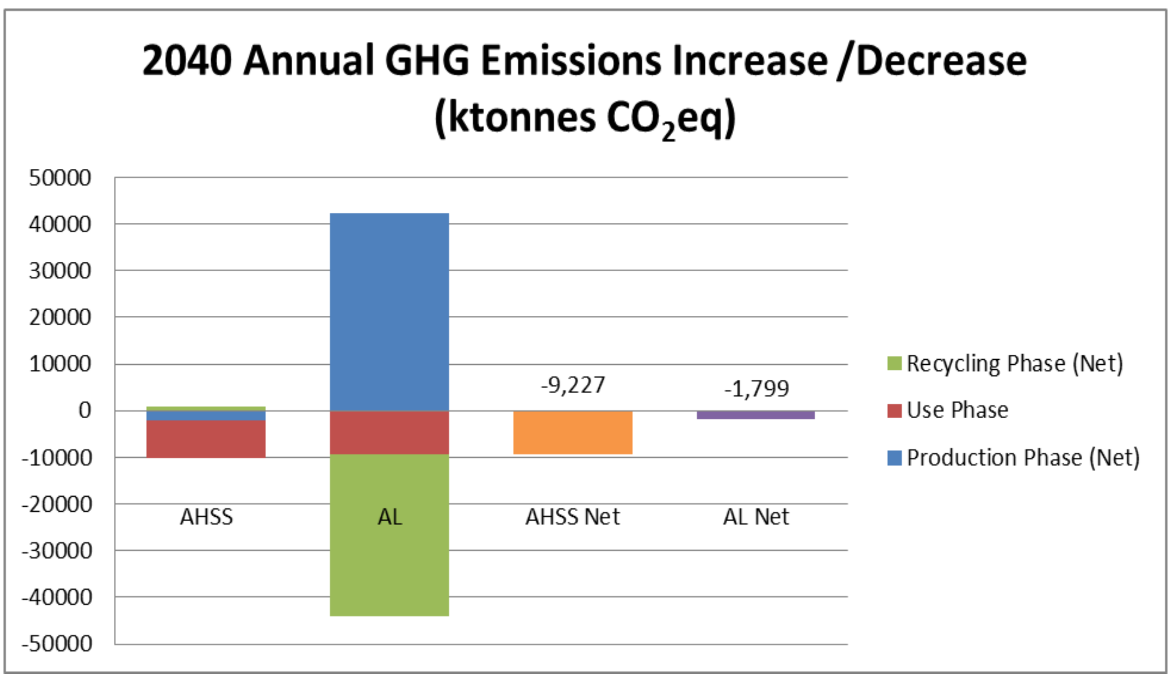
NOTE: Over 99% of the vehicles produced in 2020 will reach end-of-life before the end of the study period (2053), and 100% of the use phase benefits for vehicles produced in 2020 are accounted for within the model.



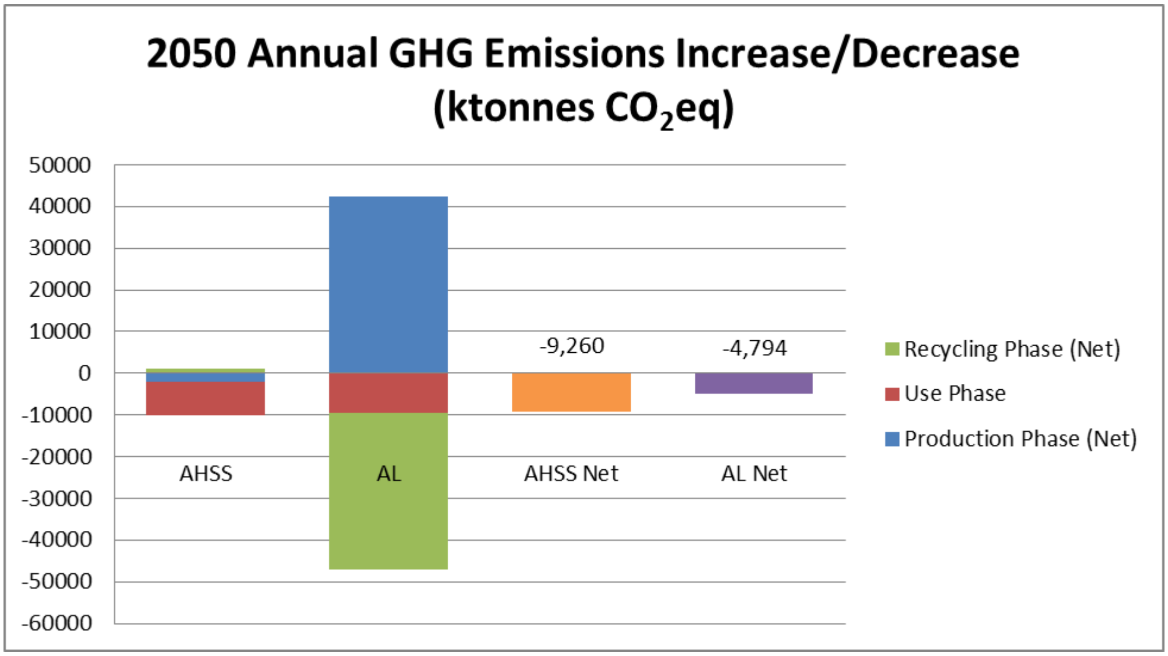
NOTE: Over 99% of the vehicles produced in 2025 will reach end-of-life before the end of the study period (2053), and 100% of the use phase benefits for vehicles produced in 2025 are accounted for within the model.



NOTE: Over 99% of the vehicles produced in 2030 will reach end-of-life before the end of the study period (2053), and 100% of the use phase benefits for vehicles produced in 2030 are accounted for within the model.



NOTE: 48% of the vehicles produced in 2040 will reach end-of-life before the end of the study period (2053), and 91% of the use phase benefits for vehicles produced in 2040 are accounted for within the model.



NOTE: Less than 1% of the vehicles produced in 2050 will reach end-of-life before the end of the study period (2053), and 23% of the use phase benefits for vehicles produced in 2050 are accounted for within the model.

5.2 Sensitivity Analysis Results

As described in Section 4.5, a sensitivity analysis was conducted for key scenarios to test the influence of variations in assumptions, methods, and data on the study conclusions. The result of each such analysis is shown in graphical format below.

Figure S1: Aluminum Material Replacement Coefficient Varied from 0.5 – 0.8 lb Alum./lb, Mild Steel and AHSS MRC Varied from 0.75 – 0.86 lb AHSS/lb Average Steel

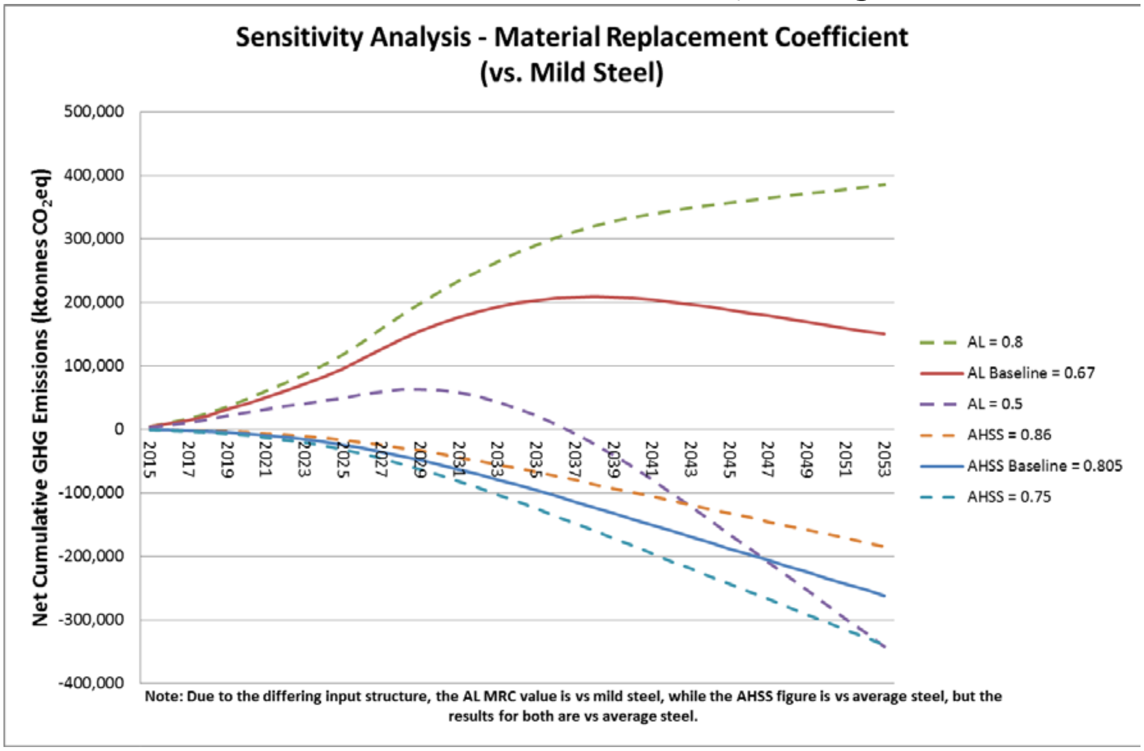


Figure S2: AHSS Greenhouse Gas Intensity Increased by 25%

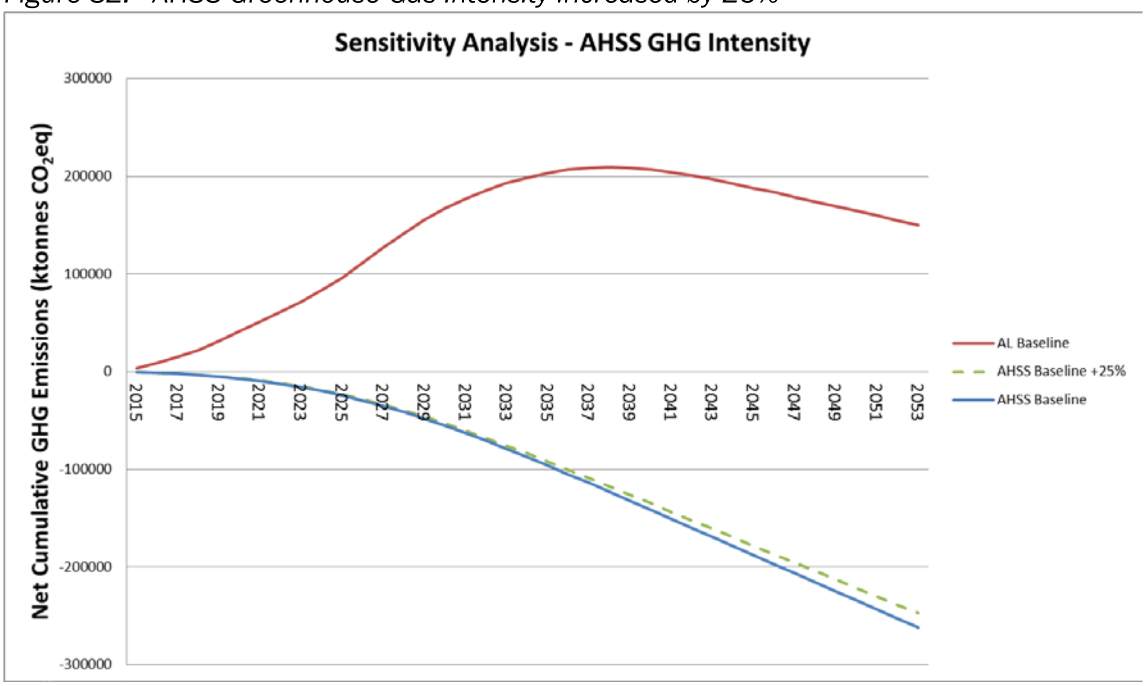


Figure S3: Open Loop, Closed Loop Prompt Scrap, and Closed Loop Prompt and EOL Scrap Scenarios Considered for Both Aluminum and AHSS

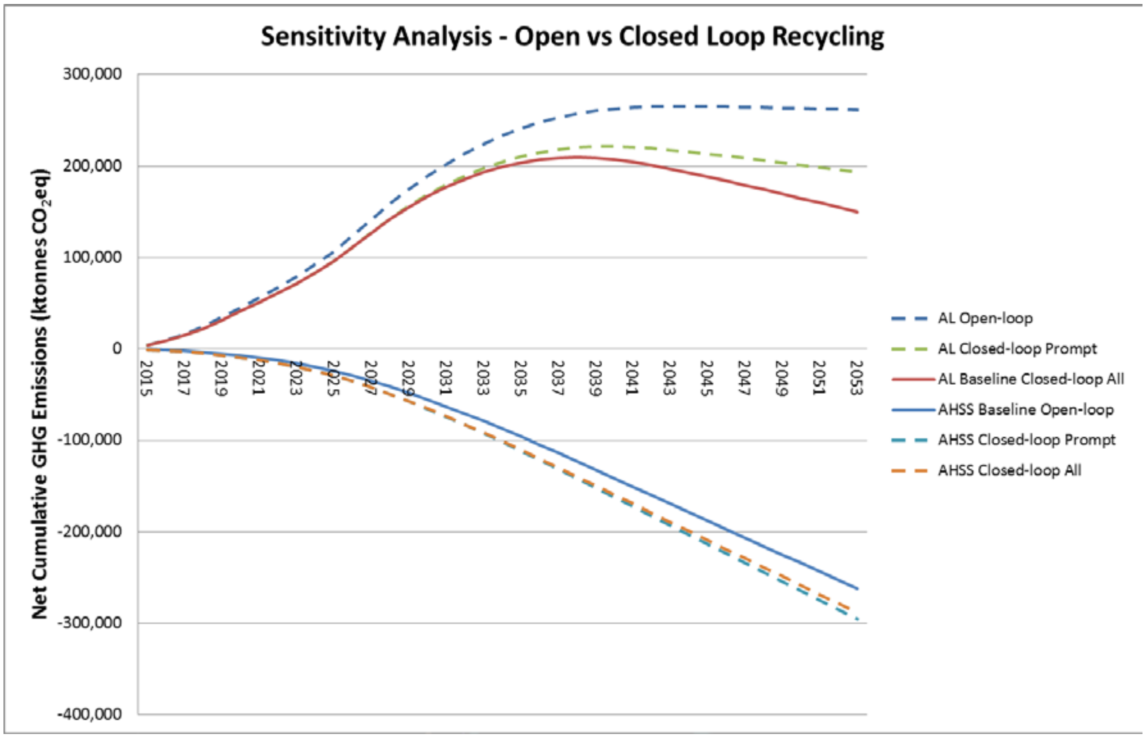


Figure S4: Secondary Mass Savings Varied from 0% to 50% for Both Aluminum and AHSS

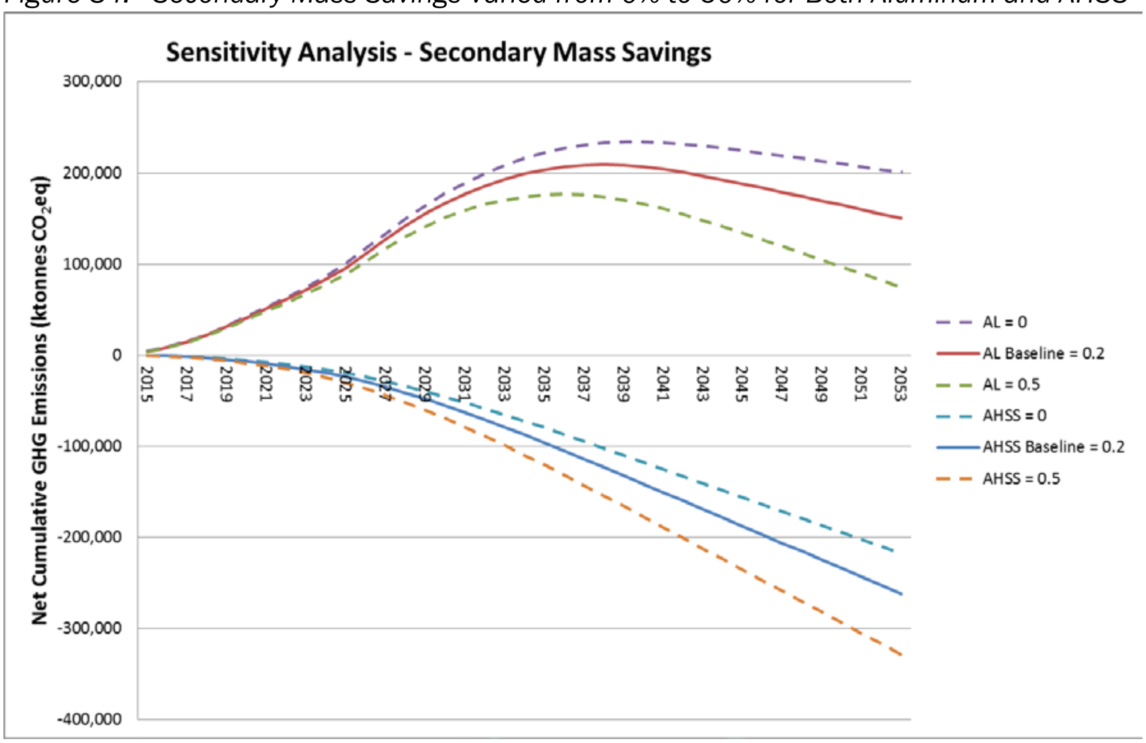


Figure S5: Percentage of Power Train Resizing Varied from 0% to 50% for Both Aluminum and AHSS

