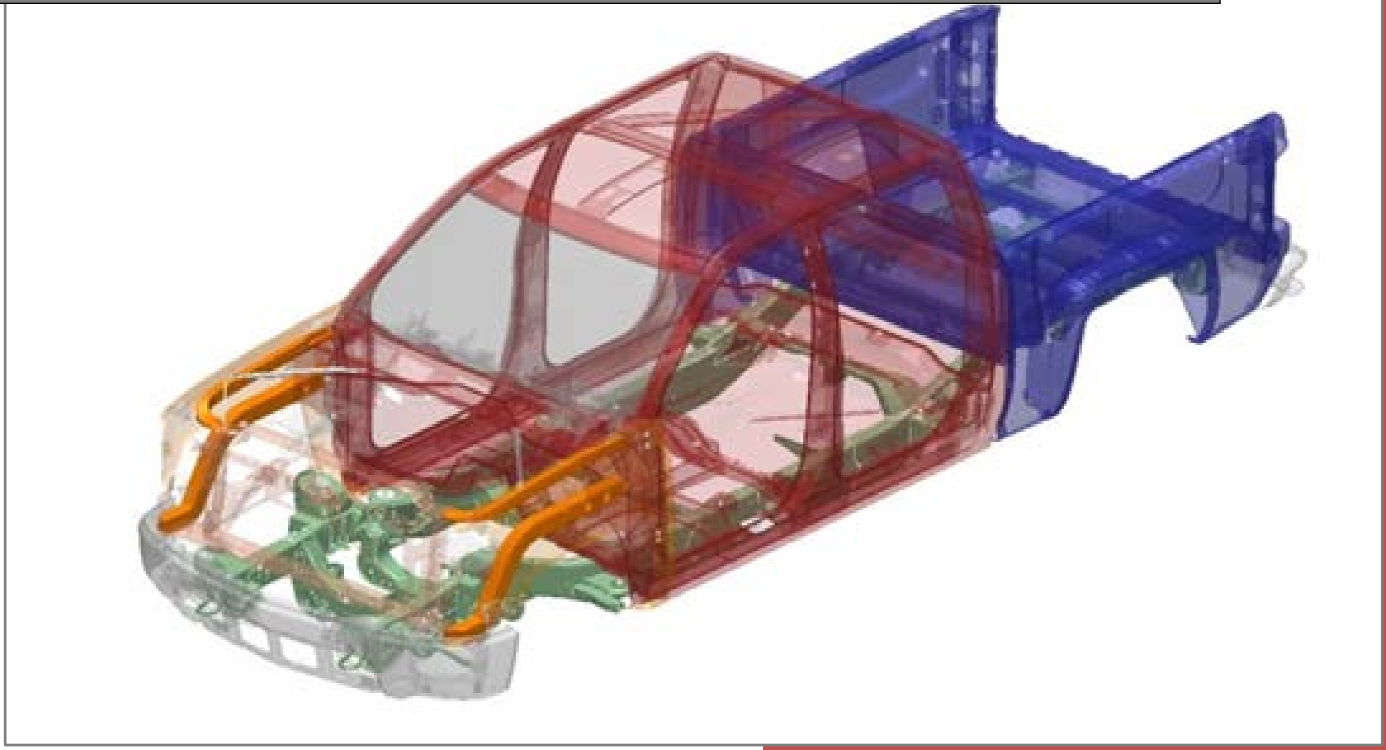
EDAG Silverado Body Lightweighting Final LCA Report

August 2018



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Final LCA Report, August 2018

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Executive Summary

This life cycle assessment (LCA) study assesses the life cycle performance of an *advanced aluminum body design of a General Motors Silverado light-weight truck* (*AA LWT body design*), in comparison to the conventional *high strength steel (HSS)* and *advanced high strength steel (AHSS) intensive body of the 2014 Silverado 1500* (*the Baseline*). This LCA study was carried out on behalf of the Aluminum Association, and has been conducted according to the requirements of the International Organization for Standardization (ISO) standard 14044 and follows the specific rules and requirements provided in the Canadian Standards Association (CSA) Group document titled "*Life cycle assessment of auto parts—Guidelines for conducting LCA of auto parts incorporating weight changes due to material composition, manufacturing technology, or part geometry*" (1), (2).

In 2016, the EDAG Group, one of the world's largest independent automotive development partners, completed a comprehensive lightweighting study for the National Highway Traffic Safety Administration (NHTSA) using a 2014 Silverado 1500 as the baseline vehicle (3). The redesigned lightweight truck of the NHTSA study has an *aluminum-intensive multi-material body* achieving 39% (198 kg) of mass reduction (3). The powertrain (P/T) for the LWT design conceived in the NHTSA study was downsized to maintain the same gross vehicle weight rating (GVWR) to horsepower (HP) ratio as the baseline vehicle (3). From a full vehicle perspective, the NHTSA LWT design (with P/T adaptation) achieved a mass saving of 16.7% (406 kg) compared to the Baseline (3).

This LCA report is focused on the subsequent work by EDAG to assess the *additional weight saving capability* of using *advanced aluminum grades* provided by the Aluminum Transportation Group of the Aluminum Association to produce an *advanced aluminum body design* on top of the NHTSA LWT body design (4). While additional mass savings beyond the body design appear possible given the substantial mass reduction in the body design, such secondary mass savings were not part of the AA LWT body design and as such not considered in the scope of this LCA.

The AA LWT *body* design was completed in 2017. Use of advanced grades of aluminum leads to an additional 32.5 kg (10.6%) mass reduction compared with the multi-material body design conceived in the NHTSA study (4). This is equivalent to a total body mass reduction of 231 kg (46%) when compared with the equivalent subsystems (504 kg) of the baseline vehicle MY2014 Chevrolet Silverado 1500 (2,432 kg) (4). Both the NHTSA LWT and AA LWT body designs used the 2014 Silverado 1500 as the prototype vehicle (3), (4).

The AA LWT body design includes three main components/assemblies: [1] the crew cab assembly (including fenders); [2] the pickup box; and [3] closers (including four doors and the hood) (4). Only design considerations that were judged to be practical based on technical feasibility and cost effectiveness were included in the AA LWT body design (4). The structure was optimized using computer aided engineering (CAE) simulation for crashworthiness safety, structural stiffness, and strength load cases (4). In comparison, the Baseline body system is dominated by steel (97.3%, 491 kg) utilizing HSS (79%), AHSS (13%), and low-strength steels (6%).

Built on the background of the EDAG study designs, the primary goal of this LCA study is to compare the life cycle environmental performance of the AA LWT body design to the Baseline body system of the 2014 Silverado 1500 (EcoTec3 5.3L-V8 engine), built and driven for 290,000 km (2), (5) in North America. The primary intended application of this LCA study is to inform the Aluminum Association, the aluminum industry, policymakers, original equipment manufacturers (OEMs), and other stakeholders about the life cycle environmental performance of the AA LWT body design compared to the Baseline. Vehicle lightweighting is a well-known and proven method to reduce fuel consumption. Less well-understood is the overall environmental impact of automotive materials in the life cycle of a vehicle due to the fact that the life cycle performance of auto parts needs to be evaluated on a case-by-case basis. The Aluminum Association believes that life cycle thinking is an important part of implementing effective environmental sustainability strategies in the automotive industry. The main findings of this LCA study are intended to provide quantitative information to any interested parties in the North American context regarding the potential environmental impacts of using advanced aluminum to further lightweight an HSS and AHSS intensive pickup truck body.

The results of the LCA study are intended to be used for *comparative assertions* to be disclosed to the public. An *external critical review* was conducted by a *panel of independent experts* in order for the study to be in conformance with ISO 14040 series of Standards and the CSA Group LCA Guidance (1), (2), (6).

The life cycle inventory (LCI) and life cycle impact assessment (LCIA) indicators assessed are total primary energy demand (TPE), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical smog formation potential (PSFP), and human health particulate potential (HHPP). The LCIA results were calculated with the SimaPro LCA software 8.4.0, 2018, using the characterization factors of the U.S. EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) version 2.1, 2012. The non-renewable and renewable energy-related LCI indicators were calculated with the SimaPro LCA software using the Cumulative Energy Demand as available in version 1.09. The life cycle stages include production, use and end-of-life. The use stage considers a total service life of 290,000 km (2), (5) on North American roads for both the AA LWT body design and the Baseline.

In the framework of this LCA study, it's deemed *technically feasible as well as highly likely* that the 231 kg weight savings in the AA LWT body design would allow for the powertrain to be adapted to maintain the same driving performance as the baseline vehicle. This would result in potential fuel savings of about 2,500 liters (L) of gasoline over the assumed vehicle's lifetime driving distance ($LTDD_V$) of 290,000 km. The mass-induced potential fuel savings by the body system lightweighting is calculated by using an F_{CP} value of 0.38 L/100 km×100 kg recommended by the CSA Group LCA Guidance, assuming P/T adaptation (2). This value represents the theoretical fuel savings with P/T adaptation, which may be limited by the engine and gearbox configurations available to the OEMs in the design process. A "no P/T adaptation" scenario is deemed *less likely* for the AA LWT body design. The application of the EDAG's "*vehicle strategic systems*" lightweighting approach would *highly likely* lead to P/T adaptation to maintain the same driving performance as the baseline vehicle, measured as the GVWR/HP ratio. A "vehicle strategic systems" lightweighting approach means a shift from *"tactical" mass management* (lightweight parts) to *aggressive mass reduction* (lightweight intensive vehicle).

The cradle-to-grave net change of the LCIA and LCI indicator results of the AA LWT body design, with P/T adaptation (base case), are shown in Table ES1. The difference between the potential environmental impact of the AA LWT body design and the Baseline is calculated as the results of the AA LWT body design minus the Baseline. The use stage emissions are only calculated as a difference from the Baseline. Thus, the use stage impact is null in value for the Baseline and carries a negative sign for the AA LWT body design. *The AA LWT body design shows lower potential environmental impacts due to lightweighting compared to the Baseline, across all selected LCIA and LCI indicators.*

Table ES1: Cradle-to-grave LCA results of AA LWT body design in comparison to the Baseline (with P/T adaptation, $LTDD_V$= 290,000 km (2), (5))

LCIA and LCI Indicators	Indicator units	Cradle-to-grave total net change of the AA LWT body design, with P/T adaptation[1),2) 5) 6)]
Acidification potential, AP	kg SO_2-eq	-7.9
Eutrophication potential, EP	kg N-eq	-1.1
Global warming potential, GWP[3)]	kg CO_2–eq	-7,800
Photochemical smog formation potential, PSFP	kg O_3-eq	-170
Human health particulate potential, HHPP	kg $PM_{2.5}$-eq	-1.0
Total primary energy demand, TPE[4)]	MJ	-110,000
Non-renewable, fossil, NRF	*MJ*	*-100,000*
Non-renewable, nuclear, NRN	*MJ*	*-1,600*
Non-renewable, biomass, NRB	*MJ*	*-0.028*
Renewable, hydropower, RH	*MJ*	*1,900*
Renewable, solar, geothermal, wind, RSGW	*MJ*	*360*
Renewable, biomass, RB	*MJ*	*-7,300*

[1)] Negative values represent a lower potential environmental impact of the AA LWT body design, since the life cycle performance is shown as the difference from the Baseline (AA LWT body minus Baseline LCA results).

[2)] AA LWT body LCA results are displayed with two-significant digits.

[3)] 100-year time horizon GWP factors are provided by the IPCC 2013 Fifth Assessment Report (AR5). Biogenic removals and emissions of atmospheric CO_2 are not accounted for in this LCA study.

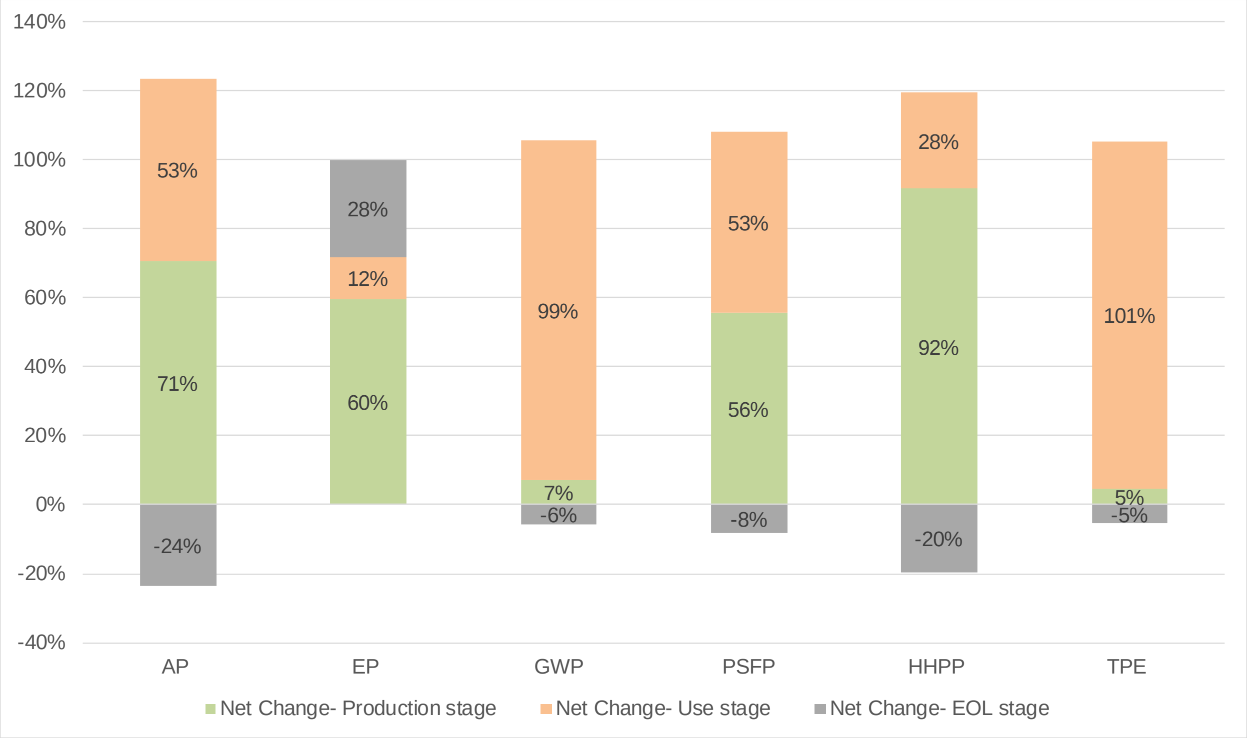
[4)] Total primary energy demand (higher heating value), also known as Cumulative Energy Demand, is a sum energy indicator of NRF, NRN, NRB, RH, RSGW, and RB.

[5)] Based on the "substitution" allocation procedure (also known as "EOL recycling", "closed-loop", or "system expansion by substitution"), the cradle-to-grave LCA results are *not* influenced by the *amount of input scrap* for both North American industry average cradle-to-gate LCI profiles of aluminum and steel products. Instead, the North American *EOL recovered scrap rate* for both the AA LWT body design and Baseline (RR_{EOL}=95%) is the defining decisive parameter.

[6)] It should be noted that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks (1).

Life cycle GWP and TPE of the AA LWT body design (with P/T adaptation), relative to the Baseline, are about -7,800 kg of CO_2-eq and -110,000 MJ, respectively. On a per km-basis, the life cycle GWP and TPE of the AA LWT body design (with P/T adaptation), relative to the Baseline, are -27 g CO_2-eq/km and -380 kJ/km, respectively. Life cycle GWP and TPE of the AA LWT body design compared to the Baseline are dominated by fossil fuel related CO_2 emissions (94%), and non-renewable fossil fuel energy (93%), respectively. From an energy perspective, the AA LWT body design shows lower fossil fuels and biomass energy demand and higher hydropower renewable energy use compared to the Baseline. The use phase (gasoline production and combustion) dominates the life cycle GWP, TPE, PSFP and AP results (Figure ES1). On the other hand, the production and EOL stages combined dominate the life cycle EP and HHPP results.

Figure ES1: Cradle-to-grave LCA results of the AA LWT body design in comparison to the Baseline by life cycle stage — in % basis (with P/T adaptation, $LTDD_V$= 290,000 km (2))



[1] The cradle-to-grave LCA results of the AA LWT body design compared to the Baseline are shown as 100%. In addition, the net change of LCA results per life cycle stage can be either positive or negative results; therefore, the contribution in percentage of a life cycle stage can be greater than 100%. However, the cradle-to-grave total net change of LCA results of all life cycle stages always equals to 100%. The positive (+) or negative (-) percentage values depends on the mathematic sign (+/-) of the net change of LCA results per life cycle stage. For example, the net change in use stage GWP is about -7,700 kg CO_2-eq. The total net change in life cycle GWP is about -7,800 kg CO_2-eq. In this case, the contribution of use stage to the life cycle GWP of the AA LWT body design is positive (99%).

[2] Please note data may not add up to totals due to rounding.

To assess how factors such as allocation methods, uncertainties in data, and assumption-based parameters would affect the reliability of the results and conclusions, a *sensitivity check* was conducted. The sensitivity check includes the results of the sensitivity and scenario analysis and uncertainty analysis (1). *Sensitivity and scenario analysis* were conducted on eleven parameters including LTDDv, F_{CO}/F_{CP} (no/with P/T adaptation) values, allocation rules for recycling, and EOL recovered scrap rate. For best identification of significant sensitivity parameters, sensitivity is calculated as the ratio (R_{SP}) of the percent change in LCA indicator result over the percent change in parameter value (2). The analysis shows that the *F_{CP}/F_{CO} values* and *LTDDv* were deemed *significant sensitivity* parameters (R_{SP}=1) for life cycle GWP and TPE results. Furthermore, the analysis shows that the *EOL recovered scrap rate* (varied from 0.95 to 0.75 for both auto body systems) was deemed *significant sensitivity* parameter (R_{SP} = 0.9 and R_{SP} = 0.8) for the life cycle AP and HHPP results. Life cycle AP, HHPP, and PSFP results were also found to be *significantly* sensitive (varied by higher than 10%) to the change of *allocation rules for recycling* ("substitution" versus "cut-off" approach).

On top of the sensitivity analysis, a Monte Carlo uncertainty analysis was conducted to assess the *combined uncertainty effect* of the *significant sensitivity parameters* ($LTDD_V$, F_{CP}/F_{CO} values, and fabrication and EOL recovered scrap rates) on the LCA results. *Uncertainty analysis results showed that the combined uncertainty effect of significant sensitivity parameters did not lead to any inverse (higher) potential environmental impacts of the AA LWT body design relative to the Baseline.*

In conclusion, the AA LWT body design shows lower potential environmental impacts due to lightweighting compared to the Baseline across all selected LCIA and TPE indicators. ***Specifically, the AA LWT body design has the potential to lower the life cycle global warming potential and total primary energy demand of the Baseline by 7.8 metric tons of CO_2-eq and 110 gigajoules, respectively****.*

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Glossary of Terms

International Organization for Standardization (ISO) 14040/44:2006 – Terms and Definition Section (1), (6)*.*

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

Life cycle
Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Life cycle assessment (LCA)
Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

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

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

Life cycle inventory (LCI)
Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Product system
Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.

Sensitivity analysis
Systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study.

System boundary
Set of criteria specifying which unit processes are part of a product system.

***Note:** the term system boundary is not used in this International Standard in relation to LCIA.*

System expansion
Expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3.

Uncertainty analysis
Systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability.

Note: *Either ranges or probability distributions are used to determine uncertainty in the results.*

CSA Group LCA Guidance for Auto Parts: 2014 – Definitions (2).

Auto part
Part, component, or sub-assembly of a road vehicle designed either for passenger or cargo transport or both.

Fabrication yield
The net quantity of material as a percentage of the original gross quantity of material required to produce a finished auto part.

Internal combustion engine (ICE)
An engine in which the combustion of a fuel (e.g., gasoline) occurs with an oxidizer (e.g., air) in a combustion chamber.

Process scrap
Scrap generated in the auto part fabrication processes.

Note: *Examples include stamping, die-casting, and extrusion. Process scrap is used synonymously with "post-industrial scrap", "post-production scrap", and "new scrap".*

Yield for recycling
The ratio of secondary material output over scrap input for a given recycling material process.

Acronyms and Abbreviations

A

AA LWT body design	Advanced aluminum body design of a General Motors Silverado light weight truck
AHSS	Advanced high strength steels
Al	Aluminum
Al CRC	Aluminum cold rolled coil
AP	Acidification potential

B

BC	Black carbon
BH	Bake hardenable steels
BOF	Basic oxygen furnace

C

C2G	Cradle-to-gate
C6H6	Benzene
C7H8	Toluene
C8H10	m,p,o Xylene
CAE	Computer-aided engineering
CAFE	Corporate average fuel economy
CFE	Combined fuel economy
CH4	Methane
CO_2	Carbon dioxide
CO	Carbon monoxide
CR^3	Center for Resource Recovery and Recycling
CSA Group	™A trade-mark of the Canadian Standards Association, operating as “CSA Group”
CP	Complex-phase steels
Cu	Copper
CV	Coefficient of variation, Monte Carlo uncertainty analysis

D

DP	Dual Phase steels

E

E10	Petroleum-based gasoline with 10% ethanol
EAF	Electric arc furnace
EOL	End-of-life
EP	Eutrophication potential

F

FB	Ferritic-bainitic steels
FESM	Front-end sheet metal
Fe	Iron

G

g	Gram
gal.	Gallon
G2G	Gate-to-gate
GHG	Greenhouse gas
GREET®	The Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
GVWR	Gross vehicle weight rating
GWP	Global warming potential

H

H+	Hydrogen ion
HC	Hydrocarbons
HDG	Hot-dipped galvanized steel
HF	Hot-formed steels
HHPP	Human health particulate potential
HHV	Higher heating value
HP	Horsepower
HSLA	High-strength, low-alloy steels
HSS	Conventional high-strength steels
HTAs	Heat-treatable alloys

I

ICE/ICEV	Internal combustion engine vehicle
IF	Interstitial-free steels
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization

K

kg	Kilogram
kJ	Kilojoule
km	Kilometer

L

L	Liter
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LSS	Low-strength steels
$LTDD_A$	Auto part lifetime driving distance
$LTDD_V$	Vehicle's lifetime driving distance

M

Mg	Magnesium
MJ	Megajoule
Mn	Manganese
mpg	Miles per gallon
MS	Martensitic steels
MOVES	EPA's MOtor Vehicle Emission Simulator
MY	Model year

N

N	Nitrogen
NA	North America, North American
NHTSA	National Highway Traffic Safety Administration
NMHC	Non- methane hydrocarbon
NMVOCs	Non-methane volatile organic compounds
NO_x	Nitrogen oxides
NRB	Non-renewable, biomass
NRF	Non-renewable, fossil
NRN	Non-renewable, nuclear
NRMR	Use of non-renewable material resources
NVH	Noise, vibration, and harshness

O

O_2	Oxygen
O_3	Ozone
OC	Organic carbon
ODP	Depletion potential of the stratospheric ozone layer
OEM	Original equipment manufacturer
OVS	Overall vehicle score

P

P	Phosphorous
PCA	Process contribution analysis
PCV	Passenger and cargo volumes
PHRC	Pickled hot-rolled coil steels
PHS	Press hardened boron steels
PM	Particulate matter
PM2.5	Particulate matter, less than or equal to 2.5 micrometers in diameter
PM10	Particulate matter, less than or equal to 10 micrometers in diameter
PSFP	Photochemical smog formation potential
PP	Polypropylene
PSR	Process scrap recycling
P/T	Powertrain
PTW	Pump-to-wheel
PUT	Pick-up truck

R

RB	Renewable, biomass
RH	Renewable, hydropower
RNA	Regional North America
RSGW	Renewable, solar, geothermal, wind.

S

S	Sulfur
SCTG	Standard Classification of Transported Goods
SD	Standard deviation, Monte Carlo uncertainty analysis
SEM	Standard error of mean, Monte Carlo uncertainty analysis
Si	Silicon
SO_2	Sulfur dioxide
SOx	Sulphur oxides
SP	Sensitivity parameter
SCP	Scenario parameter

T

T	Heat treating temper codes, aluminum alloys
TBW	Tire and brake wear
TPE	Total primary energy
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TRIP	Transformation-induced plasticity

TWIP	Twinning-induced plasticity

U

U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency
UTS	Ultimate tensile strength

V

VOCs	Volatile organic compounds

W

worldsteel	World steel association
WAC	Water consumption
WTP	Well-to-pump
WTW	Well-to-wheel

Y

YS	Yield strength

Z

Zn	Zinc

1.0 EDAG Silverado Body Lightweighting LCA Report Overview

Section 1	Provides a brief overview of the EDAG Silverado Body Lightweighting LCA Report.
Section 2	Provides an overview of the future of lightweighting.
Section 3	Briefly describes the evolution of aluminum alloys and steel grades.
Section 4	Introduces the EDAG AA LWT body design project and provides the product definition and a detailed description of the Baseline and AA LWT body design according to CSA Group LCA Guidance for auto parts.
Sections 5 and 6	Describes the goal and scope of the study according to LCA-based ISO 14044.
Section 7	Provides the rules to calculate the net change in the cradle-to-grave environmental profiles of the auto body parts. In addition, it provides the rules to calculate the environmental profile of the production, use, and EOL stage of auto body parts, and the ISO 14044 conformant allocation rules for fabrication processes, and EOL material recycling.
Section 8	Describes the life cycle inventory phase according to LCA-based ISO 14044.
Section 9	Describes the LCIA and resource use indicators and presents the LCA results for the cradle-to-grave total net change of auto body parts, built and driven for 290,000 km in North America (NA).
Section 10	Brings together the findings from the inventory analysis and the impact assessment to identify significant issues in the context of the goal and scope of the study. Issues are identified via contribution and dominance analysis for the auto body parts. This section then provides an evaluation of the study's completeness and consistency in relation to the goal and scope of the study. To assess how factors such as allocation methods, uncertainties in data, and assumption-based parameters would affect the reliability of the results and conclusions, sensitivity and Monte Carlo uncertainty analyses were conducted. Finally, the Section presents the LCA study's conclusions, limitations, and recommendations.

2.0 Future of Lightweighting

In the automotive industry, lightweighting is a continuing trend that does not show signs of declining. In fact, "vehicle mass efficiency has joined the vanguard of product development where every gram (g) lost is heralded. And it's no passing fad—escalating global fuel economy and safety regulations ensure that lightweighting, as a product-development tenet, is here to stay" (7).

In 2015, greenhouse gas emissions (GHGs) from transportation accounted for about 27% of total U.S. GHGs, making it the second largest contributor of U.S. GHGs after the electricity sector (8). Globally, 22% of GHGs are emitted by the transportation sector (9). Global trends toward CO_2 reduction and resource efficiency have significantly increased the importance of lightweight materials and design over the last years (10). The CO_2 limits are continually being lowered in the global automotive markets (11). Nine governments worldwide—Japan, the European Union, United States, Canada, China, South Korea, Mexico, Brazil, and India—have established or proposed fuel economy or greenhouse-gas emission standards for passenger vehicles and light-commercial vehicles/light trucks (12). The regulations in these markets, covering 80% of global passenger vehicle sales in 2013, influence the business decisions of major vehicle manufacturers around the world, and are among the most effective climate-change mitigation measures to have been implemented over the past decade. These governments have taken differing approaches to designing their regulations, using different drive cycles and vehicle certification test procedures.

Figures 1 and 2 show historical fleet CO_2 emissions performance and current or proposed passenger vehicle and light commercial vehicle/light truck standards as developed by the International Council on Clean Transportation. Global data are normalized to the New European Driving Cycle (12).

In Europe, and globally, regulations are forcing OEMs to significantly reduce the CO_2 emissions of their cars (10). In Europe, for example, the average emissions of all models sold by an OEM in one year need to drop from 130 g CO_2 per kilometer to 95 g in 2021, between 68 and 78 g in 2025, and between 60 and 65 g in 2030 and beyond (with some exceptions/adaptations regarding the vehicle class) (10).

In 2012 in the U.S., NHTSA established passenger car and light truck Corporate Average Fuel Economy (CAFE) standards for model years (MY) 2017-2021. As part of the same rulemaking action, the U.S. EPA issued GHG standards, which are harmonized with NHTSA's fuel economy standards that are projected to require 163 grams/mile of CO_2 emissions for the MY 2025. Currently the EPA is reexamining the GHG standards for MYs 2022-2025 and NHTSA will set new CAFE standards for those MYs.

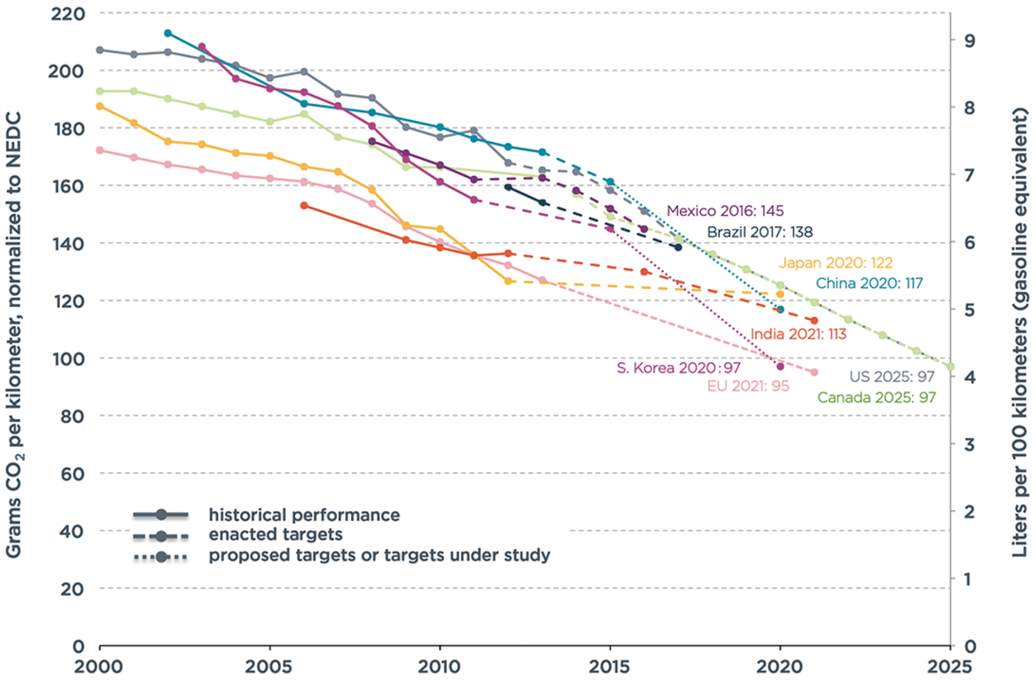


Figure 1. Historical fleet CO₂ emissions performance and current or proposed passenger vehicle standards (12)

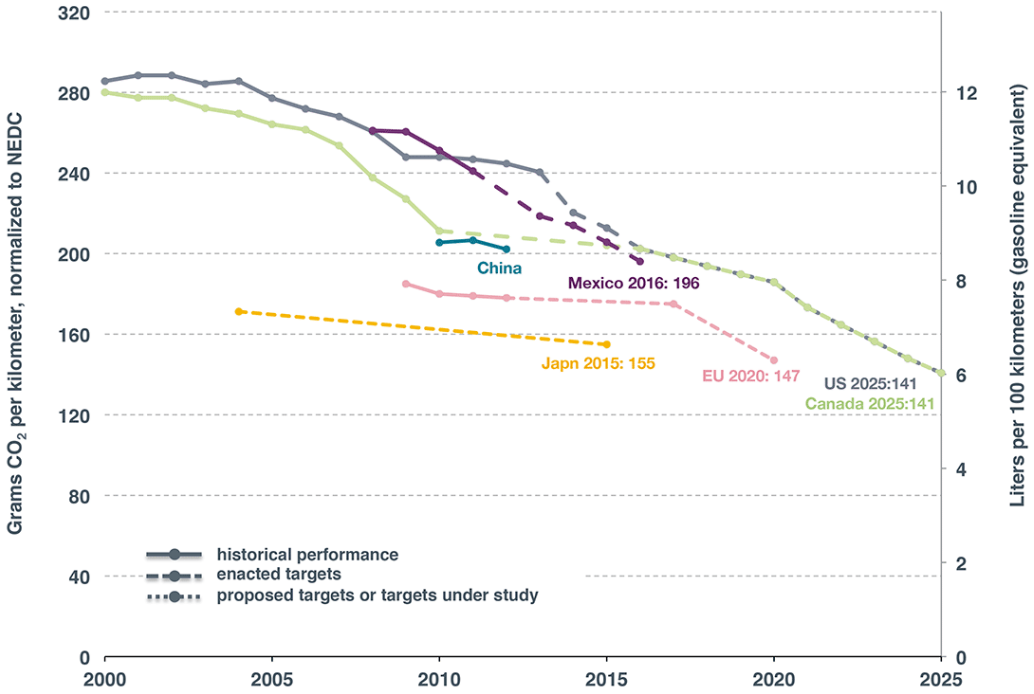


Figure 2. Historical fleet CO₂ emissions performance and current or proposed light commercial vehicle/light truck standards (12)

In the United States, CO_2 emissions and fuel economy have improved in nine out of the last eleven years while worsened only once (13). Based on the final data through MY 2015, CO_2 emissions have decreased by 103 g/mile, or 22%, since MY 2004, and fuel economy has increased by 5.5 miles per gallon (mpg), or 28%, with an average annual improvement of about 0.5 mpg per year (13).

Under current CAFE regulations and 2025 targets in the U.S., OEMs have been intensively reducing curb weights (7). According to Sherman (14), “Overall, OEMs broadly appear committed to staying the course despite the possibility of a mid-term relaxation of CAFE targets for MYs 2021-2025—a logical path given their multibillion dollar investments in technologies aimed at improving fuel efficiency and reducing CO_2 emissions, not only in the U.S. but also in global markets. They also face dramatically increased fines for noncompliance, arguably making GHG reduction slightly more important than CAFE, given that it is enforced under the Clean Air Act (15). Violation means fines up to $37,500 per vehicle and loss of sales certificates. Penalties for CAFE were recently increased to $140 for every mpg under the 19 standard, per vehicle (up from $55)”.

According to a Grand View Research report (16), “The global lightweight materials market size was estimated at USD 113.78 billion in 2016 and is expected to register a compound annual growth rate of 8.9% from 2016 to 2024. In 2015, the automotive segment dominated the overall market in terms of revenue, with an 86% share. Soaring fuel prices, implementation of emission standards, and financial implications of note adhering to these standards is expected to boost demand for lightweight materials in the automotive sector. Need to reduce fuel consumption and CO_2 emissions from vehicles are high on the list of priorities for automobile manufacturers around the world. Governments are constantly working to curb growing pollution levels resulting from vehicular emissions”.

In fact, “because much of the low-hanging fruit has already been implemented, vehicle manufacturers face real-world challenges in finding cost-effective ways to continue implementing further mass reduction solutions needed to offset weight gains due to increased demand for comfort, convenience, and safety technologies" (17). *Whatever the details, lightweighting appears certain to remain a product-development motto* (7), (18).

3.0 The Evolution of Aluminum Alloys and Steel Grades

Experts believe steel and aluminum will continue to dominate vehicle structures and chassis systems beyond the 2025 timeframe (7). Stronger and more formable alloys aimed at making lighter components and subassemblies are in the pipeline (7). According to the U.S. DOE, “Research and development into lightweight materials is essential for lowering their cost, increasing their ability to be recycled, enabling their integration into vehicles, and maximizing their fuel economy benefits” (19).

An *aluminum alloy* is a chemical composition where other elements are added to pure aluminum to enhance its properties, primarily to increase its strength. These other elements include iron (Fe), silicon (Si), copper (Cu), magnesium (Mg), manganese (Mn) and zinc (Zn) at levels that combined may make up as much as 15 percent of the alloy by weight (20). Alloys are assigned a four-digit number, in which the first digit identifies a general class, or series, characterized by its main alloying elements (Table 1). According to the Aluminum Association (20), “When the current system was originally developed in 1954, the list included 75 unique chemical compositions. Today, there are more than 530 registered active compositions and that number continues to grow”. Table 1 shows the general classification of aluminum alloys (20). *The 6XXX series heat-treatable alloys (HTAs) and 5XXX series non-heat-treatable alloys (NHTAs) are used for both Baseline and EDAG AA LWT auto body parts* (Section 4).

Table 1. Aluminum Alloys

Alloy designation	**Alloy series**	**Description** (20)
Commercially pure aluminum	1xxx series	The 1xxx series alloys are comprised of aluminum 99 percent or higher purity. This series has excellent corrosion resistance, excellent workability, as well as high thermal and electrical conductivity.
Heat-treatable alloys (HTAs)	2xxx series	In the 2xxx series, copper (Cu) is used as the principle alloying element and can be strengthened significantly through solution heat-treating.
	6xxx series	The 6xxx series are versatile, heat treatable, highly formable, weldable and have moderately high strength coupled with excellent corrosion resistance. Alloys in this series contain silicon (Si) and magnesium (Mg) to form magnesium silicide within the alloy. Extrusion products from the 6xxx series are the first choice for structural applications. Alloy 6061 is the most widely used alloy in this series and is often used in truck frames.
	7xxx series	Zinc (Zn) is the primary alloying agent for this series, and when magnesium (Mg) is added in a smaller amount, the result is a heat-treatable, very high strength alloy. Other elements such as copper (Cu) and chromium (Cr) may also be added in small quantities.
Non-heat-treatable alloys (NHTAs)	3xxx series	Manganese (Mn) is the major alloying element in this series, often with smaller amounts of magnesium (Mg) added.
	4xxx series	4xxx series alloys are combined with silicon (Si), which can be added in sufficient quantities to lower the melting point of aluminum, without producing brittleness. Because of this, the 4xxx series produces excellent welding wire and brazing alloys where a lower melting point is required. Alloy 4043 is one of the most widely used filler alloys for welding 6xxx series alloys for structural and automotive applications.

Alloy designation	**Alloy series**	**Description** (20)
	5xxx series	Magnesium (Mg) is the primary alloying agent in the 5xxx series and is one of the most effective and widely used alloying elements for aluminum. Alloys in this series possess moderate to high strength characteristics, as well as good weldability and resistance to corrosion in the marine environment.

There were 5 grades of steel available in 1960, and today there are over 175 grades (17). Automotive steels can be classified in several different ways (21). One is a metallurgical designation providing some process information (Table 2).

Table 2. Steel grades

Steel metallurgical designation	**Steel grades** (21)	**Description** (22)
Low-strength steels (LSS)	Interstitial-free (IF), Mild steels	Tensile strengths less than 295 MPa
Conventional high-strength steels (HSS)	Bake hardenable (BH), High-strength, low-alloy steels (HSLA), and C-Mn-steels.	Tensile strengths between 210 MPa to 550 MPa
Advanced high-strength steels (AHSS)	Dual Phase (DP), Complex-Phase (CP), Ferritic-Bainitic (FB), Martensitic (MS), Transformation-Induced Plasticity (TRIP), Hot-Formed (HF), and Twinning-Induced Plasticity (TWIP).	Tensile strengths higher than 550MPa. AHSS grades contain significant alloying and two or more phases.

According to WorldAutoSteel (21), “AHSSs are complex, sophisticated materials, with carefully selected chemical compositions and multiphase microstructures resulting from precisely controlled heating and cooling processes. Various strengthening mechanisms are employed to achieve a range of strength, ductility, toughness, and fatigue properties. The multiple phases provide increased strength and ductility not attainable with single phase steels, such as HSLA grades. The principal difference between conventional HSLA steels and AHSS is their microstructure. Conventional HSLA steels are single-phase ferritic steels with a potential for some pearlite in C-Mn steels. AHSS are primarily steels with a multiphase microstructure containing one or more phases other than ferrite, pearlite, or cementite—for example martensite, bainite, austenite, and/or retained austenite in quantities sufficient to produce unique mechanical properties”. Research is going on for the development of the “3rd Generation” of AHSSs with special alloying and thermo-mechanical processing to achieve improved strength-ductility combinations compared to present grades (21). *AHSS, HSS and mild steel grades are used for both Baseline and AA LWT auto body parts* (Section 4).

4.0 Description of the Baseline and AA LWT Auto Body Parts

According to Henriksson and Johansen (18), "When examining where to reduce weight in a vehicle, *the body* is a preferential subsystem due to its large contribution to overall mass and the stability of body composition over *a specific model range*. Since the body is more or less standardized throughout a model range, mass reduction in the body will contribute to a mass reduction to all trim levels of that model, whereas a mass reduction in interior or powertrain components might apply only to a select number of vehicles".

In 2016, the EDAG Group, one of the world's largest independent automotive development partners, completed a comprehensive lightweighting study for NHTSA using a 2014 Silverado 1500 as the baseline vehicle (3). Taking a wide range of factors into consideration such as significant market share in the full-size pickup segment, payload and towing capacities, powertrain combination, fuel economy ratings, body/cab configurations, and the newly 2010 major redesign, the 2014 Chevrolet Silverado 1500 (Crew Cab with Short Box (5 ½ ft.), EcoTec3 5.3L-V8 engine with a 4x4 drivetrain, trim level 1WT) was selected to be the full-size pickup reference vehicle (3). Table A1, Annex B details the main specifications of the 2014 Chevrolet Silverado 1500. The vehicle description parameters listed in Table A1, Annex B are primarily based on the EDAG 2016 Report on "*Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025*" (3) and U.S. Department of Energy website (www.fueleconomy.gov), the official U.S. Government source for fuel economy information. The reference vehicle falls under the U.S. EPA size class "pickup trucks, small", with GVWR < 6,000 lbs. (< 2,722 kg) (2).

The redesigned lightweight truck of the NHTSA study has an *aluminum-intensive multi-material body* achieving 39% (198 kg) of mass reduction (3). The powertrain for the LWT design conceived in the NHTSA study was downsized to maintain the same gross vehicle weight rating (GVWR) to horsepower (HP) ratio as the baseline vehicle (3). From a full vehicle perspective, the NHTSA LWT design (with P/T adaptation) achieved a mass saving of 16.7% (406 kg) compared to the Baseline (3).

This LCA report is focused on the subsequent work by EDAG to assess the *additional weight savings* of using *advanced aluminum grades* provided by the Aluminum Transportation Group of the Aluminum Association to produce an *advanced aluminum body* design on top of the NHTSA LWT body design (4). While additional mass savings beyond the body design appear possible given the substantial mass reduction in the body design, such secondary mass savings were not part of the EDAG design and as such not considered in the scope of this LCA.

The AA LWT body design includes three main components/ assemblies: [1] the crew cab assembly (including fenders), [2] the pickup box, and [3] closers (including front door, left and right; rear door, left and right, and the hood)— see Figure 3 (4) and Table 3 (23). *Only design* *considerations that were judged to be practical based on technical feasibility and cost effectiveness were included in the AA LWT body design* (4). The structure was optimized using computer aided engineering (CAE) simulation for crashworthiness safety, structural stiffness, and strength load cases (4). Use of advanced grades of aluminum leads to an additional 32.5 kg (10.6%) mass reduction compared with the multi-material body design conceived in the NHTSA study—see Table 4 (4). This is equivalent to a total body mass reduction of 231 kg (46%) when compared with the equivalent subsystems (504 kg) of the baseline vehicle MY2014 Chevrolet Silverado 1500 (2,432 kg) (4). Both the NHTSA LWT and AA LWT body designs used the MY2014 Silverado 1500 as the prototype vehicle (3), (4).

An auto part is defined as a part, component, or sub-assembly of a road vehicle designed either for passenger or cargo transport, or both (2). Table 3 shows the AA LWT body design mass reduction (in absolute and percent basis), per *assembly*. The cab assembly accounts for 127 kg weight reduction and is the largest contributor (55%) to the total body mass reduction (231 kg). Both Baseline and AA LWT body systems have a similar mass distribution per sub-assembly that consists of about 54% for the cab assembly, 22% for the pickup box, and 24% for closures.

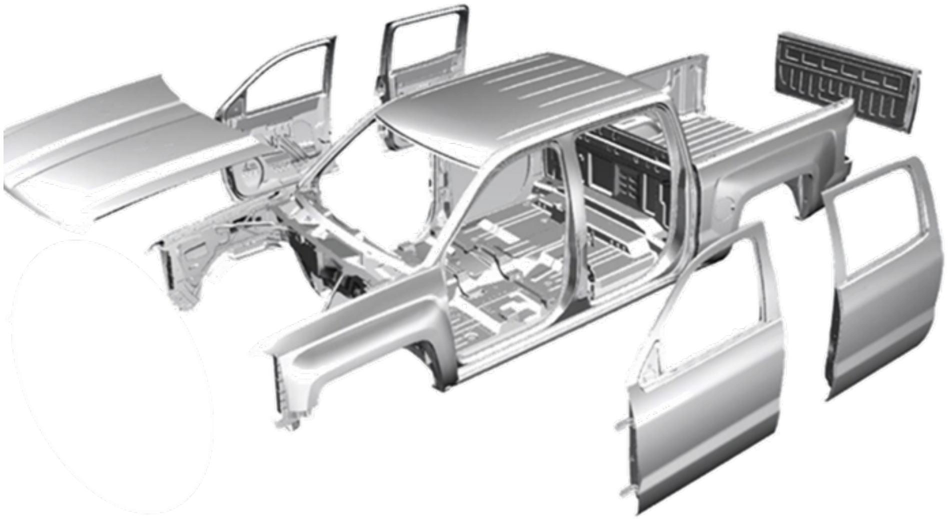


Figure 3. EDAG AA LWT body design (4)

Table 3. AA LWT body design mass reduction, per assembly (in absolute and % basis)

Assembly	**Baseline mass** (4), (23)		**AA LWT body design mass** (4), (23)		**AA LWT body design mass reduction**	
	kg	% of total	kg	% of total	kg	%
1. Cab assembly	272.6	54%	145.9	53%	126.6	46%
2. Pickup box	109.0	22%	60.1	22%	48.9	45%
3. Closures	122.9	24%	67.6	25%	55.3	45%
Total Body	**504.4**	**100%**	**273.7**	**100%**	**230.8**	**46%**

1) Please note data may not add up to totals due to rounding.

Table 4. EDAG AA LWT body design mass reduction compared to Baseline and NHTSA body design (in absolute basis) (4), (23)

Sub-assembly	**Baseline**	**NHTSA body design**		**EDAG AA LWT body design**		
	Mass (kg)	**Mass** (kg)	**Mass reduction compared with Baseline** (kg)	**Mass** (kg)	**Mass reduction compared with Baseline** (kg)	**Mass reduction compared with NHTSA Body design** (kg)
1. Cab	240.1	140.9	99.2	131.0	109.1	10.0
2. Fenders	32.5	16.2	16.3	15.0	17.5	1.2
3. Pickup box	109.0	65.0	43.9	60.1	48.9	4.9
4. Front door, left	23.5	16.3	7.2	12.4	11.1	3.9
5. Front door, right	23.5	16.4	7.1	12.5	11.0	3.9
5. Rear door, left	21.7	14.5	7.3	10.2	11.5	4.3
7. Rear door, right	21.7	14.5	7.2	10.3	11.5	4.3
8. Hood	11.2	11.2	0	11.2	0	0
9. Tailgate	21.3	11.0	10.3	11.0	10.3	0
Total Body (kg)	**504.4**	**306.1**	**198.3**	**273.7**	**230.8**	**32.5**
Mass reduction (%)	n/a	n/a	**39.3%**	n/a	**45.8%**	**10.6%**

[1)] Please note data may not add up to totals due to rounding.

Table 5 shows the AA LWT body design mass reduction (in absolute and percent basis) for each *sub-assembly* (auto parts). The cab and pickup box are the two largest auto parts (sub-assemblies) that combined contribute 70% of the total body mass. The rest of the auto parts each contribute between 4 and 5% to the total body mass.

Table 5. AA LWT body design mass reduction compared to Baseline, per auto parts (4), (23)

Auto parts (sub-assembly)	**Baseline mass**		**AA LWT body design mass**		**AA LWT body design mass reduction**	
	kg	% of total	kg	% of total	kg	%
1.Cab	240.1	48%	131.0	48%	109.1	45%
2. Fenders	32.5	6%	15.0	5%	17.5	54%
3. Pickup box	109.0	22%	60.1	22%	48.9	45%
4. Front door, left	23.5	5%	12.4	5%	11.1	47%
5. Front door, right	23.5	5%	12.5	5%	11.0	47%
6. Rear door, left	21.7	4%	10.2	4%	11.5	53%
7. Rear door, right	21.7	4%	10.3	4%	11.5	53%
8. Hood	11.2	2%	11.2	4%	0	0%
9. Tailgate	21.3	4%	11.0	4%	10.3	48%
Total Body (kg)	**504.4**	**100%**	**273.7**	**100%**	**230.8**	**46%**

1) Please note data may not add up to totals due to rounding.

Table 6 shows carry-over items from the Baseline (100 kg) per AA LWT sub-assembly (4). Carry-over (*non-structural mass*) items have not undergone any mass changes in the framework of the NHTSA LWT and EDAG AA LWT studies (3), (4). Their total net change in production, use, and EOL stage, and cradle-to-grave environmental profile is therefore "null" under the chosen calculation procedure. Note that the calculation of percentage reductions in absolute cradle-to-grave LCIA results between Baseline and AA LWT body would require the inclusion of these items. Therefore, such percentage reduction information is not feasible in this report.

Table 6. Carry-over items per AA LWT auto body parts

Auto parts (sub-assembly)	**Carry-over items** (These items are carried over from the Baseline, no changes (3))
1. Cab	Paint, sealer and anti-flutter adhesive, windshield, and rear glass.
2. Fenders	Liners and insulation.
3. Pickup box	Paint.
4. Front door, left	Hem and anti-flutter adhesive, glass, mirrors (front doors only), electrical components (switches, wiring, etc.), mechanisms (handles, hinges), locks, latches, linkages, seals, trim, and fasteners.
5. Front door, right	
6. Rear door, left	
7. Rear door, right	
8. Hood	Hem and anti-flutter adhesive, hinges, latch, and associated hardware.
9. Tailgate	Hinges, latch/lock, and striker.

4.1 Cab assembly

The cab assembly consists of the cab (or cabin) structure, front-end sheet metal (FESM), and radiator support, as shown in Figure 4 (3). According to EDAG (3), "The cab is the occupant compartment containing the seats, console, instrument panel, etc. The FESM includes the fenders and any supporting structure associated with them. For the baseline vehicle, the left hand and right hand FESM assemblies are bolted on to the cab structure. The radiator support structure is bolted to the front of the FESM. The Baseline 2014 Chevrolet Silverado 1500 body is a modern unibody monocoque structure constructed primarily from HSS". The Baseline cab structure consists of the main BH steel panels such as the body side structure, outer panels, front and rear floor, roof, and front-of-dash panel except for the back panel that uses mild steel (3).

The new EDAG AA LWT cab structure makes extensive use of 6XXX-T6 aluminum grades for the body side structure, outer panels, front and rear floor, and roof and back panel except for front-of-dash panel that uses 5XXX alloy series (3)—see Tables A2, A3, and A4, Annex B. The FESM (fenders) sub-assembly on the Baseline 2014 Chevrolet Silverado are each composed of an inner and outer panel, reinforcements, brackets, supports, fasteners, liner, and insulation (Figures 5 and 6). The left-hand fender also has a battery tray. Apart from the liners and insulation, all of these components are constructed of steel (3). The EDAG AA LWT fender construction replaces the steel stampings with aluminum and can be produced using the same presses as the baseline vehicle fender (3), (4). The Baseline radiator support on the 2014 Chevrolet Silverado is primarily constructed of stamped steel elements spot-welded together (3). The EDAG AA LWT radiator support is assumed to be the same as the Baseline. A hybrid aluminum/magnesium radiator support was not estimated to be practical from a cost perspective ($/ pound mass reduction) and was not included in the EDAG AA LWT body design study.

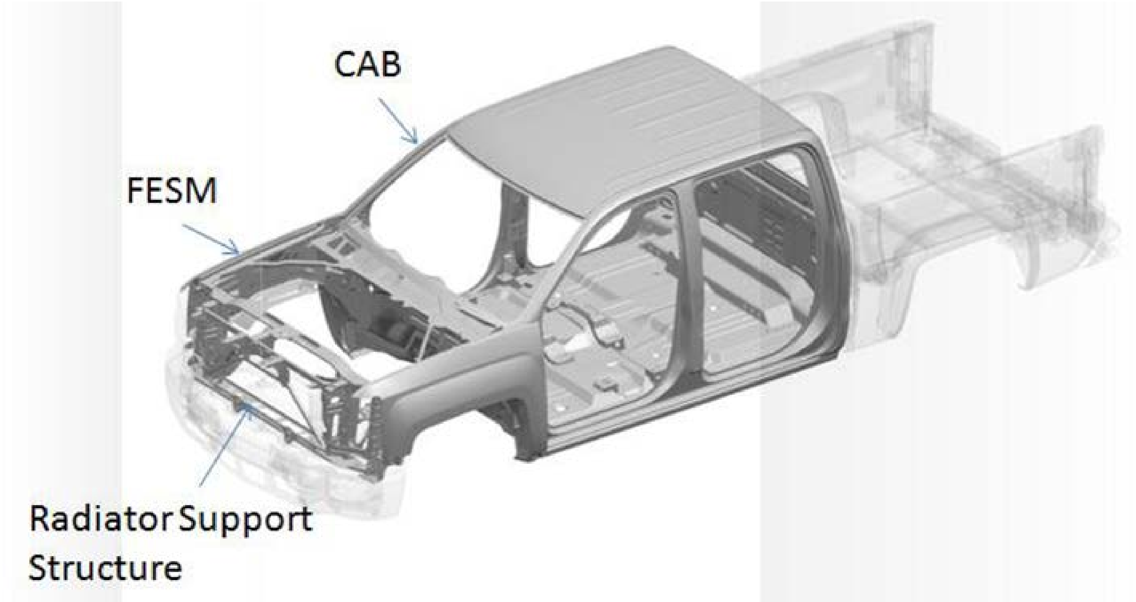


Figure 4. Baseline Chevrolet Silverado 1500 cab assembly (3)

Figure 5. Baseline right FESM sub-assembly (3)

Figure 6. Baseline left FESM exploded view (3)

4.2 Pickup box

The Baseline pickup box front panel and sides are made of stamped steel inner panels spot-welded to stamped steel outer panels (3). According to EDAG (3), “The floor structure is made of a roll formed panel spot-welded to roll formed and stamped cross members. The four sub-assemblies are spot welded together to make up the pickup box assembly”—see Figures 7 and 8. Outer and inner panel wheelhouse and box headboard (front), and bed floor panel make use of BH and HSLA, respectively (3). The EDAG AA LWT pickup box design replaces the baseline steel with aluminum (4). Manufacturing of an all-aluminum pickup box (consisting of 6XXX-T6 grade) can also be performed with the same presses and processing sequences as the Baseline steel design, though joining will require adhesive bonding and self-piercing rivets (4), (3).

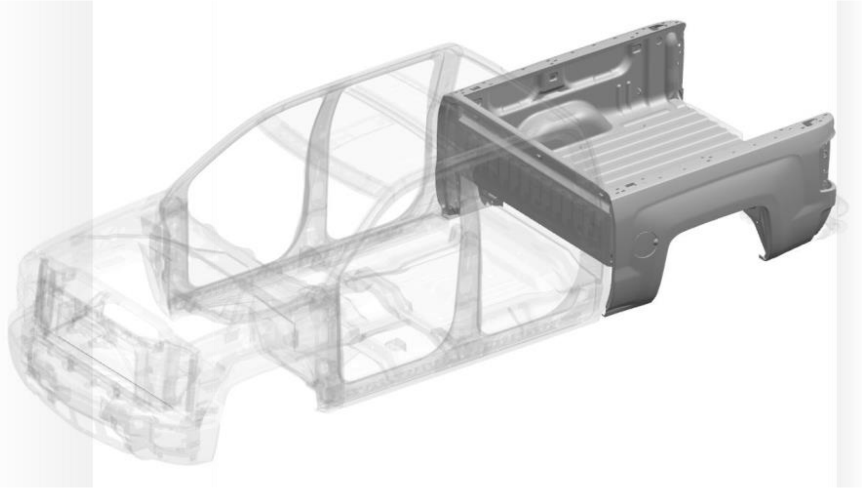


Figure 7. 2014 Chevrolet Silverado Pick-up box (3)

Item	Descriptive Part Name
1	PANEL - BED HEAD BOARD
2	FILLER D PLR UPPER RH
3	PANEL - REINF SIDE INNER RH
4	FILLER D PLR LOWER RH
5	PANEL - BED SIDE OUTER RH
6	PANEL - BED SIDE INR RH
7	REINF W HOUSE FRT INR RH
8	REINF W HOUSE MID INR RH
9	REINF W HOUSE INR REAR RH
10	REINF - E PLR REAR UPR RH
11	REINF - E PLR REAR RH
12	TAIL GATE HINGE BRACKET RH
13	BRKT E PLR REAR RH
14	BRKT E PLR REAR LH
15	REINF - E PLR REAR LH
16	REINF - E PLR REAR UPR LH
17	TAIL GATE HINGE BRACKET LH
18	BED CROSSMEMBER 05
19	BED CROSSMEMBER 04
20	BED CROSSMEMBER 03
21	BED CROSSMEMBER 01
22	BED CROSSMEMBER 02
23	DOOR FUEL TANK ASM
24	REINF W HOUSE FRT INR LH
25	REINF W HOUSE MID INR LH
26	REINF W HOUSE INR REAR LH
27	PANEL - BED SIDE INR LH
28	PANEL BED SIDE OUTER LH
29	FILLER D PLR LOWER LH
30	PANEL - REINF SIDE INNER LH
31	FILLER D PLR UPPER LH
32	PANEL - BED FLOOR
33	BRACKET REAR MOUNTING RH
34	SPACER - BED CROSS MEMBER x 6
35	BRACKET REAR MOUNTING LH
36	TIE DOWN BRACKET x 4

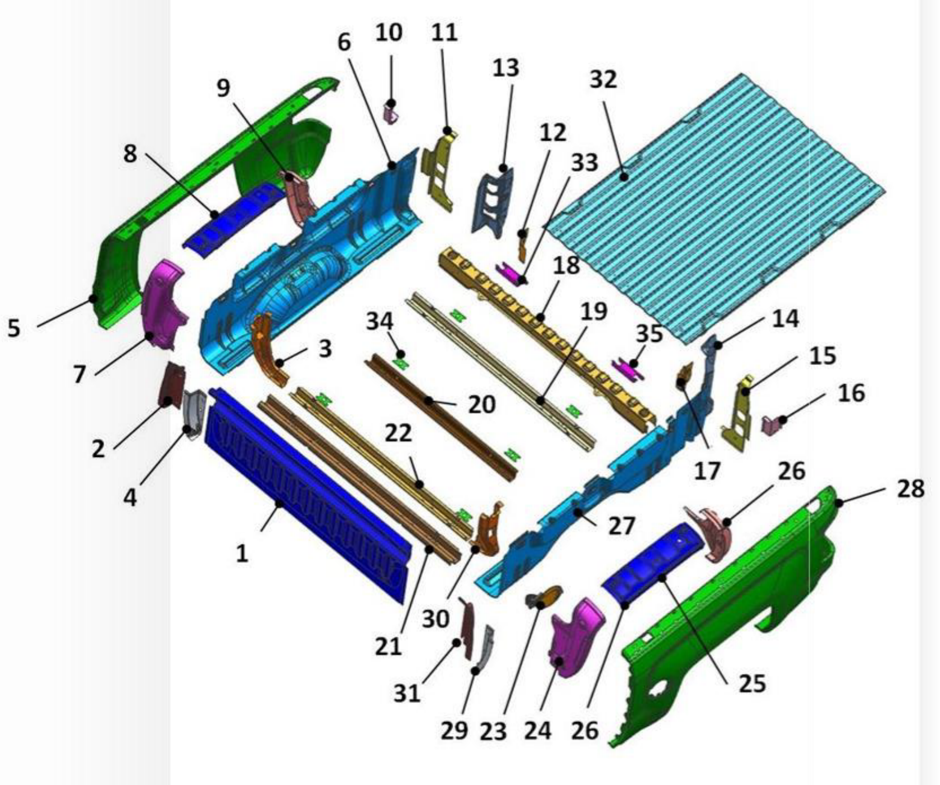


Figure 8. Baseline Pickup box exploded view (3)

4.3 Closures

According to EDAG (3), “The closures on a pick-up truck (PUT) are defined as the doors, hood and tailgate (Figure 9). The *structural mass* of these assemblies includes only the primary load carrying components such as the inner and outer panels, reinforcements, brackets, support beams, hinges, regulator guides and window frames. The structural mass does not include glass, mirrors, electrical components, mechanisms, locks, latches, linkages, seals, trim and fasteners”.

The front doors of the Baseline 2014 Chevrolet Silverado are constructed of cold rolled sheet steel of various HSS grades (Figure 10). In fact, “The major components of the complete door assembly include the frame (inner and outer panels, intrusion beam, regulator guides and various reinforcements), glass, mirror, lock, latch, handles, hinges, electrical components (switches, speakers, wiring, etc.), trim panels, seals and fasteners” (3). The new front door design utilizes aluminum stampings instead of the Baseline steel stampings (4). The stamped inner door structure, including the inner beltline and hinge reinforcement panels, the outer panel, and the outer beltline reinforcement stampings are all aluminum (3), (4). The intrusion beam is AHSS to provide adequate side impact protection (3), (4). According to EDAG (3), “Manufacturing of the aluminum design can be accomplished using the same stamping presses as the Baseline door.

As with the Baseline, the inner and outer door panels would be joined using existing roller hemming equipment".

Like the front doors, the rear doors of the Baseline 2014 Chevrolet Silverado are constructed of BH and HSS cold rolled sheet steel (Figure 11) (3), (4). The major components of the complete rear door assembly are the frame (including inner and outer panels, intrusion beam, regulator guides, brackets, and reinforcements), glass, lock, latch, handles, hinges, electrical components (switches, wiring, etc.), trim panel, and seals and fasteners (3). In fact, "The construction of the rear door frame is similar as was described for the front door, with the laser welded inner panel joined to the outer panel by roller hemming. The structural components of the rear door frame are all constructed of roll formed or stamped steel" (3).

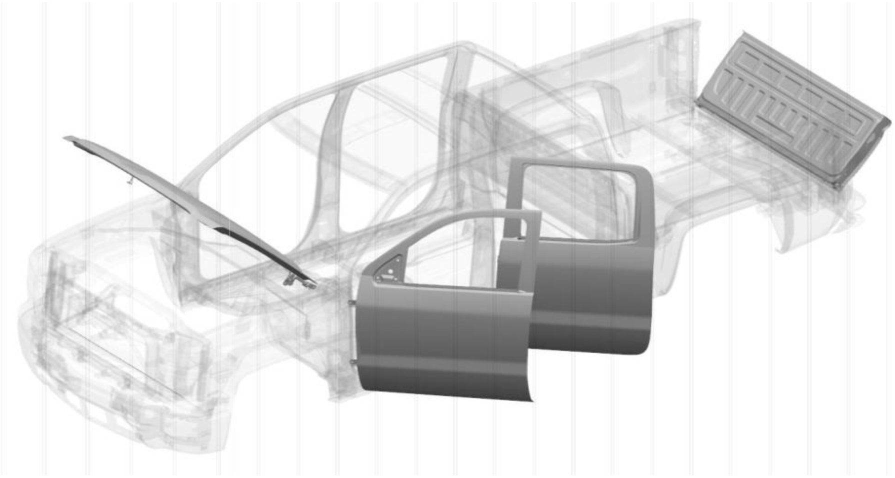


Figure 9. 2014 Chevrolet Silverado Closures (3)

Figure 10. Baseline front door frame (3)

Figure 11. Baseline rear door frame (3)

The inner and outer panels of both the Baseline 2014 Chevrolet Silverado and EDAG AA LWT hood are constructed of aluminum stampings, as are the reinforcements (3), (4). According to EDAG (3), “The inner panel is joined to the outer panel by roller hemming. The hinges, latch and associated hardware are made of high strength steel” (3). An exploded view of the hood sub-assembly can be seen in Figure 12.

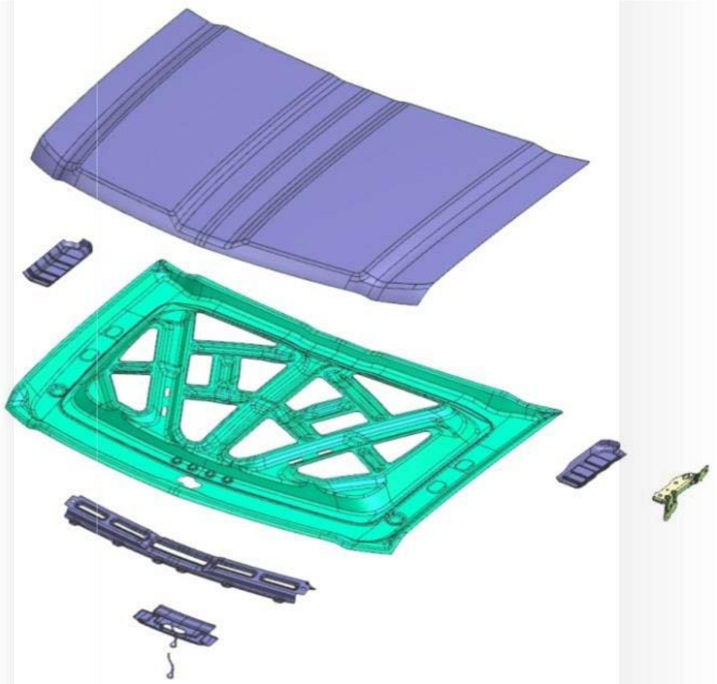


Figure 12. Baseline hood exploded view (3)

An exploded view of the tailgate structure is shown in Figure 13 (3). According to EDAG (3), "Like the doors, tailgate of the 2014 Chevrolet Silverado is composed of a laser welded inner panel roller hemmed to the steel stamped outer panel A removable access panel is bolted to the inner panel". The EDAG AA LWT tailgate replaces the baseline steel stampings with aluminum for the outer panel, inner panel, access panel and reinforcements (4). The hinges, latch/lock and striker are carried over from the baseline (3), (4)—see Table 6.

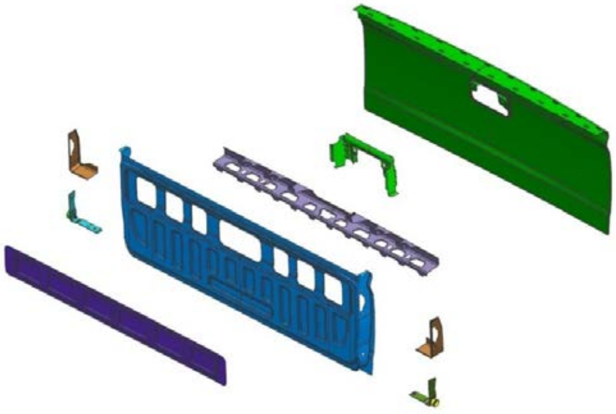


Figure 13. Baseline tailgate exploded view (3)

4.4 Baseline and AA LWT Body Design Composition by Material Type, Designation and Alloy Series and Grades

The EDAG AA LWT body design *is* identified as an "*advanced aluminum intensive"* design, and consists of advanced grade aluminum parts for mass reductions. *2014 Chevrolet Silverado 1500 Body components are* identified as "*HSS and AHSS intensive"* components.

Table 7 details the composition by material type and designation (on absolute basis) of the Baseline and AA LWT body design. Figure 14 shows the body composition by material type in percentage. Body composition by material designation, in percentage, is depicted in Figure 15. Aluminum 6XXX series heat-treatable alloys (HTAs) and 5XXX series non-heat-treatable alloys (NHTAs) dominate the AA LWT body design, 83% and 4%, respectively. In comparison, the Baseline body system is dominated by steel (97%) utilizing HSS (79%), AHSS (13%), and LSS (6%).

Figure 16 highlights the Baseline and AA LWT body design composition by material grades, in percentage. BH and HSLAs account for 48% and 31% of the Baseline weight, respectively. 6XXX and 5XXX alloy series account for 83% and 4% of the AA LWT body design weight, respectively. MS, HF, DP and mild steels contribute between 1 and 6% to the total mass body systems.

Table 7. Baseline and AA LWT body design composition, by material type and designation (in absolute basis)

Baseline (23)				**AA LWT body design** (23)			
Material type	**kg**	**Material designation**	**kg**	**Material type**	**kg**	**Material designation**	**kg**
Steel	490.9	AHSS	64.1	Steel	35.6	AHSS	9.4
		HSS	398.4			HSS	26.2
		LSS	28.4			LSS	0
Aluminum	11.3	HTAs	7	Aluminum	238.4	HTAs	226.5
		NHTAs	4.3			NHTAs	11.9
Plastics	2.2	Plastics1)	2.2	Plastics	0	Plastics1)	0
Total Body	**504.4**		**504.4**	**Total Body**	**274.0**		**274.0**

Note:
1) Injection molded part in the Baseline design was part of the radiator support. The plastic component was eliminated in the AA LWT radiator support design (23).
2) Please note data may not add up to totals due to rounding.