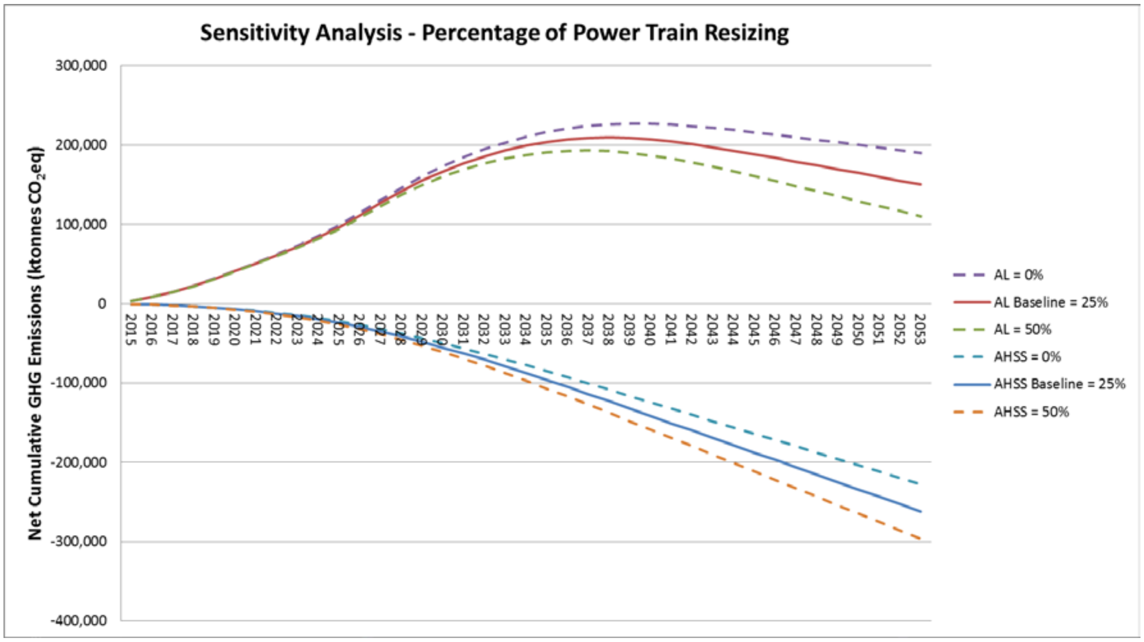


Figure S6: Growth Rate of Imported Aluminum Varied from 0% to 6%

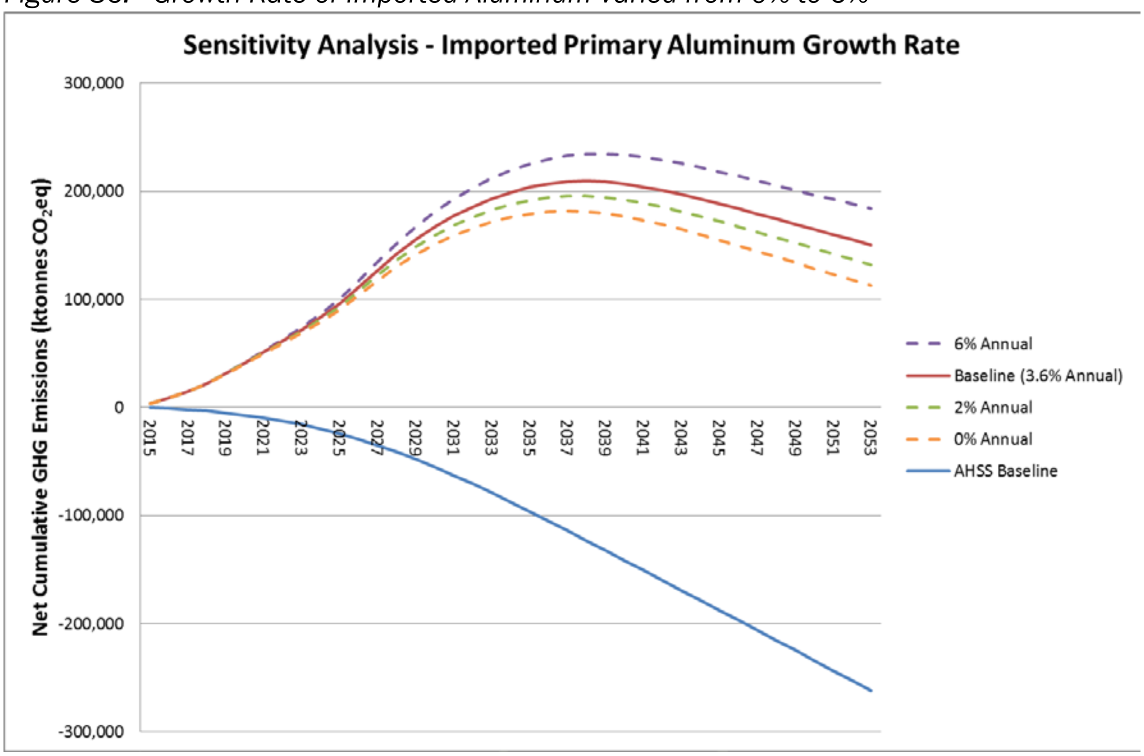


Figure S7: Flat Steel Stamping Yield Varied from 50% to 60%

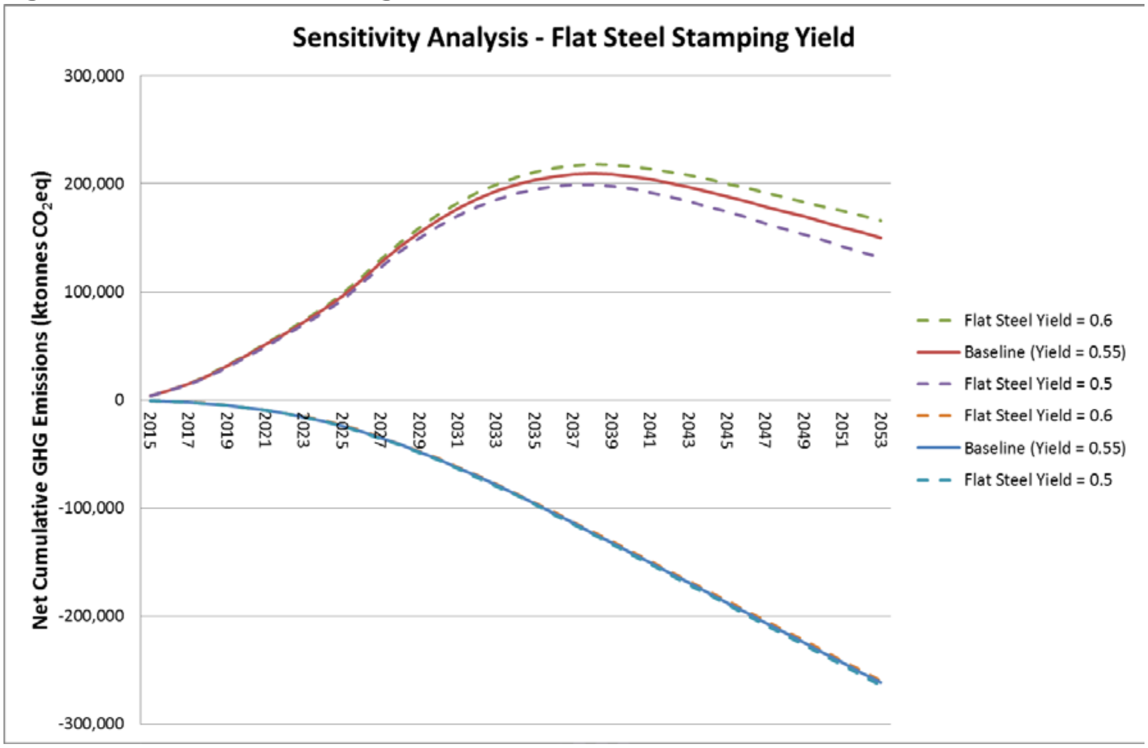


Figure S8: Aluminum Sheet Stamping Yield Varied from 50% to 55%

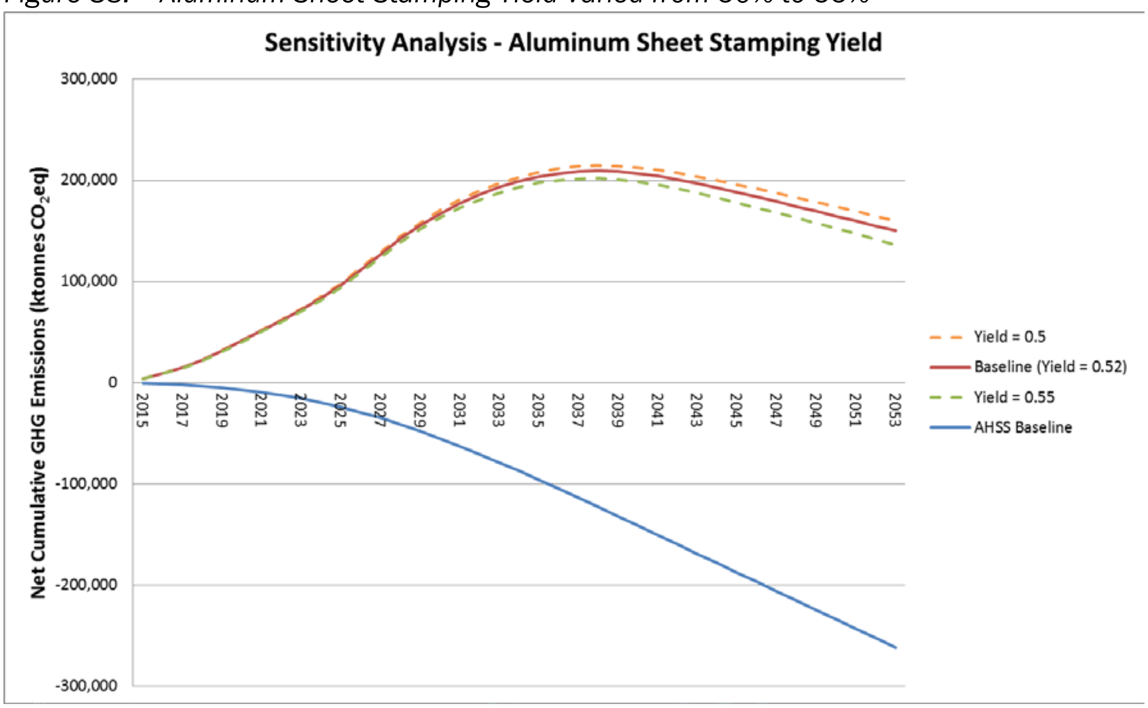


Figure S9: Imported Aluminum GHG Intensity Varied ±25% from Baseline

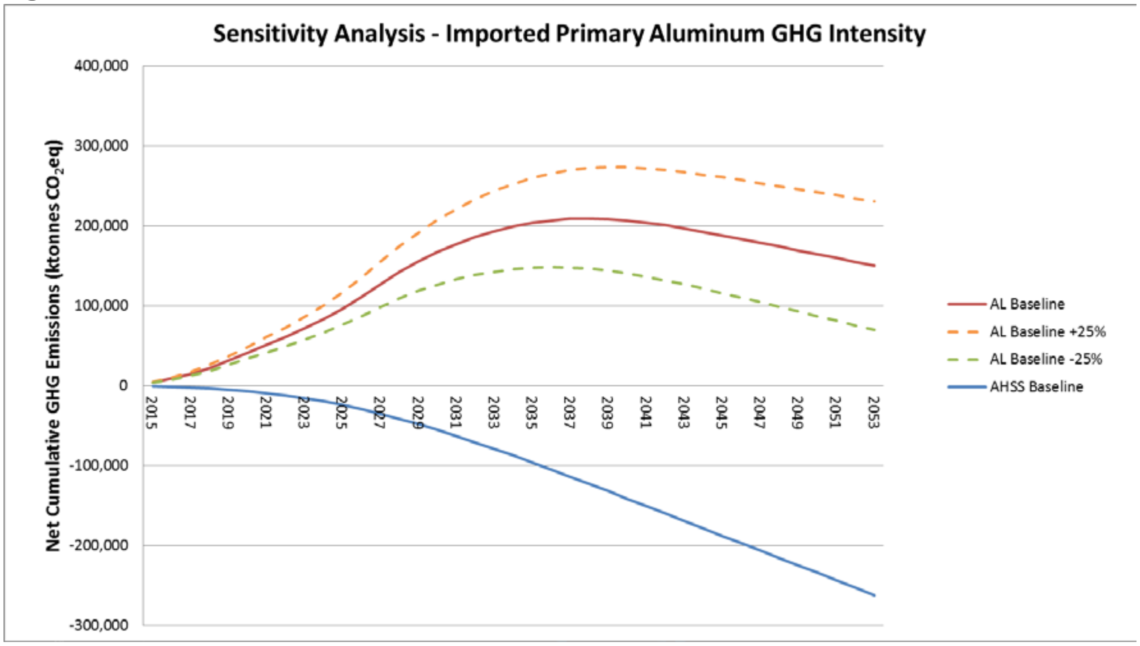


Figure S10: Mean Vehicle Lifetime Varied from 10 Years to 16 Years

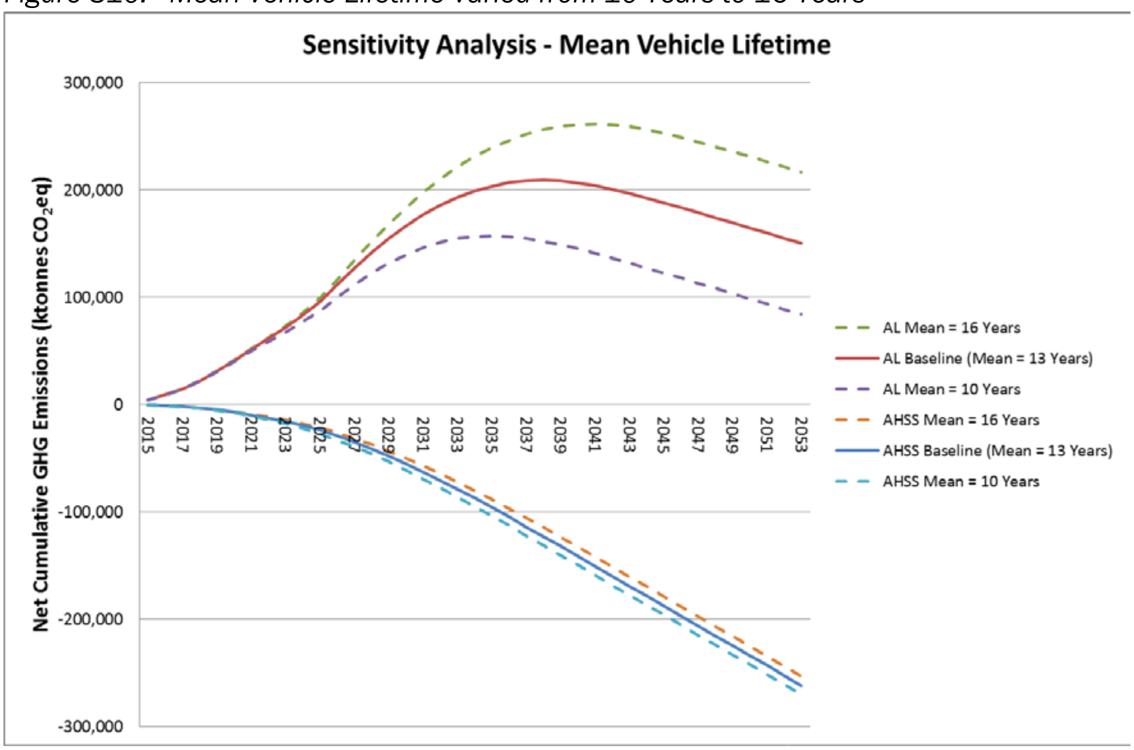
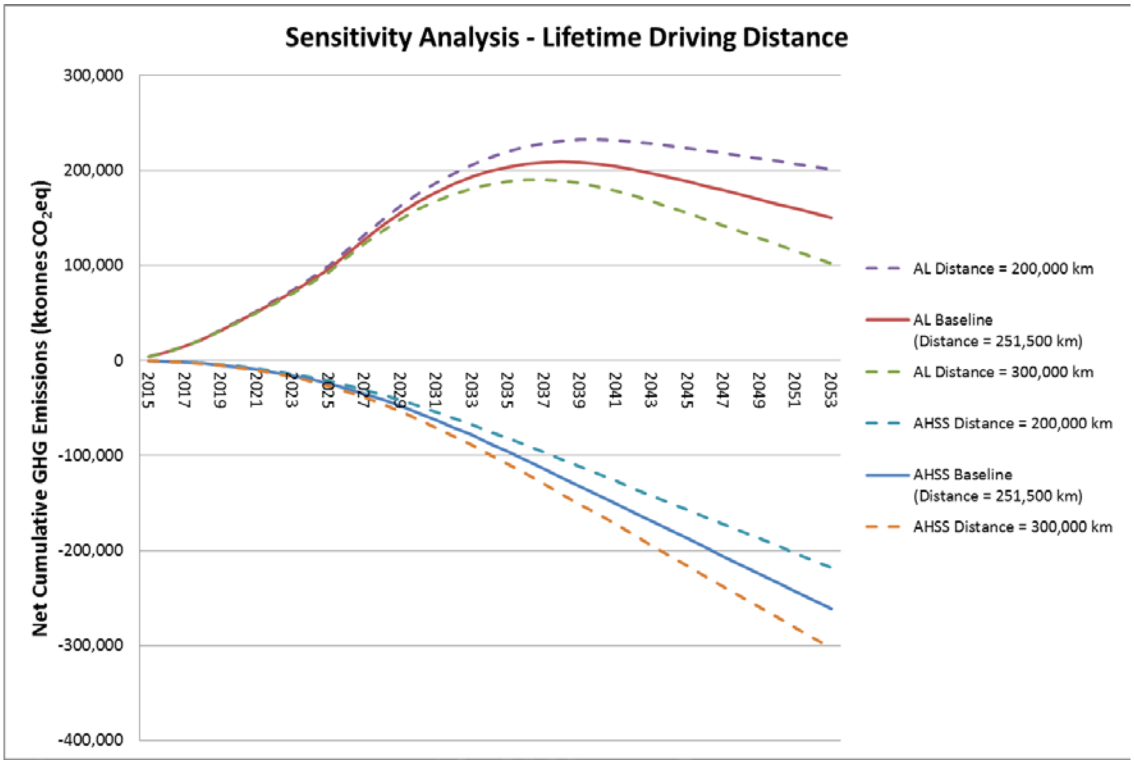