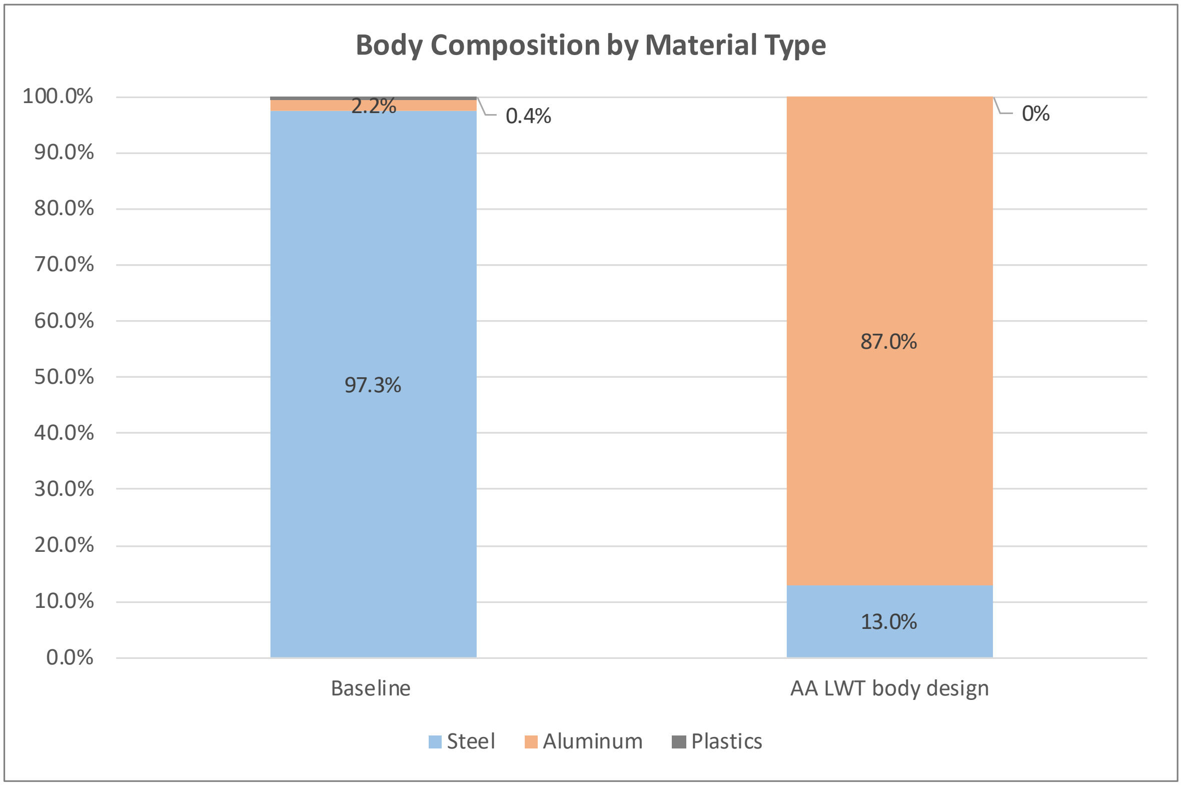


Figure 14. Baseline and AA LWT body design composition, by material type (in %)

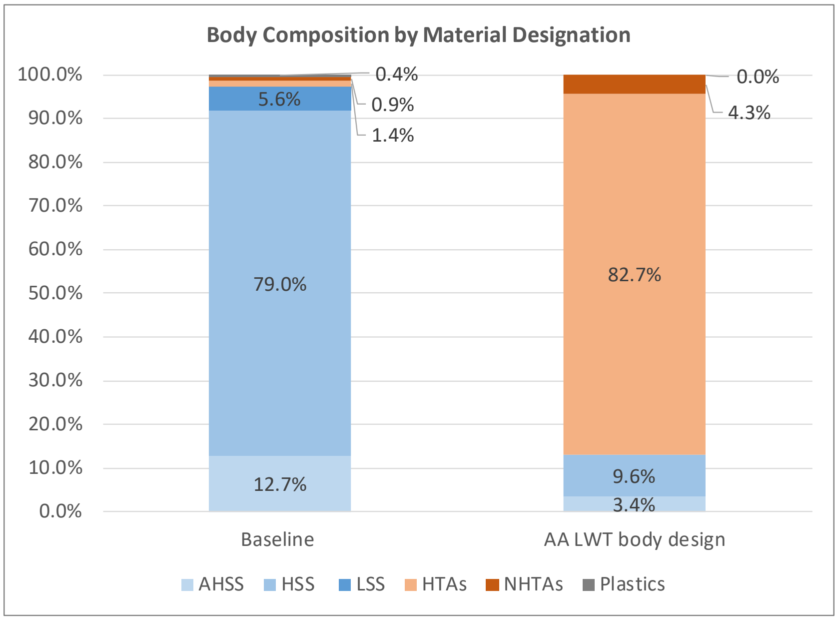


Figure 15. Baseline and AA LWT body design composition, by material designation (in %)

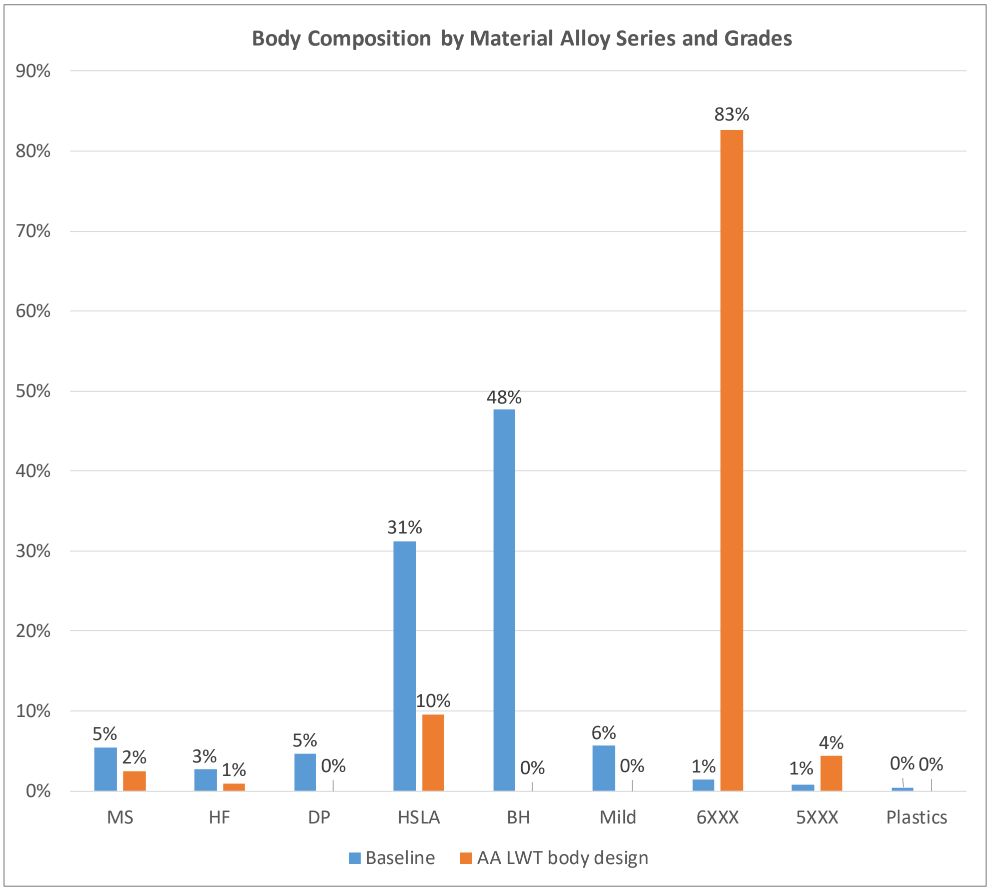


Figure 16. Baseline and AA LWT body design composition, by alloy series and grades (in %)

4.5 Main Auto Part Fabrication Technologies

Table 8 details the main auto part fabrication technologies for both Baseline and AA LWT body design (in mass percentage). *Stamping* is the major fabrication process for both auto body designs. When producing parts using a *conventional cold stamping* process there are a number of die setups that can possibly be utilized, depending on the final part geometry. Types of dies used are progressive, transfer, compound, and combination (24). *Conventional cold stamping* is used for almost all stamped auto parts of both Baseline and AA LWT body design, 91% and 90%, respectively.

Table 8. Main fabrication technologies, per Baseline and AA LWT body design (in mass %)

Main fabrication technology	**Baseline** (23), 504 kg	**AA LWT body design** (23), 274 kg
Aluminum sheet cold stamping	2.2%	80%
Aluminum extrusion	0%	6.9%
Steel sheet cold stamping	89%	9.6%
Steel sheet hot stamping	2.7%	3.4%
Steel sheet roll forming	5.7%	0%
Plastics injection molding	0.4%	0%
Total mass of auto body parts	**100%**	**100%**

1) Please note data may not add up to totals due to rounding.

AHSS hot stamping technology is a new manufacturing technology developed in recent years which combines the traditional hot forging and cold stamping technology. It is a mode of production that integrates the stamping of steel under the condition of high temperature and forming and quenching in the die (25). It is also known as hot forming, hot stamping, hot press, press hardening, or die quenching (25). The Baseline and AA LWT body design use 2.7% and 3.4% hot stamped auto parts, respectively.

Roll forming is a continuous forming process wherein a flat strip is transported through powered or unpowered metal forming stands and rollers gradually form the desired profile in a step by step process (24). Roll forming is only used for MS and HSLA 420-500 Baseline body parts (5.7%).

Extrusion is a process used to create aluminum auto parts of a fixed cross-sectional profile. Aluminum billet is pushed through a die with the desired cross-section. The extrusion process takes cast extrusion billet (round bar stock produced from direct chill molds) and produces extruded shapes (26). Extrusion is only used for aluminum AA LWT body design parts (6.9%).

Tables A2 and A3, Annex B describe in detail the fabrication technology per material type for both Baseline and AA LWT body design (23). Table A4, Annex B details the Baseline and AA LWT body design composition by alloy series and specific grades, in absolute basis (23).

5.0 Goal Definition

5.1 Goal of the Study

Built on the background of the EDAG study designs, the *goal* of this LCA study is to *compare* the life cycle environmental performance of the AA LWT body design to the Baseline body system of the 2014 Silverado 1500 (EcoTec3 5.3L-V8 engine), built and driven for 290,000 km (2), (5) in North America.

5.2 Intended Applications and Audience

The primary intended application of this LCA study is to inform the Aluminum Association, the aluminum industry, policymakers, OEMs, and other stakeholders about the potential life cycle environmental performance of the AA LWT body design compared to the Baseline. Vehicle lightweighting is a well-known and proven method to reduce fuel consumption. Less well-understood is the overall environmental performance of automotive materials in the life cycle of a vehicle due to the fact that the life cycle performance of auto parts needs to be evaluated on a case-by-case basis. The Aluminum Association believes that life cycle thinking is an important part of implementing effective environmental sustainability strategies in the automotive industry. The main findings of this LCA study are intended to provide quantitative information to any interested parties in the North American context regarding the potential environmental impacts of using advanced aluminum to further lightweight an HSS and AHSS intensive pickup truck body.

The intended audience are the Aluminum Association, aluminum industry, policymakers, auto part OEMs and suppliers, auto manufacturers, governmental organizations, industry associations, LCA practitioners, and other stakeholders who desire science-based LCA information on the AA LWT body design and lightweighting in general.

5.3 Comparative Assertions

The results of the LCA study are intended to be used for *comparative assertions* to be disclosed to the public. An *external critical review* was conducted by a *panel of independent experts* in order for the study to be in conformance with ISO 14040 series of Standards and the CSA Group LCA Guidance (1), (2), (6). A brief introduction to the ISO 14040 series of LCA standards and the CSA Group LCA Guidance for auto parts is provided in Annex C.

6.0 Scope of the Study

6.1 Product Overview

A detailed description of the Baseline and AA LWT body systems are provided in Section 4.

6.2 Functional Unit and Reference Flow

A body assembly refers to the stage in automobile manufacturing in which the truck body sheet metal (cab, pickup box and closures) has been assembled, but before other components (engine, chassis, exterior and interior trim, carpets, seats, electronics, plastic trim parts) have been added. The body assembly serves *several functions* during the transportation service (27):

- **Structural function**: To support the weight of the transported passengers and load as well as the mechanical parts required for vehicle propulsion, control, and other system functions, i.e. withstanding mechanical stresses from multiple sources;
- **Safety**: To ensure integrity of the passenger compartment in the event of a crash, while absorbing the impact energy as well as to reduce injuries to vulnerable road users (pedestrians, wheelers), in case of collision;
- **Durability and reliability:** to ensure the long-term performance of a vehicle subjected to extended usage and repetitive loading from driving, towing, and other operating conditions in all types of weather and environments;
- **Ergonomic and roominess**: To supply easy access and adequate room for the driver, passengers, and transported goods;
- **Aerodynamics**: To minimize drag due to air impact; to control air flow effects on tire-road contact and vehicle stability;
- **Insulation**: To minimize noise, vibration, and thermal transmission generated by body walls by lack of sealing between compartment and movable parts, and by thermal radiation from the surfaces of the passenger's compartment;
- **Aesthetics**: To provide a pleasing overall appearance, surface quality, and consistent details; and
- **Visibility**: To provide the highest possible day and night visibility on the environment and to host the lighting devices in the most effective way.

The 2014 Silverado 1500 (baseline vehicle) has a modern monocoque body with chassis built in the body itself and wheels directly mounted to the body with the help of the suspension system (3). In the framework of the NHTSA LWT study (3), EDAG investigated the NHTSA LWT design that underwent mass reductions relative to the baseline vehicle. The new AA LWT body design by EDAG investigated in this LCA study has undergone further mass reductions (32.5 kg) relative to the NHTSA LWT body design (4). EDAG performed extensive assessments for the new lightweight designs to make sure that they are equivalent or improved regarding the most important functions of the body assembly compared to the baseline vehicle, reported as "maintain or improve" by EDAG (3), (4). This process is done by first conducting a full teardown testing and benchmarking of the baseline vehicle (3). The new AA LWT body design was then analyzed by using CAE optimization techniques to ensure equivalent performance for the selected functional parameters (3), (4), assuming that all vehicle components not specific to the AA LWT body design remain the same as for the earlier NHTSA LWT vehicle design. It should be noted that the new AA LWT body design under study in this LCA report is assessed against the body design of the NHTSA LWT vehicle design in Table 9, which was originally assessed against the baseline vehicle (3), (4). Equivalent or better performance of the vehicle design using the AA LWT body design compared to the NHTSA design therefore suffices to demonstrate equivalent or better performance compared to the Baseline.

Table 9. Selected functional parameters and related assessment techniques (3), (4)

Functional categories	Key parameters	Performance evaluation method
Structural Stiffness & NVH	Noise, vibration and harshness (NVH)	*Normal Modes Frequency Testing.* Baseline was tested. The NHTSA LWT design was CAE analyzed and optimized to ensure *equivalent* performance with the Baseline. The AA LWT design was CAE analyzed and optimized to ensure *equivalent* performance with the NHTSA LWT design.
	Torsion and bending stiffness	*Vehicle Load and Mounting for Torsional and Bending Stiffness Tests.* Baseline was tested. The NHTSA LWT design was CAE analyzed and optimized to ensure *equivalent* performance with the Baseline. The AA LWT design was CAE analyzed and optimized to ensure *equivalent* performance with the NHTSA LWT design.
Durability & Reliability	Strength and durability load	EDAG stated that the Baseline was "an all-new design" at the time of the studies and therefore "real world history on its durability does not yet exist". For that reason, both the Baseline and the new designs were assessed by using basic durability load cases generated from an Automatic Dynamic Analysis of Mechanical Systems ride and handling mathematical model. The durability life cycle simulated was "based upon typical OEM requirements". The simulated durability load cycles during the lifetime of the vehicle was assumed to be 200,000 miles, or 322,000 km, of driving.
Crash-worthiness Safety	Crashworthiness safety	*NHTSA's New Car Assessment Program and Insurance Institute for Highway Safety Ratings Tests.* Baseline was tested. The NHTSA LWT design was CAE analyzed and optimized to ensure equivalent performance with the Baseline. The AA LWT design was CAE analyzed and optimized to ensure equivalent performance with the NHTSA LWT design.

As shown in Table 9 and documented in EDAG reports (3), (4), the lightweight designs were engineered to maintain or improve multiple key functional parameters between the baseline and the lightweight concepts. Of the design performance parameters listed in Table 9, this LCA study selected the crashworthiness safety as the most *basic* and *prominent* function of a body structure: *basic* because safety of passengers was historically the main driver for introducing closed-cabin body structures in automobiles, and *prominent* because NHTSA safety ratings are one of the key pieces of information used in marketing of new vehicle models. As such, the *functional unit* is defined as achieving five stars in the NHTSA's Overall Vehicle Score (OVS) following the same test protocol that was applied to the baseline vehicle in 2012. It should be noted that use of the term "OVS" applies only to a vehicle's overall rating, which is a combination of the overall ratings from the frontal and side crash tests — and rollover resistance. While the new AA LWT design hasn't undergone *actual* NHTSA testing yet, all the *modeled* test results from CAE simulations indicate that it would perform at least on par with the baseline vehicle (4). *For purposes of this LCA*, the vehicle's lifetime driving distance ($LTDD_V$) is set at 290,000 km (2), (5), and the level of quality is described through *comparable* NVH performance, global torsion and bending stiffness, and strength and durability loads. Note that the $LTDD_V$ of 290,000 km shall not be misconstrued to indicate that the *crashworthiness* remains constant over this mileage. It would be tested once for type approval and additional information about whether crashworthiness decreases over the vehicle lifetime or not is unavailable. As such, the functional unit is accepted to be fulfilled with the initial NHTSA safety rating.

In accordance with CSA Guidance LCA for auto parts Section 7.2.4, the reference flow of the Baseline and AA LWT body design is defined based on auto part replacement factor calculations. The body replacement factor (F_R) is calculated by dividing the baseline vehicle's lifetime driving distance of 290,000 km (2), (5) by the assumed body lifetime driving distance ($LTDD_A$). This way, F_R=1 means that the body has an $LTDD_A$ of 290,000 km and no replacement is conducted during the vehicle lifetime other than the first body installation in the vehicle architecture (Table 10). The reference flow of both Baseline and AA LWT body design is defined as 1 (F_R=1).

Table 10. Baseline and AA LWT body design reference flow

Assembly	Baseline			AA LWT body design		
	$LTDD_A$ (in km)	**F_R= $LTDD_V$/ $LTDD_A$**	**Reference flow** (in kg)	**$LTDD_A$** (in km)	**F_R= $LTDD_V$/ $LTDD_A$**	**Reference flow** (in kg)
Body	290,000	1	504.4	290,000	1	274.0

6.3 System Boundary

Figure 17 depicts a generic cradle-to-grave system boundary diagram. It shows all required life cycle stages and processes to be included in the LCA of auto body parts (2). The life cycle stages include production, use and end-of-life (2).

This LCA study follows the attributional LCA approach, which assigns elementary flows and potential environmental impacts to a specific product system typically as an account of the history of the product (6), (2), (28). Furthermore, this study applies the "substitution" allocation approach for recycling (2) (also known as “closed-loop” allocation approach, “EOL recycling”, or “system expansion by substitution”).

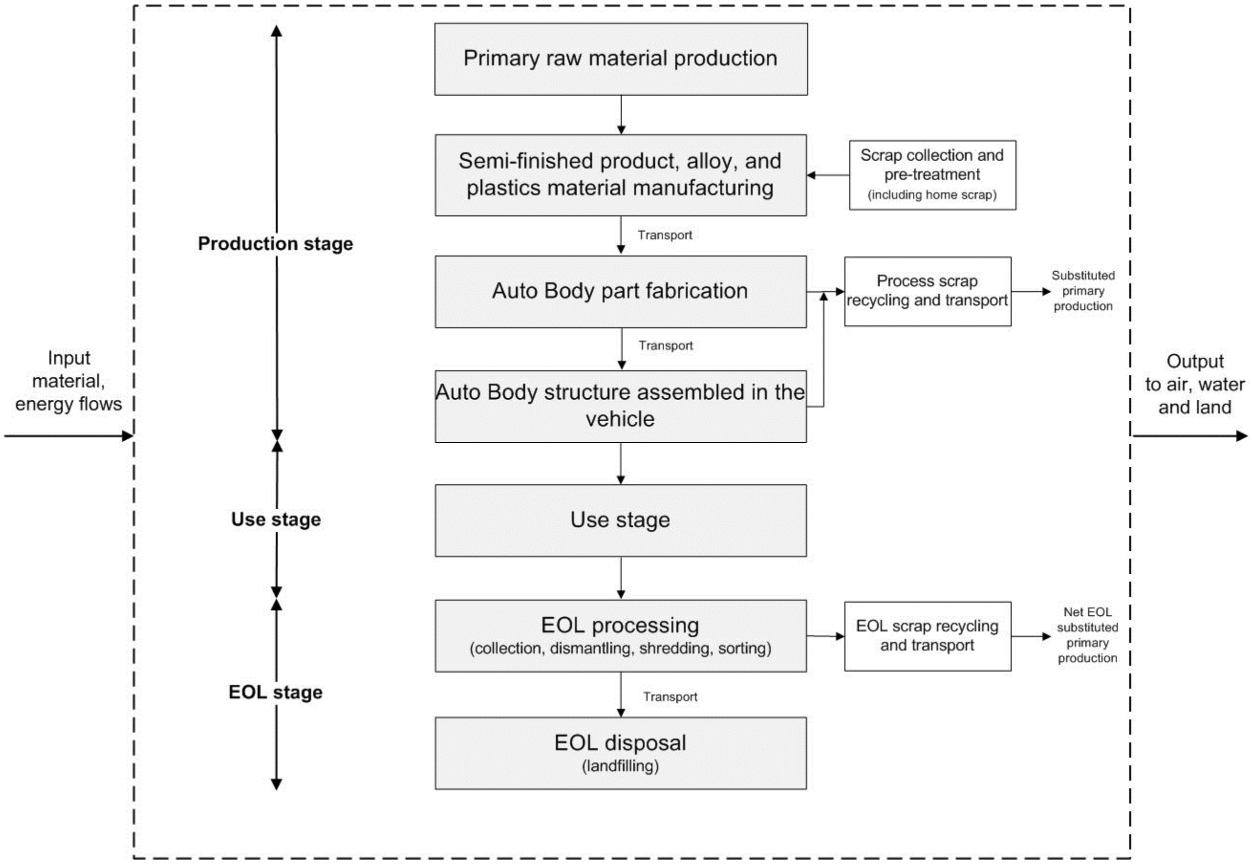


Figure 17. Cradle-to-grave system boundary of the auto body parts

The auto body parts system boundaries follow the “modularity” and “polluter pays” principles (2):

Modularity Principle	• *Where processes influence the product’s environmental performance during its life cycle, they shall be assigned to the life cycle where they occur; all environmental aspects and impacts are declared in the life cycle stage where they appear.*
Polluter pays Principle	• *Processes of waste processing including waste water treatment shall be assigned to the product system that generates the waste until the end-of-waste state is reached.*

In compliance with CSA Group LCA Guidance Section 7.3.2, the *following processes are excluded* from the system boundary (2):

- Capital infrastructure (e.g., factories, roads, trains, ships, production facilities and machinery);
- Employee commute (e.g., employees to and from their normal place of work);
- Human energy inputs to processes and/or preprocessing (e.g., hand assembly rather than by machinery); and
- Production overhead (e.g., heating, ventilation & air conditioning, lighting, offices).

It is worthwhile to point out that the exact same stamping infrastructure can be used for steel and aluminum stamping (3). The total net change in impact of all above excluded processes is expected to be minimal. Finally, auto body parts maintenance and repair processes are deemed optional in the CSA Group LCA Guidance for auto parts (2), and not applicable in the framework of this LCA.

6.4 Allocation Procedures

The allocation rules in general considered within the system boundary conform to ISO 14044 Clause 4.3.4 (1) and CSA Group LCA Guidance Document for auto parts Section 7.4.2.2 (2).

This LCA applies the ISO 14044 and CSA Group LCA Guidance for auto parts conformant "*closed-loop*" allocation procedure for recycling, also called *"substitution", "EOL recycling",* or *"system expansion by substitution"* approach (1), (2), (29), (30), (26), (31). The terminology "*EOL recycling*" approach, is typically used by the metals industry (32). For purposes of environmental modeling, decision-making, and policy discussions involving recycling of metals, the metals industry strongly supports the "*EOL recycling" approach* over the "*recycled content*" *approach* (known as "cut-off" approach) (32).

According to worldsteel (30), "Due to the maturity of the steel recycling system that has developed across the world, steelmakers and scrap merchants have harmonized the use of the steel scrap for relevant products to minimize the costs in treatment of scrap for use in the new steel products. With selection of various scrap grades, some products are recycled into lower quality products, in the same way that some scrap steel is recycled into higher quality products such as aerospace steels". A "closed-loop" approach can therefore be applied for the recycling of steel; this follows ISO 14044:2006 Clause 4.3.4.3, which describes the allocation procedures for closed-loop material recycling (30). ISO 14044 Clause 4.3.4.3.3 states: *"A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material"*.

According to the Aluminum Association (26), "The substitution approach is a recommended approach by the aluminum industry. The recommendation of the "substitution" approach is based on the characteristics of aluminum products and aluminum recycling, which preserves the full physical properties of the metal without losses of quality no matter how many times it is recycled. The aluminum recycling system is a *semi-closed*-loop system in which the recycled aluminum could end up with the same product system, e.g., extruded to extruded products, flat-rolled to flat-rolled products, and shape-casted to shape-casted products, or in other cases, the recycled aluminum from one product system could be used for other product systems depending on the efficient allocation of aluminum scraps by market forces".

The "substitution" approach is deemed applicable for steel and aluminum fabrication and EOL scrap recycling in the framework of this LCA study (26), (29), (30). Sensitivity and Monte Carlo uncertainty analyses were conducted on allocation rules for recycling—see Section 10.2.2. Allocation rules for fabrication and EOL scrap recycling are described in Sections 7.3 and 7.6.

6.5 Cut-off Criteria

The cut-off criteria for flows considered within the system boundary conform to ISO 14044 (1) and CSA Group LCA Guidance for auto parts (2):

- All inputs and outputs to a unit or system process are included in the calculation, for which data are available;
- In cases of insufficient input data or data gaps for a unit or system process, the cut-off criteria is 1% of total energy usage and 1% of the total mass input of that process;
- The total of neglected input and output flows of the cradle-to-grave auto part product system does not exceed a maximum of 5% of energy usage, mass, or environmental impact category indicator covered by this LCA study; conservative assumptions in combination with plausibility considerations and expert judgments are used to demonstrate compliance with these criteria.

6.6 Data Quality Requirements

Adequate activity and LCI primary and secondary data shall be used to model both auto body systems. LCI data should be as representative (technology-, geographically-, and time-specific), complete, consistent, reproducible and transparent as possible with regards to *the goal and scope of the study* (1), (2). A detailed description of collected data and the data quality assessment regarding the ISO 14044 (1) and CSA Group LCA Guidance for auto parts (2) requirements is provided in Tables A14, A15 and A16, Annex J.

6.7 LCA Software

The LCA model was developed using SimaPro v.8.4.0 2018 (https://simapro.com/), an LCA software used by industry and academics in more than 80 countries for 25 years (33). SimaPro LCA software contains recognized databases (e.g., U.S. LCI database and ecoinvent database) that provide LCI datasets for upstream, core, and downstream processes. It also contains the

U.S. EPA TRACI 2.1 LCIA methodology and the Cumulative Energy Demand version 1.09 which are used for this LCA study.

6.8 LCIA Methodology and Types of Impacts

In compliance with the CSA Group LCA Guidance for auto parts Section 7.8, the U.S. EPA TRACI, version 2.1, 2012 impact categories are used for this LCA (34). A detailed description of the TRACI LCIA indicators is provided in Section 9.1 and Table A13, Annex I. *It should be noted that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks* (1).

USEtox® is a scientific-consensus model endorsed by the United Nations Environment Program / Society of Environmental Toxicology and Chemistry Life Cycle Initiative for characterizing human and ecotoxicological impacts of chemicals (35). The main output is a database of recommended and interim characterization factors including fate, exposure, and effect parameters (35). The USEtox model was selected to replace the CalTOX model as the basis for the TRACI v.2.1 impact categories of human health cancer, noncancer, and ecotoxicity (36). This LCA study report does not assess the human and eco-toxicity LCIA indicators ("Human health, cancer", "Human health, non-cancer" and "Ecotoxicity"). The primary reason for exclusion is that the characterization factors for "metals" are classified as "interim" due to the relatively high uncertainty of addressing fate and human exposure for all chemicals within these substance groups (33). Given the high degree of uncertainty of "*interim*" factors for metals, no trustworthy results can be reported for these LCIA categories at this time and have therefore been excluded.

Furthermore, given the data quality of the depletion potential of the stratospheric ozone layer (ODP) emission factors for background LCI profiles, no reliable results can be reported for the ODP indicator and has therefore been excluded. In addition, TRACI v2.1 does not cover the land use impact category. Although it can have a significant impact, the land use impact indicators of NA steel and aluminum semi-finished products are not assessed in the framework of industry-average LCA studies conducted by the respective metal industry associations yet (30), (26). It should also be noted that GREET.net 2017 does not cover the land use impact category for biofuel feedstocks yet (37). Land use has therefore been excluded as an impact category.

6.9 Study Assumptions and Limitations

A detailed description of the study data and data calculations procedures is provided in Sections 4 through 8 and Annexes B, F, I and K. The same data calculation procedures are applied for both Baseline and AA LWT systems. Limitations of the study are summarized in Section 10.3.2.

6.10 Critical Review

The ISO 14040 series of standards (6), (1) require a critical review of the LCA study when the results are intended to be used for comparative assertions to be disclosed to the public. The LCA report and the underlying methodologies and approaches have undergone external, independent critical review, and comply with the requirements of the ISO 14044 standards and CSA Group LCA Guidance for auto parts. The critical review panel consists of (*in alphabetical order*):

- Arpad Horvath, Independent Consultant (otherwise Professor of Civil and Environmental Engineering at the University of California Berkeley, USA, arpad_horvath@hotmail.com);
- Christoph Koffler (Chair), Technical Director, Americas, thinkstep, USA, christoph.koffler@thinkstep.com;
- Simone Ehrenberger, Researcher, DLR, German Aerospace Center, Institute of Vehicle Concepts, Germany, simone.ehrenberger@dlr.de.

The external critical review in no way implies that the external independent reviewers endorse the results of the LCA study or the assessed products. The critical review panel's participation does not represent an endorsement of the technologies, products, or findings by any of the affiliated institutions. It ensures that the LCA study was carried out in compliance with the ISO 14040 series of standards and CSA Group 2014 LCA Guidance of Auto Parts. After incorporation of the comments and recommendations into the final report, the external critical review panel issued a critical review statement. A copy can be found in Annex A: Critical Review Statement.

6.11 LCA Report

EDAG AA LWT is an *ISO 14044 and CSA Group LCA Guidance for auto parts conformant* LCA report which documents the results of the LCA conducted for AA LWT body design in comparison to the auto body parts of the 2014 Chevrolet Silverado 1500 (EcoTec3 5.3L-V8 engine), built and driven for 290,000 km (2) in North America.

This LCA report is critically reviewed, and the final LCA report integrates comments and recommendations from the external independent reviewers. The critically reviewed EDAG AA LWT body design LCA report is deemed appropriate for both internal and external communication.

7.0 Cradle-to-Grave Data Calculation Rules

Section 7.1 provides the rules to calculate the net change in the cradle-to-grave, production, use, and EOL stage environmental profile of the AA LWT auto body parts. Sections 7.2 and 7.3 detail the rules to calculate the cradle-to-gate environmental profile of the *production stage* of auto body parts, auto body replacement factors, and process scrap recycling. The general rules of calculating the life cycle mass-induced fuel savings of the AA LWT auto body parts are described in Section 7.4. Furthermore, Sections 7.5 and 7.6 provide the rules to calculate the environmental profile of the *EOL stage* of auto parts. It also illustrates the ISO 14044 conformant allocation rules for EOL material recycling.

7.1 Total Net Change in the Cradle-to-Grave Environmental Profile of the AA LWT Auto Body Parts

The total net change in the cradle-to-grave environmental profile of the AA LWT auto body parts, with P/T adaptation ($\Delta E_{Total,Body,a}$), is calculated as follows (2):

$$\Delta E_{Total,Body,a} = \Delta E_{P,Body} + \Delta E_{Use,Body,a} + \Delta E_{Eol,Body} \tag{7.1}$$

The total net change in the ***production stage*** environmental profile of the AA LWT auto body parts, with P/T adaptation ($\Delta E_{P,Body}$), is calculated as follows (2):

$$\Delta E_{P,Body} = E_{P,m} - E_{P,b} \tag{7.2}$$

Where,

$E_{P,m}$ = environmental profile of the production stage of the AA LWT body design consisting of nine (9) auto body parts exhibiting mass changes, see Table 5.

$E_{P,b}$ = environmental profile of the production stage of the Baseline body system, consisting of nine (9) auto body parts—see Table 5.

The total net change in the ***use stage*** environmental profile of the AA LWT auto body parts, powertrain (P/T) adaptation ($\Delta E_{Use,Body,a}$), is calculated according to Equation 7.3 below (2):

$$\Delta E_{Use,Body,a} = \mathrm{C}_{\mathrm{A,Body}} \times \left(E_{FP} + E_{FC}\right) \tag{7.3}$$

Where,

$C_{A,Body}$ = the maximum total life cycle mass-induced fuel savings (decrease) of the auto body parts exhibiting mass changes, in liters or gallons (e.g., *-2,543.4 L or -672.0 gal.*—see Section 7.4).

E_{FP} = environmental profile of producing 1 L or gal. of gasoline (WTP, well-to-pump, known as well-to-tank).

E_{FC} = environmental profile of combusting 1 L or gal. of gasoline (vehicle operation, PTW, pump-to-wheel, known as tank-to-wheel).

As described in Annex D, the full fuel cycle is the combination of the WTP and PTW, which is also commonly referred to as a well-to-wheels, WTW. The WTW LCI profile (both production and combustion) of gasoline was generated by using the GREET.net 2017 Model, Argonne National Laboratory, software version 1.3.0.13239, January 16, 2018. The profile is presented in Table A9, Annex E. The Type 2 pickup truck (PUT) lightweight material (HSS lightweight version) is selected for the purposes of this LCA. The Type 2 PUT conventional and lightweight are based on U.S. EPA's 2015 teardown of a 2011 Chevrolet Silverado [conventional], which was then redesigned for the lightweight version (38), (39), (40), (41). The Type 2 PUT lightweight version is mostly achieved through high strength steels (40), (41).

Vehicle emissions in GREET.net 2017 are developed using EPA's MOtor Vehicle Emission Simulator model (MOVES), which captures emissions from cold starts, warm starts and evaporation (43). MOVES uses the Tier 3 approach for estimating exhaust emissions from road transport. (42), (43). It is a state-of-the-science emission modeling system that estimates emissions from mobile sources at the national, county, and project level for criteria air pollutants, greenhouse gases, and air toxics (42). Regarding the *vehicle operation* emissions, Group 2 reflects legislative exhaust emission requirements for vehicles and engines regulated by the EPA (42) (see Table A7, Annex D and Annex E). Parameters like driving behavior, notably acceleration, and the exhaust after-treatment design by each manufacturer are important factors that influence the regulated exhaust emissions (43). Although significant mass reduction of the vehicle usually leads to a reduction of fuel consumption on a per-km (mile) basis, and it could also lead to design changes of the exhaust after-treatment, measurable influence of lightweighting on the reduction of exhaust emissions have not been captured by generic statistical data for gasoline combustion in pickup trucks (38). For these reasons, *with the exception of Group 1, Groups 2 to 5 operation emissions are assumed to remain the same in the framework of this LCA.*

The total net change in the ***EOL stage*** environmental profile of the AA LWT auto body parts, with P/T adaptation ($\Delta E_{Eol,Body}$), is calculated as follows (2):

$$\Delta E_{Eol,Body} = E_{Eol,m} - E_{Eol,b} \tag{7.4}$$

Where,

$E_{EOL,m}$ = environmental profile of the EOL stage of the AA LWT body design consisting of nine (9) auto body parts exhibiting mass changes—see Table 5.

$E_{EOL,b}$ = environmental profile of the EOL stage of the Baseline body system, consisting of nine (9) auto body parts—see Table 5.

7.2 Production Stage

The calculation of cradle-to-gate environmental profile of the production stage of both Baseline and AA LWT body design is conformant to ISO 14044 (1) and CSA Group LCA Guidance for auto parts (2) and includes the following unit processes:

Life Cycle Stage	Processes
Production Stage	(a) Production of raw materials (see Table A14, Annex J); (b) Transportation of the raw materials from production to manufacturer, based on average distance and mode (see Tables A14 and A15, Annex J); (c) Manufacturing of semi-finished product, e.g., hot-dip galvanized coil (see Table A14, Annex J); (d) Transportation of the manufactured product from manufacturer to fabricator (see Table A15, Annex J); (e) Auto body fabrication processes (see Table 11; Tables A2 and A3, Annex B and Table A14, Annex J); location of the fabrication plant is assumed to be Flint, Michigan, U.S.; (f) Average transportation of the auto body parts from fabricator to assembler (see Table A15, Annex J); (g) Auto body parts assembly in vehicle; location of the assembly plant is assumed to be Flint, Michigan, U.S.; (h) Recycling of process scrap, as applicable (see Table 11); (i) Transport of recycled material (see Table A15, Annex J); and (j) Waste and wastewater out-bound transportation and treatment, as applicable (see Tables A14 and A15, Annex J).

7.3 Allocation Rules for Fabrication Process Scrap Recycling

The environmental impact of process scrap recycling (PSR) and/or disposal is reported as part of the production stage. The PSR covers the environmental impact associated with the collection of the process scrap, sorting, melting, refining, and “substitution” of primary material production.

The environmental impact of PSR (E_{PSR}) is calculated as follows (2):

$$E_{PSR} = W_f \times Y_f \times (E_{sec} - E_{prim}) \tag{7.5}$$

Where,

W_f = mass input of process scrap to secondary production (see Table 11);

Y_f = yield for the recycling of process scrap from manufacturing of material that will substitute primary production (see Table 11); a 1:1 substitution rate is applied (2);

E_{sec} = environmental profile per unit of mass of material due to secondary production, e.g., Al recycling ingot (100% scrap) (see Table A14, Annex J and Annex G); and

E_{prim} = environmental profile per unit of mass of material due to primary production, e.g., primary aluminum ingot (see Table A14, Annex J and Annex G).

The typical process scrap and yield values per main material and fabrication technologies are given in Table 11. Total amount of process scrap to secondary production is assumed to be generated during the auto body part fabrication processes. This analysis assumes that no process scrap is generated during the auto body parts assembly into vehicle process.

Table 11. Fabrication scrap and yield values per main material and fabrication technologies

Main auto parts fabrication technology	**Auto part fabrication**			**Process scrap recycling**	
	Yield[1] (%)	**Amount of scrap** (in kg/kg part)	**Reference(s)**	**Yield (Y_f)** (in %)	**Reference**
Aluminum sheet cold stamping[4]	54%	0.852	(44) (45)	95.7%	(26)
Aluminum extrusion	77.5%	0.290	(26)	95.7%	(26)
Steel sheet cold stamping[4]	54%	0.852	(44) (45)	91.6%	1/1.092kg (30)[3]
Steel sheet hot stamping[4]	54%	0.852	(44) (45)		
Steel sheet roll forming	95%	0.053	(46)		
Plastics injection molding[5]	95.7%	0.045	(33)	100%	(2)

[1] Fabrication yield is also known as "material efficiency", "material utilization";

[2] The Aluminum Association has developed two LCI profiles of secondary aluminum ingot (26): *Al recycling ingot (100% scrap)*, used to calculate the "Value of Al fabrication scrap" and *secondary aluminum ingot (primary metal and alloy added)*, used to calculate the "Value of Al EOL scrap". The definition of primary and secondary Al products is provided in Annex G;

[3] "Value of steel scrap" LCI profile [=Y_f × (E_{prim} - E_{sec})] is calculated and provided in a rolled-up form by worldsteel (30). To avoid any data misuse, steel primary and secondary LCI profiles are not made available to LCA practitioners. The definition of primary and secondary steel products is provided in Annex G;

[4] The material efficiency for stamping is estimated to be 54% (90% for blanking and 60% for forming) for both steel and aluminum auto parts in GREET 2017 (44), (45)—see Section 8.2. The Baseline and AA LWT body systems use 91% and 90% cold stamped auto parts, respectively. The Baseline and AA LWT body systems use 2.7% and 3.4% hot stamped auto parts, respectively.

[5] Refers to NA data for injection molding of polypropylene, the most common thermoplasts used for auto parts.

7.4 Use Stage

The use stage includes the total life cycle mass-induced fuel savings of the AA LWT body design due to mass reduction, with P/T adaptation. The AA LWT body design (274 kg) uses a combination of *advanced grades of aluminum alloys* that enabled the engineering team to reduce the AA LWT body design mass by 231 kg (46%) versus its Baseline's body system (504 kg) (4). The structure was optimized using computer aided engineering (CAE) simulation for crashworthiness safety, structural stiffness, and strength load cases (4). Use of advanced grades of aluminum leads to an additional 32.5 kg (10.6%) mass reduction compared with the multi-material NHTSA LWT conceived in the NHTSA study (4). The powertrain for the LWT design conceived in the NHTSA study was downsized to maintain the same gross vehicle weight rating (GVWR) to horsepower (HP) ratio as the baseline vehicle (3).

In the framework of this LCA study, it's deemed technically feasible as well as highly likely that the 231 kg weight savings in the AA LWT body design would allow for the powertrain to be adapted to maintain the same driving performance as the baseline vehicle. A "no P/T adaptation" scenario is deemed *less likely* for the AA LWT body design. The application of the EDAG's "*vehicle strategic systems*" lightweighting approach would *highly likely* lead to P/T adaptation to maintain the same driving performance as the baseline vehicle, measured as the GVWR/HP ratio. A "vehicle strategic systems" lightweighting approach means a shift from *"tactical" mass management* (lightweight parts) to *aggressive mass reduction* (lightweight intensive vehicle).

The total life cycle mass-induced fuel savings (decrease) of the AA LWT body design ($C_{A,Body}$), with P/T resizing, is calculated according to Equation 7.6 (2):

$$C_{A,Body} = (m_{Body} - m_b) \times F_{CP} \times LTDD_V \qquad (7.6)$$

= (273.7 – 504.4) kg × 0.38 L / (100 km×100 kg) × 290,000 km
= **- 2,543 L** or (- 672 gal).

Note: negative values (-) represent a *decrease* in fuel consumption (fuel savings) *due to lightweighting*.

Where,

$C_{A,Body}$	the total life cycle mass-induced fuel savings (decrease) of the AA LWT auto body parts exhibiting mass changes, in liters.
m_{Body}	mass in kg of the AA LWT body design exhibiting mass changes, total of 273.7 kg.
m_b	mass in kg of Baseline's body system, total of 504.4 kg.
F_{CP}	mass-induced fuel change potential value, with P/T adaptation, 0.38 L/(100 km×100 kg), (see Table 12), based on U.S. EPA combined fuel economy (CFE) of 55% City Federal Test Procedure 75, and 45% Highway Fuel Economy Test Cycle (47), (2); Table 12 is applicable for all EPA size

classes of passenger vehicles and light trucks, as specified in CSA Group LCA Guidance for auto parts Section 5.3 (2). F_{CP} represents the theoretical fuel savings with P/T adaptation, which may be limited by the engine and gearbox configurations available to the OEMs in the design process; sensitivity and Monte Carlo uncertainty analyses were conducted on the F_{CP} parameter—see Section 10.2.2, and

$LTDD_V$ baseline vehicle lifetime driving distance, 290,000 km (2), (5); sensitivity and Monte Carlo uncertainty analyses were conducted on the LTDDv parameter—see Section 10.2.2.

Table 12. Default values for mass-induced fuel consumption (no P/T adaptation) and change potential (with P/T adaptation), based on U.S. EPA CFE and 100 kg mass change (2), (47)

Engine type	**F_{CO}, no P/T adaptation** (L/(100 km × 100 kg)	**F_{CP}, with P/T adaptation** (L/(100 km × 100 kg))
Diesel	0.135	0.31
Gasoline, naturally aspirated	*0.161*	*0.38*
Gasoline, turbocharged	0.168	0.4

The calculation of the F_{CP} is based on a variety of input parameters (2), (48)-see Table 13. A Monte Carlo analysis was conducted by Koffler and Zahller (47) to assess the combined effect of the input parameter uncertainties on the mass-induced fuel reduction potential, for *naturally aspirated gasoline engines* for the U.S. EPA CFE and 100 kg mass change. Table 13 shows the key parameters of the fuel savings calculation that were varied in the Monte Carlo simulations. A multitude of simulations of drivetrain adaptations rendered fuel reduction values that are a factor of 1.7 to 3.0 higher than the values without additional drive train adaptations (average gasoline = 2.37) (47)—see Table 13. By propagating these uncertainties simultaneously, a multitude of times using random sampling (here: 10,000 runs), the Monte Carlo simulation provides a better estimate of the uncertainty of the fuel reduction potential (47). The standard deviations will also give a better indication of the more likely range of results than simple best case / worst case calculations (47).

Figure 18 shows that the resulting *mean* mass-induced fuel reduction potential is *9%* higher than for the base scenario (red line) across all 10,000 runs, with powertrain adaptation (47). The Y-axis (vertical) shows the frequency of occurrence in percentage. With P/T adaptation, the standard deviation around the *ascertained mean* is +/- 19% (47). *This way, the base factor (0.38 L/ (100 km × 100 kg) is deemed to be a conservative value for the mass-induced fuel savings potential, with P/T adaptation*. Figure 18 also displays the best- and worst-case results according to the parameter specifications indicated in Table 13. For powertrain adaptation, the worst possible fuel reduction would be 38% lower than the base case, while the best possible fuel reduction would be 73% higher than the base case.

Table 13. Intervals in use phase Monte Carlo simulation (10,000 runs, uniform distribution) (47)

Parameter	Lower Limit	Base Scenario	Upper Limit
Deceleration in city driving cycle (no fuel consumption) [%]	0^{b}	**25**	25^{w}
Deceleration in highway driving cycle (no fuel consumption) [%]	0^{b}	**8**	8^{w}
f_R, rolling resistance coefficient	0.007^{w}	**0.01**	0.014^{b}
Automatic gearbox losses [%]	5^{w}	**5**	10^{b}
Ratio of fuel savings with adaptation to no adaptation (gasoline)	1.66^{w}	**2.37**	3.08^{b}

^{w}: worst-case specification; ^{b}: best-case specification

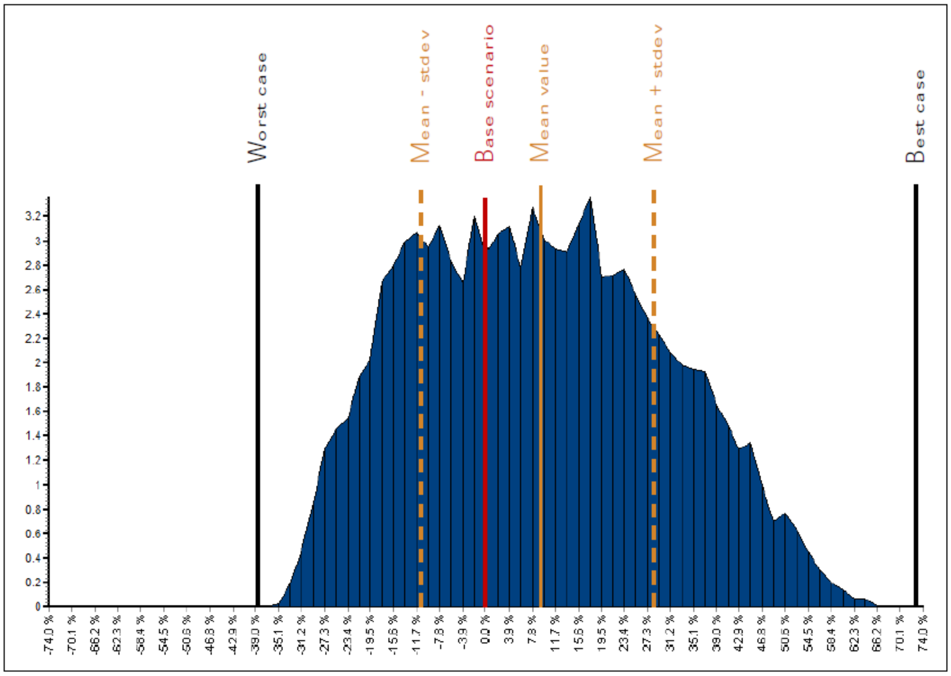


Figure 18. Fuel reduction potential- Monte Carlo simulation results with P/T adaptation (47)

It should be noted that F_{CP} does not express the auto parts' mass-induced fuel consumptions. Instead, it represents a change in fuel consumption as compared to the Baseline body parts. The multiplication of the baseline auto parts' net weight by the F_{CP} is generally not feasible if, for the sake of full functional equality, powertrain adaptations are to be considered. This is because these adaptations do not apply to the Baseline body parts, but solely to the lightweight concepts. *The corresponding F_{CP} can therefore only be combined with weight differences* (2), (48).

7.5 End-of-Life Stage

The calculation of environmental profile of the EOL stage of both Baseline and AA LWT auto body parts is conformant to ISO 14044 (1) and CSA Group LCA Guidance for auto parts (2), and includes all unit processes listed below, as applicable:

Life Cycle Stage	Processes
End-of-Life Stage	(a) Collection and processing, including transportation, dismantling, shredding, and separation (see Tables A14 and A15, Annex J); (b) Transportation of waste to disposal (see Table A15, Annex J); (c) Disposal, including landfilling (see Table A14, Annex J); (d) Transportation of scrap to the recycling facility (see Table A15, Annex J); and (e) Secondary material production and substituted primary material production from EOL material recycling (see Section 7.6).

7.6 Allocation Rules for EOL Scrap Recycling

Where applicable, the “substitution” allocation approach is applied for all metals. In addition, EOL scrap output is balanced out with scrap input into manufacturing of the semi-finished metal products to avoid double-counting. The appropriate mass of the remaining net EOL scrap is then modeled as being sent to material recycling at end-of-life.

If more scrap is generated by the product system than is used in the manufacturing stage (a positive net amount of EOL scrap), the product system receives a “credit” based on the technical substitutability of the secondary and primary materials. Similarly, if less scrap is generated by the product system than is used in the manufacturing stage (a negative net amount of EOL scrap), the product system receives a “debit”—see Table 14 and Annex H for examples. The credit (or debit) is modeled based on the “value-of-scrap” approach as published by (30).

In compliance with the CSA Group LCA Guidance for auto parts, the EOL recovery rate of old vehicles (also known as old vehicle collection rate) is assumed to be 95% (2), (49). The yield of shredding and sorting (downstream separation) process (Sy), also known as EOL material collection rate, is assumed to be 100% for both the AA LWT body design and Baseline (50). This assumption is based on a recent study conducted by the Center for Resource Recovery and Recycling (CR^3), Worcester Polytechnic Institute, that shows the weighted-average material collection rate for end-of-life vehicles that flow through a dismantling operation and a downstream separation system is 99.7% in the United States (50). A 100% (Sy) is a “theoretical” assumption as some of the aluminum may end up in the steel fraction and some of the steel may end up in the light metal fraction. In both cases, steel and aluminum are considered alloy materials that “substitute” the primary alloy material production. In addition, this LCA study assumes that *none* of the EOL auto parts are recovered for reuse or remanufacturing. Sensitivity and Monte Carlo uncertainty analyses were conducted on EOL recovered scrap rate (RR_{EOL}) parameter—see Section 10.2.2.

Regarding secondary steel data, there’s only one LCI profile developed by worldsteel named *“Value of steel scrap”*. This LCI profile is used for both fabrication and EOL scrap (AHSS, HSS and mild steel).

In terms of the metal recovery yield/rate during the remelting process, the 2016 WPI and CR^3 report states: "*When a heavy gauge scrap class is charged (i.e. Aluminum bumper), an average metal yield of 95% is attained. Light gauge scrap melting is estimated to result in an average metal yield of 91%* (50). *Many factors attribute to these yield values including cleanliness of the melt and surface area to volume ratio"* (50). It should be noted the averaged light gauge yield factor of 91% does *not* account for the addition of primary aluminum metal and alloying elements. The scope of the 2016 WPI and CR^3 study is exclusively the United States. It should be noted that the objective of the 2016 WPI and CR^3 study was to obtain a more quantitative understanding of the fate of automotive aluminum at the end of its service life. The project determined the recycling rate of aluminum and its alloys within the United States' automotive sector.

The 2013 LCA profiles of secondary Al products as generated by the Aluminum Association for the reference year 2010 are applicable for NA situation and were used for this LCA project. As previously stated, the Aluminum Association has developed two LCI profiles of secondary aluminum ingot: *Al recycling ingot (100% scrap)* and *secondary aluminum ingot (primary metal and alloy added)* (26). The difference of the two formats is in the involvement of primary aluminum metal and alloying elements (26).

- *Aluminum recycling ingots (100% scrap)*— there is no involvement of primary metal and alloying elements in this case. The 2013 Aluminum Association LCA study uses a yield factor of 95.7% (1,000/1,044kg) (26); and
- *Secondary aluminum ingots (primary metal and alloy added)*— this LCI profile assumes that aluminum products are recycled in a less-sorted, or mixed manner, in which certain alloys may be mixed together. In this case, a certain amount of primary aluminum metal and alloying elements are used to adjust the alloy compositions to the required specifications (26). The added primary metal and alloying agents here carry a "cradle-to-gate" burden tracing back to the mining process. It is important to understand the differences in reported yield values for Al recycling in various studies. The 2013 Aluminum Association LCA profile of *secondary aluminum ingots (primary metal and alloy added) shows a yield factor of 96.0% as it includes the amount of added primary metal and alloys* (26).

The typical input scrap, process (or fabrication) scrap, net amount of EOL scrap (in kg per kg auto body part) and EOL recycling yield values (in %) per main material and fabrication technologies are given in Table 14. The same "end-of-life" recycling approach is applied for both aluminum and steel auto body parts as shown in Table 14. Plastic parts are assumed to be disposed to landfill (2). The EOL disposition (e.g., recycled, landfilled) for each automotive material is based on the NA industry practices in place for the auto body parts. Sensitivity analysis and Monte Carlo uncertainty analyses were conducted to determine the influence of allocation rules for recycling on LCA study results (see Section 10.2.2).

Table 14. Net amount of EOL scrap and EOL recycling yield values per material

Auto parts	**Input scrap** (kg/kg fabricated auto body part)	**Fabrication scrap**1) (kg/kg auto body part)	**Net amount of EOL scrap to recycler** (2) (kg/kg auto body part)	**EOL recycling yield value** (%)
AHSS, HSS and mild steel2)				
HDG (51) *sheet stamping*	0.813 = 0.439*1.852	0.852	0.137 = 0.95 – 0.813	91.6%4) (1/1.092) (30)
PHRC (51) sheet *stamping*	0.367 = 0.198*1.852	0.852	0.583 = 0.95 – 0.367	
HDG (51) sheet roll forming	0.462 = 0.439*1.053	0.053	0.488 = 0.95 – 0.462	
PHRC (51) sheet roll forming	0.208 = 0.198*1.053	0.053	0.742 = 0.95 – 0.208	
Aluminum				
Al CRC (26), (52) *cold stamping*3)	1.202 = 0.649*1.852	0.852	-0.252 = 0.95 - 1.202	96.0%5) (26)
Al extrusion (26), (52)	0.426	0.29	0.524 = 0.95 - 0.426	

1) Refer to Table 11 for details; the "substitution" approach for fabrication scrap recycling is already applied in the production stage (see Section 7.3).

2) U.S. SRI and worldsteel LCI profiles are provided per 1 kg of steel semi-fabricated product such as HDG and PHRC. Amount of input scrap per kg of steel stamped part is based on the amount of input scrap per kg of steel semi-fabricated product (see Table 16) and calculated as per the CSA Group LCA Guidance for auto parts Section 7.7 End-of-life stage (2).

3) Amount of input scrap per kg of Al stampings is based on the amount of input scrap per kg of Al CRC (see Table 16) and calculated as per the CSA Group LCA Guidance for auto parts Section 7.7 End-of-life stage (2).

4) "Value of steel scrap" LCI profile [$=Y_f \times (E_{prim} - E_{sec})$] is calculated and provided in a rolled-up form by worldsteel (9). To avoid any data misuse, steel primary and secondary LCI profiles are not made available to LCA practitioners. The definition of primary and secondary steel products is provided in Annex G.

5) The yield value of *secondary aluminum ingot* used to calculate the "value of Al EOL scrap" includes the amount of added primary aluminum metal and alloys.

8.0 Life Cycle Inventory

8.1 Data Collection and Calculation

Detailed data on the auto part name, number of constituent parts per auto body system, mass per auto part in kg, material composition, and fabrication process were provided by EDAG Inc. in 2017 (23). The EDAG team has extensive experience in the areas of automotive engineering, development and vehicle crash test modeling, and analysis (3). Auto body system specifications data is provided in Annex B: Baseline and AA LWT body design description.

This comparative LCA study uses adequate LCI dataset (including material production, energy generation, transportation, auto part fabrication & assembly, fuel production and combustion, and EOL processes) provided by:

- North American and global metals and plastic industry associations (see Table A14, Annex J);
- North American and global LCI databases such as the U.S. National Renewable Energy Laboratory LCI database, September 2015 (http://www.nrel.gov/lci/), and ecoinvent 3.3, allocation, recycled content database, October 2016 (http://www.ecoinvent.org/). Both are included in the LCA software SimaPro v.8.4.0 2018 (33); and
- GREET.net 2017 (GREET 1 fuel cycle (38) and GREET 2 vehicle cycle (45)) (https://greet.es.anl.gov/index.php); GREET.net 2017 LCI data is entered in 2017 EDAG AA LWT body design SimaPro project for the purposes of this LCA (see Table A14, Annex J).

As indicated in ISO 14044, LCI datasets are integrated over space and time (1). The applied LCI datasets for the Baseline and AA LWT auto body parts are shown in Table A14, Annex J. This *attributional LCA* study implicitly assumes that *activity and emission levels scale linearly* with the quantities required for the reference unit of one auto body system. Behind this *linearity* are several assumptions such as fixed input/output relationships and unlimited supply of inputs (53).

Table A15, Annex J shows the transportation modes, distances, and Standard Classification of Transported Goods (SCTG) codes for all materials, per type of activity based on the most up-to-date U.S. Commodity Flow Survey, undertaken through a partnership between the U.S. Census Bureau and the U.S. Bureau of Transportation Statistics (54). Transportation activities are included consistently in the respective life cycle stages. Trucking is the primary mode of transport for materials, auto body parts, scrap, and waste flows, followed by rail. “Combination truck, long-haul (> 200 miles) and short-haul (< 200 miles), diesel powered” are used for road transportation.

Data calculation procedures are explicitly documented, and the assumptions made are clearly stated in Section 7, according to ISO 14044 (1) and CSA Group LCA Guidance for auto parts (2). The same calculation procedures are applied for both the Baseline and AA LWT auto body parts.

8.2 Auto Body Parts Stamping

Stamping is the main fabrication process for the Baseline and AA LWT body systems—see Tables A2 to A6, Annex B. Cold stamping is used for almost all stamped auto body parts, with the exception of 13.5 and 9.4 kg hot stamped steel parts of the Baseline and AA LWT body systems, respectively—see Annex B.

Sheet metal stamping is used to form three-dimensional parts from flat sheet metal shapes known as ‘blanks’. It is widely used in the automotive industry to form inner and outer body panels (hoods, doors, fenders etc.) (55). Energy factors for stamped auto parts depend on many parameters such as stamping technology and operations, auto part geometry, material density and strength, etc. In a recent report published by ANL, it was observed that there is no substantial difference in the energy requirement for steel stamping and Al stamping (44). In addition, Al stamped panels are formed on the same presses as steel, with similar forming processes. Therefore, the same energy intensity is used for steel stamping and Al stamping in GREET 2017.

It should also be noted that stamping by hydraulic presses is more energy-intensive than by mechanical presses (44), (55). In fact, “This is partly because the hydraulic press has a much higher standby power; the fixed speed motors continue circulating hydraulic fluid even during idling or low speed jogging. As energy use is proportional to the cube of the flow rate in the hydraulic system this leads to large energy requirements” (55). Since both types of presses are used for vehicle production, and the ratio of parts produced by mechanical presses to those produced by hydraulic presses is not available, an energy intensity more representative of hydraulic presses is used in GREET 2 2017 as a conservative estimate (44).

The energy intensity for stamping is estimated to be 1.0 MJ/kg for both steel and Al in GREET 2017 to account for energy consumption for other peripheral processes, such as blanking, cutting, and handling (44). The consumed energy is assumed to be 100% electricity (44). The material efficiency for stamping is estimated to be 54% (90% for blanking, and 60% for forming) for both steel and Al in GREET 2017 (44). The cut-off materials associated with the stamping processes should be well-sorted and fully recycled within modern production facilities, therefore the recovery factor for stamping is estimated as 1 (recovery rate of fabrication scrap, RR_F= 100%) in GREET 2017 (44). Table 15 shows the most up-to-date cold stamping (for both steel and aluminum parts) and hot stamping data (for the steel parts) used for this LCA project.

Table 15. LCI data for 1 kg stamped auto body parts

Technical data	**Aluminum**	**Steel** (AHSS)	**Reference**	**Comments**
Cold stamping				
Material efficiency (%)	54%	54%	(44) (45)	Generic NA data based on GREET 2017 (44) (45)
Average scrap factor (in kg/ kg stamped part)	0.852	0.852		
Electrical energy (in MJ/ kg stamped part)	1	1		
Hot stamping (AHSS steel)				
Material efficiency (%)	n/a	54%	(44) (45)	Generic NA data based on GREET 2017 (44) (45)
Average scrap factor (in kg/ kg stamped part)		0.852		
Electrical energy (in MJ/ kg stamped part)		1		
Natural gas (in MJ/ kg stamped part)		1.67	(56)	Generic NA natural gas data for *hot stamping* (56); it's based on the maximum total heat input of 7.2 MM British thermal unit/hour per maximum processing rate of 5 tons of blanks per hour.

8.3 NA Aluminum and Steel Products LCI Data

The Baseline and AA LWT body systems are identified as "*HSS and AHSS*" and "*advanced aluminum*" intensive systems. In accordance with the CSA Group LCA guidance for auto parts, Section 7.4.3.3 the most up-to-date North American industry average "cradle-to-gate" LCI data of both aluminum and steel products are used in the framework of this LCA study. Annexes D and H provide the definitions of all aluminum and steel products applicable for this LCA study. Table 16 presents the input scrap and CO_2 emissions for the selected NA steel and aluminum products used for the manufacturing of the Baseline and AA LWT body systems.

Table 16. Input scrap and CO_2 emissions for the selected NA aluminum and steel products

Aluminum (cradle-to-gate)[3]	**Input scrap**[2] (kg/kg Al product)	**CO_2**[1] (kg/kg Al product)	**Steel** (cradle-to-gate)[3]	**Input scrap**[2] (kg/kg steel	**Carbon dioxide**[1] (kg/kg steel product)
Al CRC (26), (52)	***0.649***	***4.622***	***HDG*** (51)[6]	***0.439***	***2.054***
Al extrusion (26), (52)	0.426	5.620	*PHRC* (51)	*0.198*	*0.198*

Aluminum (cradle-to-gate)[3]	**Input scrap**[2] (kg/kg Al product)	**CO_2**[1] (kg/kg Al product)	**Steel** (cradle-to-gate)[3]	**Input scrap**[2] (kg/kg steel	**Carbon dioxide**[1] (kg/kg steel product)
Al primary (26), (52)	0	7.478[4]	Steel primary[5] (BOF slab) (theoretical value) (30)	0	1.92
Al recycling (100% scrap) (26)	1.045	0.634	Steel secondary[5] (EAF slab) (30)	1.092	0.386
Secondary ingot (primary metal and alloy added) (26), (52)	0.978	1.109			

[1] CO_2 emissions should not be mistaken for the GWP indicator (in kg CO_2 eq), which is calculated based on the potency of GHGs (including CO_2, CH_4, N_2O, fluorinated gases etc.) relative to CO_2.

[2] These scrap input factors are for multisectoral (non-automotive sector specific) aluminum and steel profiles.

[3] These cradle-to-gate LCI datasets do not account for semi-finished aluminum and steel imports to the NA market.

[4] In 2016, the North American primary aluminum consumption mix consisted of 81% of the NA domestic primary aluminum production (see Table A16). The net imports from different countries made up the rest of 19% (57). Due to ongoing changes in the industry and closures of smelters, the share of hydro and other renewable power for smelting in 2016 increased to 80%, coal power decreased to 17%, and natural gas power increased to 3% (58).

[5] BOF and EAF stand for basic oxygen furnace and electric arc furnace, respectively; to avoid any data misuse, steel primary and secondary LCI profiles are not made available to LCA practitioners. The system process (rolled-up) NA LCI profiles of steel products including the "value of steel scrap" are provided by worldsteel. Similarly, the system process NA LCI profiles of aluminum products are provided by the Aluminum Association.

[6] A hot-dip galvanized LCI dataset is used to model the MS, HF, DP and BH auto parts. Pickled hot-rolled coil is used to model HSLA (YS > 300) auto parts (59). As per personal communication with WorldAutoSteel, the proportion generally used for a body-in-white is over 75% hot-dip galvanized and 25% pickled hot-rolled coil (60). In the framework of the EDAG Silverado Body lightweighting LCA data collection process, a 75% HDG/25% PHRC proportion was confirmed as appropriate by EDAG for mild steel LCI modeling purposes (23). In addition, it is expected that the difference in the environmental profile for HSS and AHSS is negligible (60), (61). While there may be some increases for rolling, there are often savings in heat treatment. In other words, for some of the batch annealed grades of AHSS, the annealing temperatures may be lower than for some mild steel grades (60).

9.0 Life Cycle Impact Assessment

LCIA is the phase in which the set of results of the inventory analysis – input/output flows – are further classified, characterized and interpreted in terms of potential environmental impacts. According to LCA-based ISO 14040/44 (6), (1), the mandatory elements of LCIA are:

- Selection of impact categories, category indicators, and characterization models;
- Assignment of LCI results (classification) to the impact categories; and
- Calculation of category indicator results (characterization).

9.1 LCA Indicators

Table 17 shows the U.S. EPA TRACI version 2.1, 2012 impact categories used in the AA LWT LCA study as required in the CSA Group LCA Guidance for auto parts (34), (36), (2). These five impact categories are deemed mature enough to be included in this LCA study. Unlike the LCI which only reports sums for individual emissions to air, water, and land, and raw materials, the LCIA includes methodologies for characterization and combining different emissions into a metric for the *potential impacts* of LCI flows. A detailed description of TRACI 2.1 LCIA categories is provided in Annex I. Climate change follows IPCC method, which contains the IPCC climate change factors with a timeframe of 100 years. Table 18 shows the primary energy demand indicators as required in the CSA Group LCA Guidance for auto parts (2).

Table 17. U.S. EPA TRACI v2.1 Life Cycle Impact Assessment categories (34), (36)

LCIA Categories	Indicator	Unit equivalence basis (indicator units)	Source of the characterization method
Acidification	Acidification potential, AP	kg SO_2-eq	TRACI v2.1
Eutrophication	Eutrophication potential, EP	kg N-eq	TRACI v2.1
Climate change	Global warming potential, GWP	kg CO_2–eq	TRACI v2.1/ Updated with IPCC 2013 AR5
Smog	Photochemical smog formation potential, PSFP	kg O_3-eq	TRACI v2.1
Human health Particulate	Human health particulate potential, HHPP	kg $PM_{2.5}$-eq	TRACI v2.1

Table 18. Life Cycle Inventory indicators (2)

I.D.	LCI Indicator	Unit
TPE	Total primary energy demand (higher heating value), also known as Cumulative Energy Demand (sum energy indicator of *NRF, NRN, NRB, RH, RSGW, and RB*)	MJ
NRF	Non-renewable, fossil (natural gas, crude oil, hard coal, lignite, coal mining off-gas, peat)	
NRN	Non-renewable, nuclear	
NRB	Non-renewable, biomass (wood and biomass from primary forests-clear cut)	
RH	Renewable, hydropower (hydropower)	
RSGW	Renewable, solar, geothermal, wind (solar, geothermal, wind)	
RB	Renewable, biomass (wood, food products, biomass from agriculture)	

9.2 LCA Results

The life cycle environmental performance results of the AA LWT auto body parts compared to the Baseline are presented in this section. The LCIA results were calculated with the SimaPro LCA software 8.4.0, 2018, using the characterization factors of U.S. EPA TRACI version 2.1, 2012 (updated with IPCC 2013 AR5 GWPs). The non-renewable and renewable energy-related LCI indicators were calculated with the SimaPro LCA software using the Cumulative Energy Demand as available in version 1.09.

The cradle-to-grave LCIA and LCI indicator results of the AA LWT (with P/T adaptation) compared to the Baseline are shown in Table 19. The difference between the potential environmental impact of the AA LWT body design and the Baseline (HSS and AHSS intensive body system) is calculated as the results of the AA LWT body design minus the Baseline. The use stage emissions are only calculated as the difference from the Baseline. Thus, the use stage impact is null for the Baseline and carries a negative sign for the AA LWT body design. In the framework of this LCA study, it's deemed *technically feasible as well as highly likely* that the 231 kg weight savings in the AA LWT body design would allow for the powertrain to be adapted to maintain the same driving performance as the baseline vehicle. This would result in potential fuel savings of about 2,500 L of gasoline over the assumed vehicle's lifetime driving distance of 290,000 km. The mass-induced potential fuel savings by the body system lightweighting is calculated by using an F_{CP} value of 0.38 L/100 km×100 kg recommended by the CSA Group LCA Guidance, assuming P/T adaptation (2).

The AA LWT body design shows lower potential environmental impacts due to lightweighting compared to the Baseline, across all selected LCIA and LCI indicators. It should be noted that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks (1). The life cycle GWP and TPE of the AA LWT body design (with P/T adaptation), relative to the Baseline body system, are about -7,800 kg of CO_2-eq and -110,000 MJ, respectively (Table 19).

On a per km-basis, the life cycle GWP and TPE of the AA LWT body design (with P/T adaptation), relative to the Baseline, are about -30 g CO_2-eq/km and -380 kJ/km, respectively (Figure 19). Life cycle GWP and TPE of the AA LWT body design compared to the Baseline are dominated by fossil fuel related CO_2 emissions (94%), and non-renewable fossil fuel energy demand (93%), respectively. From an energy perspective, the AA LWT body design shows lower fossil fuels and biomass energy demand and higher hydropower renewable energy use compared to the Baseline.

Table 19. Cradle-to grave LCA results of AA LWT body design in comparison to the Baseline—(with P/T adaptation, $LTDD_V$= 290,000 km (2), (5))

LCIA and LCI Indicators	Indicator units	Cradle-to-grave total net change of the AA LWT body design, with P/T adaptation[1), 2) 5)]
Acidification potential, AP	kg SO_2-eq	-7.9
Eutrophication potential, EP	kg N-eq	-1.1
Global warming potential, GWP[3)]	kg CO_2–eq	-7,820
Photochemical smog formation potential, PSFP	kg O_3-eq	-165
Human health particulate potential, HHPP	kg $PM_{2.5}$-eq	-1.0
Total primary energy demand, TPE[4)]	MJ	-109,019
Non-renewable, fossil, NRF	*MJ*	*-102,343*
Non-renewable, nuclear, NRN	*MJ*	*-1,641*
Non-renewable, biomass, NRB	*MJ*	*-0.028*
Renewable, hydropower, RH	*MJ*	*1,931*
Renewable, solar, geothermal, wind, RSGW	*MJ*	*365*
Renewable, biomass, RB	*MJ*	*-7,331*

[1)] Negative values represent a lower potential environmental impact of the AA LWT body design, since the life cycle performance is shown as the difference from the Baseline (AA LWT body minus Baseline LCA results).

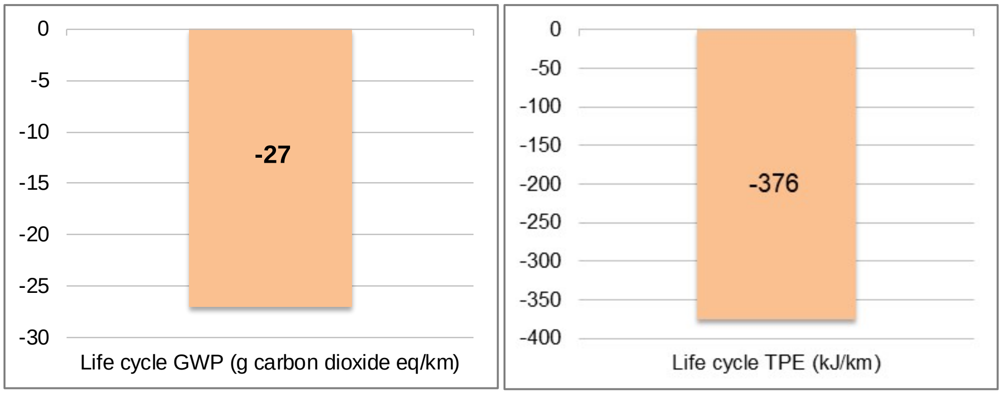
[2)] Displayed digits of the AA LWT body LCA results calculated with SimaPro LCA Software do not represent significant digits.