Figure S11: Vehicle Lifetime Driving Distance Varied from 200,000 km (Approx. 124,000 Miles) to 300,000 km (Approx. 186,000 Miles)

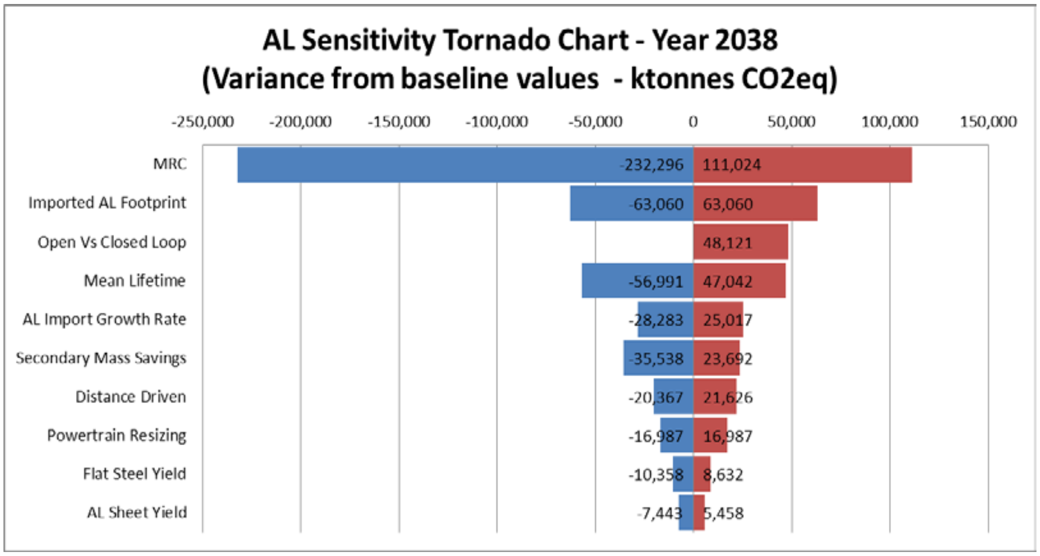


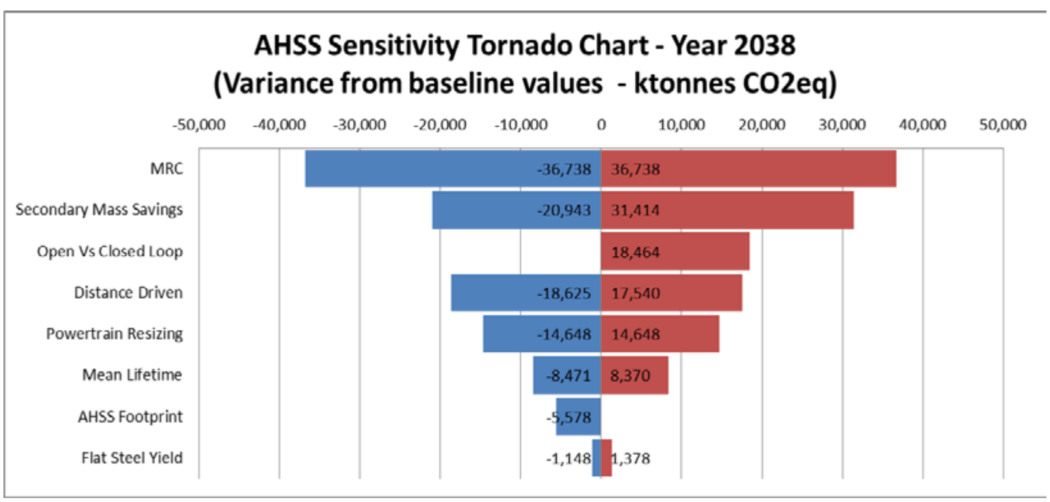
These sensitivity analyses show that while varying key inputs does have an effect on the gap in emissions between the aluminum and AHSS scenarios, in no case do they fundamentally alter the shape of either curve. The fundamental finding of an increase in emissions followed by a gradual reduction for aluminum, and an immediate and sustained decrease for AHSS, remains unaltered.

The sensitivity analysis which showed the most significant effect was clearly the aluminum material replacement coefficient (S1), followed by the GHG intensity of imported aluminum (S9). In S9, the most favorable case for aluminum approaches net zero GHG emissions near the end of the study period. However, the cumulative GHG emissions of the aluminum option do not come close to matching the GHG emissions savings in the AHSS option. In S1, for the extreme low end of the range for aluminum MRC, the net cumulative GHG emissions of the aluminum option reach a peak of over 60 million metric tons, before eventually reaching the same level of net emissions as the AHSS option in Year 2046. At the extreme high end of the aluminum MRC range, in the same year (2046), the aluminum option exhibits higher net cumulative GHG emissions than the AHSS baseline option by over 500 million metric tons.

The analyses for open vs closed loop recycling (S3) and mean vehicle lifetime (S10) showed that these factors have a much smaller effect on AHSS than aluminum. This is due to the comparatively small GHG intensity of AHSS, as well as its ability to be readily created from and recycled into other steel products and sectors through the existing steel recycling system.

As additional information, the following tornado diagrams show the effect of individual variables on the net cumulative GHG emissions results. These are based on a specific point in time, specifically Year 2038, which represents the point of the peak cumulative GHG emissions in the aluminum option base case.





6. INTERPRETATION

6.1 Key Findings

The base case scenario in this study consists of two parts, for which separate Model runs were conducted. The first Model run assessed the consequences of a significant increase in the use of aluminum in vehicle body and closure panels, and the second Model run assessed the consequences of a similar increase in the use of AHSS in vehicle body and closure panels. The results of these two Model runs are shown on a single graph. (See Section 5.1) The results show that the aluminum option exhibits a peak cumulative increase in GHG emissions of about 209 million metric tons CO_2eq, with this peak occurring at approximately Year 2038. (Note that this increase is relative to a baseline of "no lightweighting".) The AHSS option results in an immediate and continuous decrease in cumulative GHG emissions. In fact, because AHSS is lighter than the mild steel it is replacing and has a similar GHG intensity, the use of AHSS results in a net GHG benefit even without considering the associated use phase savings. The cumulative GHG emissions savings in the AHSS case reach a level of over 123 million metric tons CO_2eq in 2038, and a maximum value of over 261 million metric tons CO_2eq in 2053. At Year 2038, the net difference in GHG emissions between the aluminum and AHSS options is approximately 332 million metric tons CO_2eq, and this net difference continues to grow throughout the study period until it reaches over 411 million metric tons CO_2eq by 2053.

It is important to note that there is a peak followed by a downward trend in the aluminum results only because of the steady-state aluminum production assumption described in Section 3.2. This is a conservative assumption due to the lack of automotive aluminum production projections following 2028. If aluminum production continues to increase instead of leveling off to a steady-state after this time, the baseline aluminum results would continue to increase instead of peaking and declining even as the use phase and recycling benefits of the lightweighted vehicles are realized.

Sensitivity analyses of several key parameters show that while varying some key input parameters, especially the aluminum material replacement coefficient, does have an effect on the gap in emissions between the aluminum and AHSS results, in no case do they change the overall study conclusions. This means, the fundamental finding that a large-scale shift to the use of increasing amounts of aluminum for automotive body and closure lightweighting in North America results in a significant increase in GHG emissions followed by a gradual decline, whereas the use of AHSS to lightweight the same automotive body and closure parts results in an immediate and sustained decrease in GHG emissions.

6.2 Assumptions and Limitations

The following is a list of key assumptions and limitations that apply to this study:

- Only global warming potential (GHG emissions) are assessed, instead of a more complete set of LCIA indicators. Therefore, trade-offs amongst other potential environmental impacts were not evaluated.

- Values for many variables are estimated for future years. The details of the assumptions inherent in these estimates are described in detail in the report. (See Section 4.1.)

- Secondary data sources are used to establish specific values for several relevant variables, including global average steel production data from 2006-2009 to reflect North American production conditions, North American aluminum primary and secondary production data from 2011, and global average primary aluminum ingot production data from 2010 to represent North American aluminum imports in lieu of country-specific data.

- The recycling of aluminum scrap from auto part stamping and forming (prompt scrap) and from vehicles once they reach end-of-life was modeled as a closed loop recycling process as a conservative case. It remains unknown whether the infrastructure will exist to effectively separate and recover most or all aluminum prompt scrap and aluminum scrap from automotive disassembly and shredding processes during the study period.

- In LCA, the recycling of steel is often modeled as a closed loop process. However, due to the Model calculations and structure, the recycling of steel scrap is modeled as an open loop to avoid artificial increases in EAF steel production used in automotive applications. Steel scrap from one product application or sector is recycled into many other product applications depending on the demand for steel scrap. Furthermore, steel scrap is recycled as an input to all integrated steel production in North America. EAF steel production for automotive applications is projected to increase; however, this increase is not dependent on the amount of prompt or end-of-life steel scrap recovered from vehicles.

- There is a degree of uncertainty associated with some input parameters due to limited published research and data availability.

- The production of aluminum for North American automotive applications is assumed to reach a steady-state following 2028. This is a simplifying assumption of this study due to the lack of aluminum industry projections regarding production trends after this time.

- The key parameter assumptions of this study have been tested by evaluating various scenarios in the sensitivity analysis (see Section 4.5), which have shown the results to be robust. Note that uncertainty in background datasets has not been addressed specifically aside from the variation of the foreground parameters, such as for the GHG intensity of steel and aluminum production. Key assumptions and limitations have been carefully considered during the interpretation phase of this study and in developing conclusions.

6.3 Conclusions

Based on the goal and scope of the study and considering the study limitations described above, the following conclusions can be drawn:

1. A significant increase in the use of aluminum to lightweight the vehicles in this study, based on the aluminum industry's own projections, results in a significant cumulative increase in GHG emissions, even when use phase savings and GHG benefits due to recycling are considered. In the base case, this increase reached a peak of 209 million metric tons of GHG emissions in 2038.

2. The increase in GHG emissions for the aluminum base case is not offset by use phase savings (due to improved fuel efficiency) and GHG credits for recycling aluminum scrap until the Year 2084, more than 65 years in the future.

3. Alternately, if the body and closure components of the vehicles in this study were instead lightweighted with AHSS, the result is an immediate and continuous decrease in cumulative GHG emissions. The cumulative GHG emissions savings reaches a level of over 123 million metric tons CO_2eq in 2038, and a maximum value of over 261 million metric tons CO_2eq in 2053.

4. Based on the scope of this study, and when the aluminum and AHSS lightweighting scenarios are considered together, the use of AHSS for lightweighting results in a dramatic and sustained decrease in GHG emissions versus the use of aluminum for lightweighting of the same vehicles. At Year 2038 (where the aluminum cumulative GHG results peak), the net difference in GHG emissions between lightweighting with aluminum versus AHSS is approximately 332 million metric tons CO_2eq, which grows throughout the study period to a maximum of over 411 million metric tons CO_2eq in 2053.

APPENDIX A: CONSEQUENTIAL LIFE CYCLE ASSESSMENT MODEL USER GUIDE AND PROJECT REPORT

Consequential Life Cycle Greenhouse Gas Assessment of Replacing Steel with Aluminum in North American Vehicle Production

Methodology Report

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On behalf of SMDI – Steel Market Development Institute

17 November 2016

TABLE OF CONTENTS

Frequent Acronyms

AISI	American Iron and Steel Institute
ALCA	Attributional life cycle assessment
BEV	Pure battery electric vehicle
CLCA	Consequential life cycle assessment
CO_2eq	Carbon dioxide equivalent
EAF	Electric arc furnace
GHG	Greenhouse gas
HEV	Gasoline-based hybrid electric vehicle
ICEV-D	Diesel-based pure internal combustion engine vehicle
ICEV-G	Gasoline-based pure internal combustion engine vehicle
ISO	International Organization for Standardization
LDV	Light duty vehicle
MJ	Mega Joule
PHEV	Plug-in hybrid electric vehicle
SMDI	Steel Market Development Institute

1 Introduction

1.1 General aspects

The consequential life cycle assessment (CLCA) reported here was commissioned by the Steel Market Development Institute (SMDI), a business unit of the American Iron and Steel Institute (AISI). It was executed by Dr. Roland Geyer and Joe Palazzo from the Bren School of Environmental Science and Management at the University of California, Santa Barbara (UCSB). This report was completed on February 16, 2016. The CLCA was conducted according to the requirements of ISO 14044:2006. The sole selected impact category is climate change, so strictly speaking this study is a consequential life cycle greenhouse gas assessment. However, for simplicity the acronym CLCA will be used in the remainder of this report. It is also important to keep in mind that ISO 14044 was written with attributional life cycle assessment (ALCA) in mind and therefore some disambiguation or interpretation is necessary when it is applied to CLCA.

1.2 Goal of the study

SMDI is interested in understanding the greenhouse gas (GHG) implications of a potential large-scale shift of closure and body part material from steel to aluminum in North American production of light duty vehicles (LDV). The intended application of this study is communication with internal and external stakeholders. The target audience includes all internal and external stakeholders with an interest in understanding the GHG implications of large-scale automotive material substitution for reasons of vehicle mass reduction. The developed methodology could potentially be used to support comparative assertions intended to be disclosed to the public after successful critical review by a panel of interested parties. Due to its sole focus on climate change impacts, the study does not investigate any potential trade-offs across different impact categories.

The CLCA model is completely parameterized and the user is encouraged to conduct extensive scenario analysis by varying parameters of interest. The parameterization of the model is motivated by the desire to completely separate computational structure and input data, which is not customarily done in LCA studies (Geyer 2008). The Excel-based CLCA model is populated with a complete set of default input data which generate a default result for illustration purposes. Such a model design makes it possible to review the computational structure of the CLCA separately from the default input data and the default model results. Previous experience has shown that agreement over computational structure is significantly easier to reach than agreement over correct or appropriate input data values and parameter choices.

1.3 Scope of the study

The **functional unit** of the study consists of the transportation services (total vehicle miles traveled) provided between 2012 and 2050 by all light duty vehicles produced in North America between 2012 and 2050. In other words, only vehicles produced between 2012 and 2050 are considered, and vehicle use or end-of-life (eol) management after 2050 is excluded. This definition implies that not all included vehicles reach the end of their lives within the study period.

The alternative would be to stop considering vehicle production at a given year, but include vehicle use until all of the included vehicles reach end of life. This creates annual GHG emissions that are somewhat artificial and difficult to interpret, since vehicle production, use, and eol goes on concurrently. Therefore, the method explained in the first paragraph was chosen. Defining the functional unit in such a way means that the total amount of vehicle miles traveled within the study period is not simply the total number of vehicles produced multiplied by their average lifetime vehicle mileage. Instead, the total amount of vehicle miles traveled within the study period depends in a nontrivial way on a variety of input parameter choices, such as lifetime vehicle mileage (in km), average vehicle lifetime (in years), and trend in vehicle production (i.e. annual vehicle production for each year).