[3)] 100-year time horizon GWP factors are provided by the IPCC 2013 AR5. Biogenic removals and emissions of atmospheric CO_2 are not accounted for in this LCA study.

[4)] Total primary energy demand (higher heating value), also known as Cumulative Energy Demand, is a sum energy indicator of NRF, NRN, NRB, RH, RSGW, and RB.

[5)] Based on the "substitution" allocation procedure (also known as "*EOL recycling", "closed-loop", or "system expansion by substitution"*), the *cradle-to-grave LCA results* are not influenced by the *amount of input scrap* for both North American industry average cradle-to-gate LCI profiles of aluminum and steel products. Instead, the North American EOL recovered scrap rate for both AA LWT body design and Baseline (RR_{EOL}=95%) is the defining decisive parameter.

Figure 19. Life cycle GWP and TPE of the AA LWT body design compared to the Baseline — in g CO_2-eq/km and kJ/km — (with P/T adaptation, $LTDD_V$= 290,000 km (2))



10.0 Interpretation

Interpretation is the phase of LCA in which the findings from the *inventory analysis* and the *impact assessment* are brought together and *significant issues* are identified and considered in the context of the *study goal and scope* (6). In addition, the study's completeness, consistency of all applied information, and sensitivity to key assumptions or parameters as they relate to the goal and scope of the study are evaluated. Lastly, the interpretation phase ends by drawing conclusions, stating the study's limitations, and making recommendations (1).

10.1 Identification of the Significant Issues

ISO 14044 recommends several possible methods to identify significant issues in an LCA study. Based on established LCA practices, the following analytical techniques were applied for the interpretation phase of this LCA study:

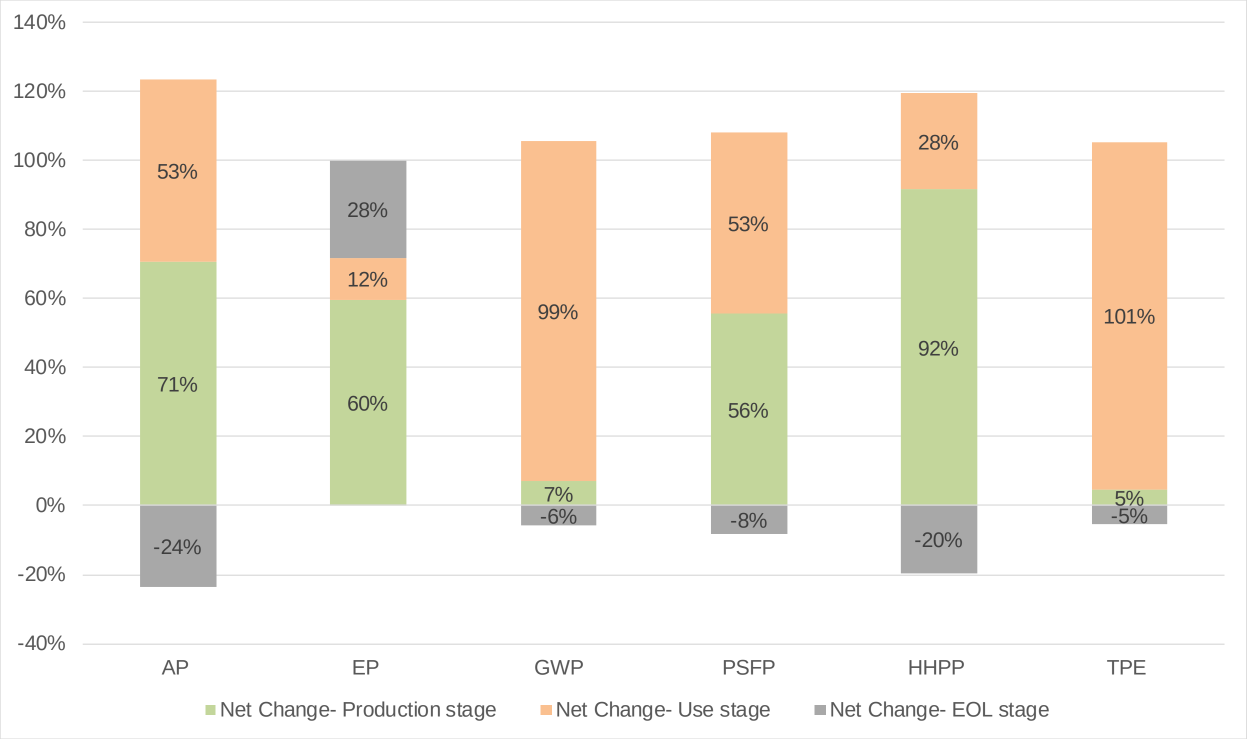
- **Contribution Analysis**, in which the contribution of *life cycle stages*, *groups of processes*, or *specific substances* to the total results are examined (1);
- **Dominance Analysis**, in which significant contributions are examined (1).

10.1.1 Contribution and Dominance Analysis

10.1.1.1 Total Net Change of AA LWT Body Design LCA Results per Life Cycle Stages

The life cycle performance results of the AA LWT body design compared to the Baseline are structured according to the production, use, and EOL stages in Figure 20 (2), (48). The *use phase* (gasoline production and combustion) dominates the life cycle GWP, TPE, PSFP and AP of the AA LWT body design (with P/T adaptation). On the other hand, the production and EOL stages combined dominate the life cycle EP and HHPP results.

Figure 20. Cradle-to-grave LCA results of the AA LWT body design in comparison to the Baseline by life cycle stage — in % basis (with P/T adaptation, LTDD$_V$= 290,000 km (2))



[1)] The cradle-to-grave LCA results of the AA LWT body design compared to the Baseline are shown as 100%. In addition, the net change of LCA results per life cycle stage can be either positive or negative results; therefore, the contribution in percentage of a life cycle stage can be greater than 100%. However, the cradle-to-grave total net change of LCA results of all life cycle stages always equals to 100%. The positive (+) or negative (-) percentage values depends on the mathematic sign (+/-) of the net change of LCA results per life cycle stage. For example, the net change in use stage GWP is about -7,700 kg CO_2-eq. The total net change in life cycle GWP is about -7,800 kg CO_2-eq. In this case, the contribution of use stage to the life cycle GWP of the AA LWT body design is positive (99%).

[2)] Please note data may not add up to totals due to rounding.

The *production stage* LCA results of the AA LWT body design are largely attributed to the substantial mass reduction (231 kg) due to advanced-aluminum-intensive design that replaces the HSS- and AHSS-intensive body system. In addition, the intensive use of scrap as an input material during the auto part manufacturing process helps lower the embedded environmental footprint and thus contribute to the net change of the production stage. The *use stage* LCA results of the AA LWT body design are largely attributed to the *potential* decrease in fuel consumption due to lightweighting of the new design. The mostly negative *EOL stage* LCA results of the AA LWT body design are largely attributed to the "substitution" allocation approach applied to this study. The auto body systems are both debited and credited for the net EOL amount of scrap at the end-of-life stage.

10.1.1.2 Total Net Change of AA LWT Body Design LCA Results per Process

A process contribution analysis (PCA) was conducted to examine the contribution of individual life cycle processes to the life cycle GWP and TPE of the AA LWT body design. Tables 20 and 21 show that fuel production and combustion are the top two contributors, followed by the value of aluminum scrap (recycling credit) and the significant reduction in steel use (BH, HSLA, and DP) by the new AA LWT body design. It should be noted that the non-displayed value (e.g., 1.1% for GWP) indicates that the rest of non-displayed processes combined to contribute 1.1% of the total net change. For information on individual process contribution to other impact indicators such as AP, EP, PSFP and HHPP, please refer to Tables A18 to A21, Annex K.

Table 20. PCA — Top 10 significant processes contributing to total net change of life cycle GWP of the AA LWT body design (with P/T adaptation, $LTDD_V$= 290,000 km (2))- in kg CO_2 eq

No.	Process	Total net change of life cycle GWP of the AA LWT body design	Net Change-Production stage	Net Change-Use stage	Net Change-EOL stage
Total of all processes		**-7,820**	**-554**	**-7,707**	**440**
Non-displayed processes (1.1%)		*-341*	*-282*	*0*	*-58*
1	Pump-to-Wheel (Operation) Gasoline (E10)-PUT SI ICEV GREET.net 2017	-5,651	0	-5,651	0
2	Well-to-Pump Gasoline (E10)- PUT SI ICEV GREET.net 2017	-2,055	0	-2,055	0
3	Value of aluminum process scrap (100% scrap)	-1,271	-1,271	0	0
4	BH, Bake hardenable steel (C2G), NA HDG	-979	-979	0	0
5	HSLA, High-strength, low-alloy steels (>300 psi) (C2G), NA PHRC	-547	-547	0	0

No.	Process	Total net change of life cycle GWP of the AA LWT body design	Net Change-Production stage	Net Change-Use stage	Net Change-EOL stage
6	DP, Dual phase steel (C2G), NA HDG	-96	-96	0	0
7	Aluminum extrusion products (C2G)	116	116	0	0
8	Value of aluminum EOL scrap (primary metal + alloy added)	285	0	0	285
9	Value of steel scrap	775	561	0	213
10	Aluminum cold-rolled coils (C2G)	1,944	1,944	0	0

1) Please note data may not add up to totals due to rounding.

2) Displayed digits of the AA LWT body design LCA results calculated with SimaPro LCA software do not represent significant digits.

3) It is worthwhile to be reminded that the total net change of LCIA and TPE indicators per process and per life cycle stage can be either positive or negative results; therefore, the contribution in percentage of a process per life cycle stage can be greater than 100%. However, the cradle-to-grave total net change of LCIA indicator results of all life cycle stages always equals to 100%.

Table 21. PCA — Top 10 significant processes contributing to total net change of life cycle TPE of the AA LWT body design (with P/T adaptation, $LTDD_V$= 290,000 km (2))- in MJ

No.	Process	Total net change of life cycle GWP of the AA LWT body design	Net change-Production stage	Net change-Use stage	Net change-EOL stage
Total of all processes		**-109,019**	**-5,131**	**-109,767**	**5,880**
Non-displayed processes (1.1%)		*-4,939*	*-3,963*	*0*	*-976*
1	Pump-to-Wheel (Operation) Gasoline (E10)- PUT SI ICEV GREET.net 2017	-85,356	0	-85,356	0
2	Well-to-Pump Gasoline (E10)- PUT SI ICEV GREET.net 2017	-24,412	0	-24,412	0
3	Value of aluminum process scrap (100% scrap)	-22,461	-22,461	0	0
4	BH, Bake hardenable steel (C2G), NA HDG	-12,973	-12,973	0	0
5	HSLA, High-strength, low-alloy steels (>300 psi) (C2G), NA PHRC	-6,453	-6,453	0	0
6	DP, Dual phase steel (C2G), NA HDG	-1,266	-1,266	0	0

No.	Process	Total net change of life cycle GWP of the AA LWT body design	Net change- Production stage	Net change- Use stage	Net change- EOL stage
7	Aluminum extruded products (C2G)	2,062	2,062	0	0
8	Value of aluminum EOL scrap (primary metal + alloy added)	5,032	0	0	5,032
9	Value of steel scrap	6,622	4,799	0	1,823
10	Aluminum cold-rolled coils (C2G)	35,124	35,124	0	0

1) Please note data may not add up to totals due to rounding.

2) Displayed digits of the AA LWT body design LCA results calculated with SimaPro LCA software do not represent significant digits.

10.1.1.3 Substance and Raw Material Contribution Analysis and Other Additional Communication of the AA LWT Body Design LCA results

Table A22, Annex K provides input for the substance and raw material contribution analyses. It shows the main contributors to the LCA results for the cradle-to-grave total net change of the AA LWT body design (with P/T adaptation) compared to the Baseline. In addition, the non-renewable material-related LCI indicator is reported as the sum of elementary non-renewable material resource input flows calculated with SimaPro. Since the renewable elementary flows (such as CO_2 in air, N in air, O_2 in air, argon, carbon organic) are not rigorously covered across different LCI databases such as the ecoinvent database, U.S. LCI database, and GREET.net 2017, no reliable results can be reported for the renewable material resource input flows. Furthermore, Tables A23 and A25, Annex K depict the LCA results of the Baseline and AA LWT body design on a life cycle stage basis, such as production, use, and end of life stages.

10.2 Completeness, Consistency, and Sensitivity Checks

Evaluating the study's completeness, consistency and sensitivity helps to establish and enhance confidence in, and the reliability of, the results of the LCA study, including the significant issues identified in the first element of the interpretation (1).

10.2.1 Completeness and Consistency Checks

The objective of the **completeness check** is to ensure that all relevant information and data needed for the interpretation are available and complete (1). The Baseline and AA LWT body design systems were checked for data completeness. All input and output data were found to be complete and no data gaps were identified at auto body system production, use, and EOL disposal stages (see Tables A2, A3 and A4, Annex B and Tables A14 and A15, Annex J).

The objective of the **consistency check** is to determine whether the assumptions, methods, models and data are consistent with the goal and scope of the study (1). Through a rigorous process, consistency was ensured between the two auto body systems in terms of calculation rules, methods, models, and data quality, including data source, time-related coverage, technology, and geographical coverage (see Sections 7 and 8, and Tables A14 and A15, Annex J). Table A17, Annex J summarizes the data quality assessment conducted in the framework of this LCA study.

10.2.2 Sensitivity Check

To assess how factors such as allocation methods, uncertainties in data, and assumption-based parameters would affect the reliability of the results and conclusions, a *sensitivity check* was conducted. The sensitivity check includes the results of the *sensitivity and scenario analysis* and *uncertainty analysis* (1).

10.2.2.1 Sensitivity and Scenario Analysis

The procedure of sensitivity analysis is a comparison of the LCA results obtained using certain given assumptions, methods, or data, with the LCA results obtained using altered assumptions, methods, or data (1). ISO 14044 Clause B.3.3 states: “Sensitivity can be expressed as the *percentage of change* or as the absolute deviation of the results. On this basis, significant changes in the results (e.g., larger than 10%) can be identified” (1). It is worth to note that *sensitivity analysis* is appropriate for parameters that can be continuously varied within a range (hereinafter referred to as “SP”). For those parameters or methodological choices that cannot be varied continuously within a certain range (hereinafter referred to as “SCP”), *scenario analysis* is conducted by changing discrete scenario values or assumptions. For best identification of significant SP, sensitivity is calculated as the ratio (R_{SP}) of the percent change in LCA indicator result over the percent change in parameter value (2).

Table 22 details a summary of the selected key SP and SCP in accordance with the CSA Group LCA guidance for auto parts, Section 7.4.4. The sensitivity and scenario analysis results are presented in detail in Table A26, Annex L. For simplification, Table 23 only presents the deviation of the LCIA and TPE results in percentage. The positive (+) or negative (-) signs of deviation (in %) depend on the mathematical signs (+/-) of both the value of base case and the deviation of the LCIA and TPE indicators (see Table A26, Annex L). For example, the influence of SP1 to life cycle GWP of the AA LWT body design compared to the Baseline (base case, -7,800 kg CO_2-eq) is negative (-14% = 1,100 kg CO_2-eq/-7,800 kg CO_2-eq) and indicates a 14% lower GWP compared to the base case.

Table 22. Sensitivity and scenario analysis procedure

SP and SCP	Description
SP1: $LTDD_V$	LTDDv parameter is varied by -14% (from 290,000 (2), (5) to 250,000 km (2)).
SP2: F_{CO} (no P/T adaptation)	F_{CP} is varied by -58% (from F_{CP} to F_{CO} (0.161 L/(100 km×100 kg) (2), (47)).
SP3: F_{CP} (with P/T adaptation)	F_{CP} is varied by +9% (47); *mean* mass-induced fuel reduction potential is 9% higher than for the base case, 0.38 L/(100 km×100 kg) (2), (47)– see Section 7.4, Figure 18.
SP4: EOL recovered scrap rate	To highlight the contribution of the EOL stage, sensitivity analysis is conducted on the EOL recovered scrap rate parameter varied by -21% (from 0.95 to 0.75) for both auto body systems.
SP5: Cradle-to-gate GWP of NA primary aluminum ingot consumption mix	Sensitivity analysis is conducted to check the impact of a potential change in the cradle-to-gate GWP of the NA aluminum products, (due to a potential change in the baseline NA primary aluminum consumption mix), to the life cycle GWP of the AA LWT body design. The cradle-to-gate GWP of NA primary aluminum ingot consumption mix is varied by +10%.
SP6: Cradle-to-gate GWP of HSS and AHSS	Sensitivity analysis is conducted to check the impact of a potential change in the cradle-to-gate GWP of HSS and AHSS, to the life cycle GWP of the AA LWT body design. The cradle-to-gate GWP of HSS and AHSS semi-finished products is varied by +5%.
SCP1: Allocation rules for recycling	Cut-off rules are applied for the fabrication and EOL scrap. Both auto body systems are not credited/debited for fabrication and EOL scrap.
SCP2: IPCC GHG characterization factors	TRACI 2.1 was originally based on IPCC 2007 AR4 100a GWP factors. IPCC 2013 AR5 is the successor of the IPCC 2007 AR4 method. Sensitivity analysis is conducted on IPCC 2007 AR4 100a GWP factors. The GWPs of three major GHGs are as follows: IPCC 2013 AR5 100a (in kg CO_2 eq.): CO_2=1; CH_4, fossil=30; CH_4, biogenic=28; N_2O=265; IPCC 2007 AR4 100a (in kg CO_2 eq.): CO_2=1; CH_4, fossil =25; CH_4, biogenic=22.25; N_2O=298.
SCP3: GREET's selected year for fuel production technologies	Sensitivity analysis is conducted for 2025 modeling year in GREET.net 2017— see Table A10, Annex E.
SCP4: Truck transportation	Sensitivity analysis is conducted to illustrate the consequences of replacing the LCI data set "*combination truck*, short-haul, diesel" with "*single truck*, short-haul, diesel".
SCP5: Electricity grid	Sensitivity analysis is conducted to illustrate the consequences of replacing the LCI data set "Electricity, medium voltage {Michigan, U.S.}| market for | Alloc Rec, U- MI, U.S" with "Electricity, medium voltage {US}| market group for | Alloc Rec, U", for the auto body part fabrication processes.

Table 23. Sensitivity and scenario analysis: Cradle-to-grave total net change of LCIA and TPE indicators of the AA LWT body design (with P/T adaptation, $LTDD_V$= 290,000 km (2)) — Deviation, in percent basis

SP and SCP	AP	EP	GWP	PSFP	HHPP	TPE
SP1 (varied by -14%)	-7%	-2%	-14%	-7%	-4%	-14%
SP2 (varied by -58%)	-30%	-7%	-57%	-30%	-16%	-58%
SP3 (varied by +9%)	5%	1%	9%	5%	2%	9%
SP4 (varied by -21%)	-18%	-1%	-2%	-7%	-16%	-4%
SP5 (varied by +10%)	n/a	n/a	-2%	n/a	n/a	n/a
SP6 (varied by +5%)	n/a	n/a	1%	n/a	n/a	n/a
SCP1	-51%	-1%	-3%	-19%	-32%	10%
SCP2	n/a	n/a	1%	n/a	n/a	n/a
SCP3	-10%	-2%	-0.3%	-9%	-3%	-0.5%
SCP4	4.5%	2%	0.8%	5.6%	3%	0.9%
SCP5	-0.4%	-9%	-0.1%	-0.1%	-5%	-0.04%

[1)] Displayed digits of the AA LWT body design sensitivity analysis results calculated with SimaPro LCA software do not represent significant digits.

The *sensitivity analysis* shows that the *F_{CP}/F_{CO} values* and *LTDDv* were deemed *significant sensitivity parameters* (R_{SP} = 1) for the life cycle GWP of the AA LWT body design relative to the Baseline. For example, a 58% decrease of F_{CP} (SP2) results in a 57% lower life cycle GWP of the base case (R_{SP} = 1). A 14% decrease in $LTDD_V$ (SP1) leads to a 14% lower life cycle GWP of the base case (R_{SP} = 1).

A 10% increase in the cradle-to-gate GWP of primary aluminum ingot (a mixture of NA domestic produced and imported ingot) (SP5), results in a 2% lower life cycle GWP of the base case (R_{SP} = 0.2). This low R_{SP} value is influenced by the high NA EOL recovered scrap rate of automotive aluminum products (RR_{EOL}=95%), and the “substitution” approach. Similarly, a 5% increase in the cradle-to-gate GWP of NA HSS and AHSS products (SP6) results in 1% higher life cycle GWP of the base case (R_{SP} = 0.2). This low R_{SP} value is also influenced by the high NA EOL recovered scrap rate of automotive steel products (RR_{EOL}=95%), and the “substitution” approach. The *sensitivity analysis* shows that the EOL recovered scrap rate (SP4) was deemed *significant sensitivity parameter* (R_{SP} = 0.9 and R_{SP} = 0.8) for the life cycle AP and HHPP of the AA LWT body design, respectively.

The cut-off allocation approach (SCP1) lowers the life cycle GWP of the base case by 3%. This percentage value is mainly influenced by the moderate percentage of input scrap for NA aluminum and steel products and substantial mass reduction of the AA LWT body design (around 46%). The life cycle GWP of the base case (about -7,800 kg CO_2-eq) varied by less than 2% over a variation of the rest of the selected scenario parameters.

In addition, life cycle AP, PSFP, and HHPP of the AA LWT body design relative to the Baseline were found to be *significantly* sensitive (varied by higher than 10%) to the change of allocation rules for recycling (SCP1). In general, cradle-to-grave LCIA and TPE indicators of the AA LWT body design compared to the Baseline varied by less than 10% over a variation of the rest of the selected scenario parameters (see Table 23). *Finally, the sensitivity and scenario analysis results (Table 23) show that none of the sensitivity and scenario parameters led to any inverse (higher) potential environmental impacts of the AA LWT body design compared to the Baseline.*

10.2.2.2 Monte Carlo Uncertainty Analysis

A Monte Carlo uncertainty analysis was conducted to assess the *combined uncertainty effect* of the *significant sensitivity parameters* ($LTDD_V$, F_{CP}/F_{CO} values, and fabrication and EOL recovered scrap rates) on the LCA results. Table 24 shows the identified significant parameters for this LCA study, used in the base case and Monte Carlo uncertainty analysis. As a statistical method to process data uncertainty, Monte Carlo analysis is used to establish the uncertainty range, which expresses the variance between the upper and lower confidence limit [97.5%, 2.5%], in the calculated LCA results (Figure 21). The base case LCIA and TPE results of the AA LWT body design relative to the Baseline are shown as 0% in Figure 21. With a confidence level of 95%, the confidence interval of life cycle GWP and TPE of the AA LWT body design relative to the Baseline, are [+45%, -40%] and [+49%, -44%], respectively (Figure 21). In other words, with a confidence level of 95%, the life cycle GWP of the AA LWT body design compared to the Baseline is between -3.9 metric tons of CO_2-eq and -10 metric tons of CO_2-eq. Similarly, the life cycle TPE of the AA LWT body design relative to the Baseline is between -47 gigajoules and -135 gigajoules. Since it was not feasible to include a discrete distribution to randomize the choice between the “cut-off” and “substitution” approach in an equally probable manner, the analysis applied a continuous uniform distribution to the fabrication and EOL recovered scrap rates (RR_F and RR_{EOL}) to check the influence of the respective recovered scrap rates across the maximum range between 0% and 100%. Such a treatment, however, would theoretically cover the impact on the choice of allocation rules for recycling (e.g., 0% represents “cut-off” and 100% represents “substitution”).

It should be noted that North American LCI datasets (e.g., the aluminum and steel products, and gasoline production and combustion), do not specify any input/output flow uncertainty information. Furthermore, U.S. EPA TRACI version 2.1 methodology has not specified any uncertainty information of the characterization factors per impact category. Therefore, the uncertainty analysis is only limited to the *combined uncertainty effect* of the significant sensitivity parameters (see Table 24). In addition, Figures A6, A7, and Table A27, Annex M show the Monte Carlo *probability distributions charts* for life cycle GWP and TPE of the AA LWT body design relative to the Baseline and the summary results of the uncertainty analysis (mean, median, standard deviation, coefficient of variation, 2.5%, 97.5%, and standard error of median values).

Table 24. Significant sensitivity parameters used in the base case and Monte Carlo uncertainty analysis

Parameter	Base case	Distribution
LTDDv (km)	290,000 (2), (5)	Triangular with 250,000 (2) as min and 360,000 (62) as max
F_{CP}/F_{CO} values L/(100 km×100 kg)	0.38 (2), (47)	Triangular with F_{CO}=0.161 (2), (47) as min (no P/T adaptation) and F_{CP}=3.08 * F_{CO}=0.496 (47) as max
Fabrication and EOL recovered scrap rate (RR_F and RR_{EOL})	"substitution" approach (2) (RR_F=100%, RR_{EOL}=95%)	Uniform between 0% and 100% (2)

1) Base case is used in triangular distributions as the most likely estimate.

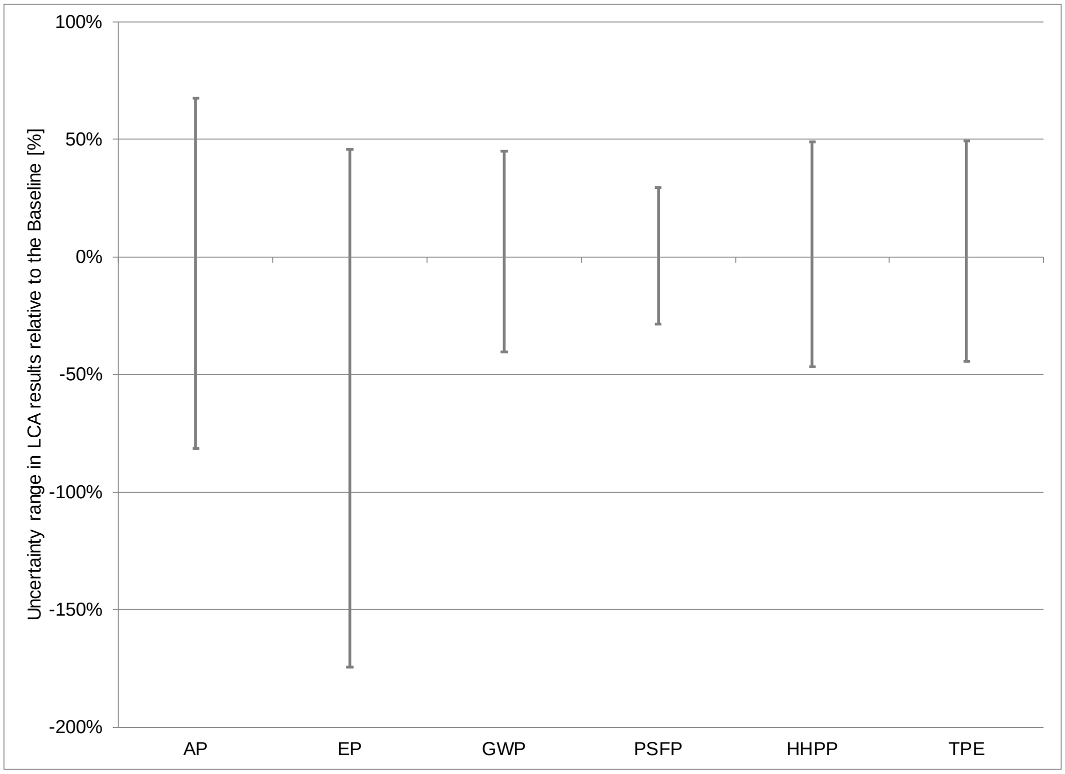


Figure 21. Monte Carlo uncertainty range in the cradle-to-grave LCIA and TPE results of the AA LWT body design relative to the Baseline (confidence interval: 95%, 10,000 runs, exported from SimaPro LCA software 8.4.0.0)

In conclusion, the uncertainty analysis results show that the combined uncertainty effect of significant sensitivity parameters did not lead to any inverse (higher) potential environmental impacts of the AA LWT body design relative to the Baseline.

10.3 Conclusions, Limitations and Recommendations

10.3.1 Conclusions

Based on the goal and scope of this LCA, life cycle inventory, impact assessment, and interpretation phases, the following conclusions can be reached:

1. The AA LWT body design shows *lower potential environmental impacts* due to lightweighting compared to the Baseline across all selected LCIA and TPE indicators. These indicator results remain robust when tested for the combined uncertainty of significant parameters. Specifically, *the AA LWT body design (with P/T adaptation) has the potential to lower the life cycle global warming potential and total primary energy demand of the Baseline by 7.8 metric tons of* CO_2*-eq and 110 gigajoules, with 95% confidence intervals of [-3.9, -10.0] for GWP and [-47, -135] for TPE, respectively.*
2. The AA LWT body design achieves an overall 231 kg (around 46%) mass reduction, that would *highly likely* lead to P/T adaptation, resulting in life cycle mass-induced potential fuel savings of about 2,500 L or 670 gallons (*use phase*).
3. The *use phase* (gasoline production and combustion) dominates the life cycle GWP, TPE, PSFP and AP of the AA LWT body design compared to the Baseline. On the other hand, the *production and EOL stages* combined dominate the life cycle EP and HHPP of the AA LWT body design relative to the Baseline.
4. The uncertainty analysis results show that the combined uncertainty effect of significant sensitivity parameters did not lead to any *inverse (higher)* potential environmental impacts of the AA LWT body design relative to the Baseline.

10.3.2 Limitations

- In compliance with ISO 14040/44 and the CSA Group LCA guidance for auto parts, this LCA study only addresses *environmental aspects* and *potential environmental impacts* throughout the life cycle of the AA LWT body design. It does not address any *economic, social* or *safety and durability* aspects.
- LCA addresses *potential environmental impacts* and *does not predict absolute or precise environmental impacts* due to, a) the relative expression of potential environmental impacts to a reference unit, b) the integration of environmental data over space and time, c) the inherent uncertainty in modelling of environmental impacts, and d) the fact that some possible environmental impacts are clearly future impacts (1).
- This attributional LCA study implicitly assumes that activity and emission levels scale *linearly* with the quantities required for the reference unit of one auto body system (28). Behind this *linearity* are several assumptions such as fixed input/output relationships and unlimited supply of inputs (53).

- This LCA study assess the life cycle performance of the AA LWT body design compared to the Baseline, both built and driven in *North America*. Thus, the results are not applicable to *other regions or globally*.
- The results of this LCA study are *only* specific to the Baseline and the AA LWT body design parts, and *can't* be used for auto body parts in general. The LCA results for the production, use, and EOL stages are a function of auto body design material composition, fabrication technology, and geometry.
- This LCA study report does not cover *human and eco-toxicity* indicators ("Human health, cancer", "Human health, non-cancer" and "Ecotoxicity"). Given the high degree of uncertainty for the characterization factors for metals, no trustworthy results can be reported for these end-point categories at this time and have therefore been excluded. Furthermore, given the data quality of the ODP emission factors for background LCI profiles, no reliable results can be reported for the ODP indicators and have therefore been excluded. In addition, TRACI v2.1 does not cover the land use impact category. Although it can have a significant impact, the land use impact indicators of NA steel and aluminum semi-finished products are not assessed in the framework of industry-average LCA studies conducted by the respective metal industry associations yet. It should also be noted that GREET.net 2017 does not cover the land use impact category for biofuel feedstocks yet (37). Land use has therefore been excluded as an impact category.
- This LCA study does not cover the *water consumption* indicator, as water data for steel and aluminum products were not available in the same comparable format at the time this LCA report was completed.
- The EOL disposal of each automotive material (e.g., recycled or landfilled) is based on North American industry-practices in place for the selected auto body systems. In other words, this LCA study uses "up-to-date" LCI data and parameters to evaluate the environmental impact of the EOL disposal of auto parts. All EOL processes are forecasted to take place at the end of the vehicle's life time driving distance of 290,000 km, about 10 to 15 years into the future. Since EOL processing technologies of automotive materials will likely progress over time (in particular the light weighting one), there is a lack of time-related and technological representativeness of the EOL LCI data of auto parts. This limitation is not expected to be significant or disfavor the Baseline body system.

10.3.3 Recommendations

- The AA LWT body design LCA study results can serve as a *baseline* for future benchmarking of North American auto body designs for pick-up trucks, with the goal of reducing the *potential environmental impact* of auto body parts over their life cycle.
- The EDAG Silverado Body Lightweighting LCA findings are appropriate for *both internal and external communication.*

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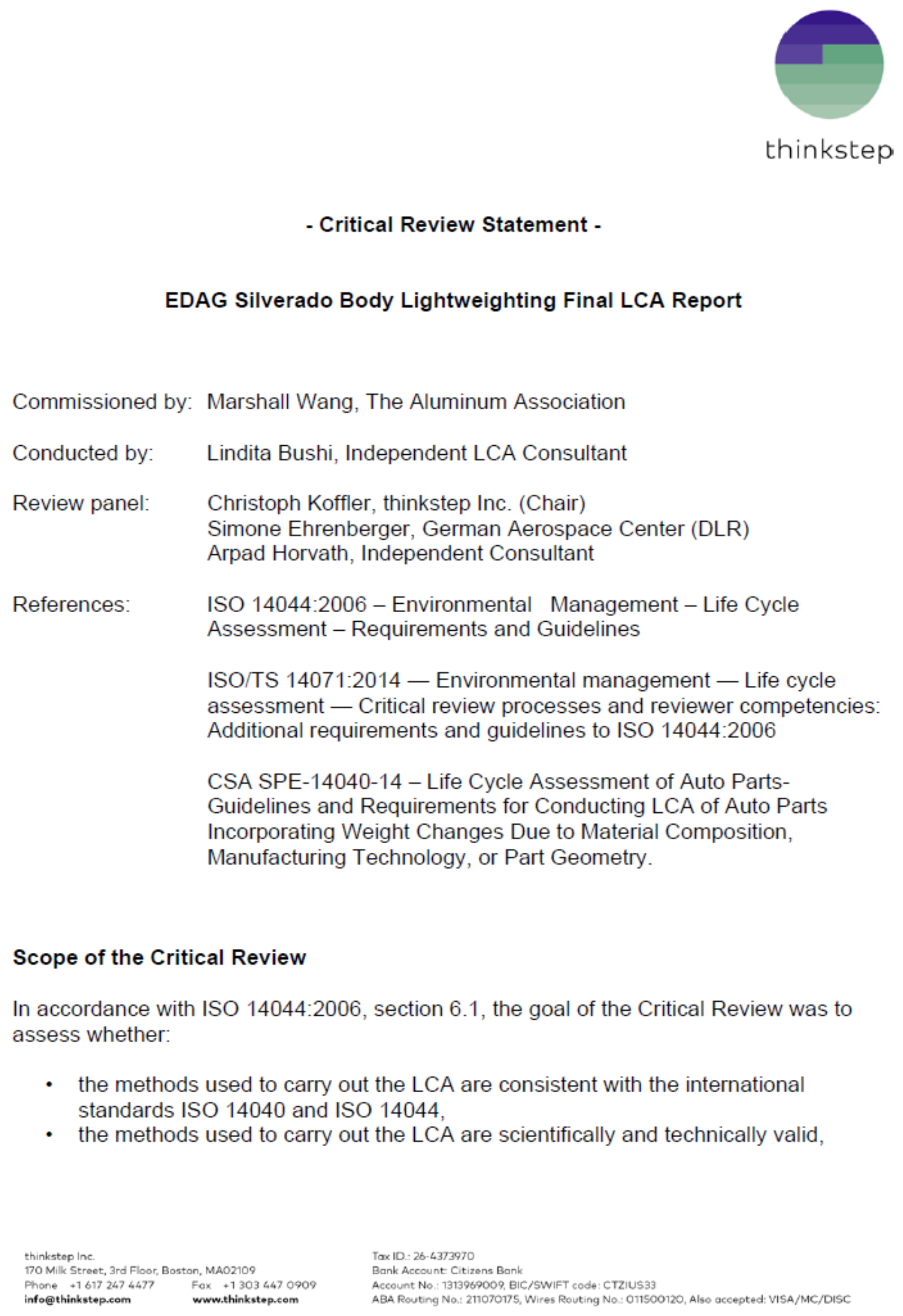
Annex A: Critical Review Attestation



thinkstep

- Critical Review Statement -

EDAG Silverado Body Lightweighting Final LCA Report

Commissioned by:	Marshall Wang, The Aluminum Association
Conducted by:	Lindita Bushi, Independent LCA Consultant
Review panel:	Christoph Koffler, thinkstep Inc. (Chair) Simone Ehrenberger, German Aerospace Center (DLR) Arpad Horvath, Independent Consultant
References:	ISO 14044:2006 – Environmental Management – Life Cycle Assessment – Requirements and Guidelines ISO/TS 14071:2014 — Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006 CSA SPE-14040-14 – Life Cycle Assessment of Auto Parts- Guidelines and Requirements for Conducting LCA of Auto Parts Incorporating Weight Changes Due to Material Composition, Manufacturing Technology, or Part Geometry.

Scope of the Critical Review

In accordance with ISO 14044:2006, section 6.1, the goal of the Critical Review was to assess whether:

- the methods used to carry out the LCA are consistent with the international standards ISO 14040 and ISO 14044,
- the methods used to carry out the LCA are scientifically and technically valid,

- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

As the study is intended to support comparative assertions intended to be disclose to the public, the review was performed as a panel review following ISO 14044:2006, section 6.3.

This review statement is only valid for this specific report titled “EDAG Silverado Body Lightweighting Final LCA Report” and dated August 2018.

The review was performed exclusively on the LCA study report and supplementing information available in the public domain.

Critical Review process

The review was conducted by exchanging comments and responses using an Excel spreadsheet based on Annex A of ISO/TS 14071:2014.

The critical review was carried out between 5/11/2018 (online kick-off meeting) and 8/31/2018 (delivery of the final review statement). There were two formal rounds of comments and several email conversations in-between. A copy of the review report containing all comments and responses is available from the study commissioner upon request.

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 any of the reviewers or the commissioner or practitioner upon finalization of the review.

General evaluation

The study is well scoped and capable of supporting the goal of establishing the environmental differences in impact profiles of the advanced aluminum lightweight (AA LWT) body design over the conventional, high strength steel intensive baseline design. The study used ample primary data on material choices and weight savings designed and tested by EDAG Inc. to ensure representativeness and accuracy of the results and shows a high level of technical knowledge and methodological proficiency.

Through the review process, the study was improved particularly in terms of the definition of the functional unit as well as by adding a formal uncertainty analysis to test the robustness of the conclusions towards uncertainty in key model parameters.

Conclusion

Based on the revised study report, it can be concluded that the methods used to carry out the LCA are consistent with the international standard ISO 14044, that they are scientifically and technically valid, that the data used are appropriate and reasonable in relation to the goal of the study, and that the interpretations reflect the limitations identified and the goal of the study. The study report is considered sufficiently transparent and consistent.

Since the LCA results are to be communicated to third parties other than the practitioner or the commissioner, ISO 14044, section 5.2 requires that a third-party report be made available to any such third parties. The third-party report will be made available by the study commissioner in a publicly accessible forum. Confidential contents will be removed from the report prior to sharing it with third parties.

The reviewers sign this review statement as individual experts. Their signatures do not imply an endorsement of the study's scope or results by any of the affiliated organizations.

Christoph Koffler
Technical Director, thinkstep Inc.

Simone Ehrenberger
German Aerospace Center (DLR)

Arpad Horvath
Independent Consultant

Valid as of August 31, 2018

Annex B: Baseline and AA LWT Body Design Description

Table A1. 2014 Chevrolet Silverado 1500 reference vehicle description (3)

Vehicle Specifications	**2014 Chevrolet Silverado 1500 reference vehicle description** (3)	
Vehicle brand, model and model year	2014 Chevrolet Silverado 1500, Crew Cab with Short Box (5 ½ ft.), EcoTec3 5.3L-V8 engine with a 4x4 drivetrain, trim level 1WT. 	
Engine types	EcoTec3 5.3L V-8 engine with aluminum block and heads. The FlexFuel, spark-ignition, direct-injection engine with active fuel management was rated at 355 hp at 5600 rpm and 383 lb-ft torque at 4100 rpm when operating with gasoline. The overall mass of the engine is 222.74 kg. The highest weight contributor to the engine is steel at 46% (101.3 kg), followed closely by aluminum at 43.0% (96.0 kg).	
Aspiration modes	Naturally aspirated	
Transmission types	Automatic 6-speed Hydra-Matic 6L80. This transmission is electronically controlled with automatic overdrive, electronic engine grade braking, and tow/haul mode (3).	
Vehicle weight, with a full gas tank	2,432 kg	
Vehicle fuel economy as per EPA combined fuel economy (CFE)	18 miles per gallon (mpg); 13.2 liters per 100 kilometers	
EPA vehicle size class	Pickup truck	
Total Driving Range	The baseline Silverado is fitted with a 26.0-gallon (98.4 L) fuel tank. EPA estimates of 16 mpg (city), 22 mpg (highway) and 18 mpg (combined) yield driving ranges of 416, 572 and 468 miles, respectively. The Ecotec3 5.3L-V8 is a flex fuel engine, capable of operating with gasoline or E85.	
Additional info: dimensions	Length (mm)	5,843
	Width (mm)	2,032
	Height (mm)	1,879
	Wheelbase (mm)	3,645
	Track, front (mm)	1,745
	Track, rear (mm)	1,716
	Turning Circle (m)	14.39

Table A2. Baseline body system material designation and fabrication technologies (23)

Baseline 2014 Silverado	MS 1250-1500	HF 1050-1500	DP 700-1000	HSLA 550-650	HSLA 420-500	HSLA 350-450	BH 280-400	BH 260/370	BH 210-340	Mild 140-270	6XXX T6 (270)	6XXX T7 (200)	5XXX (120)	Plastics	Total
Cold stamping			23.5	6	67	83	33.8	71	136	28.4	5	2	4.3		460
Hot stamping		13.5													13.5
Roll forming	27.1				1.6										28.7
Injection Moulding														2.2	2.2
Total	**27.1**	**13.5**	**23.5**	**6**	**68.6**	**83**	**33.8**	**71**	**136**	**28.4**	**5.0**	**2.0**	**4.3**	**2.2**	**504.4**

[1] Please note data may not add up to totals due to rounding.

Table A3. AA LWT body design material designation and fabrication technologies (23)

EDAG AA LWT Body design	MS 1250-1500	HF 1050-1500	HSLA 550-650	HSLA 350-450	6XXX-T6 295/340	6XXX-T6 270/310	6XXX-T6 250/285	6000 T6 (270)	6XXX T7 (200)	6XXX T6 (300)	6XXX T7 (230)	5XXX (180)	5XXX (120)	6XXX-T6 260-295	6XXX-T6 340-370	6XXX-T6 180-230	Total
Cold stamping			10.6	15.6	51.11		9.7	38.6	27.5	48.7	5.3	7.41	3.8	11.5	2.9	13	245.7
Hot stamping	6.8	2.6															9.4
Extrusion					3.79	10.6				3.8		0.69					18.9
Total	**6.8**	**2.6**	**10.6**	**15.6**	**54.9**	**10.6**	**9.7**	**38.6**	**27.5**	**52.5**	**5.3**	**8.1**	**3.8**	**11.5**	**2.9**	**13**	**274.0**

[1] Please note data may not add up to totals due to rounding.

Table A4. Baseline and AA LWT body design composition, by alloy series and grades (in absolute basis)

Baseline (23)					**AA LWT body design** (23)				
Mat. designation	**Mat. alloy series and grades**	**kg**	**Specific grades**	**kg**	**Mat. designation**	**Mat. alloy series and grades**	**kg**	**Specific grades**	**kg**
AHSS	MS	27.1	MS 1250/1500	27.1	AHSS	MS	6.8	MS 1250/1500	6.8
	HF	13.5	HF 1050/1500	13.5		HF	2.6	HF 1050/1500	2.6
	DP	23.5	DP 700/1000	23.5		DP	n/a		
HSS	HSLA	157.6	HSLA 550/650	6.0	HSS	HSLA	26.2	HSLA 550/650	10.6
			HSLA 420/500	68.6				HSLA 420/500	n/a
			HSLA 350/450	83.0				HSLA 350/450	15.6
	BH	240.8	BH 280/400	33.8		BH	n/a		
			BH 260/370	71.0					
			BH 210/340	136					
LSS	Mild	28.4	Mild 140/270	28.4	LSS	Mild	n/a		
HTAs	6XXX	7	6XXX T6 (270)	5.0	HTAs	6XXX	226.5	6XXX T6 (270)[4]	38.6
			6XXX T7 (200)	2.0				6XXX T7 (200)	27.5
			6XXX-T6 295/340	n/a				6XXX-T6 295/340	54.9
			6XXX-T6 270/310					6XXX-T6 270/310	10.6
			6XXX-T6 250/285					6XXX-T6 250/285	9.7
			6XXX T6 (300)					6XXX T6 (300)	52.5
			6XXX T7 (230)					6XXX T7 (230)	5.3
			6XXX-T6 260/295					6XXX-T6 260/295	11.5
			6XXX-T6 340/370					6XXX-T6 340/370	2.9
			6XXX-T6 180/230					6XXX-T6 180/230	13
NHTAs	5XXX	4.3	5XXX (120)	4.3	NHTAs	5XXX	11.9	5XXX (120)	3.8
			5XXX (180)	n/a				5XXX (180)	8.1
Plastics		2.3	Polypropylene (PP)	2.3	Plastics		0	PP	0
Total Body		**504.4**		**504.4**	**Total Body**		**274.0**		**274.0**

[1] Mild 140/270- "140" indicates the minimum yield strength (YS) in Mega Pascal (MPa); "270" indicates the minimum ultimate tensile strength (UTS) in MPa (21);

[2] 5XXX (120)- "120" in brackets indicates the typical YS in Mpa (23);

[3] 6XXX-T6 295/340- "295" indicates the minimum YS in MPa; "340" indicates the UTS in MPa (23);

[4] "T" stands for heat treating temper codes; it's used for products that have been strengthened by heat treatment, with or without subsequent strain hardening. The designation is followed by one or more numbers (http://www.matweb.com/reference/aluminumtemper.aspx).

[5] Please note data may not add up to totals due to rounding.

Table A5. Aluminum material designation, applications and processes

LCI Aluminum Products	**Aluminum Material Designation** (23)	**Auto body parts**		
		Baseline	**AA LWT body design**	**Forming Process**
Cold-rolled aluminum	6XXX series	Yes	Yes	Cold stamping
	5XXX series	Yes	Yes	Cold stamping
Extruded aluminum	6XXX series	n/a	Yes	Extrusion
	5XXX series	n/a	Yes	Extrusion

Table A6. Steel material designation, applications and processes

LCI Steel Products	**Steel Material Designation** (23), (21)	**Auto body parts**		
		Baseline	**AA LWT body design**	**Forming Process**
MS, Martensitic	AHSS (tensile strengths higher than 550 MPa)	n/a	Yes	Stamping
		Yes	n/a	Rollforming
HF, Hot Formed		Yes	Yes	Stamping
DP, Dual Phase		Yes	n/a	Stamping
BH, Bake Hardenable	HSS (tensile strengths 210 MPa to 550 MPa)	Yes	n/a	Stamping
HSLA, high strength, low alloy		Yes	Yes	Stamping
		Yes	n/a	Rollforming
HDG, Hot-dip galvanized steel	Mild steel (tensile strengths less than 295 MPa)	Yes	n/a	Stamping
PHRC, Pickled hot-rolled coil		Yes	n/a	Stamping

Annex C: Brief Introduction to ISO 14040 Series of LCA Standards and CSA Group LCA Guidance for Auto Parts

Life cycle assessment (LCA) is a structured, comprehensive and internationally standardized method (63). LCA is an analytical tool used to comprehensively quantify and interpret the energy and material flows to and from the environment over the entire life cycle of a product, process, or service. Environmental flows include emissions to air, water, and land, as well as the consumption of energy and material resources. By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product and a more complete picture of potential environmental trade-offs in product design.

1 ISO 14040 Series of LCA Standards

The two core ISO standards 14040:2006 (6) and ISO 14044:2006 (1) describe an iterative four-phased indispensable methodology framework for completing an LCA: [1] goal and scope definition, [2] life cycle inventory (LCI), [3] life cycle impact assessment (LCIA), and [4] interpretation.

> **Goal and Scope Definition** — An LCA starts with an explicit statement of the goal and scope of the study, the functional unit, the system boundaries, the assumptions and limitations, the allocation methods used, and the impact categories chosen (see Sections 5 and 6). The goal and scope include a definition of the context of the study, which explains how and to whom the results are to be communicated. The ISO standards require that the goal and scope of an LCA be clearly defined and consistent with the intended application. The functional unit defines what is being studied. The purpose of the functional unit is to quantify the service(s) delivered by the product system and provide a reference to which the inputs and outputs can be related. Allocation is the method used to partition the environmental load of a process when several products or functions share the same process.
>
> *A clear, initial goal definition is therefore essential for a correct later interpretation of the results. This includes ensuring, as far as possible, that the deliverables of the LCI/LCA cannot unintentionally and erroneously be used or interpreted beyond the initial goal and scope for which it was carried out.*
>
> **Life Cycle Inventory** — In inventory analysis, a flow model of the technical system is constructed using data on inputs and outputs (see Section 8). The flow model is often illustrated with a flow chart that includes the activities that are going to be assessed and gives a clear picture of the technical system boundary. The input and output data needed for the construction of the model (such as materials and energy flows, emissions to air and water, and waste generation) are collected for all activities within the system boundary. Then the environmental flows of the defined system are calculated and related back to the functional unit, and the flow model is finished.
>
> **Life Cycle Impact Assessment** — Inventory analysis is followed by impact assessment, in which the LCI data are characterized in terms of their potential environmental impacts; for example, resulting in acidification, ozone depletion, and global warming. The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts based on the LCI flow results (see Section 9). Classical LCIA consists of the following mandatory elements — selection of impact categories, category indicators, and characterization models — and continues with the classification stage, where the inventory parameters are sorted and assigned to specific impact categories. The

categorized LCI flows are then characterized using one of many possible LCIA methodologies into common equivalence units and summed to provide an overall impact category total. This equivalency conversion is based on characterization factors as specified by the selected LCIA methodology. In addition to the mandatory LCIA elements (selection, classification, and characterization), other optional LCIA elements (normalization, grouping, and weighting) may be conducted depending on the goal and scope of the LCA study. In normalization, the results of the impact categories from the study are usually compared with the total impact in the region of interest. Grouping consists of sorting and possibly ranking the impact categories. During weighting, the different environmental impacts are weighted against each other to get a single number for the total environmental impact. Per ISO 14044, “Weighting shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public.” Weighting and other optional LCIA elements are excluded to be consistent with the goal and scope of the LCA study and ISO 14044.

Interpretation — In life cycle interpretation, the results found during a life cycle assessment are appraised in order to answer questions posed in the goal definition (63). The outcome of the interpretation phase is a set of conclusions and recommendations for the study (see Section 10). According to ISO 14040, the interpretation should include the following: [1] Identification of significant issues based on the results of the LCI and LCIA phases of LCA; [2] Evaluation of the study considering completeness, sensitivity, and consistency checks; and [3] Conclusions, limitations and recommendations.

For best interpretation and adequate use of the LCA results, it’s important to highlight the *inherent limitations and assumptions of the LCA technique*. LCA addresses “*potential environmental impacts*” and does not predict *absolute or precise environmental impacts* due to: (a) the *relative expression* of potential environmental impacts to a reference unit (e.g., one AA LWT body design), (b) the integration of environmental data over *space and time*, (c) the *inherent uncertainty* in modelling of environmental impacts (e.g., the uncertainty in environmental mechanisms of TRACI impact categories), and (d) the fact that some possible environmental impacts are *clearly future impacts* (e.g., impacts of use and EOL stages) (1).

At the end, the results and conclusions of the LCA should be completely and accurately reported to the intended audience. The data, methods, assumptions, limitations, and results should be transparently presented in sufficient detail to allow the interested parties to comprehend the complexities and trade-offs inherent in the LCA. The interpretation should present the results of the LCA in an unambiguous, understandable, and non-misleading way and help the user of the LCI/LCA appraise the robustness of the conclusions and understand any potential limitations of the LCI/LCA (63).

2 CSA Group LCA Guidance for Auto Parts

The AA LWT body design LCA has been conducted in compliance with the ISO 14040 standards series that provide general rules and requirements for conducting an LCA study. This framework, however, leaves the individual LCA practitioner with a range of choices, which can affect the legitimacy of the results of an LCA study (64), (63). The flexibility of LCA methodology enables its use across industries and in varying levels of specificity, but also creates variability in scope, boundaries, and assumptions that can make comparing LCAs difficult (65). While flexibility is essential in responding to the large variety of questions addressed, further guidance is needed to support consistency and quality assurance (64), (63).

ISO 14040/44 are multisectoral LCA standards that cover, but are not specifically tailored for, the auto sector (66). Without auto sector specific rules, comparative LCA studies of identical auto parts conducted by different LCA practitioners can lead to significantly different results and recommendations. While each of the LCA studies may be conformant with the ISO 14040 series of LCA standards, discrepancies in life cycle inventory modeling, data sources, and automotive technical parameters can explain significant variations in the LCA results. To add to the complexity, the automotive sector remains highly competitive regarding the alternative lightweight materials applications for auto parts. Globally, there's a noticeable increase in the number of comparative LCA studies of auto parts, commissioned by a wide range of interested parties, which typically intend to highlight the potential environmental benefits of selected lightweight materials versus the main competitors (65).

In response to global automotive market changes and to complement the ISO 14040 series framework, the CSA Group LCA Guidance for Auto Parts document was developed in 2014 and establishes *auto sector specific* technical parameters, and LCA calculation rules and requirements for conducting comparative LCA studies for auto parts in North America (2). The guidance document was peer reviewed for technical accuracy, conformance with ISO 14040/44 principles, and general relevance and applicability.

The AA LWT body design LCA was carried out using the methodology consistent with ISO 14040/44 and following the specific rules and guidance provided in the CSA document (Figure A1). The document provides clear and consistent guidance for assessing potential environmental impacts throughout the cradle-to-grave life cycle of an auto part, with a focus on weight differences between design options due to material composition, manufacturing technology or part geometry. The LCA guidance document is tailored for ICE vehicles in the NA context and covers all U.S. EPA passenger vehicle size classes (sedan, station wagons, pickup trucks, vans and sport utility vehicles). The framework of the guidance document is adaptable to include advanced powertrains (e.g., hybrid and electric).

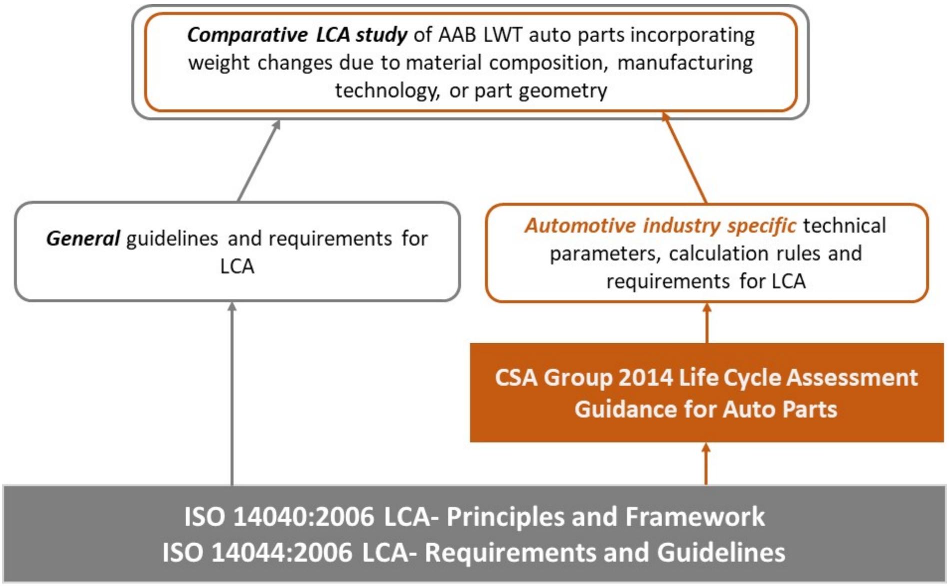


Figure A1. LCA framework of the comparative LCA study of AA LWT auto body parts

Annex D: Well-to-Wheels Vehicle Emissions and Group Types in LCA

Figure A2 shows the full fuel cycle is the combination of the well-to-pump (WTP) and pump-to-wheels (PTW), which is also commonly referred to as a well-to-wheels (WTW) analysis. The WTP stage includes resource extraction, initial processing, transportation, fuel production, and distribution of the fuel to pump. PTW stage covers the end use of fuel in vehicle operations. WTW LCI profiles account for all the energy and emissions necessary to produce the fuel used in the car and the operation energy and emissions associated with the vehicle technology (tail pipe emissions, other emissions and energy efficiency of the vehicle) (38).

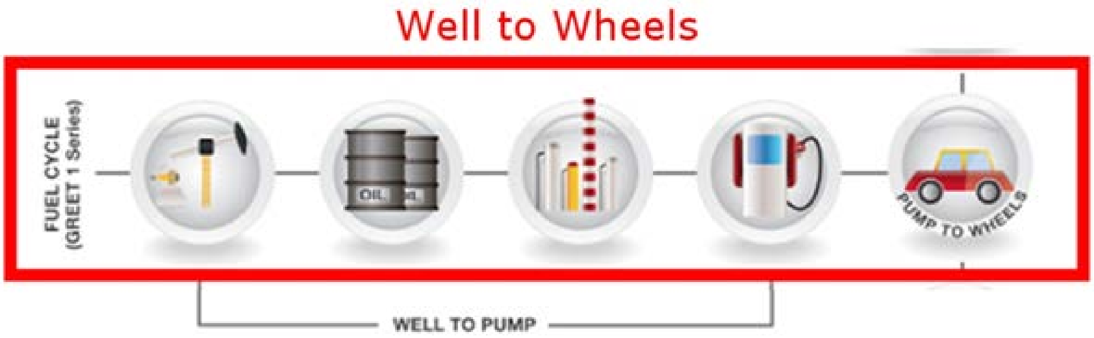


Figure A2. Well-to-wheels: well-to-pump and pump-to-wheels *[Photo courtesy: GREET® Model]*

On-road motor vehicle emissions can be classified in two categories: *exhaust* emissions, generated as by-products of the fuel combustion process, and *evaporative* emissions, generated directly from the fuel in a variety of ways (67). Exhaust emissions are divided into two types, based on the engine temperature: (1) *cold start* emissions that are generated from vehicle startup until the engine and emission control system have reached steady state temperature; and (2) *hot* emissions that are generated when the vehicle operates at steady state temperature (67). Evaporative emissions result from the direct escape of hydrocarbons from the fuel (67). Vehicle emissions in GREET 2017 are developed using EPA's MOtor Vehicle Emission Simulator model, which captures emissions from cold starts, warm starts and evaporation (42).

Exhaust emissions from road transport arise from the combustion of fuels such as gasoline, diesel, liquefied petroleum gas (LPG), and natural gas in ICEs. The air/fuel charge may be ignited by a spark ('spark-ignition' or 'positive-ignition' engines), or it may ignite spontaneously when compressed ('compression-ignition' engines) (43). The combustion process produces CO_2 and H_2O as the main products (43). Unfortunately, combustion also produces several by-products which either originate from incomplete fuel oxidation (such as carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM)) or from the oxidation of non-combustible species present in the combustion chamber (such as nitrogen oxides (NO_x) from nitrogen (N_2) in the air, sulphur oxides (SO_x) from sulfur (S) in the fuel and lubricant, etc.). In order to comply with emission legislation, vehicle manufacturers have installed various after treatment devices such as catalytic converters and diesel particle filters to reduce pollutant emissions. However, such devices may, as a result of their action, also produce small quantities of pollutants such as ammonia (NH_3) and nitrous oxide (N_2O) (43). From the LCA perspective, the WTW emissions are classified in Group 1 to 6 (68)—Table A7 details operation (also known as combustion) emissions by group type (available in GREET.net 2017).

Table A7. Grouping of Well-to-Wheels vehicle emissions

Group type	**Well-to-wheels vehicle emissions in GREET 2017** (38)	**Description of operation emissions per group type** (68)
Group 1	Carbon dioxide (CO_2), Sulphur oxides (SO_x), and Sulphur dioxide (SO_2)	Exhaust emissions dependent on fuel consumption and composition
Group 2	Carbon monoxide (CO), Nitrogen oxides (NO_x, NO and NO_2), Particulate matter 10 µm diameter (PM_{10}), and Particulate matter 2.5 µm diameter ($PM_{2.5}$) including particulate black carbon (BC) and organic carbon (OC)[1].	Regulated exhaust emissions
Group 3	Methane (CH_4), and Non-methane volatile organic compounds (NMVOCs)	Hydrocarbon (HC) exhaust emission profiles, which are derived as a fraction of total non-methane hydrocarbon (NMHC) emissions
Group 4	Nitrous oxide (N_2O)	Other exhaust emissions
Group 5	BC_, OC_, PM_{10}_ and $PM_{2.5}$_ tire and brake wear (TBW)	Non-exhaust abrasion particle emissions including fractions of heavy metals
Group 6	Not available in GREET 2017	Heavy metal emissions to soil and water due to tire abrasion

[1] BC and OC contribute to the adverse impacts associated with particulate matter with an aerodynamic diameter of 2.5 µm or less (PM2.5) on visibility and human health, and they affect climate through multiple mechanisms such as direct effect, snow/ice albedo effect, and other effects (69).

[2] NMHC emissions are reported under NMVOCs in GREET 2007.

A number of new technologies are designed to reduce both energy consumption and pollutant emissions. These technologies include the following (43):

- New types of ICEs, such as gasoline direct injection (GDI), controlled auto-ignition (CAI), homogeneous charge compression ignition (HCCI);
- Alternative fuels, such as compressed natural gas (CNG), reformulated grades of gasoline and diesel, and hydrogen;
- Alternative powertrains, such as hybrids (i.e. a combination of an ICE and an electric motor), plug-in hybrids that can be recharged from the grid power, fuel cell vehicles, electric, etc.

As presented in Table A8, the vehicle emissions included are (8), (43), (70): *Greenhouse gases* (GHGs): CO_2, CH_4, and N_2O; and *air pollutants*: ground level ozone (O_3) precursors (CO, NO_x, NMVOCs); acidifying substances (SO_x, NO_x); and particulate matter (PM) including black carbon (BC) and organic carbon (OC).

The impacts of GHGs and air pollutants (also called the criteria pollutants) are well known and documented, (8), (70), (36), (34). Under the Clean Air Act, the U.S. EPA has set national air quality standards for these common air pollutants to protect public health. CO, NO_2, and SO_2 are emitted directly. Ozone is not directly emitted, but is formed when oxides of nitrogen (NO_x) and volatile organic compounds (VOCs) react in the presence of sunlight. Ozone at ground level is a harmful air pollutant because of its effects on people and the environment and it is the main ingredient in photochemical “smog". PM can be emitted, or it can be formed when emissions of NO_x, sulfur oxides (SO_x), ammonia, organic compounds, and other gases react in the atmosphere (70). The majority of GHGs from transportation are CO_2 emissions resulting from the combustion of petroleum-based products, like gasoline, in ICEs (8). The largest sources of transportation-related GHGs include passenger cars and light-duty trucks, including sport utility vehicles, pickup trucks, and minivans. These sources account for over half of the emissions from the sector (8). Relatively small amounts of CH_4 and N_2O are emitted during fuel combustion (8). Different GHGs have varying global warming impacts according to their radiative forcing or "heat trapping" potential, which refers to the amount that the gas alters the energy transfer in and out of the Earth's atmosphere. To evaluate the aggregate impacts of GHGs, for a 100-year time-period, a standard measure of the global warming potential (GWP) of each gas relative to CO_2 is used to convert all GHGs into CO_2 equivalents (CO_2 eq.) (8), (36), (34).

Table A8. Brief description of vehicle combustion emissions (GHGs and air pollutants) (8), (67), (43), (68), (70)

Vehicle pollutants	Emissions to air	Description
GHGs	Carbon dioxide	CO_2, a product of the complete combustion of automotive fuels, is the most significant component of all greenhouse gas emissions. GWP (100-year): 1$^{1)}$
	Methane	CH_4 is a flammable gaseous product of fuel combustion and evaporative emissions. GWP CH4, fossil (100-year): 30 kg CO_2 eq.$^{1)}$ GWP CH4, biogenic (100-year): 28 kg CO_2 eq.$^{1)}$
	Nitrous oxide (known also as dinitrogen monoxide)	N_2O is a gaseous product of incomplete combustion of automotive fuels as well as a by-product of catalytic converters. GWP N_2O (100-year): 265 kg CO_2 eq.$^{1)}$
Air pollutants	Nitrogen oxides	NOx (of which nitrogen dioxide, NO_2, is the most common) are a group of highly reactive gases of the burning of nitrogen (N) in fossil fuels and nitrogen compounds in air. NOx reacts with other chemicals in the air to form both PM and O_3. Both are also harmful when inhaled due to effects on the respiratory system.
	Carbon monoxide	CO is a toxic, colorless, and odorless gas of incomplete combustion of gasoline and diesel fuel present in all tailpipe exhaust. CO is harmful when inhaled in large amounts as it reduces the amount of oxygen (O_2) that can be transported in the blood stream to critical organs like the heart and brain.
	Volatile organic compounds	VOCs are a large group of carbon-containing gases and vapours that are products of fuel combustion. Main VOCs, including benzene (C_6H_6), toluene (C_7H_8), m,p,o Xylene (C_8H_{10}), are classified as Hazardous Air Pollutants by the U.S. EPA. While the VOC emissions are usually low concentrations, these substances are also precursors to ground-level ozone and $PM_{2.5}$.
	Sulphur oxides	SO_2 is a product of the combustion of fossil fuels with a high sulfur content. SOx gases are harmful to human health and the environment.
	Particulate matter	PM is generated as secondary products of motor vehicle fuel consumption, formed from gaseous vehicle emissions like NO_x or SO_2. PM refers to solid or liquid particles that are released to the atmosphere from a gaseous suspension. PM is classified into two size ranges ($PM_{2.5}$, PM_{10}), as the particle size is the primary determinant of the health and environmental impacts.

$^{1)}$ Based on the IPCC 2013 AR5 (71). The IPCC is the international body for assessing the science related to climate change.

Annex E: GREET.net 2017 WTW Gasoline LCI Data

Table A9. WTW gasoline LCI data [GREET.net 2017, version 1.3.0.13239, 01-16-2018] (38)

Vehicle Name:	**PUT: SI ICEV - E10 (Type 2 Lightweight Material)**			
HHV gasoline (E10)1)	33568	MJ/m3	33.56820	MJ/l
Density gasoline (E10)	749.1	kg/m3	0.75	kg/l
MPG- gasoline	18	mi/gal		
Target Year for Simulation	2015	The modeling year in GREET defines the selected year for fuel production technologies		
Target Year for Vehicle Technology	2014	LTDD	290,000 km (180,197.6 miles)	
LCI Results	**WTP- Well-to-Pump**	**Operation Only**	**WTW- Well-to-Wheel**	**Airborne emissions group type**
Total Energy	285.60 kJ/MJ	1000.00 kJ/MJ	1286 kJ/MJ	n/a
Fossil Fuel	1200 kJ/MJ	0 J/MJ	1200 kJ/MJ	
Coal Fuel	20.63 kJ/MJ	0 J/MJ	20.63 kJ/MJ	
Natural Gas Fuel	167.57 kJ/MJ	0 J/MJ	167.57 kJ/MJ	
Petroleum Fuel	1012 kJ/MJ	0 J/MJ	1012 kJ/MJ	
Total Emissions				
CO2	18.60 g/MJ	70.94 g/MJ	89.54 g/MJ	Group 1
CO2_Biogenic2)	-2.91e-5 kg/MJ	-4.73e-3 kg/MJ	-4.76e-3 kg/MJ	Group 1
SOx	22.51 mg/MJ	0.43 mg/MJ	22.94 mg/MJ	Group 1
SO2	0 kg/MJ	0 kg/MJ	0 kg/MJ	Group 1
CO	16.90 mg/MJ	1.07 g/MJ	1.09 g/MJ	Group 2
NOx	36.80 mg/MJ	72.17 mg/MJ	0.11 g/MJ	Group 2
PM10	3.46 mg/MJ	1.65 mg/MJ	5.11 mg/MJ	Group 2
PM2.5	2.34 mg/MJ	1.46 mg/MJ	3.80 mg/MJ	Group 2
BC	*0.35 mg/MJ*	*0.31 mg/MJ*	*0.66 mg/MJ*	*Group 2*
POC	*0.60 mg/MJ*	*0.72 mg/MJ*	*1.32 mg/MJ*	*Group 2*
VOC	28.31 mg/MJ	25.40 mg/MJ	53.71 mg/MJ	Group 3
CH4	0.16 g/MJ	2.39 mg/MJ	0.16 g/MJ	Group 3
VOC_evap	0	14.69 mg/MJ	14.69 mg/MJ	Group 3
N2O	2.67 mg/MJ	5.82 mg/MJ	8.50 mg/MJ	Group 4
PM2.5_tire and brake wear (TBW)	0	1.03 mg/MJ	1.03 mg/MJ	Group 5
BC_TBW	*0*	*0.11 mg/MJ*	*0.11 mg/MJ*	*Group 5*
POC_TBW	*0*	*0.16 mg/MJ*	*0.16 mg/MJ*	*Group 5*
PM10_TBW	0	2.88 mg/MJ	2.88 mg/MJ	Group 5

1) U.S. EIA 2016: Blends of petroleum-based gasoline with 10% ethanol, commonly referred to as E10, account for more than 95% of the fuel consumed in motor vehicles with gasoline engines (72).

2) In GREET, the negative values of CO_2 biogenic for biofuels, indicate CO_2 biogenic uptake in feedstock. The CO_2 biogenic calculations assume biofuel carbon neutrality ("net-zero" carbon biogenic mechanism). It should be noted that GREET does not include the emissions of land use change and soil organic carbon change for biofuel feedstocks (37). This limitation is "*conservative*" as the WTW CO_2 total (including land use change and soil organic carbon change) is expected to be higher. In addition, it's worth noting that the biofuel carbon neutrality issue is highly debatable in the U.S. and globally (73), (74), (53). In the framework of this LCA study, biofuel carbon neutrality is assumed.

3) Please note data may not add up to totals due to rounding.

4) Displayed digits of the LCI results calculated with GREET.net Software do not represent significant digits.