The **reference flow** of the study consists of two separate parts. The first is a time series of annual North American light vehicle production, $N(T)$, given in cars per year from 2012 to 2050. For each year the total production number is broken into five different power train types, $N_i(T)$, which are gasoline- and diesel-powered internal combustion vehicles (ICVs), standard and plug-in hybrid electric vehicles (HEVs), and pure battery electric vehicles (BEVs).

The second part of the reference flow is a time series of annual amount of additional aluminum body and closure parts, $TA(T)$, used instead of steel body and closure parts in North American light vehicle production. For each year the total amount is broken into aluminum sheet, extru-

sions, and castings, $MC_l^a(T)$. The total amount is further converted into average amount per vehicle, as a function of powertrain type and vehicle class composition of each power train type.
The modelling methodology does not restrict the selection of input data for $N(T)$ and $TA(T)$ in any way. However, the default input data uses forecasts from Ducker Worldwide (Ducker 2014, 2015) for the years 2012 to 2025 and is then kept level between 2026 and 2050. Keeping $N(T)$ and $TA(T)$ level for another 25 years has several advantages. First, it is a conservative modeling approach that allows for the use phase savings to make up for the GHG increases during vehicle production. Second, it creates a steady state once the last cars of production year 2025 have reached end of life. This enables the model to calculate a cross-over time, i.e. the time at which use phase savings have completely made up for the GHG increase during vehicle production and cumulative GHG emissions have reached zero.

The **system boundary** is selected in order to capture the main GHG emission changes caused by the material substitution described in the reference flow. The aim of a CLCA is to account for all significant changes caused by the reference flow rather than to account for every significant part of a product life cycle, which is the typical objective of an attributional LCA. This means that all life cycle stages or processes that do not experience significant GHG emission changes due to the material substitution are omitted. Examples are the production of tires, vehicle fluids, non-structural materials, as well as vehicle assembly. The cut-off criterion of this study is to capture at least 95% of all GHG emission changes caused by the studied replacement of steel closures and body parts with equivalent aluminum closures and body parts. Equivalent means that the material substitution does not affect the technical specifications and safety rating of the vehicles. The system boundary that results from the cut-off criterion is described in Section 2.

1.4 Life cycle inventory analysis

The scope of the study results in the following set of unit processes:

- Cradle-to-gate production of primary aluminum and steel ingots
    - Used in vehicle production
    - Displaced due to production and end-of-life scrap recycling
- Scrap-to-gate production of secondary aluminum and steel ingots
    - Used in vehicle production
    - From automotive production and end-of-life scrap

- Gate-to-gate aluminum rolling, extrusion, and casting, steel rolling and casting
- Cradle-to-gate gasoline, diesel, and electricity production
- In-vehicle gasoline and diesel combustion

Since the model results are particularly sensitive to the GHG intensity of primary aluminum ingot production, this data is modeled as a time series, so that temporal trends in primary aluminum production can be included.

The default input data has been collected from a variety of secondary data sources, which are provided in Section 5 (Default input data) and Section 7 (References). Of particular importance were previous (attributional) LCAs (ALCAs) of automotive material substitution conducted for the World Steel Association by the practitioner of this study. These previous studies have a much larger scope then this CLCA, i.e. they include many more processes, such as production of tires, batteries, vehicle fluids, and non-structural materials, and life cycle stages, such as vehicle assembly. Version 4 of the ALCA model was used to compare the GHG results of the original scope with those of the reduced scope used in the CLCA model. The comparison shows that the reduced scope captures well above 95% of the original scope.

CLCA does not require allocation procedures since all significant changes in process activities are included through system expansion. In this study, system expansion is required when the changes in scrap inputs to metal production and scrap outputs from material forming and vehicle end-of-life management are recycled in an open loop (see Figure 1). The model equations are detailed in Section 4 (Appendix A: Consequential system expansion). The two critical model parameters are $\propto$, which quantifies the response of the scrap market to scrap flow changes, and β, which quantifies the response of the material market to changes in open-loop (external) scrap recycling. Choosing $\alpha = 0$ models a scrap market response that is equivalent to the so-called recycled content method in ALCA. Choosing $\alpha = 1$ and $\beta = 1$ models scrap and material market responses that are equivalent to the so-called avoided burden method in ALCA.
Central to CLCA are the causal relationships used to model and quantify the consequences of the initial change described by the reference flow. Important relationships in this study are

- The primary and secondary mass reductions caused by replacing steel with aluminum
- The fuel economy improvements caused by vehicle mass reduction

- The scrap markets responses caused by changes in scrap supply and demand
- The changes in primary aluminum and steel production caused by changes in secondary aluminum and steel production

The equations used to model these relationships can be found in Section 3.

1.5 Life cycle impact assessment

This CLCA considers only one impact category, which is climate change. It is thus a life cycle greenhouse gas assessment, rather than a traditional LCA which considers a range of impact categories. However, the goal of this study is to assess the GHG implications of a potential large-scale shift of closure and body part material from steel to aluminum in North American production of light duty vehicles (LDV). In other words, the goal is to identify and quantify GHG emission trade-offs across different consequences of automotive material substitution, not trade-offs across different impact categories. The exclusion of other impact categories therefore simply reflects the goal and scope of the CLCA. In fact, the study could be readily extended to include additional impact categories if this was desired at some later point.

In the CLCA model, unit processes are described directly in kg CO_2eq per unit output, i.e. the elementary flows have already been classified, characterized and summed up to the indicator result. Due to the linear nature of unit process scaling and impact assessment it does not matter in which order those two calculations are executed. To ensure completeness of the impact assessment all process inventories should at least include carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, and perfluorinated compounds (PFCs).

Current 100-year global warming potentials (GWPs) from the Intergovernmental Panel on Climate Change (IPCC) have been built into the model for characterization. This is the case for the GHG intensities used in the default dataset. Characterization models and GWPs can be found in the Assessment Reports of the IPCC. Different characterization methods, such as GWP_{20} or GWP_{500} can be applied by entering the applicable emission intensity values. In its current iteration, the model does not track GHGs individually. Therefore, the following limitations apply: i) it is not possible to quantify the contributions of individual GHGs to the model results; and ii) it is not possible to test time-dependent characterization factors, such as those used in dynamic characterization models. GWP is a so-called midpoint indicator and model results are therefore relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

1.6 Life cycle interpretation

Section 6 presents the results of the CLCA when the default input data are used and interprets these default results. However, the focus of the model is to generate different plausible scenarios rather than one authoritative solution to the research question. The results presented in Section 6 should therefore been seen as an illustration of the model, the model output, and the presentation of the model output. It is important to keep this in mind while reading Section 6.

2 Overall description of the CLCA model

The aim of this consequential life cycle assessment (CLCA) is to identify and quantify the main greenhouse gas (GHG) emission consequences of a shift from steel-based to aluminum-based body and closure parts in the fleet of light duty vehicles produced in North America between 2012 and 2050. Four distinct sets of changes within and outside of the vehicle life cycles have been identified as significant and were therefore modeled. They are changes in

1) the production of the steel and aluminum used in the modeled body and closure parts, and the secondary mass savings
2) the fuel economy of the mass-reduced vehicles,
3) the generation and use of steel and aluminum scrap from material forming processes, and
4) the generation and use of steel and aluminum scrap from vehicle end-of-life management.

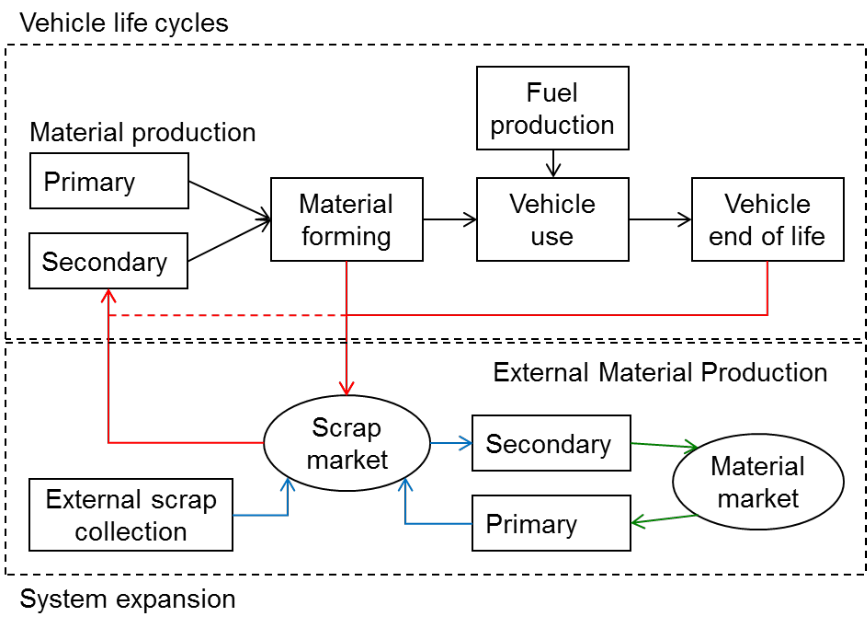

Figure 1: System boundaries of the Consequential Life Cycle Assessment

Figure 1 shows a high-level process flow diagram of the resulting inventory model. In terms of unit processes, the assessment focuses on how the change in automotive material composition impacts primary and secondary steel and aluminum production, vehicle fuel economy, and fuel production and use. The direct GHG emissions changes of other unit processes, such as forming and joining, are estimated to be at least one order of magnitude smaller than the modeled ones.

The first consequence of the studied change in automotive material composition is a change in the amount of steel and aluminum produced for and consumed in North American light vehicle production. All other things remaining equal, this means a reduction in steel production and forming and an increase in aluminum production and forming. These changes in material production and forming and the resulting changes in GHG emissions, $GHGP^a(t)$ and $GHGP^s(t)$, are modeled on the spreadsheet 'Material production'. The recycled content of the aluminum body and closure parts can be set exogenously or is calculated endogenously by assuming closed-loop recycling of their production or end-of-life scrap. Figure 2 shows the data flow between the Excel spreadsheets for the calculation of the GHG emission changes from material production.

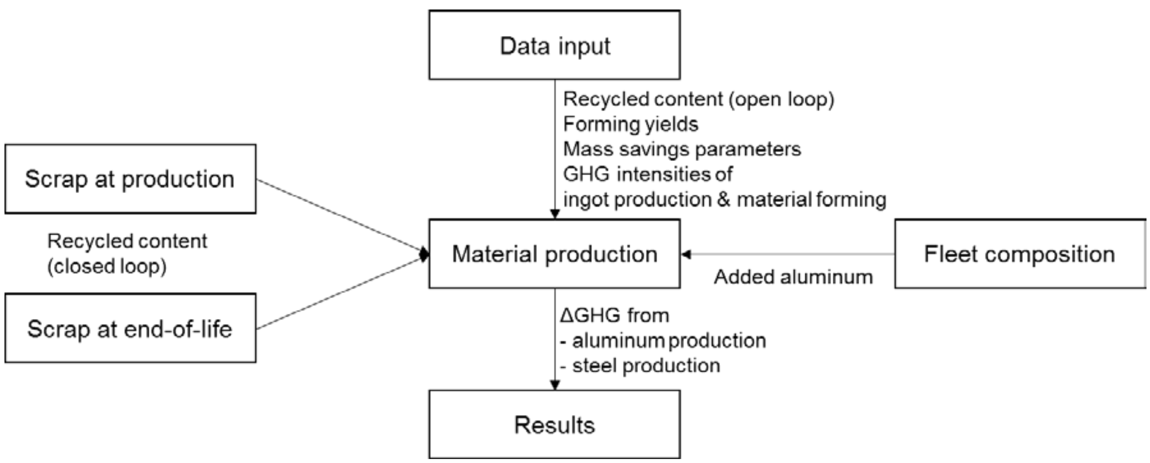

Figure 2: Data flow for calculating changes GHG emissions from material production, $GHGP^a(t)$ and $GHGP^s(t)$

The second consequence of replacing automotive steel with aluminum, and the motivation behind it, is a reduction in vehicle mass which results in an increase in fuel economy, i.e. a decrease in vehicle energy demand per mile. A variety of factors determine the relationship between vehicle mass reduction and fuel economy. The two most important ones are the powertrain type of the vehicle and whether the powertrain is downsized after the vehicle has been mass-reduced. Both are modeled explicitly in this CLCA, which therefore contains a breakdown of the vehicle fleet into powertrain segments. The power train segmentation of the vehicle fleet is modeled on the spreadsheet 'Fleet composition'. The vehicle mass reductions, fuel economy improvements, and the GHG emission reductions, $GHGS(t)$, from the resulting gasoline, diesel, and electricity savings are modeled on the spreadsheet 'Vehicle use'. This spreadsheet also contains a vehicle lifetime model, which accounts for the fact that the life of a vehicle is distributed around a mean value. Figure 3 shows the data flow between the Excel spreadsheets for the calculation of the GHG emission savings during vehicle use. Figure 4 shows the vehicle lifetime distribution model.

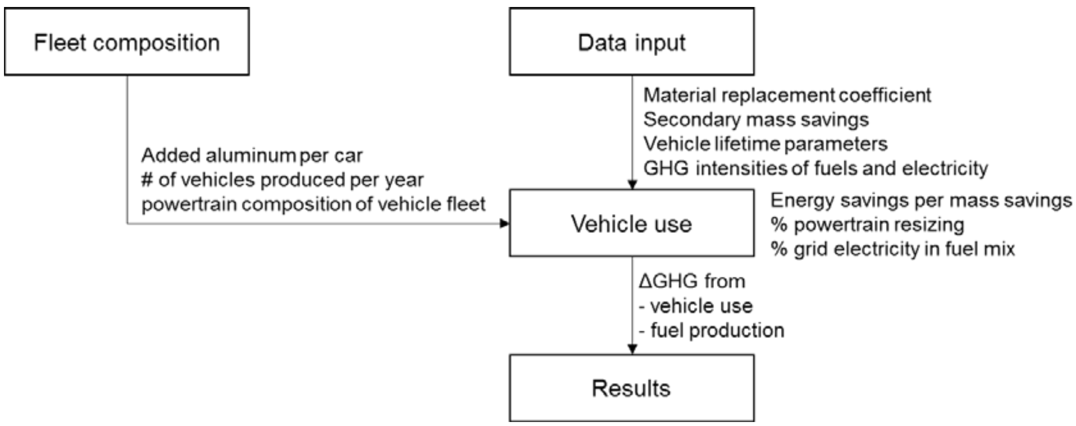

Figure 3: Data flow for calculating use phase GHG emission savings $GHGS(t)$

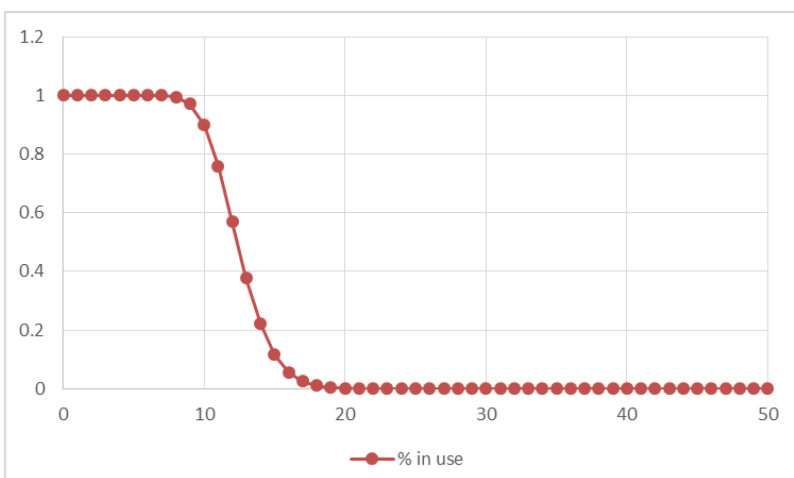

Figure 4: Fraction of vehicles still in use after t years of driving, $FIU(t)$, is modeled as one minus a cumulative log-normal distribution (example for mean 12 years and standard deviation 2 years)

Changes in automotive material production and forming also cause changes in the amount of scrap consumed during automotive material production and generated during material forming, such as rolling, extruding, stamping, and casting. For the added aluminum the CLCA offers two different ways to assess the GHG implications of these scrap input and output changes. One way models aluminum production scrap recycling in a closed loop, i.e. all production scrap from aluminum body and closure forming is recycled back into body and closure parts. The scrap flow changes take place entirely within the vehicle life cycles, which is illustrated by the dashed red line in Figure 1. The other way models the recycled content of aluminum body and closure parts and the recycling of aluminum production scrap in an open loop. In other words, aluminum scrap used in body and closure production comes from an external scrap market and the production scrap goes back into it. For the removed steel, this is the only method used in the model. In CLCA, such changes in scrap flows across the initial system boundaries require system expansion in order to include significant GHG emission changes outside of the vehicle life cycles, $GHGProS^{a}(t)$ and $GHGProS^{s}(t)$. The processes included through system expansion are external automotive aluminum and steel scrap collection and recycling and external primary aluminum and steel production. The expanded system is shown in Figure 1. The model calculations can be found on the spreadsheet ‘Scrap at production’. Figure 5 shows the data flow between the Excel spreadsheets for calculating $GHGProS^{a}(t)$ and $GHGProS^{s}(t)$ caused by open loop recycling of production scrap.

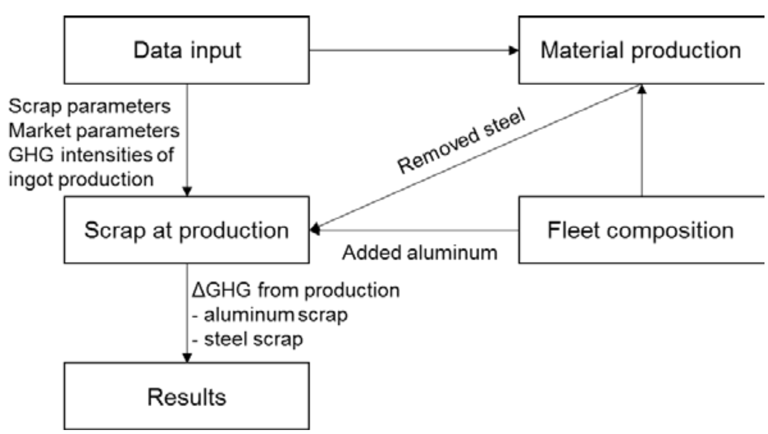

Figure 5: Data flow for calculating the GHG implications of production scrap generation and use (open loop recycling only), $GHGProS^{a}(t)$ and $GHGProS^{s}(t)$

Finally, changing the material composition of the North American light vehicle fleet also changes the composition of end-of-life vehicle scrap. Again, end-of-life aluminum scrap recycling can be modeled in an open and a closed loop. End-of-life steel scrap recycling is always modeled in an open loop. Another system expansion is required when end-of-life recycling is modeled in an open loop and the changes in end-of-life scrap flows cross the initial system boundaries. The processes included through system expansion are external automotive aluminum and steel scrap collection and recycling and external primary aluminum and steel production (as shown in Figure 1). The model calculations can be found on the spreadsheet 'Scrap at end-of-life'. Figure 7 shows the data flow between the Excel spreadsheets when the GHG emission implications, $GHGEolS^a(t)$ and $GHGEolS^s(t)$, are calculated through open loop end-of-life scrap recycling. Figure 7 illustrates the time delay between automotive material substitution and the generation of automotive end-of-life scrap. The time delay is due to the vehicle lifetime and modeled using the vehicle lifetime distribution $FIU(t)$ shown in Figure 4.

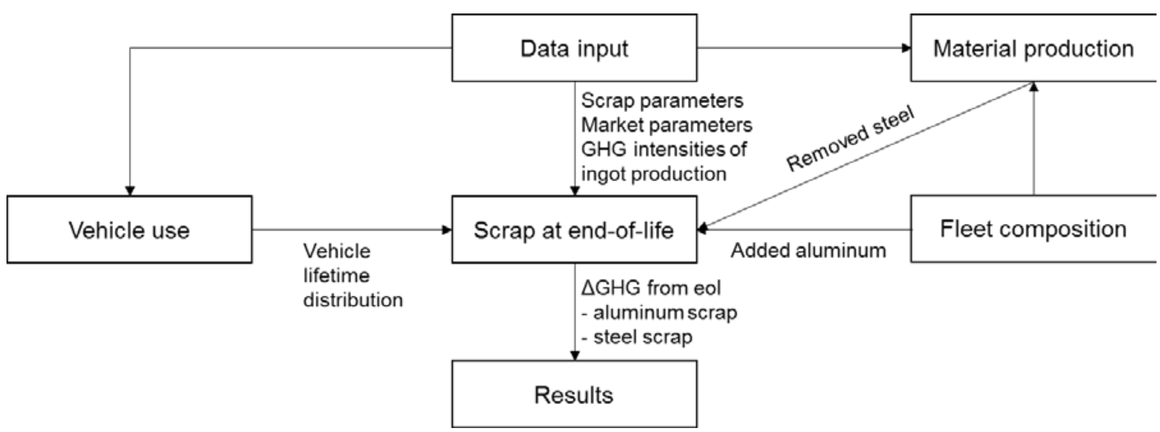

Figure 6: Data flow for calculating the GHG implications of end-of-life scrap generation and use (open loop recycling only), $GHGEolS^a(t)$ and $GHGEolS^s(t)$

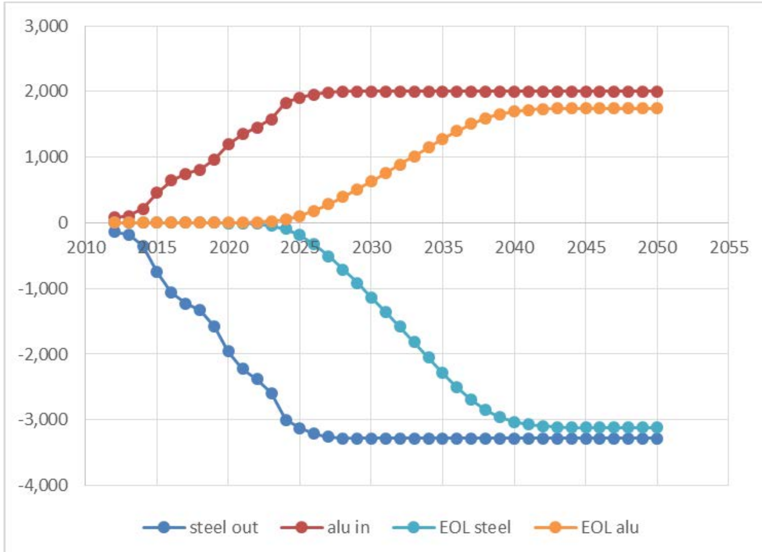

Figure 7: Illustration of the time delay between automotive material substitution and changes in end-of-life (eol) scrap generation (all in million kg)

3 Description of the individual spreadsheets

3.1 Fleet composition

For each year of the modelling period (2012-2050), this spreadsheet calculates the power train composition of the light duty vehicles assumed to be produced in North America during that year. It also calculates, for each production year T and power train type i, the average amount of body and closure parts made from aluminum, $AC_i(T)$.

The resulting **output table** contains 5 power train types *i*, which are Gasoline ICV, Diesel ICV, Standard HEV, Plug-in HEV, and BEV. For each power train type *i* and production year *T* is lists

- $AC_i(T)$: Average amount of body and closure parts made from aluminum (in kg per vehicle).
- $TA_i(T)$: Total amount of body and closure parts made from aluminum (in kg). This is the average amount multiplied by the total number of vehicles of that power train type produced during that year, $TA_i(T) = AC_i(T) \cdot N_i(T)$.
- $PT_i(T)$: Share of the power train type *i* as % of the total number of vehicles produced during production year *T*. This is the number of vehicles of that power train type divided by the total number of vehicle produced during year *T*.

A significant amount of **input data** is required to calculate the outputs described above. Below is a comprehensive table:

- Total amount of aluminum body and closure parts in light duty vehicles produced each year (in kg), $TA(T)$. This data is also broken down into sheet, extrusions, and castings for other modelling purposes, $MC_l^a(T)$ with $\sum_l MC_l^a(T) = TA(T)$.
- Total number of light duty vehicles assumed to be produced each year, $N(T)$ in #.
- For each year, the share of annually produced vehicles that are ICVs, $PT_{ICV}(T)$.
- For each year, the share of annually produced ICVs that are Gasoline ICVs.
- For each year, the share of annually produced vehicles that are HEVs, $PT_{HEV}(T)$.
- For each year, the share of annually produced HEVs that are Standard HEVs.

- The share of each vehicle class as % of the total number of vehicles produced in 2015, VC_{all}^{j} with *j* being the vehicle class.
- For each vehicle class *j*, the average amount of aluminum in vehicles produced in 2015 (in lbs).
- The vehicle class composition of HEVs produced in 2014, VC_{HEV}^{j}. Assumed to be constant over the modelling period and the same for Standard and Plug-in HEVs.
- The vehicle class composition of BEVs produced in 2014, VC_{BEV}^{j}. Assumed to be constant over the modelling period.

Eight different vehicle classes are considered. They are A/B, C, D, E, MPV, SUV, VAN, PUP. Calculating the average amount of body and closure aluminum per vehicle for each power train type is complicated by the fact that each power train type has a different composition of vehicle classes and vehicle classes differ in the amount of aluminum they contain.

The first step is to calculate $AC^{all}(T)$, the body and closure aluminum added to each average vehicle in production year *T*. This is done by dividing the total amount of body and closure aluminum added in year *T* by the total number of vehicles produced in year *T*. The results are in cells T55:T93. The next step is to express the amount of aluminum per 2015 vehicle for each vehicle class (in lbs/vehicle) relative to the amount of aluminum per 2015 vehicle across all vehicle classes (in lbs/vehicle), which was 398 pounds. The results are in cells L53:S53 and denote the amount of aluminum per vehicle class as percent of average amount of aluminum across all vehicles. Multiplying the added body and closure aluminum per vehicle and production year, $AC^{all}(T)$, with those ratios yields the added body and closure aluminum per vehicle and production year for each vehicle class, $AC^{j}(T)$. This data is stored in cells L55:S93. On more intermediate step needed to calculate the added body and closure aluminum per vehicle for each power train type and production year is to calculate the vehicle class composition for ICVs:

$$PT_{ICV}(T) \cdot VC_{ICV}^{j} + PT_{HEV}(T) \cdot VC_{HEV}^{j} + PT_{BEV}(T) \cdot VC_{BEV}^{j} = VC_{all}^{j}$$

$$\Rightarrow VC_{ICV}^{j}(T) = \frac{VC_{all}^{j} - PT_{HEV}(T) \cdot VC_{HEV}^{j} - PT_{BEV}(T) \cdot VC_{BEV}^{j}}{PT_{ICV}(T)}$$

with *j* being the vehicle class.

Since $PT_i(T)$ varies with each production year this calculation is repeated for each vehicle class *j* and each production year T. The results are stored in cells L110:S148.

Finally, the added body and closure aluminum per vehicle for each power train and production year, $AC_i(T)$, can be calculated:

$$AC_i(T) = \sum_j AC^j(T) \cdot VC_i^j(T)$$

Note that the calculated values are the same for Gasoline and Diesel ICVs, i.e. $AC_{ICV-G}(T) = AC_{ICV-D}(T) = AC_{ICV}(T)$, and for Standard and Plug-in Hybrids, i.e. $AC_{HEV-S}(T) = AC_{HEV-P}(T) = AC_{HEV}(T)$, since the vehicle class shares VC_i^j are assumed to be identical for the two ICV types and the two HEV types. The total amount of added body and closure aluminum as a function of power train and production year, $TA_i(T)$ is calculated as follows:

$$TA_i(T) = AC_i(T) \cdot N_i(T) = AC_i(T) \cdot PT_i(T) \cdot N(T)$$

Variable	Description	Location of data
$AC_i(T)$	Average amount of body and closure parts made from aluminum for powertrain type *i* and production year *T* (in kg/car)	B5:B43, E5:E43, H5:H43, K5:K43, N5:N43
$TA_i(T)$	Total amount of body and closure parts made from aluminum for powertrain type *i* and production year *T* (in kg)	C5:C43, F5:F43, I5:I43, L5:L43, O5:O43
$PT_i(T)$	Share of the power train type as % of the total number of vehicle produced during production year *T*	D5:D43, G5:G43, J5:J43, M5:M43, P5:P43

Table 1: Output data from the spreadsheet ‘Fleet composition’

3.2 Vehicle use

For each calendar year *t* of the modelling period (2012-2050), this spreadsheet calculates the total amount of GHG savings (in million kgCO2eq) that result from driving the mass-reduced vehicle fleet modeled on the spreadsheet ‘Fleet composition’. These total GHG savings per calendar year are reported in cells AO232:AO269. The total GHG savings in each calendar year *t* are a function of the age composition of the fleet during year *t*, i.e. how many vehicles of each production year *T* were in use. Each production year is characterized by the total number of vehicle produced, $N(T)$, and the total amount of aluminum closures and body parts, $TA(T)$, added to those vehicles. For each calendar year *t*, the total use phase GHG reductions are thus calculated as the sum of use phase GHG reductions from the vehicles of each production year *T*. The table of use phase GHG savings for each year of driving *t* and each year of vehicle production *T* is given in cells B232:AN269.

Use phase savings are calculated separately for each power train type, but the calculation process is identical. The starting point is the added amount of aluminum body and closure parts per vehicle, $AC_i(T)$, which is given in kg per vehicle. The first step is to calculate the resulting mass reductions per vehicle, $\Delta M_i(T)$, which are given in kg per vehicle and are calculated as

$$\Delta M_i(T) = AC_i(T) \cdot (1+s)\frac{(k-1)}{k}$$

With *k* being the material replacement coefficient of aluminum relative to steel (in kg aluminum/kg steel) and *s* being the secondary mass savings (in kg secondary mass savings/kg primary mass savings). The next step is to calculate the life time fuel and electricity savings per car, FS_i (in liters per car) and ES_i (in MJ per car), according to the following equations:

$$FS_i(T) = (1-EL) \cdot \Delta M_i(T) \cdot \Delta F_i(T) \cdot TM \cdot 0.0001$$

$$ES_i(T) = EL \cdot \Delta M_i(t) \cdot \Delta E_i(T) \cdot TM \cdot 0.0001$$

with *EL* being the share of life time driving powered by plug electricity (in %), $\Delta F_i(T)$ the fuel savings per mass savings (in liters per 100km driven and 100kg mass reduction), $\Delta E_i(T)$ the electricity savings per mass savings (in MJ per 100km driven and 100kg mass reduction), and TM the assumed vehicle life (in km). Life time fuel and electricity savings per vehicle are converted into lifetime GHG emissions savings per vehicle, $GHGS_i(T)$, according to this equation:

$$GHGS_i(T) = FS_i(T) \cdot GHG_f + ES_i(T) \cdot GHG_e$$

with GHG_f and GHG_e being the GHG intensities of the fuel and the electricity, in kg CO_2eq per liter and kg CO_2eq per MJ respectively. The final step in calculating the life time use phase GHG savings per power train type and production year is to multiply the life time use phase savings per car with the total number of vehicles of the given power train *i* being produced in each given production year *T*, i.e. $GHGS_i(T) \cdot N_i(T)$.

The calculations above require various additional input parameters, such as the material replacement coefficient *k*, the secondary mass savings coefficient *s*, the plug electricity share *EL*, the life time vehicle driving *TM*, the GHG intensities of fuel and electricity GHG_f and GHG_e, and finally the fuel and electricity savings per mass savings $\Delta F_i(T)$ and $\Delta E_i(T)$. The last two parameters can be modeled as time dependent but are currently assumed to be constant over time, i.e. $\Delta F_i(T) = \Delta F_i$ and $\Delta E_i(T) = \Delta E_i$. For each power train type the energy savings per mass savings are calculated from a set of input parameters. Energy savings per mass savings are significantly higher in the case that the power train of the vehicle is resized, i.e. optimized to the new, reduced vehicle mass. However, this is not always feasible or cost-effective. Also, fuel consumption models show that energy savings per mass savings vary across power train types and vehicle classes. For this reason, they are calculated as follows for each power train type *i*:

$$\Delta F_i = RE \cdot Avg\left(\Delta F_{i,re}^j\right) + (1 - RE) \cdot Avg\left(\Delta F_{i,no-re}^j\right)$$

$$\Delta E_i = RE \cdot Avg\left(\Delta E_{i,re}^j\right) + (1 - RE) \cdot Avg\left(\Delta E_{i,no-re}^j\right)$$

where *RE* is the fraction of power train resizing benefit that mass-reduced vehicles can realize on average, superscript *j* denotes the vehicle class, and subscripts *re* and *no-re* stand for resizing and no-resizing, respectively. The average is calculated over the input values for the different vehicle classes (the yellow cells on the spreadsheet in columns J to V). Different numbers of vehicle classes may be used to characterize different power trains.