Table A10. Sensitivity- 2025 WTW gasoline LCI data (38)

Vehicle Name:	**PUT: SI ICEV - E10 (Type 2 Lightweight Material)**			
HHV gasoline (E10)	33568	MJ/m3	33.56820	MJ/l
Density gasoline (E10)	749.1	kg/m3	0.75	kg/l
MPG- gasoline	18	mi/gal		
Target Year for Simulation	2025	The modeling year in GREET defines the selected year for fuel production technologies		
Target Year for Vehicle Technology	2014	LTDD	290,000 km (180,197.6 miles)	
LCI Results	**WTP- Well-to-Pump**	**Operation Only**	**WTW- Well-to-Wheel**	**Airborne emissions group type**
Total Energy	279.78 kJ/MJ	1000.00 kJ/MJ	1280 kJ/MJ	n/a
Fossil Fuel	1195 kJ/MJ	0 J/MJ	1195 kJ/MJ	
Coal Fuel	16.82 kJ/MJ	0 J/MJ	16.82 kJ/MJ	
Natural Gas Fuel	169.50 kJ/MJ	0 J/MJ	169.50 kJ/MJ	
Petroleum Fuel	1009 kJ/MJ	0 J/MJ	1009 kJ/MJ	
Total Emissions				
CO2	18.37 g/MJ	70.94 g/MJ	89.31 g/MJ	Group 1
CO2_Biogenic	-1.67e-5 kg/MJ	-4.73e-3 kg/MJ	-4.75e-3 kg/MJ	Group 1
SOx	18.16 mg/MJ	0.43 mg/MJ	18.59 mg/MJ	Group 1
SO2	0 kg/MJ	0 kg/MJ	0 kg/MJ	Group 1
CO	15.62 mg/MJ	1.07 g/MJ	1.09 g/MJ	Group 2
NOx	30.00 mg/MJ	72.17 mg/MJ	0.10 g/MJ	Group 2
PM10	3.10 mg/MJ	1.65 mg/MJ	4.76 mg/MJ	Group 2
PM2.5	2.07 mg/MJ	1.46 mg/MJ	3.53 mg/MJ	Group 2
BC	*0.28 mg/MJ*	*0.31 mg/MJ*	*0.59 mg/MJ*	*Group 2*
POC	*0.52 mg/MJ*	*0.72 mg/MJ*	*1.24 mg/MJ*	*Group 2*
VOC	28.03 mg/MJ	25.40 mg/MJ	53.43 mg/MJ	Group 3
CH4	0.16 g/MJ	2.39 mg/MJ	0.16 g/MJ	Group 3
VOC_evap	*0*	14.69 mg/MJ	14.69 mg/MJ	Group 3
N2O	2.48 mg/MJ	5.82 mg/MJ	8.30 mg/MJ	Group 4
PM2.5_tire and brake wear (TBW)	*0*	1.03 mg/MJ	1.03 mg/MJ	Group 5
BC_TBW	*0*	*0.11 mg/MJ*	*0.11 mg/MJ*	*Group 5*
POC_TBW	*0*	*0.16 mg/MJ*	*0.16 mg/MJ*	*Group 5*
PM10_TBW	0	2.88 mg/MJ	2.88 mg/MJ	Group 5

1) GREET.net 2017, version 1.3.0.13239, 01-16-2018 (38)

2) Please note data may not add up to totals due to rounding.

3) Displayed digits of the LCI results calculated with GREET.net software do not represent significant digits.

Annex F: Automotive Aluminum and Steel Product Definitions

The following aluminum and steel products are applicable for the purposes of this LCA.

Table A11. Definitions of aluminum products used in the Baseline and AA LWT body design

Aluminum Product	**Definition** (26)
Extruded aluminum	The extrusion process takes cast extrusion billet (round bar stock produced from direct chill molds) and produces extruded shapes. The process begins with an inline preheat that takes the temperature of the billet to a predetermined level depending on the alloy. The billet is then sheared if not already cut to length and deposited into a hydraulic press. The press squeezes the semi-plastic billet through a heated steel die that forms the shape. The shape is extruded into lengths defined by the take-off tables and is either water quenched or air cooled. The shape is then clamped and stretched to form a solid straightened length. The straighten lengths are cut to final length multiples and may be placed in an aging furnace to achieve a desired temper. Lengths are then finished (drilled and shaped) and placed into a coating process. The types of coatings include anodized, painted, and lacquered finishes (26).
Hot-rolled aluminum	Hot rolling is the method of rolling metal at a temperature high enough to avoid strain-hardening (work-hardening) as the metal is deformed. The ingots are preheated to about 1000 F and fed through a hot reversing mill. In the reversing mill, the coil passes back and forth between rolls and the thickness is reduced to 4 to 5 inches with a corresponding increase in length. This part of the hot rolling process is also called a Breakdown rolling process. Following the reversing mills, the slabs are fed to a continuous hot mill where the thickness is further reduced to as thin as 1/10 inch in thickness. The metal, called re-roll or hot band, is edge trimmed and rolled into a coil and is ready to be transferred to the *cold mill* (26).
Cold-rolled aluminum	Cold rolling is the rolling of the metal at a temperature low enough for strain-hardening (work-hardening) to occur, even if the metal would feel hot to human senses. The purpose of cold rolling is to give aluminum sheet a desired strength and temper; or to provide a final surface finish; or to reduce the sheet to very small thicknesses. Prior to the cold mill, the coils may be annealed to give the metal the workability for down-stream working. The coils are then passed through multiple sets of rolls to reduce the gauge. The resulted coils are cut to the width and length as required by customers (26).

Table A12. Definitions of steel products used in the Baseline and AA LWT body design

Steel Product	**Definition** (21)
AHSS, Advanced High-Strength Steel A series of high-strength steels containing microstructural phases *other than ferrite and pearlite*. These other phases include *martensite, bainite, retained austenite, and/or austenite* in quantities sufficient to produce unique mechanical properties. Most AHSS have a multi-phase microstructure (21).	
MS, Martensitic steel	A body-centered tetragonal crystalline phase of steel. It is the primary strengthening phase in Dual Phase steels and Martensitic steels are 100% martensite. It is a hard phase that can form during the quenching of steels with sufficient carbon equivalents. Martensite can also be formed by the work hardening of austenite (21).
HF, Hot-Formed steel	A quenchable steel that is heated to transform the microstructure to *austenite* and then immediately hot-formed and in-die quenched. Final microstructure is *martensite*. HF steel provides a combination of good formability, high tensile strength, and no springback issues. Most common HF steels are *boron* based (21).
DP, Dual Phase steel	Steel consisting of a *ferrite* matrix containing a hard second phase, usually islands of *martensite* (21).
HSS, High-Strength steel Any steel product with initial yield strength greater than 210 MPa or a tensile strength greater than 270 MPa (21).	
HSLA	Steels that generally contain microalloying elements such as titanium, vanadium, or niobium to increase strength by grain size control, precipitation hardening, and solid solution hardening (21).
BH, Bake hardenable steels	A low carbon, cold formable sheet steel that achieves an increase in strength after forming due to a combination of straining and age hardening. Increasing the temperature accelerates the aging-hardening process (21).
Mild steel Low strength steels with essentially a ferritic microstructure and some strengthening techniques.	
HDG, Hot-dip galvanized steel	Obtained by passing cold-rolled coil through a molten Zn bath, to coat the steel with a thin layer of Zn to provide corrosion resistance; can be further processed. Has excellent forming properties, paintability, weldability, and is suitable for fabrication by forming, pressing and bending. Automotive applications include e.g., body-in-white for vehicles, underbody auto parts, etc. Typical thickness between 0.3 and 3 mm. Typical width between 600 and 2,100 mm (30).
PHRC, Pickled hot-rolled coil	Hot-rolled steel from which the iron oxides present at the surface have been removed in a pickling process; can be further processed. Applications in virtually all sectors of industry: transport, construction, shipbuilding, gas containers, pressure vessels, energy pipelines, etc. Typical thickness between 2 and 7 mm. Typical width between 600 and 2,100 mm (30).

Annex G: Primary and Secondary Steel and Aluminum Production

1 Primary and Secondary Steel Production

From the LCA perspective, the following *three terms and definitions of steel products* are important (30),

Primary steel	• generally refers to the manufacture of iron (hot metal) from iron ore in a blast furnace (BF), which is subsequently processed in the basic oxygen furnace (BOF) to make steel.
Secondary steel	• refers to the "recycling" route, and is typically the electric arc furnace (EAF) process, which converts scrap into new steel by re-melting old steel.
Value of steel scrap	• is calculated as the difference between producing a given amount of material from 100% primary steel (i.e. virgin) material and producing the same amount of material through secondary steel (recycled scrap metal) production means, and multiplied by the yield of the EAF process to consider losses in the process.

However, "primary steel" production is not unique to the BOF route and similarly "secondary steel" production is not unique to the EAF. For example, it is common practice to use 10-30% scrap as iron input in the BOF route. Primary steel production occurs in the EAF route also, when pre-reduced iron is used as a feedstock to the EAF process (30). Figure A3 shows that both EAF and BOF processes produce primary and secondary steel.

Value of steel scrap (both fabrication and EOL scrap), is provided in a rolled-up form by worldsteel (51). The $CO_{2\ \text{Value of steel scrap}}$ is equal to the credit associated with the avoided primary production of steel (assuming 0% scrap input), minus the burden associated with the recycling of steel scrap to make new steel, and multiplied by the yield of this process to consider losses in the process (30). It should be clear that *it is not the steel scrap itself that replaces the primary steel, as the scrap needs to be processed or recycled (EAF process) to make new steel*.

$$\text{LCI value of steel scrap} = Y \times (\text{LCI}_{\text{prim}} - \text{LCI}_{\text{sec}}) \qquad \text{(A-1)}$$

The CO_2 value per 1 kg of steel scrap would therefore be calculated as follows:

$$CO_{2\ \text{Value of steel scrap}} = Y \times (CO_{2\ \text{prim}} - CO_{2\ \text{sec}}) \qquad \text{(A-2)}$$

$$CO_{2\ \text{Value of steel scrap}} = 0.916 \times (1.92 - 0.386) = \mathbf{1.409}\ \text{kg}\ CO_2\ (30) \qquad \text{(A-3)}$$

0.916 is the process yield of the EAF (1.092 kg scrap is required to produce 1 kg steel),

1.92 is the theoretical amount of CO_2 emissions (in kg) per 1 kg of 100% primary metal production (1 kg of BOF slab), from the BOF route, assuming 0% scrap input- see Table 16, and

0.386 is the amount of CO_2 emissions (in kg) per 1 kg of 100% secondary metal production from scrap in the EAF (1 kg of EAF slab), assuming 100% scrap input- see Table 16.

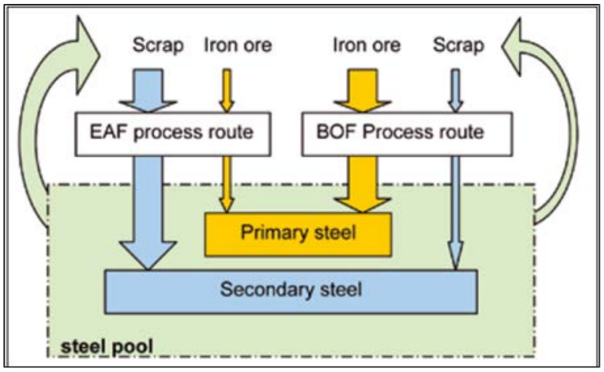


Figure A3. Connection between primary and secondary steel production (30)

2 Primary and Secondary Aluminum Production

From the LCA perspective, the following terms and definitions of aluminum products are important (26),

Primary aluminum production	•Includes the component processes of bauxite mining, alumina refining, electrolysis (including anode production and smelting), and primary ingot casting.
Secondary aluminum production	•Uses aluminum scrap as raw material. There are two types of secondary aluminum data: •*Aluminum recycling ingot (100% scrap), and* •*Secondary aluminum ingot (primary metal and alloy added).*
Value of aluminum scrap	•Includes two types of *value of aluminum scrap* data: •*Value of aluminum fabrication scrap, and* •*Value of aluminum EOL scrap.*

There are *two distinctive routes* of aluminum production:

- from natural resources – a special rock called bauxite, and
- from man-made resources – aluminum scrap.

Theoretically, metals made from these two different resources share the same properties and perform the same functions. From an environmental footprint point of view, however, there are significant differences (26).

Recycling is a critical step for the sustainability of a man-made metal like aluminum since it significantly saves both energy and scarce natural resources (50)*. In fact, "Aluminum can be recycled over and over and over again without loss of properties"* (75). Aluminum scrap is collected and melted everywhere in the world. For most countries, there is a well-established market for recycled aluminum with firmly defined distribution chains. Aluminum recycling plays a particularly leading role in Europe, *North America* and Japan, with 273, *316* and 120 industrial recycling facilities, respectively (75). A fully developed aluminum recycling industry, including both *refiners* and *remelters,* transforms aluminum scrap into standardized aluminum. *Refiners* supply foundries with casting alloys and *remelters* supply rolling mills and extruders with wrought alloys (75). *"End-of-life" recycling performance and "recycled metal content" are often misunderstood* (75). According to the International Aluminum Institute (75), "From a technical point of view, there is no problem to produce a new aluminum product from the same used product. There are no quality differences between a product entirely made of primary metal and a product made of recycled metal. *However, recycled aluminum is used where it is deemed most efficient in economic and ecological terms.* Due to the overall limited availability of aluminum scrap, any attempt to increase the recycled content in one particular product would just result in decreasing the recycling content accordingly in another. It would also certainly result in inefficiency in the global optimization of the scrap market, as well as wasting transportation energy. The high market value of aluminum means that, if scrap is available, it will be recycled and not stockpiled. *Industry continues to recycle, without subsidy, all the aluminum collected from end-of-life products as well as from fabrication and manufacturing process scrap*.

Secondary aluminum production- After scrap is "mined," or collected, it is sorted and cleaned before it is used in metal production. The core of secondary aluminum production is the melting and casting processes. Scrap is fed into melting furnaces to liquefy the metal. It is then purified, adjusted to the desired alloy, and produced into a form suitable for subsequent processing/fabrication (26).

There are two LCI data formats of **secondary aluminum** ingot:

1. **Aluminum recycling ingot (100% scrap),** used to calculate the avoided burden of *fabrication scrap recycling.* This data format assumes that aluminum products are recycled in a carefully and finely sorted manner, almost equivalent to a "closed-loop" recycling in which the same alloy products are sorted together and recycled into the same alloy. There is no involvement of primary metal and alloying elements in this case. The resulted metal is either not adjusted into special specifications or there is no need for adjustment. This is technologically feasible, and a proportion of the recycling industry carries out its production in this manner (26).

   Value of aluminum fabrication scrap is calculated as the difference between producing a given amount of material from 100% primary aluminum (i.e. virgin) material and producing the same amount of material through aluminum recycling (100% scrap) means, and multiplied by the yield of this process.

   $$\text{LCI value of Al fabrication scrap} = Y_f \times (LCI_{prim} - LCI_{100\%\ scrap}) \tag{A-4}$$

   The CO_2 value per 1 kg of Al fabrication scrap would therefore be calculated as follows:

   $$CO_{2\ \text{Value of Al fabrication scrap}} = 0.957 \times (7.478 - 0.634) = \mathbf{6.550}\ \text{kg } CO_2 \tag{A-5}$$

   95.7% is the yield for the recycling of fabrication scrap (Y_f) (26),

   7.478 is the amount of CO_2 emissions (in kg) per 1 kg of primary ingot – see Table 16, 0.634 is the amount of CO_2 emissions (in kg) per 1 kg of aluminum recycling ingot (100% scrap) – see Table 16.

2. **Secondary aluminum ingot (primary metal and alloy added),** used to calculate the avoided burden of *EOL scrap recycling*. This format assumes that aluminum products are recycled in a none-sorted, or highly mixture manner in which different alloys and product categories are mixed together, as is widely in practice in today's recycling processes. In this case, certain amount of primary aluminum metal and alloying elements are used to adjust the alloy compositions to the required specifications. The added primary metal and alloying agents here carry a "cradle-to-gate" burden tracing back to the mining process (26).

   Value of aluminum EOL scrap is calculated as the difference between producing a given amount of material from 100% primary aluminum (i.e. virgin) material and producing the same amount of material through secondary aluminum (primary metal and alloy added) production means, and multiplied by the yield of this process.

   $$\text{LCI value of aluminum EOL scrap} = Y_{EOL} \times (LCI_{prim} - LCI_{EOL\ scrap}) \qquad \text{(A-6)}$$

   The CO_2 value per 1 kg of Al EOL scrap would therefore be calculated as follows:

   $$CO_{2\ \text{Value of Al EOL scrap}} = 0.96 \times (7.478 - 1.109) = \mathbf{6.114}\ \text{kg}\ CO_2 \qquad \text{(A-7)}$$

   96% is the yield for the recycling of Al EOL scrap (26),

   7.478 is the amount of CO_2 emissions (in kg) per 1 kg of primary ingot – see Table 16,

   1.109 is the amount of CO_2 emissions (in kg) per 1 kg of secondary aluminum ingot (with primary metal and alloy added) – see Table 16.

The difference between the two LCI data formats is in the involvement of primary aluminum metal and alloying elements. The "aluminum recycling (100% scrap)" LCI dataset does not involve the addition of primary metal and alloying elements while the secondary aluminum production LCI dataset does. As the aluminum recycling ingot (100% scrap) has a lower impact (e.g., 0.634 vs 1.109 kg CO_2/kg ingot) relative to secondary ingot (primary metal and alloy added), the benefit of "fabrication scrap recycling" is higher than for "EOL scrap recycling" (e.g., 6.550 vs 6.114 kg CO_2/kg scrap).

In the 2013 Aluminum Association LCA report, alloying elements are substituted by the same quantities of primary aluminum for the purpose metal balancing for primary aluminum ingots suitable for rolling, extruding or shape casting (26). There are three major considerations for such substitution (26).

1. *The first consideration* is that there is a great variety of alloyed aluminum ingots produced in the cast house and the alloying elements are all slightly different depending on the end-use of the ingots.
2. *The second consideration* is that the proportion of alloying elements is very small in most cases, usually smaller that 5 percent, and that some of the alloying elements and their exact quantities are proprietary information of individual producers and they are mostly protected by patents.
3. *The third consideration* is that substituting alloy materials with primary aluminum does not end up with under-counting of the life cycle inventories since the approach of substitution used here is *fairly conservative*.

Annex H: Example of EOL Allocation Approach for Stamped Auto Body Parts

1 Example of EOL Allocation Approach for Stamped Steel Auto Body Parts

This section presents an example of how the cradle-to-gate (C2G) LCI of a steel auto body part (in this case the CO_2 emissions for a stamped HDG auto body part), including the *fabrication scrap recycling*, is calculated.

$$\mathrm{LCI}_{\text{C2G with fabrication scrap}} = 3.804 - 0.852 \times 1.409 \qquad \text{(A-8)}$$
$$\mathrm{LCI}_{\text{C2G with fabrication scrap}} = \mathbf{2.604}\ \text{kg } CO_2$$

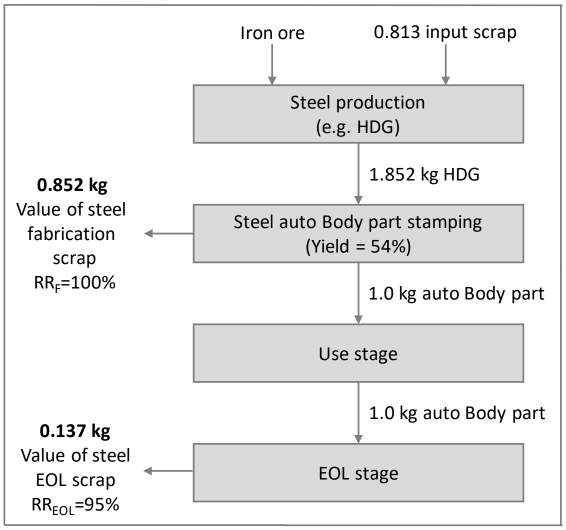


Figure A4. Example of EOL allocation approach for stamped steel auto body parts

Where,

3.804	is the amount of CO_2 emissions (in kg) per 1.852 kg NA HDG steel; 3.804 is calculated by multiplying 1.852 kg by the factor 2.054 kg CO_2 per kg NA HDG steel (51)
1.852	is the amount of NA HDG steel (in kg) used to fabricate 1 kg of Baseline stamped HDG auto body part (76)
0.852	is the amount of fabrication scrap (in kg) recovered for kg of stamped HDG auto body part (RR_F=100%) (76), and
1.409	is the value of CO_2 (in kg) per kg of steel scrap (30), (51)

Similarly, the cradle-to-gate LCI of the exemplary steel auto part, including EOL scrap recycling, is calculated as follows:

$$\mathrm{LCI}_{\text{C2G with EOL recycling}} = 2.604 - (0.95 - 0.813) \times 1.409 \qquad \text{(A-9)}$$
$$\mathrm{LCI}_{\text{C2G with EOL recycling}} = \mathbf{2.411}\ \text{kg } CO_2$$

Where,

0.95	is the EOL recovered scrap (in kg)/per kg auto body part (RR_{EOL}=95%) (49), and
0.813	is the amount of input scrap (in kg) in 1.852 kg NA HDG steel; 0.813 is calculated by multiplying 1.852 kg by the factor of 0.439 kg scrap per kg NA HDG steel (51)

CO_2 is used as an illustrative flow in this example- see Figure A4. The same calculation method applies to all inputs and outputs of the LCI. As can be seen from the formula A-9, ***the EOL recovered scrap rate of 95% is the defining parameter***, and the “cradle-to-gate” LCI of the metal product, with EOL recycling, is less a function of the “input scrap” than the net EOL recovered scrap for the system. For example,

- if the input amount of scrap is *low* (e.g., 0.10 kg), then at the end-of-life the metal product will be *credited* for the net value of EOL scrap 0.85 kg (=*0.95*- 0.10); and
- if the input amount of scrap is *high* (e.g., 0.99 kg) then at the end-of-life the metal product will be *debited* for the net EOL value of scrap -0.04 kg (=0.*95*- 0.99).

Overall the cradle-to-grave recovered scrap rate per kg steel stamped auto body part is **97%** [= (0.852 kg + 0.95 kg)/1.852 kg].

2 Example of EOL Allocation Approach for Stamped Aluminum Auto Body Parts

This section presents an example of how the cradle-to-gate LCI of an aluminum auto body part (in this case the CO_2 emissions for a stamped Al CRC auto body part), including the *fabrication scrap recycling*, is calculated.

$$LCI_{\text{C2G with fabrication scrap}} = 8.560 - 0.852 \times 6.550 \qquad \text{(A-10)}$$

$$\text{LCI C2G with fabrication scrap} = 2.980 \text{ kg } CO_2$$

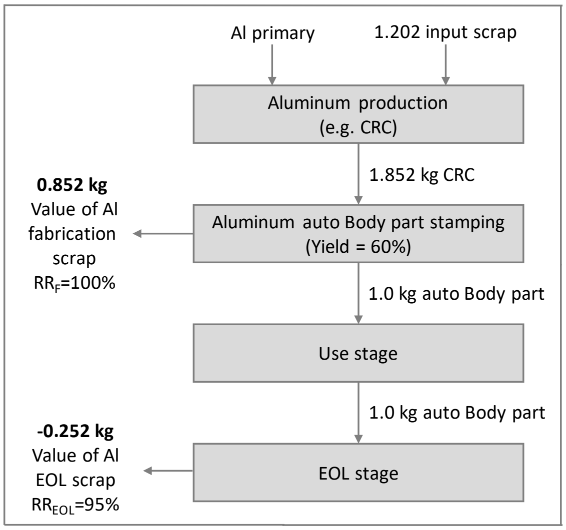


Figure A5. Example of EOL allocation approach for stamped aluminum auto body parts

Where,

8.560	is the amount of CO_2 emissions (in kg) per 1.852 kg NA Al CRC; 8.560 is calculated by multiplying 1.852 kg by the factor 4.622 kg CO_2 per kg NA Al CRC (26),
1.852	is the amount of NA Al CRC (in kg) used to fabricate 1 kg of stamped CRC auto body part (76),
0.852	is the amount of fabrication scrap (in kg) recovered for kg of stamped CRC auto body part ($RR_{F=}$100%) (76), and
6.550	is the CO_2 value (in kg) per kg of Al fabrication scrap (see Equation A-5)

Similarly, the cradle-to-gate LCI of the exemplary aluminum auto body part, including *EOL scrap recycling*, is calculated as follows:

$$LCI_{\text{C2G with EOL recycling}} = 2.980 - (0.95 - 1.202) \times 6.114 \qquad \text{(A-10)}$$
$$LCI_{\text{C2G with EOL recycling}} = \mathbf{4.520}\ \text{kg } CO_2$$

Where,

0.95	is the EOL recovered scrap (in kg)/per kg auto body part (RR_{EOL}=95%) (49),
1.202	is the amount of input scrap (in kg) in 1.852 kg NA Al CRC; 1.202 is calculated by multiplying 1.852 kg by the factor of 0.649 kg scrap per kg NA Al CRC,
6.114	is the CO_2 value (in kg) per kg of Al EOL scrap (see Equation A-7).

CO_2 is used as an illustration flow in this example- see Figure A5. The same calculation method applies to all inputs and outputs of the LCI. Overall the cradle-to-grave recovered scrap rate per kg aluminum stamped auto part is **97%** [= (0.852 kg + 0.95 kg)/1.852 kg].

Annex I: TRACI 2.1 LCIA Categories

Table A13. Description of TRACI 2.1 LCIA categories and impact indicators (36), (34).

LCIA Categories	Description
Acidification	According to TRACI 2.1, acidification comprises processes that increase the acidity (hydrogen ion concentration, [H^+]) within a local environment. This can be the result of the addition of acids (e.g., nitric acid and sulfuric acid) into the environment, or by the addition of other substances (e.g., ammonia) which increase the acidity of the environment due to various chemical reactions and/or biological activity, or by natural circumstances such as the change in soil concentrations because of the growth of local plant species (36). Acidification is a more regional rather than global impact affecting water and soil. Consistent with the focus on providing midpoint assessments, TRACI 2.1 uses an acidification model which incorporates the increasing hydrogen ion potential within the environment without incorporation of site-specific characteristics such as the ability for certain environments to provide buffering capability. Acidification is expressed in kg SO_2 equivalent.
Eutrophication	In TRACI 2.1, eutrophication is defined as the fertilization of surface waters by nutrients that were previously scarce. This measure encompasses the release of mineral salts and their nutrient enrichment effects on waters – typically made up of nitrogen (N) and phosphorous (P) compounds and organic matter flowing into waterways. The result is expressed on an equivalent mass of nitrogen basis. The characterization factors estimate the eutrophication potential of a release of chemicals containing N or P to air or water, per kg of chemical released, relative to 1 kg N discharged directly to surface freshwater. Eutrophication is expressed in kg N equivalent.
Climate change	TRACI calculates global warming potential, a midpoint metric proposed by the IPCC, for the calculation of the potency of GHGs relative to carbon dioxide (CO_2). The 100-year time horizons recommended by the IPCC and used by the US for policy making and reporting are adopted within TRACI. The methodology and science behind the global warming potential calculation is considered one of the most accepted LCIA categories. Within TRACI 2.1, GWPs published by IPCC were used for each substance. GWP_{100} is expressed in kg CO_2 equivalent.
Smog	Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level where, in the presence of sunlight, they produce photochemical smog, a symptom of photochemical smog formation potential (PSFP). While ozone is not emitted directly, it is a product of interactions of volatile organic compounds (VOCs) and nitrogen oxides (NOx). Smog is expressed in kg O_3 equivalent.
Human health: particulate	Particulate matter is a collection of small particles in ambient air, which has the ability to cause negative human health effects including respiratory illness and death (34). Emissions of SO_2 and NO_x lead to formation of the secondary particulates (sulphates and nitrates). Particles can be suspended in the air for long periods of time. Some particles are large or dark enough to be seen as soot or smoke. Others are so small that individually they can only be detected with an electron microscope. Many man-made and natural sources emit PM directly or emit other pollutants that react in the atmosphere to form PM. These solid and liquid particles come in a wide range of sizes. Particles less than 10 micrometers in diameter (PM10) pose a health concern because they can be inhaled into and accumulate in the respiratory system. Particles less than 2.5 micrometers in diameter (PM2.5) are referred to as "fine" particles and are believed to pose the greatest health risks. Because of their small size (approximately 1/30th the average width of a human hair), fine particles can lodge deep within the lungs. Respiratory effects are expressed as a microDALY normalized to PM2.5 equivalent mass basis.

Annex J: LCI and Transportation Data

Table A14. Summary of LCI datasets for AA LWT body design LCA study

LCI data sets	Source	LCI dataset	Comments
AHSS, HSS and Mild steel products			
BH, Bake hardenable steels	SRI 2014 (51)	Cradle-to-gate, Hot-dip galvanized steel	Reference year: 2006-2010[1] Geography: NA Technology: Industry average
HSLA, High-strength, low-alloy steels (>300 psi)	SRI 2014 (51)	Cradle-to-gate, Pickled hot-rolled coil steel	Reference year: 2006-2010 Geography: NA Technology: Industry average
MS, Martensitic steels	SRI 2014 (51)	Cradle-to-gate, Hot-dip galvanized steel	Reference year: 2006-2010 Geography: NA Technology: Industry average
HF, Hot Formed (and quenched) steels	SRI 2014 (51)	Cradle-to-gate, Hot-dip galvanized steel	Reference year: 2006-2010 Geography: NA Technology: Industry average
DP, Dual phase steel	SRI 2014 (51)	Cradle-to-gate, Hot-dip galvanized steel	Reference year: 2006-2010 Geography: NA Technology: Industry average
HDG, Hot-dip galvanized steel	SRI 2014 (51)	Cradle-to-gate, Hot-dip galvanized steel	Reference year: 2006-2010 Geography: NA Technology: Industry average
PHRC, Pickled hot-rolled coil	SRI 2014 (51)	Cradle-to-gate, Pickled hot-rolled coil steel	Reference year: 2006-2010 Geography: NA Technology: Industry average
Aluminum products[2],			
Al cold-rolled coil, sheet or plate	Aluminum Association 2018 (52), (26)	Cradle-to-gate, Al cold-rolled coil, sheet or plate	Reference year: 2010-2016 Geography: Global[3] and NA Technology: Industry average
Aluminum extrusions	Aluminum Association 2018 (52), (26)	Cradle-to-gate, Al extrusions	Reference year: 2010-2016 Geography: Global and NA Technology: Industry average

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[1] The reference year for the SRI steel production data is for 2006 to 2010, depending on each company providing data. Some upstream data is based on 2008 data (51).

[2] The reference year for the Aluminum Association Al production data is for 2010 to 2016. The Al CRC and extruded aluminum cradle-to-gate LCI profiles are based on the 2013 Aluminum Association LCA report (26) with an update of NA primary aluminum consumption profile for the production year of 2016 (see Table A16) (52).

[3] Few upstream unit processes are global data e.g., bauxite mining, anode production. In addition, the 2016 North American primary aluminum consumption mix consisted of 81% of the NA domestic primary aluminum production. The net imports from different countries made up the rest of 19% (57).

LCI data sets	Source	LCI dataset	Comments
Plastic (thermoplasts)			
PP, Polypropylene	US LCI (33)	Cradle-to gate, Polypropylene, resin, at plant, CTR (Cradle-to-Resin)/kg/RNA (Regional North America)	Reference year: 2005 Geography: NA Technology: Industry average
Fabrication processes			
Steel cold stamping	GREET 2 2017 (45)	Gate-to-gate, Metal stamping {RNA}, | Alloc Rec, U	Reference year: 2012 Geography: NA Technology: conventional (generic data)
Steel hot stamping	GREET 2 2017 (45) and (56)	Gate-to-gate, Metal stamping adjusted {RNA}, | Alloc Rec, U	Reference year: 2012 Geography: NA Technology: conventional
Steel roll forming	ecoinvent 3.3 (33)	Gate-to-gate, Sheet rolling, steel {RER}| processing | Alloc Rec, U	Reference year: 2012 Geography: Adjusted to NA[4] Technology: conventional
Aluminium cold stamping	GREET-2 2017 (45)	Gate-to-gate, Metal stamping {RNA}, | Alloc Rec, U	Reference year: 2012 Geography: NA Technology: conventional
Plastics injection molding	US LCI (33)	Gate-to-gate, Injection molding, rigid polypropylene part, at plant/kg/RNA	Reference year: 2010 Geography: NA Technology: conventional
Assembly processes			
Welding, Painting, and Compressed air	GREET 2 2017 (45)	Gate-to-gate	Reference year: 2012 Geography: NA Technology: conventional
EOL disassembly processes			
Vehicle system disassembly	GREET 2 2017 (45)	Gate-to-gate	Reference year: 2012 Geography: NA Technology: conventional
Electricity grid, heat and fossil fuels			

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[4] The term “adjusted to NA” means that ecoinvent 3.3 LCI datasets (European) are adjusted for NA conditions by replacing electricity grid, heat, and transportation technosphere flows with the NA ones.

LCI data sets	Source	LCI dataset	Comments
Electricity, medium voltage {US}| market for | Alloc Rec, U	ecoinvent 3.3 (33)	Used for upstream and downstream generic processes	Reference year: 2012 Geography: NA Technology: conventional
Electricity, medium voltage {Michigan, US}| market for | Alloc Rec,U	ecoinvent 3.3 (33)	Used in fabrication and assembly processes	Reference year: 2012 Geography: NA Technology: conventional
WTP and WTW gasoline	GREET.net 2017 (38)	Well-to-pump (WTP); Well-to-wheel (WTW), Annex E	Reference year: 2015 Geography: NA Technology: conventional
Heat, natural gas	ecoinvent 3.3 (33)	Heat, district or industrial, natural gas {US}| heat production, natural gas, at industrial furnace >100kW | Alloc Rec, U	Reference year: 2008 Geography: NA Technology: conventional
Heat, light fuel oil	ecoinvent 3.3 (33)	Heat, district or industrial, other than natural gas {US}| heat production, light fuel oil, at industrial furnace 1MW | Alloc Rec, U	Reference year: 2008 Geography: NA Technology: conventional
Transport			
Combination truck, long-haul (>200 miles)	US LCI (33)	Transport, combination truck, long-haul, diesel powered/tkm/RNA	Reference year: 2010 Geography: NA Technology: conventional
Combination truck, short-haul (<200 miles)	US LCI (33)	Transport, single unit truck, diesel powered, US	Reference year: 2010 Geography: NA Technology: conventional
Train	ecoinvent 3.3 (33)	Transport, freight train {US}| diesel | Alloc Rec, U	Reference year: 2008 Geography: NA Technology: conventional
End-of-life (EOL) processes			
Steel, value of scrap	SRI 2014	Gate-to-gate	Reference year: 2010 Geography: Global and NA Technology: industry average
Aluminum, recycling (100% scrap)	Aluminum Association 2013 (26)	Gate-to-gate	Reference year: 2010 Geography: NA Technology: industry average
Aluminum, primary ingot	Aluminum Association 2018 (52)	Cradle-to-gate	Reference year: 2016 Geography: Global and NA Technology: industry average

LCI data sets	Source	LCI dataset	Comments
Aluminum, secondary ingot (primary metal and alloy added)	Aluminum Association 2013 (26), (52)	Gate-to-gate	Reference year: 2010-2016 Geography: NA Technology: industry average
EOL disposal processes			
Plastics– waste to landfill	ecoinvent 3.3 (33)	Gate-to-Gate LCI profile Waste plastic, mixture {CH}| treatment of, sanitary landfill | Alloc Rec, U	Year: 2000 (extrapolated to 2016 by ecoinvent) Geography: Adjusted to NA Technology: conventional

Table A15. Transportation mode and distances

Transportation, one-way	From	To	Rail (miles)	Road (miles)	SCTG code
Semi-finished materials to fabrication site					
Aluminum	Transportation is included in the Aluminum Association LCI profiles of Al extrusions and Al CRC products with exception of the Al stampings (26)				
Al cold stamping	U.S.	Michigan, U.S.	590 (25%)	200 (75%)	32
AHSS, HSS, mild steel	U.S.	Michigan, U.S.	590 (25%)	200 (75%)	32
Plastics	U.S.	Michigan, U.S.	840 (40%)	230 (60%)	24
Fabrication scrap to recycler or disposal site					
Aluminum	Transportation is already included in the Aluminum Association LCI profile of Al recovered (100% scrap) (26)				
Steel	Michigan, US	Recycler, US	310 (25%)	150 (75%)	41
Plastics	Michigan, US	Recycler, US			
Fabricated parts to assembly site					
Aluminum	Michigan, US	Michigan, US	-	50 (100%)	n/a
Steel					
Plastics					
EOL transportation					
EOL vehicle to shredder	End-user	Shredder, US	-	100 (100%)	n/a
Aluminum	Transportation is already included in the Aluminum Association LCI profile of Al secondary ingot (primary metal and alloy added) (26)				
Steel	Shredder, US	Recycler, US	310 (25%)	150 (75%)	41
Plastics	Shredder, US	Landfill, US			

Table A16. North American Primary Aluminum Consumption Mix (for 2016 Production Year NA Primary Aluminum Consumption LCA Model)

Region	Metric Tons	Weight Factor
NA Domestic (U.S. and Canada)	4,027,514	0.812
Russia	517,905	0.104
United Arab Emirates	176,252	0.036
Argentina	96,292	0.019
Brazil	14,460	0.003
Bahrain	14,983	0.003
Venezuela	36,810	0.007
Rest of World	75,542	0.015
Total	4,959,757	1.000

Notes of the Table A16 from The Aluminum Association:

1) Data Source: The Aluminum Association (NA domestic production); GTIS.COM (U.S. non-alloyed aluminum ingot imports, subscription required); Bureau of Census, U.S. Department of Commerce (U.S. aluminum imports and exports); Statistics Canada (Canada aluminum imports and exports).