$GHGS(T)$ are the lifetime GHG use phase savings from all vehicles produced in year *T* and calculated as follows:

$$GHGS(T) = \sum_i GHGS_i(T) \cdot N_i(T)$$

These values need to be converted into the GHG use phase savings that occur during each calendar year of the modeling period. The first step is to convert the lifetime savings into annual savings according to the following equation:

$$AS(T,t) = \begin{cases} FIU(t) \cdot \dfrac{GHGS(T)}{lifetime} & for\ T < t \\ 0 & for\ T \geq t \end{cases}$$

where *lifetime* is the average lifetime of each vehicle (assumed to be constant across time and all vehicles), and *FIU(t)* is the fraction of vehicles still in use after *t* years of driving. *FIU(t)* is defined as $FIU(t) = 1 - lognormal(lifetime, SD)$, with *lifetime* as the mean and an additional parameter *SD*, the standard deviation. The total GHG use phase savings in each calendar year is now calculated as the sum of all annual savings across all production years:

$$GHGS(t) = \sum_{T} AS(T,t)$$

In the model, vehicles are being produced every year of the modeling period (2012-2050). This means that not all vehicles will reach the end of their lives and as a result the use phase savings accruing during the modeling period are smaller than the sum of the lifetime savings of all cars produced during the modeling period, i.e. the following inequality holds:

$$\sum_{t} GHGS(t) < \sum_{T} GHGS(T)$$

Variable	Description	Location of data
$GHGS(t)$	Total GHG use phase savings per calendar year t (in million kg CO_2eq)	AO232:AO269

Table 2: Output data from spreadsheet 'Vehicle use"

3.3 Material production

The aim of this spreadsheet is to calculate all changes in GHG emissions from material production, both for the added aluminum and the removed steel. The spreadsheet calculates and tallies all direct emission changes, i.e. it reflects to what extent the added aluminum and removed steel come from primary or secondary production. In other words, the results on this spreadsheet reflect the recycled content of the added and removed material. The implications of changes in scrap input and output are calculated on two separate, dedicated spreadsheets.

The starting point for calculating the changes in production GHGs from the added aluminum are the total amount of aluminum body and closure parts added to light duty vehicles produced each year (in million kg), broken down into sheet, extrusions, and castings. The three time series are denoted by $MC_l^a(t)$, with subscript *l* standing for sheet, extrusions, and castings. The first calculation step is to convert the aluminum contained in the vehicles as body and closure parts into shipped primary and secondary aluminum, denoted by $SM_l^{pa}(t)$ and $SM_l^{sa}(t)$, where superscript *pa* stands for primary aluminum and *sa* for secondary aluminum. The calculations are as follows:

$$SM_l^{pa}(t) = \left(1 - RC_l^a(t)\right) \cdot \frac{MC_l^a(t)}{\gamma_l^a}$$

$$SM_l^{sa}(t) = RC_l^a(t) \cdot \frac{MC_l^a(t)}{\gamma_l^a}$$

where $RC_l^a(t)$ is the recycled (secondary) content of aluminum type *l* in production year *t*, and γ_l^a is the manufacturing yield of aluminum type *l*. The results of these calculations are also in million kg and stored in cells B6:G44. The next step is to calculate the resulting production GHG emissions for each aluminum type by multiplying the shipped material quantities with the GHG intensities of aluminum production:

$$GHGP_l^{pa}(t) = SM_l^{pa}(t) \cdot \left(GHG_{ingot}^{pa}(t) + GHG_l^a\right)$$

$$GHGP_l^{sa}(t) = SM_l^{sa}(t) \cdot \left(GHG_{ingot}^{sa} + GHG_l^a\right)$$

where GHG_{ingot}^{pa} and GHG_{ingot}^{sa} are the GHG intensities of primary and secondary aluminum ingot production and GHG_l^a the GHG intensities of aluminum ingot rolling, extruding, and casting. The final step is to sum over all aluminum types *l* in order to calculate the GHG emissions that result from increases in aluminum production and forming in any given production year:

$$GHGP^a(t) = \sum_l \left(GHGP_l^{pa}(t) + GHGP_l^{sa}(t)\right)$$

The changes in GHG emissions due to increased aluminum production $GHGP^a(t)$ are stored in cells R6:R44. Calculating the changes in production GHGs from the removed steel has the same computational structure, once the total amount of removed steel has been determined. The latter is complicated somewhat by the fact that it needs to account for both primary and secondary mass savings and the different steel types *l*, which are flat, long, and cast. The total amount of steel type *l* removed from all vehicles produced in year *t* is calculated as follows:

$$MC_l^s(t) = -\frac{TA(t)}{k} \cdot pf_l - \frac{TA(t)}{k}(1-k) \cdot s \cdot sf_l$$

where $TA(t)$ is the total amount of aluminum body and closure parts added to the vehicles produced in year *t*, *k* is the material replacement coefficient of aluminum relative to steel (in kg aluminum/kg steel), *s* is the secondary mass savings coefficient (in kg secondary mass savings/kg primary mass savings), and pf_l and sf_l are the fractions of primary and secondary mass savings that are of steel type *l*. Note that $TA(t) = \sum_l MC_l^a(t)$ and is one of the central data inputs into the model. The subsequent calculation steps are the same as for the added aluminum. First, the amount of no longer shipped primary and secondary steel, $SM_l^{ps}(t)$ and $SM_l^{ss}(t)$, is calculated:

$$SM_l^{ps}(t) = \left(1 - RC_l^s(t)\right) \cdot \frac{MC_l^s(t)}{\gamma_l^s}$$

$$SM_l^{ss}(t) = RC_l^s(t) \cdot \frac{MC_l^s(t)}{\gamma_l^s}$$

where $RC_l^s(t)$ is the electric arc furnace (EAF) content of steel type *l* in production year *t*, and γ_l^s is the manufacturing yield of steel type *l*. The next step is to calculate the avoided production GHG emissions for each steel type by multiplying the no longer shipped material quantities with the GHG intensities of steel production:

$$GHGP_l^{ps}(t) = SM_l^{ps}(t) \cdot \left(GHG_{ingot}^{ps} + GHG_l^s\right)$$

$$GHGP_l^{ss}(t) = SM_l^{ss}(t) \cdot \left(GHG_{ingot}^{ss} + GHG_l^s\right)$$

where GHG_{ingot}^{ps} and GHG_{ingot}^{ss} are the GHG intensities of primary and secondary steel ingot production and GHG_l^s the GHG intensities of steel ingot rolling and casting. The final step is to add over all steel types *l* in order to calculate the GHG emissions that result from reductions in steel production and forming in any given production year:

$$GHGP^s(t) = \sum_l \left(GHGP_l^{ps}(t) + GHGP_l^{ss}(t)\right)$$

The changes in GHG emissions due to reduced steel production $GHGP^s(t)$ are stored in cells R52:R90.

There are three different ways in which recycled content is modeled for aluminum. The first models recycling as an open loop, which means that scrap inputs and outputs are independent from each other and modeled exogenously. In this case the recycled content of aluminum sheet, extrusions, and castings is given through time-dependent input values, which means that recycled content could be different every year. In the default setting the values are assumed to be constant over time and are set to zero for the recycled content of sheet and extrusions, and 0.85 for the recycled content of castings. This open loop methodology is the only way available to model the EAF fraction for flat, long, and cast steel. In the default setting the EAF fractions are assumed to be constant over time and are set to 5% for flat, 85% for long, and 100% for cast steel. As with all input variables, the values can be changed by the model user. The other two approaches available for aluminum model recycling as a closed loop, i.e. the scrap inputs into production of aluminum body and closure parts come from scrap generated within the modeled North American light duty vehicle life cycles. In option one of the closed-loop model, only production scrap is used in a closed loop, i.e. for aluminum body and closure production; the scrap at vehicle end-of-life is still recycled externally, i.e. in an open loop. The calculations for shipped primary and secondary aluminum are now as follows:

$$SM_l^{sa}(t) = \frac{ProS_l^a(t)}{s_r^a}$$

$$SM_l^{pa}(t) = \frac{MC_l^a(t)}{\gamma_l^a} - SM_l^{sa}(t)$$

where $ProS_l^a(t)$ is the amount of prompt scrap of aluminum type *l* generated and collected during calendar/production year *t*, and s_r^a is the amount of scrap used to produce one kg of recycled (secondary) aluminum ingot. In option two of the closed-loop model, production and end-of-life scrap is used in a closed loop, i.e. for aluminum body and closure production. The calculations for shipped primary and secondary aluminum change to the following:

$$SM_l^{sa}(t) = \frac{ProS_l^a(t) + EolS_l^a(t)}{s_r^a}$$

$$SM_l^{pa}(t) = \frac{MC_l^a(t)}{\gamma_l^a} - SM_l^{sa}(t)$$

where $EolS_l^a$ is the amount of end-of-life (eol) scrap of aluminum type *l* generated and collected during calendar/production year *t*.

Variable	Description	Location of data
$GHGP^a(t)$	GHG emission changes from increases in aluminum production and forming in calendar year *t* (in million kg CO_2eq)	R6:R44
$GHGP^s(t)$	GHG emission changes from reductions in steel production and forming in calendar year *t* (in million kg CO_2eq)	R52:R90

Table 3: Output data from spreadsheet ‘Material production’

3.4 Scrap at production

Changing the material composition of North American light duty vehicles produced between 2012 and 2050 changes the quantities and types of scrap that are generated during vehicle production. The aim of this spreadsheet is to calculate the GHG implications of changes in the use and generation of scrap during material production and forming. In rows 2 to 45 this is done for aluminum, and in rows 48 to 90 it is done for steel.

For aluminum, the starting point is the total amount of aluminum body and closure parts in light duty vehicles produced each year (in million kg), broken down into sheet, extrusions, and castings, i.e. $MC_l^a(t)$, with subscript *l* standing for sheet, extrusions, and castings. These values are turned into amounts of generated and collected production scrap as follows:

$$ProS_l^a(t) = c_{pro}^a \cdot \frac{(1-\gamma_l^a)}{\gamma_l^a} \cdot MC_l^a(t)$$

where c_{pro}^a is the production scrap collection rate for aluminum and γ_l^a is the forming yield of aluminum type *l*.

The next step depends on which recycling model is chosen for aluminum production scrap. If closed-loop recycling is selected, the values for collected production scrap, $ProS_l^a(t)$, are forwarded to the 'Material production' spreadsheet and used to calculate the recycled content of the aluminum body and closure parts in North American light vehicle production (see Section 3.3). If open-loop recycling is selected, the first step is to calculate the scrap input into vehicle production according to this equation:

$$SIn_l^a(t) = \left(s_p^a \cdot \left(1 - RC_l^a(t)\right) + s_r^a \cdot RC_l^a(t)\right) \cdot \frac{MC_l^a(t)}{\gamma_l^a}$$

where s_p^a the scrap input into primary aluminum production (in kg/kg), s_r^a the scrap input into secondary (recycled) aluminum production (in kg/kg), and $RC_l^a(t)$ is the exogenously given recycled (secondary) content of aluminum type *l* used in body and closure parts in production year *t*. The second step is to calculate the net change in external secondary aluminum production caused by the net scrap flow into or out of vehicle production according to the following equation:

$$\alpha_a \cdot \frac{ProS_l^a(t) - SIn_l^a(t)}{s_r^a - \beta_a \cdot s_p^a}$$

where α_a models the response of the aluminum scrap market to a change in automotive aluminum scrap generation and use, and β_a models the response of external primary aluminum production to a change in external secondary aluminum production. A detailed explanation of those two parameters and the equation above can be found in Section 4. The penultimate step of the open-loop recycling model is to calculate the GHG implications of the net change in external secondary aluminum production:

$$GHGProS_l^a(t) = \alpha_a \cdot \frac{ProS_l^a(t) - SIn_l^a(t)}{s_r^a - \beta_a \cdot s_p^a}\left(GHG_{ingot}^{sa} - \beta_a \cdot GHG_{ingot}^{pa}(t)\right)$$

In the final step, the total external GHG implications due to changes in aluminum scrap use and generation during material production and forming are calculated by summing over aluminum sheet, extrusions, and castings:

$$GHGProS^a(t) = \sum_l GHGProS_l^a(t)$$

For steel, the calculations are identical to the open-loop recycling calculations for aluminum. Here, the starting point is the amount of steel removed from the vehicles, $MC_l^s(t)$, which has been calculated in the 'Material production' spreadsheet. These values are converted into amounts of production scrap no longer generated and collected, $ProS_l^s(t)$, and amounts of steel scrap no longer used into vehicle production, $SIn_l^s(t)$:

$$ProS_l^s(t) = c_{pro}^s \cdot \frac{(1 - \gamma_l^s)}{\gamma_l^s} \cdot MC_l^s(t)$$

$$SIn_l^s(t) = \left(s_p^s \cdot (1 - RC_l^s) + s_r^s \cdot RC_l^s\right) \cdot \frac{MC_l^s(t)}{\gamma_l^s}$$

where c_{pro}^s is the collection rate for steel production scrap, γ_l^s is the forming yield of steel type *l*, RC_l^s is the secondary content of steel type *l*, s_p^s is the scrap input into primary steel production (in kg/kg), and s_r^s is the scrap input into secondary steel production (in kg/kg). The net change in external secondary steel production is now calculated as follows:

$$\alpha_s \cdot \frac{ProS_l^s(t) - SIn_l^s(t)}{s_r^s - \beta_s \cdot s_p^s}$$

where α_s models the response of the steel scrap market to a change in automotive steel scrap generation and use, and β_s models the response of external primary steel production to a change in external secondary steel production. As in the case of aluminum production scrap, the last two steps are to calculate and aggregate the GHG implications of the net change in external secondary steel production:

$$GHGProS_l^s(t) = \alpha_s \cdot \frac{ProS_l^s(t) - SIn_l^s(t)}{s_r^s - \beta_s \cdot s_p^s}\left(GHG_{ingot}^{ss} - \beta_s \cdot GHG_{ingot}^{ps}(t)\right)$$

$$GHGProS^s(t) = \sum_l GHGProS_l^s(t)$$

Variable	Description	Location of data
$GHGProS^a(t)$	GHG changes due to changes in external use of aluminum production scrap in calendar year t (in million kg CO_2eq)	R6:R44
$GHGProS^s(t)$	GHG changes due to changes in external use of steel production scrap in calendar year t (in million kg CO_2eq)	R51:R89

Table 4: Output data from spreadsheet 'Scrap at production"

3.5 Scrap at end-of-life

Changing the material composition of the vehicles produced between 2012 and 2050, means that the quantities of end-of-life aluminum and steel scrap change when these vehicles reach the end of their lives. The aim of this spreadsheet is to calculate the GHG implications of these changes in automotive end-of-life scrap generation, collection, and recycling.

The main data input into this spreadsheet is the total amount of aluminum body and closure parts added to the vehicles produced in year T, $TA(T) = \sum_l MC_l^a(T)$, and the amount of steel removed from all vehicles produced in year T, $TS(T) = \sum_l MC_l^s(T)$. The first step is to calculate the changes in end-of-life scrap generated and collected in calendar year t, taking into account the lifetime distribution of the vehicles. For aluminum and steel the calculations are identical and as follows:

$$EolS^a(t) = c_{eol}^a \cdot ssr_{eol}^a \cdot \sum_{T=2012}^{t-1} TA(T) \cdot \left(FIU(T-t-1) - FIU(T-t)\right)$$

$$EolS^s(t) = c_{eol}^s \cdot ssr_{eol}^s \cdot \sum_{T=2012}^{t-1} TS(T) \cdot \left(FIU(T-t-1) - FIU(T-t)\right)$$

where c_{eol}^a and c_{eol}^s are the end-of-life collection rates for aluminum and steel scrap, ssr_{eol}^a and ssr_{eol}^s are the shredder separation rates for end-of-life aluminum and steel scrap. $FIU(T-t)$ is the fraction of vehicles still in use after $T-t$ years of driving, and $FIU(T-t-1)$ is the fraction of vehicles still in use after $T-t-1$ years of driving (see also Section 3.2). Therefore, $\left(FIU(T-t-1)-FIU(T-t)\right)$ is the fraction of vehicles that reach end of life during calendar year $T-t$.

If closed-loop recycling is selected for the end-of-life aluminum scrap, $EolS^a(t)$ is broken out into sheet, extrusions, and castings, $EolS_i^a(t)$, forwarded to the 'Material production' spreadsheet, and used to calculate the recycled content of the aluminum body and closure parts in North American light vehicle production (see Section 3.3).

If open-loop recycling is selected for end-of-life aluminum scrap, $EolS^a(t)$ is recycled externally and has the following GHG implications:

$$GHGEolS^a(t) = \alpha_a \cdot \frac{EolS^a(t)}{s_r^a - \beta_a \cdot s_p^a}\left(GHG_{ingot}^{sa} - \beta_a \cdot GHG_{ingot}^{pa}(t)\right)$$

where α_a models the response of the aluminum scrap market to a change in automotive aluminum scrap generation and use, and β_a models the response of external primary aluminum production to a change in external secondary aluminum production. The open-loop model used to calculate the GHG consequences of changes in end-of-life scrap flows is the same as the one used for changes in prompt scrap flows. A detailed explanation of the two central model parameters, α and β, can be found in Section 4. Other parameters used in the calculation above are the GHG intensities of primary and secondary aluminum ingot production (in $kgCO_2eq/kg$), GHG_{ingot}^{pa} and GHG_{ingot}^{sa}, and the scrap input into primary and secondary (recycled) aluminum production (in kg/kg), s_p^a and s_r^a.

The changes in end-of-life steel scrap are always modeled in an open loop. The GHG implications of reducing the amount of end end-of-life steel scrap are calculated as follows:

$$GHGEolS^s(t) = \alpha_s \cdot \frac{EolS^s(t)}{s_r^s - \beta_s \cdot s_p^s}\left(GHG_{ingot}^{ss} - \beta_s \cdot GHG_{ingot}^{ps}(t)\right)$$

where α_s models the response of the steel scrap market to a change in automotive steel scrap generation and use, and β_s models the response of external primary steel production to a change in external secondary steel production. Other parameters used in the calculation above are the GHG intensities of primary and secondary steel ingot production (in $kgCO_2eq/kg$), GHG_{ingot}^{ps} and GHG_{ingot}^{ss}, and the scrap input into primary and secondary (recycled) steel production (in kg/kg), s_p^a and s_r^a.

Variable	Description	Location of data
$GHGEolS^a(t)$	GHG changes due to changes in external use of end-of-life aluminum scrap in calendar year t (in million kg CO_2eq)	O5:O43
$GHGEolS^s(t)$	GHG changes due to changes in external use of end-of-life steel scrap in calendar year t (in million kg CO_2eq)	M5:M43

Table 5: Output data from spreadsheet ‘Scrap at end-of-life”

4 Appendix A: Consequential system expansion

The reference flow of this CLCA is an increasing replacement of steel with aluminum in body and closure parts used in North American light vehicle production between 2012 and 2050. Such a change in automotive material composition causes changes in scrap flows into and out of the vehicle life cycles. If automotive scrap recycling is modeled in a closed loop, the changes in scrap input to automotive material production are equal to the changes in automotive production or end-of-life scrap generation, and there is thus no need to expand the system boundaries beyond the modeled vehicle life cycles. If production or end-of-life scrap recycling are modeled in an open loop, however, system expansion is required to describe the consequences of these scrap flow changes.

Specifically, the system boundaries are expanded to include the impact of automotive scrap flow changes on the external scrap market and the impact of the external scrap market changes on external secondary and primary steel and aluminum production. External here means scrap recycling and metal production outside of the modeled vehicle life cycles. Flows of automotive scrap out of or into the scrap market change at two separate times in the life cycles of the modeled vehicles; during vehicle production and during vehicle end-of-life management (scrapping). Figure 8 shows the system expansion during vehicle production. Note that scrap flow changes can be positive or negative. The arrows in Figure 8 indicate positive flow changes.

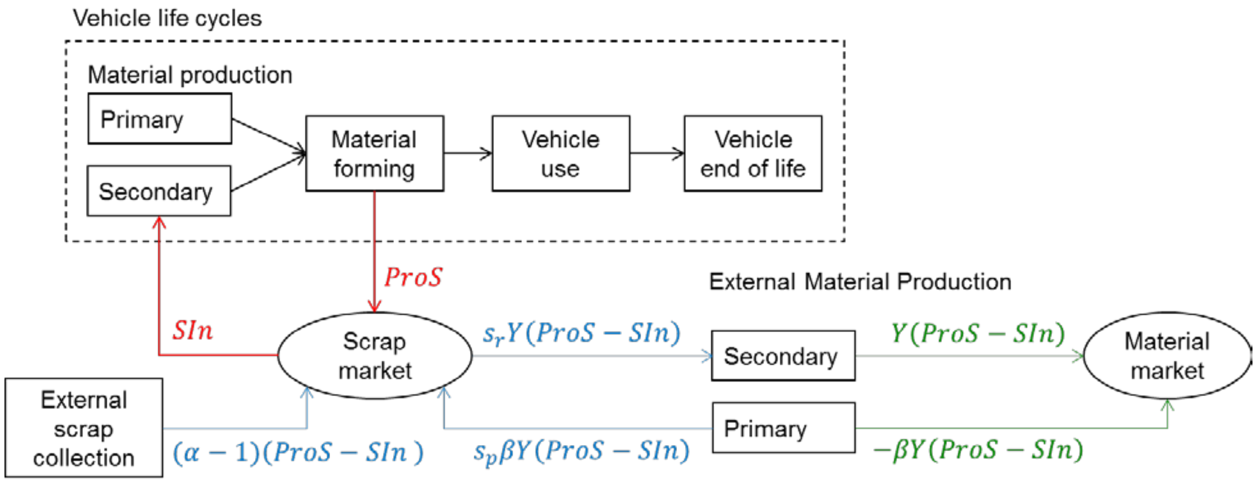

Figure 8: Consequential system expansion for scrap input to and output from automotive material production and forming

In the open loop recycling scenario, changes in automotive material composition cause changes in scrap input to material production, SIn, and scrap output from material forming, $ProS$. Since it is assumed that scrap stocks are constant in the long run, the scrap market can respond to the net change in scrap flow, $SIn - ProS$, by changing external scrap collection or changing external scrap consumption, i.e. recycling. The parameter $\alpha \in [0; 1]$ quantifies the impact the net change $SIn - ProS$ has on external scrap collection. For example, an increase in scrap supply by one unit increases external scrap collection by $(\alpha - 1)$ units.

The impact of $SIn - ProS$ on external recycling is slightly more complicated if primary material production also consumes production or end-of-life scrap, as is the case with steel. This creates an additional scrap flow, which creates a feedback loop between the material market and the scrap market as shown in Figure 8 and Figure 9. In general, a change in external recycling impacts the production of the equivalent primary material since they compete with each other on the material market. The response of primary production to changes in external recycling (secondary production) is quantified by the parameter $\beta \in [0; 1]$. For example, an increase in external secondary production by one unit decreases external primary production by β units.

The assumption that all scrap flow changes balance, i.e. stocks are constant in the long run, means that the interim parameter Y can be calculated by balancing all scrap flows, as shown in the equation below:

$$ProS + (\alpha - 1)(ProS - SIn) + s_p\beta Y(ProS - SIn) = SIn + s_r Y(ProS - SIn)$$

$$\Rightarrow Y = \frac{\alpha}{s_r - s_p\beta}$$

where s_p is the scrap input into primary production (in kg/kg) and s_r the scrap input into secondary (recycled) production (in kg/kg). In the case of aluminum, $s_p^a = 0$, which simplifies the system expansion. Figure 9 shows the consequential system expansion model during vehicle end-of-life management, i.e. scrapping. The modeling approach is identical, and the scrap balance equation therefore yields the identical result for the interim parameter Y:

$$EolS + (\alpha - 1)EolS + s_p\beta YEolS = s_r YEolS$$

$$\Rightarrow Y = \frac{\alpha}{s_r - s_p\beta}$$

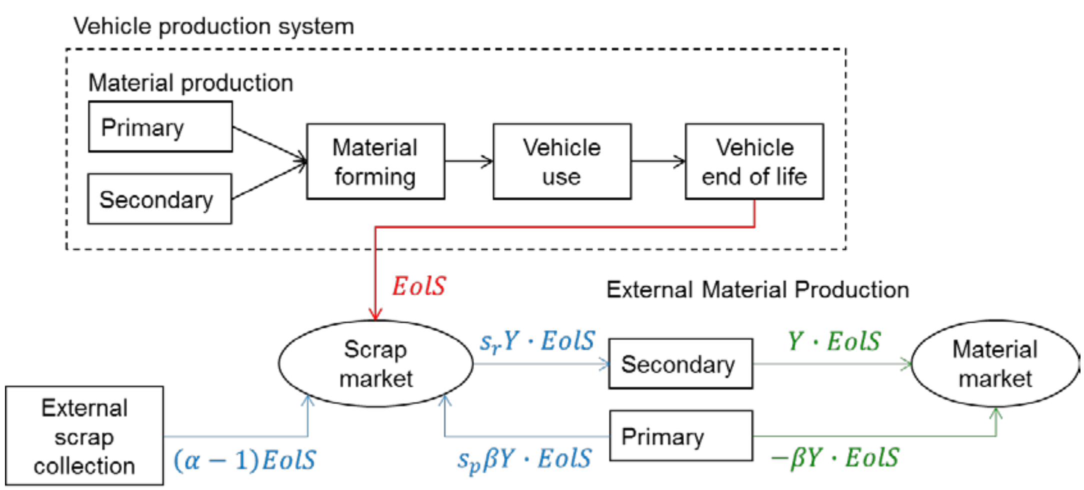

Figure 9: Consequential system expansion for scrap output from vehicle end-of-life management

The final step in the system expansion is to calculate the changes in GHG emissions that are caused by the changes in external secondary and primary production. For the changes in scrap input to and output from automotive material production and forming they are calculated as follows:

$$GHGProS_l^{sx}(t) = \alpha_s \cdot \frac{ProS_l^x(t) - SIn_l^x(t)}{s_r^x - \beta_x \cdot s_p^x}\left(GHG_{ingot}^{sx} - \beta_x \cdot GHG_{ingot}^{px}(t)\right)$$

where *x* indicates the material and *l* the material type. GHG_{ingot}^{sx} and GHG_{ingot}^{px} are the GHG intensities of primary and secondary ingot production. The equation above is used on the spreadsheet 'Scrap at production' if open loop recycling is chosen for production scrap (see Section 3.4). For the changes in end-of-life scrap generation the GHG implications are calculated as follows:

$$GHGEolS^x(t) = \alpha_x \cdot \frac{EolS^x(t)}{s_r^x - \beta_x \cdot s_p^x}\left(GHG_{ingot}^{sx} - \beta_x \cdot GHG_{ingot}^{px}(t)\right)$$

The equation above is used on the spreadsheet 'Scrap at end-of-life' if open loop recycling is chosen for end-of-life scrap (see Section 3.5). If α is set to zero, the two expressions above are also zero. This is the CLCA equivalent to the recycled content approach in ALCA, which ignores scrap inputs to and outputs from the studied product system. If α and β are both set to one, the two expressions above are identical to the avoided burden approach in ALCA, which also goes under the names of 'closed loop approximation method', '0/100 method', 'end-of-life approach', 'substitution method', and occasionally even simply 'system expansion'. Using the parameters α and β allows the user of the CLCA model to study the impact of different scrap and material market dynamics in great detail. Unfortunately, there is currently no research available that allows for a scientifically sound selection of parameter values.

5 Appendix B: Default input data

This section contains the default input data. While the default input data has been carefully selected, its main purpose is to illustrate how the model works rather than to generate definitive results. Model users are highly encouraged to use their own input data and also study the sensitivity of the model results to changes in input data values. Firm conclusions about the GHG impacts of a wide-spread diffusion of aluminum into North American light duty vehicle production can only be done in studies where the representativeness of the default data and parameters are well established and adequate range and sensitivity analyses are conducted.

5.1 Results & data input spreadsheet

Table 1: General input data

Parameter	Value	Source
Material replacement coefficient (aluminum to steel)	0.65	SMDI 2016
Flat steel fraction of total replaced steel	0.9	Geyer 2013
Secondary mass savings coefficient	0.2	SMDI 2016
Flat share of secondary mass savings	0.4	Geyer 2013
Long share of secondary mass savings	0.3	Geyer 2013

Table 2: Aluminum recycling parameters

Parameter	Value	Source
Scrap input to primary production	0	IAI 2007
Scrap input to secondary production	1.048	SMDI 2016
Prompt scrap collection rate	0.99	Geyer 2013
EOL scrap collection rate	0.97	Geyer 2013
Shredder separation rate	0.9	Geyer 2013
Alpha	0.9	Geyer 2013, 2015
Beta	1	Geyer 2013, 2015

Table 3: Steel recycling parameters

Parameter	Value	Source
Scrap input to primary production	0.209	SMDI 2016
Scrap input to secondary production	1.05	WSA 2010
Prompt scrap collection rate	0.99	Geyer 2013
EOL scrap collection rate	0.97	Geyer 2013
Shredder separation rate	0.98	Geyer 2013
Alpha	0.9	Geyer 2013, 2015
Beta	1	Geyer 2013, 2015

Table 4: GHG intensities of aluminum production and forming (in $kgCO_2eq/kg$ output)

Process	GHG intensity	Source
Primary ingot (North America) (cradle-to-gate)	8.937	TAA 2013
Secondary ingot (cradle-to-gate)	1.23	SMDI 2016
Rolled aluminum (ingot-to-gate, aluminum rolling)	0.589	thinkstep 2015 (PE, EU 27)
Extruded aluminum (ingot-to-gate, aluminum extrusion)	0.689	thinkstep 2015 (PE, EU 27)
Cast aluminum (ingot-to-gate, aluminum casting)	0.590	thinkstep 2015 (PE, DE)

Table 5: GHG intensities of steel production and forming (in $kgCO_2eq/kg$ output)

Process	GHG intensity	Source
BF/BOF slab	1.870	WSA 2010
EAF slab (slab-to-gate)	0.399	WSA 2010
Flat steel (slab-to-gate)	0.485	WSA 2010
Long steel (gate-to-gate, steel rolling)	0.290	WSA 2010
Cast steel (gate-to-gate, steel casting)	0.135	WSA 2010

Table 6: Vehicle use phase parameters

Parameter	Value	Unit	Source
NCV of gasoline	32.27	MJ/liter	thinkstep 2015 (PE, EU27)
GHG intensity of gasoline production (cradle-to-gate, at gas station))	15.50	gCO2eq/MJ	thinkstep 2015 (PE, EU27)
GHG intensity of gasoline combustion (gate-to-gate, combustion in light duty vehicle)	72	gCO2eq/MJ	thinkstep 2015 (PE, GLO)
NCV of diesel	36.00	MJ/liter	thinkstep 2015 (PE, EU27)
GHG intensity of diesel production (cradle-to-gate, at gas station))	7.74	gCO2eq/MJ	thinkstep 2015 (PE, EU27)
GHG intensity of diesel combustion (gate-to-gate, combustion in light duty vehicle)	75	gCO2eq/MJ	thinkstep 2015 (PE, GLO)
GHG intensity of electricity production (cradle-to-gate, U.S. average, at consumer)	0.278	kgCO2eq/MJ	thinkstep 2015 (PE, US)
Share of plug electricity as energy source	0.5	%	Geyer 2013
Vehicle lifetime driving	245,000	km	SMDI 2016
Mean vehicle lifetime	12	years	SMDI 2016
Standard deviation of vehicle lifetime	2	years	Estimate

Table 7: Forming yields

Material	Yield	Source
Aluminum, Sheet	0.52	Geyer 2014
Aluminum, Extrusion	0.8	Geyer 2013
Aluminum, Castings	0.8	Geyer 2013
Steel, Flat	0.55	Geyer 2014
Steel, Long	0.75	Geyer 2013
Steel, Castings	0.8	Geyer 2013

Table 8: Primary aluminum ingot production GHGs
(Sources: Hao 2015, Thinkstep 2015, IAI 2014, SMDI 2016)

Year	Imported Al kgCO2/kg	% Imported
2012	16.59	0.20
2013	16.45	0.24
2014	16.30	0.28
2015	16.15	0.32
2016	16.01	0.36
2017	15.86	0.40
2018	15.72	0.44
2019	15.58	0.48
2020	15.44	0.52
2021	15.30	0.56
2022	15.17	0.60
2023	15.03	0.64
2024	14.90	0.68
2025	14.76	0.72
2026-2050	14.76	0.72

5.2 Fleet Composition

Table 9: Light duty vehicle production forecast (Source: Ducker 2015 p. 55)

Year	# of Vehicles
2012	16,181,282
2013	16,200,000
2014	16,752,614
2015	17,500,000
2016	17,323,946
2017	17,609,612
2018	17,900,000
2019	18,180,944
2020	18,200,000
2021	18,752,277
2022	19,000,000
2023	19,323,609
2024	19,609,275
2025-2050	20,000,000

The resulting cumulative light duty vehicle production between 2012 and 2015 is therefore 752,533,558, i.e. just over 750 million cars.

Table 10: Powertrain type inputs (Source: Ducker 2015 p. 21 & 22)

Year	ICV Share	Gasoline Share of ICV	Hybrid Share	Standard Share of Hybrid
2012	0.982	0.932	0.018	0.500
2013	0.976	0.931	0.024	0.500
2014	0.972	0.935	0.026	0.500
2015	0.965	0.936	0.034	0.500
2016	0.952	0.932	0.046	0.500
2017	0.947	0.931	0.050	0.500
2018	0.938	0.932	0.057	0.500
2019	0.924	0.931	0.070	0.500
2020	0.913	0.934	0.081	0.500
2021	0.909	0.932	0.084	0.500
2022	0.900	0.931	0.092	0.500
2023	0.892	0.932	0.100	0.500
2024	0.883	0.931	0.108	0.500
2025	0.874	0.934	0.110	0.500
2026-2050	0.870	0.934	0.110	0.500

Table 11: Projected amount of aluminum body & closure parts in North American light vehicle production (Source: Ducker 2014 p. 20)

Year	Sheet (million kg)	Extrusions (million kg)	Castings (million kg)
2012	81.9	0.0	0.0
2013	100.3	7.3	0.0
2014	200.5	12.7	1.8
2015	420.9	20.0	18.2
2016	592.2	32.8	23.7
2017	681.6	38.2	27.3
2018	738.1	41.9	29.1
2019	878.4	56.4	29.1
2020	1,078.8	69.2	45.5
2021	1,228.2	80.1	45.5
2022	1,303.0	81.9	65.5
2023	1,419.7	87.4	74.6
2024	1,640.1	111.0	78.3
2025	1,707.6	112.9	85.6
2026	1,755	114	91
2027	1,778	115	93
2028-2050	1,790	115	95

Table 12: Vehicle class data

Class	lbs of aluminum	NA LDV fleet share	HEV share	BEV share
Source	**Ducker 2014 p. 9**		**ANL 2014**	
A/B	251.60	0.03	0.09	0.18
C	273.90	0.17	0.35	0.51
D	363.30	0.21	0.42	0.31
E	546.90	0.03	0.11	0.00
MPV	396.50	0.04	0.00	0.00
SUV	410.30	0.33	0.02	0.01
VAN	273.20	0.02	0.00	0.00
PUP	548.90	0.17	0.00	0.00

5.3 Vehicle Use

Table 13: Energy and Electricity savings per mass savings with and without powertrain resizing (Source: FKA 2011)

		No powertrain resizing (MJ/100km100kg)			Powertrain Resizing (MJ/100km100kg)		
PT type	**Fuel**	**Compact**	**Midsize**	**SUV**	**Compact**	**Midsize**	**SUV**
ICEV-G	Gasoline	3.586	2.981	3.406	8.034	10.374	9.331
ICEV-D	Diesel	3.405	2.739	3.415	6.421	8.584	7.260
HEV-S	Gasoline	2.994	3.329	2.927	4.998	6.324	6.409
HEV-P	Gasoline	3.856	4.146	n/a	4.291	4.964	n/a
HEV-P	Electricity	1.434	1.349	n/a	1.516	1.490	n/a
BEV	Electricity	1.381	1.515	n/a	1.407	1.495	n/a

Note: Values could be varied over time, i.e. entered as time series

6 Appendix C: Default results and interpretation

While the default input data has been carefully selected, its main purpose is to illustrate how the model works rather than to generate definitive results. Model results are very sensitive to some input parameters and less so to others. Sensitivity analysis of the model is outside of the scope of this study, which is exclusively about computational structure and model methodology. Firm conclusions about the GHG impacts of a wide-spread diffusion of aluminum into North American light duty vehicle production can only be done in studies where the representativeness of the default data and parameters are well established and adequate range and sensitivity analyses are done.

The main objective of this report section is to explain how the results are displayed on the spreadsheet ‘Results and data input’ and should thus be interpreted. The example chosen for this task are the results generated by the default input data. As explained in Section 1.6, the focus of the CLCA model is to generate plausible scenarios rather than one authoritative solution of the research question. This focus reflects the significant uncertainties inherent in consequential analysis in general and in particular the one reported here. For every year of the study period (2012-2050) the seven GHG emission changes introduced in Section 2 and explained in Section 3 are reported:

Variable name	GHG emission change due to change in	Location
$GHGP^a(t)$	automotive aluminum production and forming	B5-B43
$GHGP^s(t)$	automotive steel production and forming	C5-C43
$GHGS(t)$	fuel combustion and fuel and drive electricity production	D5-D43
$GHGProS^a(t)$	aluminum production scrap generation and open-loop recycling	E5-E43
$GHGProS^s(t)$	steel production scrap generation and open-loop recycling	F5-F43
$GHGEolS^a(t)$	aluminum end-of-life scrap generation and open-loop recycling	G5-G43
$GHGEolS^s(t)$	steel scrap end-of-life generation and open-loop recycling	H5-H43

Table 6: For every year of the study period (2012-2050) these seven GHG changes are reported on the ‘Results & data input’ spreadsheet

A positive GHG emission value means that GHG emissions increase due to the modeled changes, a negative value indicates a GHG emission decrease. In addition to the results explained in Table 6, the annual net GHG emission changes are calculated as $GHGA(t) = \sum_{m=a,s} GHGP^m(t) + GHGS(t) + GHGProS^m(t) + GHGEolS^m(t)$ and displayed in cells J5-J43. Finally, for each year the cumulative net GHG emission changes, $GHGC(\tau) = \sum_{t=2012}^{\tau} GHGA(t)$, are calculated by summing over all previous calendar years and displayed in cells K5-K43.

All time series of all results are also visualized in two figures, which are shown for default data input results on the next page. Figure 10 shows the annual and cumulative GHG emission changes, $GHGA(t)$ and $GHGC(\tau)$. Figure 11 shows the individual annual GHG emission changes of material production, vehicle use, and scrap generation and recycling. The X-axis in Figures 10 and 11 can be interpreted as a "base case" signifying no shift of closure and body part materials from steel to aluminum. This case would result in no GHG emission changes.

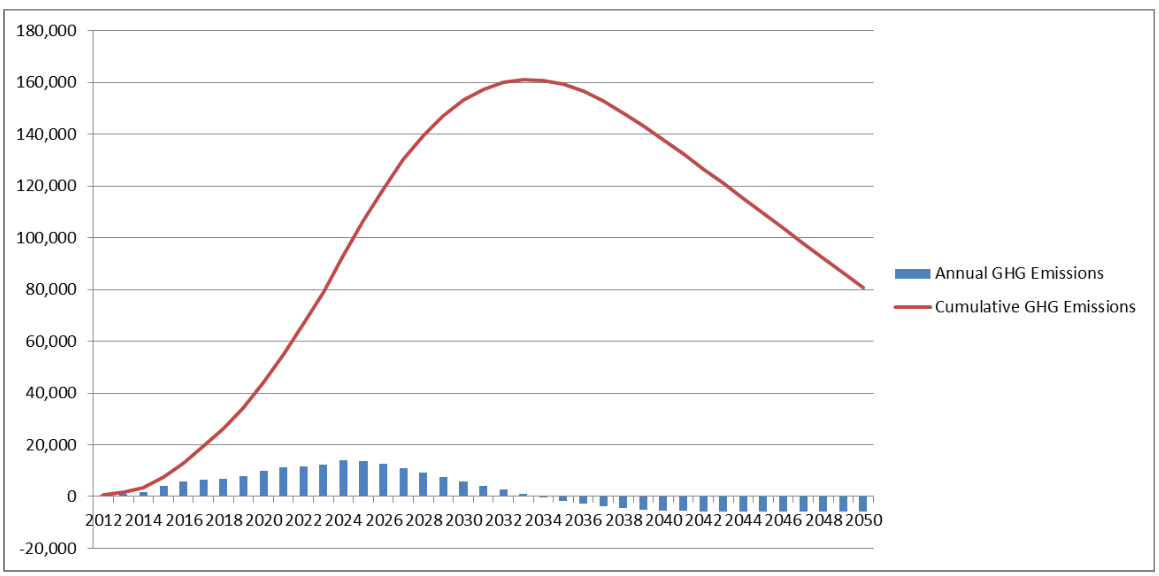

Figure 10: Annual and cumulative GHG emission changes (in million kg CO_2eq), $GHGA(t)$ and $GHGC(\tau)$, for the default input data

The cumulative GHG emission changes $GHGC(\tau)$ provide the highest level overview of the results. Figure 10 shows a steady increase in GHG emissions until they reach a peak of 161 million metric tons of CO_2eq in the year 2033 and a steady decrease thereafter. In 2050, the cumulative GHG emission increase is still 81 million metric tons of CO_2eq, but the annual GHG emission change $GHGA(t)$ has reached a negative steady state of 5.8 million metric tons of CO_2eq/year, which means that $GHGC(\tau)$ will eventually reach zero and go negative. The year in which $GHGC(\tau)$ crosses the X-axis is calculated in cell I46. For the default data input results the year is 2064.

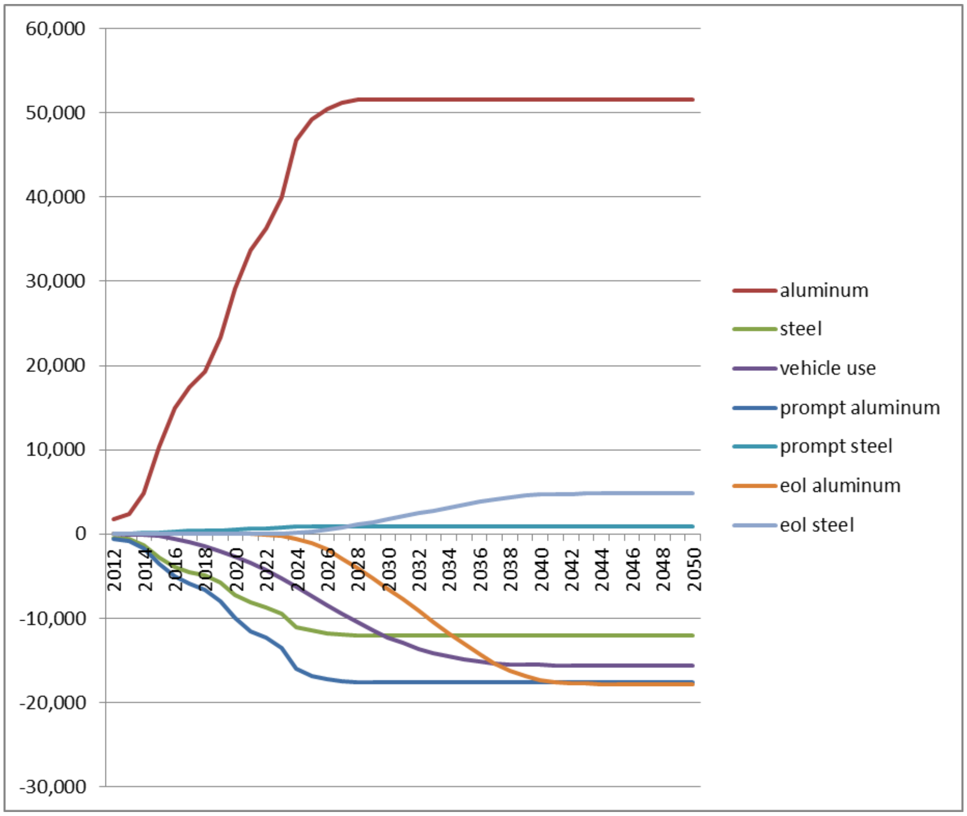

Figure 11: Annual GHG emission changes (in million kg CO_2eq) due to changes in material production and forming, vehicle use, and production (prompt) and end-of-life (eol) scrap generation and use, for the default input data

Figure 11 shows how the overall result from Figure 10 comes about. It shows that the growth in GHG emissions until 2033 is caused by automotive aluminum production, which significantly outweighs the simultaneous GHG emission reductions from production aluminum scrap recycling and the avoided steel production. Figure 11 also shows that the GHG emission reductions from vehicle fuel economy improvements and end-of-life scrap generation and recycling take place with a significant time delay. Only when the annual GHG emission reductions from end-of-life aluminum scrap recycling exceed 12 million metric tons of CO_2eq/year in 2034 does the annual net change become negative. Relatively soon thereafter, the system reaches a steady state in which the GHG increases of automotive aluminum production and forming are outweighed by the combined effect of avoided steel production, fuel economy improvements, and production and end-of-life aluminum scrap recycling. Figure 11 shows that those four effects have the same order of magnitude (12-18 million metric tons of CO_2eq/year) and that the effects of production and end-of-life aluminum scrap recycling are somewhat larger than that of fuel economy improvements. The effect of avoided steel production is the smallest of the four.

The large GHG impact of aluminum scrap generation and use explains why the model results are so sensitive to the aluminum recycling parameters of the CLCA model, in particular α and β of the consequential system expansion (see Section 4). In the default setting, aluminum scrap recycling is modeled as an open loop with $\alpha = 0.9$ and $\beta = 1$. Choosing closed-loop recycling for production scrap reduces the crossover year to 2053, choosing it for production and end-of-life scrap to 2048. However, if aluminum scrap recycling is modeled as an open loop with parameter settings $\alpha = 0.8$ and $\beta = 0.9$, $GHGC(\tau)$ would reach 265 million metric tons of CO_2eq by 2050 and continue to increase in perpetuity.

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Critical Review by Independent Third Party

For this study, the Critical Review Panel was charged with providing comments on the consequential life cycle assessment (CLCA) of replacing steel with aluminum in North American vehicles, as well as a second round of comments to determine whether the first round of comments was adequately addressed by AISI and Dr. Roland Geyer, Bren School of Environmental Science and Management, University of California, Santa Barbara.

The scope of the CLCA includes the greenhouse gas (GHG) consequences of replacing conventional steel with aluminum in North American light duty vehicles for vehicle mass reduction. The principal investigators prepared an Excel-based model for this purpose that contained the following GHG consequences:

- Changes in material production emissions due to primary and secondary mass reductions
- Changes in GHG emissions due to changes in prompt scrap recycling
- Changes in vehicle use phase emissions due to vehicle mass reduction
- Changes in GHG emissions due to changes in end-of-life (EOL) scrap recycling

In accordance with ISO/TS 14071:2014, an expert panel was assembled that included proficiency in the applicable ISO standards; the LCA methodology, both attribution and consequential techniques; the critical review practice; scientific disciplines relevant to the impact categories used in the study; automotive, steel, and aluminum industry expertise; and the language used in the study.

The panel of reviewers of the study included:

Thomas Gloria, PhD (Chair)
Program Director, Sustainability, Harvard University
Managing Director, Industrial Ecology Consultants
Newton, Massachusetts, US

Alissa Kendall, PhD
Associate Professor, Civil and Environmental Engineering
University of California Davis
Davis, California, US

John Sullivan, PhD
Research Associate II, University of Michigan
Principal, EcoSpherica LLC
Ann Arbor, Michigan, US

Review Process

The scope of this ISO 14040:2006 and 14044: 2006 critical review was limited to the methodology, comprehensiveness, and functionality of the study. The default input parameters built into the model by the principal investigators were outside the scope of this review. While it is the ultimate intent of AISI to select credible input parameters, develop a baseline scenario, conduct sensitivity assessments, and publish the findings, this will be handled by a separate, subsequent review process and was outside of the scope of the review.

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Review Results

Based on the objectives set forth to review this study, the Critical Review Panel concludes that the study conforms to the LCA requirements of ISO 14040:2006 and 14044: 2006 standards. As determined by the second round of review, all responses by AISI and Dr. Roland Geyer to the first round of comments submitted by the Critical Review Panel have been adequately addressed.

Respectfully,

Thomas P. Gloria, Ph.D.

22 November 2016
Newton, Massachusetts, US

APPENDIX B: CRITICAL REVIEW FOR THIS STUDY

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Critical Review by Panel of External Experts

The Critical Review Panel was charged with reviewing and commenting on the consequential life cycle assessment (CLCA) study titled "**Consequential Life Cycle Greenhouse Gas Study of Automotive Lightweighting with Advanced High Strength Steel (AHSS) and Aluminum**". The study was conducted by the Steel Recycling Institute, a business unit of the American Iron and Steel Institute, using the spreadsheet model described in the UC Santa Barbara report *Consequential Life Cycle Greenhouse Gas Assessment of Replacing Steel with Aluminum in North American Vehicle Production - Methodology Report* developed by Dr. Roland Geyer, dated November 17, 2016. The goal of the study was to identify and quantify the main GHG emissions consequences of a significant increase in the use of aluminum for vehicle body and closure parts, and to compare these consequences to the GHG emissions consequences of the use of AHSS for the same parts, as part of an overall vehicle fleet light weighting strategy. AISI retained this panel to conduct a rigorous assessment of the study scope, assumptions, inputs, and results. The following is the final review statement by the external review panel based on the July 30th, 2018 Final Report version.

Panel Members

Thomas Gloria, Ph.D. (Panel Chair), Industrial Ecology Consultants
William O. Collinge, Ph.D., Independently contracted by AISI
Troy A. Hottle, Ph.D., Independently contracted by AISI

Critical Review Tasks & Objectives

Reviewers were asked to review responses to the comments and accompanying revisions of the LCA report until adequately addressed by AISI.

Per International Organization of Standardization (ISO) 14044:2006(E) *Environmental management – Life cycle assessment – Requirements and guidelines*, the critical review process included the following objectives to ensure conformance with applicable standards:

- The methods used to carry out the LCA were consistent with the applicable international standards
- The methods used to carry out the LCA were scientifically and technically valid
- The data used were appropriate and reasonable in relation to the goal of the study
- The interpretations reflected the limitations identified and the goal of the study, and
- The study report was transparent and consistent.

Review Results

The overall review was conducted in an equitable and constructive manner. All comments were addressed, and all open issues resolved. There were no dissenting opinions held by the reviewers or the commissioner upon finalization of the review. Please note that the reviewer panel's statements of conformance are as individual experts.

Respectfully,

Thomas P. Gloria, Critical Review Panel Chair

Thomas P. Gloria

15 August 2018
Newton, Massachusetts