2) The primary aluminum consumption mix for North American region is an approximate estimation. Theoretically, the consumption mix should be "domestic" production plus NET imports from the rest of the world. NET imports refer to the difference between imports and exports.

3) In reality, however, NET import data is complicated by several factors including: a) "primary aluminum ingot" is not readily identifiable by international trade codes; b) cross trading within the "domestic" region, e.g. U.S. and Canada; c) separate trading of the "domestic" region with the rest of the world.

4) For the purpose of an NA primary aluminum ingot consumption LCA model, a simplified approach has been taking since the 2013 semi-fabricated aluminum LCA study. That is, if the region consumes less than it produces in a particular year, imports will not be considered; if the region consumes more than it produces, the consumption mix will be "domestic" production plus total imports from the rest of the world (Canada excluded) by the United States. The reason for U.S. alone being considered is that Canada is an export country and more than 80% of its export is to the U.S. during the past decade.

5) The harmonized tariff schedule (HTS) codes for aluminum "ingot", defined as unwrought aluminum, include two categories: non-alloyed and alloyed. The codes do not differentiate primary, secondary or mixed aluminum. For the purpose of avoiding double counting aluminum product's environmental footprint, alloyed aluminum ingot import from the rest of the world by the U.S. is not included in the NA consumption mix calculation. This decision is due to the fact that a large proportion of alloyed aluminum usually involves scrap input during the remelting, alloying and casting process. This is particularly true for aluminum extrusion and rolling ingots.

Table A17. Baseline and AA LWT body design data quality assessment

Data Quality Requirements	Description
Technology Coverage	Baseline and AA LWT auto body parts specific data were provided by EDAG Inc. (23). Whenever available, for all upstream, core, and downstream material and processes, North American typical or average industry LCI datasets were utilized (see Table A14, Annex J). The study uses worldsteel/SRI LCI data for mild steel to represent HSS and AHSS grades. The difference in the LCIA profile is expected to be negligible (60), (61). *Technological representativeness is characterized as "moderate to high".*
Geographic Coverage	The geographic region considered is limited to the North American auto market, with focus on the United States. The geographic coverage of all LCI datasets is given in Table A14, Annex J. *Geographical representativeness is characterized as "high".*
Time Coverage	Activity data for the Baseline and AA LWT body design are representative as of 2014 to 2017, respectively (see Tables A1, A2, A3, and A4, Annex B). worldsteel/SRI steel LCI data has a reference year of 2006-2010 while Aluminum Association LCI data is from 2010 (fabrication) and 2016 (primary ingot), see Table A14, Annex J. Since more recent LCI data on North American steel was not available, a sensitivity analysis was carried out to test the sensitivity of the LCA results towards changes in steel's cradle-to-gate impact profile. Due to the applied "substitution" approach and the high EOL recovered scrap rate (RR_{EOL}=95%, LCA results are insensitive to moderate changes in the material's impact profile. *Temporal representativeness is characterized as "moderate to high".*
Completeness	Primary activity data was collected and validated for both auto body systems, as shown in Annex B. Peer-reviewed LCI datasets are given high priority and applied for this LCA study (see Table A14, Annex J). The completeness of the cradle-to-grave process chain in terms of process steps is rigorously assessed for both Baseline and AA LWT body design and documented in Section 7.
Consistency	Special efforts have been made to ensure that differences in LCA results occur due to actual differences between the Baseline and AA LWT body systems, and not due to inconsistencies in modeling choices and data sources. The selection of adequate industry data agreed upon technical data, parameters, and identical calculation methods have been carried out uniformly for both auto body systems.
Reproducibility	Internal reproducibility is ensured since the data and the models are stored and available in the EDAG AA LWT Body Design SimaPro project, 2018. External reproducibility is also possible as a high level of transparency is provided throughout the LCA report and LCI data sources are summarized in Table A9, Annex E and Tables A14 and A15, Annex J.
Transparency	Activity and LCI datasets are transparently disclosed in the LCA report, including data sources and assumptions (see Tables A2, A3, and A4, Annex B, and Tables A14 and A15, Annex J).
Uncertainty	*A sensitivity check* was conducted to assess the reliability of the LCA results and conclusions by determining how they are affected by uncertainties in the data, allocation methods, or on calculation of category indicator results. The sensitivity check includes the results of the *sensitivity analysis* and Monte Carlo uncertainty analysis (see Section 10.2.2).

Annex K: Process, Substance and Raw Material Contribution Analysis and Other Additional Results

Table A18. PCA- Top 10 significant processes contributing to total net change of life cycle AP of the AA LWT body design (with P/T adaptation, LTDD$_V$= 290,000 km (2))- in kg SO_2-eq.

No.	Process	Total net change of life cycle AP of the AA LWT body design	Net change- Production stage	Net change- Use stage	Net change- EOL stage
Total of all processes		**-7.9**	**-5.6**	**-4.2**	**1.9**
Non-displayed processes (3%)		*-1.3*	*-1.0*	*-0.04*	*-0.3*
1	Value of aluminum process scrap-100% scrap	-7.3	-7.3	0	0
2	BH, Bake hardenable steel (C2G), NA HDG	-5.2	-5.2	0	0
3	WTP- Well-to-Pump Gasoline (E10)- SI ICEV GREET.net 2017	-4.1	0	-4.1	0
4	HSLA, High-strength, low-alloy steels (>300 psi) (C2G), NA PHRC	-1.9	-1.9	0	0
5	DP, Dual phase steel (C2G), NA HDG	-0.5	-0.5	0	0
6	Mild steel (C2G), NA HDG	-0.5	-0.5	0	0
7	Aluminum extruded products (C2G)	0.6	0.6	0	0
8	Value of aluminum EOL scrap (primary metal + alloy added)	1.6	0	0	1.6
9	Value of steel scrap	1.8	1.3	0	0.5
10	Aluminum cold-rolled coils (C2G)	8.9	8.9	0	0

[1] Please note data may not add up to totals due to rounding.
[2] Displayed digits of the AA LWT LCA results calculated with SimaPro LCA software do not represent significant digits.

Table A19. PCA- Top 10 significant processes contributing to total net change of life cycle EP of the AA LWT body design (with P/T adaptation, LTDD$_V$= 290,000 km (2))- in kg N-eq.

No.	Process	Total net change of life cycle EP of the AA LWT body design	Net change- Production stage	Net change- Use stage	Net change- EOL stage
Total of all processes		**-1.1**	**-0.7**	**-0.1**	**-0.3**
Non-displayed processes (3%)		-0.1	-0.1	0	-0.01
1	Spoil from lignite mining {GLO}| treatment of, in surface landfill[1]	-0.7	-0.4	0	-0.3

No.	Process	Total net change of life cycle EP of the AA LWT body design	Net change-Production stage	Net change-Use stage	Net change-EOL stage
2	BH, Bake hardenable steel (C2G), NA HDG	-0.2	-0.2	0	0
3	Value of aluminum process scrap-100% scrap	-0.1	-0.1	0	0
4	WTP- Well-to-Pump Gasoline (E10)- SI ICEV GREET.net 2017	-0.1	0	-0.1	0
5	Spoil from hard coal mining {GLO}| treatment of, in surface landfill[1)]	-0.1	-0.1	0	-0.06
6	HSLA, High-strength, low-alloy steels (>300 psi) (C2G), NA PHRC	-0.1	-0.1	0	0
7	Waste plastic, EOL mixture {US}| treatment of, sanitary landfill	-0.03	0	0	-0.03
8	Value of aluminum EOL scrap (primary metal + alloy added)	0.03	0	0	0.03
9	Value of steel scrap	0.1	0.1	0	0.03
10	Aluminum cold-rolled coils (C2G)	0.2	0.2	0	0

[1)] Downstream processes for Electricity, medium voltage {Michigan, US}| and Electricity, medium voltage {US}| generation- see Table A14, Annex J.

[2)] Please note data may not add up to totals due to rounding.

[3)] Displayed digits of the AA LWT body design LCA results calculated with SimaPro LCA software do not represent significant digits.

Table A20. PCA- Top 10 significant processes contributing to total net change of life cycle PSFP of the AA LWT body design (with P/T adaptation, LTDD$_V$= 290,000 km (2))- in kg O_3-eq.

No.	Process	Total net change of life cycle PSFP of the AA LWT body design	Net change-Production stage	Net change-Use stage	Net change-EOL stage
Total of all processes		**-165.3**	**-91.9**	**-86.8**	**13.5**
Non-displayed processes (3%)		-19.4	-15.3	0.00	-4.1
1	WTP- Well-to-Pump Gasoline (E10)- SI ICEV GREET.net 2017	-86.8	0.0	-87	0
2	BH, Bake hardenable steel (C2G), NA HDG	-77.0	-77.0	0	0
3	Value of aluminum process scrap-100% scrap	-56.8	-57	0.0	0
4	HSLA, High-strength, low-alloy steels (>300 psi) (C2G), NA PHRC	-26.9	-26.9	0	0
5	DP, Dual phase steel (C2G), NA HDG	-7.5	-7.5	0	0
6	Mild steel (C2G), NA HDG	-6.8	-6.8	0	0
7	Aluminum extruded products (C2G)	5.2	5.2	0	0
8	Value of aluminum EOL scrap (primary metal + alloy added)	12.7	0.0	0	12.7

No.	Process	Total net change of life cycle PSFP of the AA LWT body design	Net change- Production stage	Net change- Use stage	Net change- EOL stage
9	Value of steel scrap	17.8	12.9	0	4.9
10	Aluminum cold-rolled coils (C2G)	80.3	80.3	0	0

[1] Please note data may not add up to totals due to rounding.
[2] Displayed digits of the AA LWT body design LCA results calculated with SimaPro LCA software do not represent significant digits.

Table A21. PCA- Top 10 significant processes contributing to total net change of life cycle HHPP of the AA LWT body design (with P/T adaptation, $LTDD_V$= 290,000 km (2))- in kg $PM_{2.5}$-eq.

No.	Process	Total net change of life cycle HHPP of the AA LWT body design	Net change- Production stage	Net change- Use stage	Net change- EOL stage
Total of all processes		**-1.0**	**-1.0**	**-0.3**	**0.2**
Non-displayed processes (7%)		-0.3	-0.2	0.00	-0.1
1	Value of aluminum process scrap-100% scrap	-1.0	-1.0	0	0
2	BH, Bake hardenable steel (C2G), NA HDG	-0.8	-0.8	0	0
3	HSLA, High-strength, low-alloy steels (>300 psi) (C2G), NA PHRC	-0.3	-0.3	0	0
4	WTP- Well-to-Pump Gasoline (E10)- SI ICEV GREET.net 2017	-0.3	0	-0.3	0
5	Electricity, medium voltage {Michigan, US}| used in production stage	-0.2	-0.2	0	0
6	DP, Dual phase steel (C2G), NA HDG	-0.1	-0.1	0	0
7	Aluminum extruded products (C2G)	0.1	0.1	0	0
8	Value of aluminum EOL scrap (primary metal + alloy added)	0.2	0	0	0.2
9	Value of steel scrap	0.5	0.3	0	0.1
10	Aluminum cold-rolled coils (C2G)	1.2	1.2	0	0

[1] Please note data may not add up to totals due to rounding.
[2] Displayed digits of the AA LWT body design LCA results calculated with SimaPro LCA software do not represent significant digits.

Table A22. Substance and raw material contribution analysis: Net change LCA indicators, cradle-to-grave (with P/T adaptation, LTDD$_V$= 290,000 km (2)) — in absolute basis (non-displayed flows: 0.5-1.5%)

LCIA and LCI indicators	Substance	Compartment in SimaPro 8.4.0	Cradle-to grave net change of the AA LWT body design, with P/T adaptation
AP (kg SO_2-eq)	**Total of all compartments** (non-displayed flows: 1%)		**-7.9**
	Nitrogen oxides	Air	-4.5
	Sulfur oxides	Air	-3.3
	Sulfur dioxide	Air	-0.45
	Nitrogen dioxide	Air	0.14
	Hydrogen sulfide	Air	0.23
EP (kg N-eq)	**Total of all compartments** (non-displayed flows: 1.5%)		**-1.1**
	Phosphate	Water	-0.79
	Nitrogen oxides	Air	-0.29
	Nitrogen, total	Water	-0.03
	Nitrate	Water	-0.02
	COD, Chemical Oxygen Demand	Water	-0.02
GWP (kg CO_2-eq)	**Total of all compartments** (non-displayed flows: 0.5%)		**-7,820**
	Carbon dioxide, fossil	Air	-7,378
	Methane, fossil	Air	-403
	Dinitrogen monoxide	Air	-63
PSFP (kg O_3-eq)	**Total of all compartments** (non-displayed flows: 0.5%)		**-165**
	Nitrogen oxides	Air	-160
	NMVOC, non-methane volatile organic compounds	Air	-9.6
	Nitrogen dioxide	Air	3.4
HHPP (kg PM2.5-eq)	**Total of all compartments** (non-displayed flows: 1.5%)		**-1.0**
	Particulates, total	Air	-0.97
	Nitrogen oxides	Air	-0.05
	Sulfur dioxide	Air	-0.03
NRF	**Total of all compartments** (non-displayed flows: 1.0%)		**-102,343**
	Energy, from oil	Raw material	-87,489
	Energy, from gas, natural	Raw material	-10,097
	Energy, hard coal	Raw material	-2,187
	Energy, from coal	Raw material	-1,761
	Energy, from lignite	Raw material	1,647
NRN	**Total of all compartments** (non-displayed flows: 1%)		**-1,641**
	Energy, from uranium	Raw material	-1,158
	Uranium, 560 GJ per kg	Raw material	-475

LCIA and LCI indicators	Substance	Compartment in SimaPro 8.4.0	Cradle-to grave net change of the AA LWT body design, with P/T adaptation
NRB	**Total of all compartments** (non-displayed flows: 1%)		**-0.028**
	Energy, gross calorific value, in biomass, primary forest	Raw material	-0.028
RH	**Total of all compartments** (non-displayed flows: 0.5%)		**1,931**
	Energy, from hydro power	Raw material	1,931
RSGW	**Total of all compartments** (non-displayed flows: 0.5%)		**365**
	Energy, solar	Raw material	295
	Energy, wind	Raw material	66.5
	Energy, geothermal	Raw material	6.2
RB	**Total of all compartments** (non-displayed flows: 0.5%)		**-7,331**
	Energy, from biomass	Raw material	-7,324
Additional LCI indicator			
NRMR3)	**Total of all ores, minerals and chemical elements**		**-679**
	Iron ore	Raw material	-867
	Bauxite	Raw material	308
	Dolomite	Raw material	-65
	Limestone	Raw material	22
	Clay	Raw material	16
	All other NRMR	Raw material	-93

1) Please note data may not add up to totals due to rounding.
2) Displayed digits of the AA LWT body design LCA results calculated with SimaPro LCA software do not represent significant digits.
3) NRMR LCI indicator is calculated as a sum of elementary non-renewable resource input flows calculated with SimaPro.

Table A23. LCA results of Baseline body system (null fuel savings) — (LTDD$_V$= 290,000 km (2))

LCIA and LCI Indicators	Indicator units	LCA results of Baseline2)	Baseline-Production stage	Baseline-Use stage1) (null fuel savings)	Baseline-EOL stage
AP	kg SO$_2$-eq	**9.3**	9.2	0	0.1
EP	kg N-eq	**2.6**	1.86	0	0.77
GWP	kg CO$_2$–eq	**1,553**	1,650	0	-97
PSFP	kg O$_3$-eq	**140**	138	0	2
HHPP	kg PM$_{2.5}$-eq	**2.0**	1.81	0	0.22
TPE	MJ	**24,977**	24,669	0	308
NRF	*MJ*	*20,072*	20,767	0	-694
NRN	*MJ*	*3,471*	2,789	0	682

LCIA and LCI Indicators	Indicator units	LCA results of Baseline[2]	Baseline-Production stage	Baseline-Use stage[1] (null fuel savings)	Baseline-EOL stage
NRB	*MJ*	*0*	0	0	0
RH	*MJ*	*1,166*	892	0	274
RSGW	*MJ*	*249*	214	0	35
RB	*MJ*	*19*	8	0	12

[1] As mentioned in Section 9.2, the use stage emissions are only calculated as a difference from the Baseline. The use stage impact is null for the Baseline and carries a negative sign for the AA LWT body design (see Table A24).

[2] The potential environmental impact of carry-over items (see Table 6) is not included.

[3] Please note data may not add up to totals due to rounding.

[4] Displayed digits of the AA LWT body design LCA results calculated with SimaPro LCA software do not represent significant digits.

Table A24. LCA results of the AA LWT body design (-2,543 L fuel savings) — (with P/T adaptation, $LTDD_V$= 290,000 km (2))

LCIA and LCI Indicators	Indicator units	LCA results of AA LWT body design[2]	AA LWT body design Production stage	AA LWT body design Use stage[1]- (-2,543 L fuel savings)	AA LWT body design EOL stage
AP	kg SO_2-eq	**1.4**	3.6	-4.2	1.9
EP	kg N-eq	**1.5**	1.18	-0.14	0.45
GWP	kg CO_2–eq	**-6,268**	1,096	**-7,707**	343
PSFP	kg O_3-eq	**-25**	46	-87	15
HHPP	kg $PM_{2.5}$-eq	**0.99**	0.86	-0.29	0.42
TPE	MJ	**-84,042**	19,538	-109,767	6,188
NRF	*MJ*	*-82,271*	*16,438*	*-102,444*	*3,735*
NRN	*MJ*	*1,830*	*1,538*	*0*	*292*
NRB	*MJ*	*0*	*0*	*0*	*0*
RH	*MJ*	*3,097*	*986*	*0*	*2,111*
RSGW	*MJ*	*614*	*571*	*0*	*43*
RB	*MJ*	*-7,312*	*5*	*-7,324*	*6*

[1] As mentioned in Section 9.2, the use stage emissions are only calculated as a difference from the Baseline. The use stage impact is null for the Baseline (see Table A23) and carries a negative sign for the AA LWT body design. The AA LWT body design weighs 231 kg less than the Baseline, that would highly likely lead to P/T adaptation, resulting in less fuel consumption (about 2,500 L) and combustion emissions.

[2] The potential environmental impact of carry-over items (see Table 6) is not included.

[3] Please note data may not add up to totals due to rounding.

[4] Displayed digits of the AA LWT body design LCA results calculated with SimaPro LCA software do not represent significant digits.

Table A25. LCA results of the AA LWT body design relative to the Baseline — (with P/T adaptation, LTDD$_V$= 290,000 km (2))

LCIA and LCI Indicators	**Indicator units**	**LCA results of AA LWT body design, with P/T adaptation**[1] (-2,543 L fuel savings)	**LCA results of Baseline**[1] (null fuel savings)	**Cradle-to-grave total net change of the AA LWT body design, with P/T adaptation**
AP	kg SO_2-eq	1.4	9.3	**-7.9**
EP	kg N-eq	1.5	2.6	**-1.1**
GWP	kg CO_2–eq	-6,268	1,553	**-7,820**
PSFP	kg O_3-eq	-25	140	**-165**
HHPP	kg $PM_{2.5}$-eq	0.99	2.03	**-1.0**
TPE	MJ	-84,042	24,977	**-109,019**
NRF	*MJ*	*-82,271*	*20,072*	*-102,343*
NRN	*MJ*	*1,830*	*3,471*	*-1,641*
NRB	*MJ*	*0*	*0*	*0*
RH	*MJ*	*3,097*	*1,166*	*1,931*
RSGW	*MJ*	*614*	*249*	*365*
RB	*MJ*	*-7,312*	*19*	*-7,331*

[1] The potential environmental impact of carry-over items (see Table 6) is not included.
[2] Please note data may not add up to totals due to rounding.
[3] Displayed digits of the AA LWT body design LCA results calculated with SimaPro LCA software do not represent significant digits.

Annex L: Sensitivity and Scenario Analysis

Table A26. Sensitivity and scenario analysis: Net change of LCIA indicators and TPE, cradle-to-grave (Base case: with P/T adaptation, $LTDD_V$= 290,000 km (2))— Deviation, in absolute and percent basis

LCIA indicators and TPE	Unit	Base case	Sensitivity and scenario case	Deviation - in absolute basis	Deviation - in %
SP1. LTTDv parameter is varied by -14% (2)**.**					
AP	kg SO_2-eq	-7.9	-7.3	0.6	-7%
EP	kg N-eq	-1.1	-1.1	0.02	-2%
GWP	kg CO_2–eq	-7,820	-6,757	1,063	-14%
PSFP	kg O_3-eq	-165	-153	12	-7%
HHPP	kg $PM_{2.5}$-eq	-1.04	-1.00	0.04	-4%
TPE	MJ	-109,019	-93,879	15,140	-14%
SP2. F_{CP} is varied by -58% (2), (47)**.**					
AP	kg SO_2-eq	-7.9	-5.5	2.4	-30%
EP	kg N-eq	-1.1	-1.1	0.1	-7%
GWP	kg CO_2-eq	-7,820	-3,379	4,441	-57%
PSFP	kg O_3-eq	-165	-115	50	-30%
HHPP	kg $PM_{2.5}$-eq	-1.04	-0.87	0.17	-16%
TPE	MJ	-109,019	-45,759	63,261	-58%
SP3. F_{CP} is varied by +9% (47)**.**					
AP	kg SO_2-eq	-7.9	-8.2	-0.4	5%
EP	kg N-eq	-1.1	-1.2	-0.01	1%
GWP	kg CO_2–eq	-7,820	-8,510	-690	9%
PSFP	kg O_3-eq	-165	-173	-8	5%
HHPP	kg $PM_{2.5}$-eq	-1.04	-1.07	-0.03	2%
TPE	MJ	-109,019	-118,841	-9,821	9%
SP4. The EOL recovered scrap rate is varied by -21%.					
AP	kg SO_2-eq	-7.9	-6.4	1.4	-18%
EP	kg N-eq	-1.1	-1.1	0.02	-1%
GWP	kg CO_2–eq	-7,820	-7,654	166	-2%
PSFP	kg O_3-eq	-165	-154	11	-7%
HHPP	kg $PM_{2.5}$-eq	-1.04	-0.88	0.16	-16%
TPE	MJ	-109,019	-104,812	4,207	-4%
SP5. The cradle-to-gate GWP of NA primary aluminum ingot consumption mix is varied by +10%.					
GWP	kg CO_2-eq	-7,820	-7,679	141	-2%
SP6. The cradle-to-gate GWP of HSS and AHSS semi-finished products is varied by +5%.					
GWP	kg CO_2-eq	-7,820	-7,906	-85	1%
SCP1. Allocation rules for recycling.					
AP	kg SO_2-eq	-7.9	-3.9	4.0	-51%

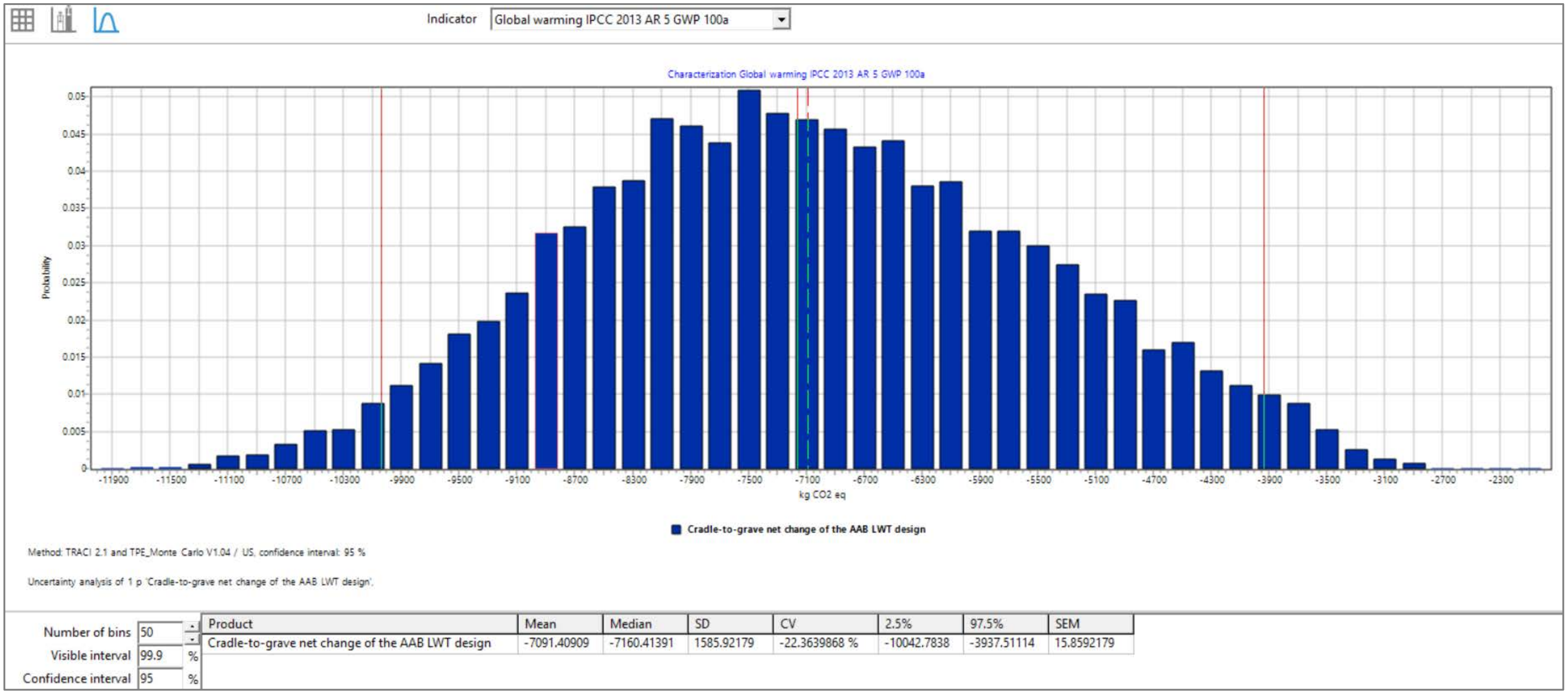
LCIA indicators and TPE	Unit	Base case	Sensitivity and scenario case	Deviation - in absolute basis	Deviation - in %
EP	kg N-eq	-1.1	-1.1	0.01	-1%
GWP	kg CO_2–eq	-7,820	-7,589	232	-3%
PSFP	kg O_3-eq	-165	-135	31	-19%
HHPP	kg $PM_{2.5}$-eq	-1.04	-0.71	0.33	-32%
TPE	MJ	-109,019	-97,908	11,112	-10%
SCP2. IPCC 2013 AR5 versus 2007 AR4 100a GHGs characterization factors.					
GWP	kg CO_2–eq	-7,820	-7,758	62	1%
SCP3. 2025 selected year for fuel production technologies.					
AP	kg SO_2-eq	-7.9	-7.1	0.8	-10%
EP	kg N-eq	-1.1	-1.1	0.03	-2%
GWP	kg CO_2–eq	-7,820	-7,798	23	-0.3%
PSFP	kg O_3-eq	-165	-151	14	-9%
HHPP	kg $PM_{2.5}$-eq	-1.04	-1.01	0.03	-3%
TPE	MJ	-109,019	-108,507	512	-0.5%
SCP4. Truck transportation.					
AP	kg SO_2-eq	-7.9	-8.2	-0.4	4.5%
EP	kg N-eq	-1.1	-1.2	-0.02	2%
GWP	kg CO_2–eq	-7,820	-7,884	-64	0.8%
PSFP	kg O_3-eq	-165	-175	-9	5.6%
HHPP	kg $PM_{2.5}$-eq	-1.04	-1.07	-0.03	3%
TPE	MJ	-109,019	-109,989	-969	0.9%
SCP5. Electricity grid.					
AP	kg SO_2-eq	-7.9	-7.8	0.03	-0.4%
EP	kg N-eq	-1.1	-1.0	0.11	-9%
GWP	kg CO_2–eq	-7,820	-7,815	6	-0.1%
PSFP	kg O3-eq	-165	-165	0	-0.1%
HHPP	kg PM2.5-eq	-1.04	-0.99	0.05	-5%
TPE	MJ	-109,019	-108,973	46	-0.04%

1) Please note data may not add up to totals due to rounding.

2) Displayed digits of the AA LWT body design LCA results calculated with SimaPro LCA software do not represent significant digits.

Annex M: Monte Carlo Uncertainty Analysis

Figure A6. Monte Carlo probability distributions chart for life cycle GWP of the AA LWT body design relative to the Baseline (confidence interval: 95%, 10,000 runs, SimaPro 8.4.0.0 screenshot)



Indicator: Global warming IPCC 2013 AR 5 GWP 100a

Method: TRACI 2.1 and TPE_Monte Carlo V1.04 / US, confidence interval: 95 %

Uncertainty analysis of 1 p 'Cradle-to-grave net change of the AAB LWT design'.

Number of bins: 50

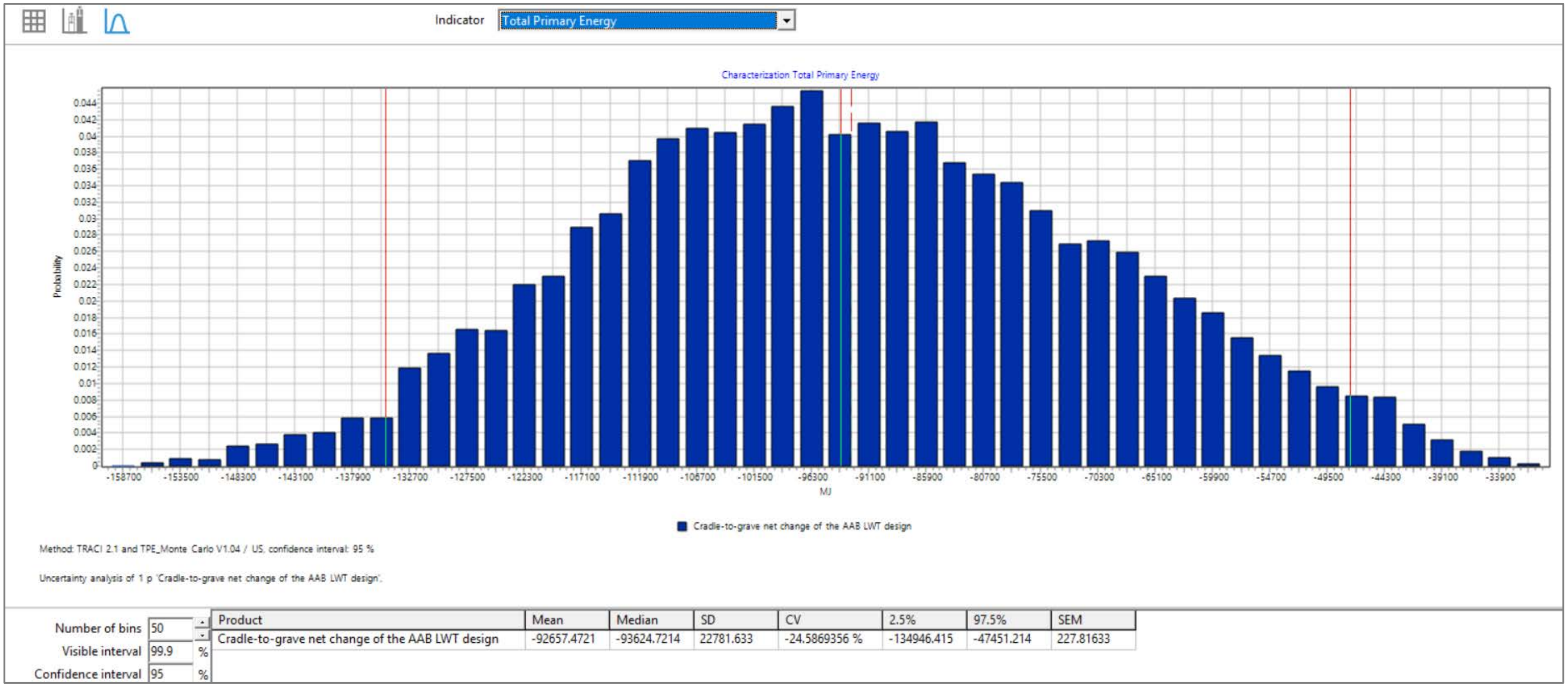
Visible interval: 99.9 %

Confidence interval: 95 %

Product	Mean	Median	SD	CV	2.5%	97.5%	SEM
Cradle-to-grave net change of the AAB LWT design	-7091.40909	-7160.41391	1585.92179	-22.3639868 %	-10042.7838	-3937.51114	15.8592179

[1] Displayed digits of the AA LWT body design uncertainty results calculated with SimaPro LCA software do not represent significant digits.

Figure A7. Monte Carlo probability distributions chart for life cycle TPE of the AA LWT body design relative to the Baseline (confidence interval: 95%, 10,000 runs, SimaPro 8.4.0.0 screenshot)



Indicator: Total Primary Energy

Method: TRACI 2.1 and TPE_Monte Carlo V1.04 / US, confidence interval: 95 %

Uncertainty analysis of 1 p 'Cradle-to-grave net change of the AAB LWT design'.

Number of bins: 50

Visible interval: 99.9 %

Confidence interval: 95 %

Product	Mean	Median	SD	CV	2.5%	97.5%	SEM
Cradle-to-grave net change of the AAB LWT design	-92657.4721	-93624.7214	22781.633	-24.5869356 %	-134946.415	-47451.214	227.81633

[1] Displayed digits of the AA LWT body design uncertainty results calculated with SimaPro LCA software do not represent significant digits.

Table A27. Monte Carlo uncertainty analysis: Cradle-to-grave net change of LCIA and TPE results of the AA LWT body design (confidence interval:95%, 10,000 runs, exported from SimaPro LCA software 8.4.0.0)

LCIA and TPE indicators	Indicator units	Mean	Median	SD	CV	2.5%	97.5%	SEM
AP	kg SO_2-eq	-4.0	-3.9	1.5	-37%	-7.1	-1.3	0.01
EP	kg N-eq	-1.1	-1.0	0.6	-53%	-2.7	-0.5	0.01
GWP	kg CO_2–eq	-7,091	-7,160	1,586	-22%	-10,043	-3,938	16
PSFP	kg O_3-eq	-132.9	-133.4	20.1	-15%	-171.6	-93.8	0.2
HHPP	kg $PM_{2.5}$-eq	-0.7	-0.7	0.2	-24%	-1.0	-0.3	0.002
TPE	MJ	-92,657	-93,625	22,782	-25%	-134,946	-47,451	228

1) SD=standard deviation, CV= coefficient of variation, SEM= standard error of mean.

2) Displayed digits of the AA LWT body design uncertainty results calculated with SimaPro LCA software do not represent significant digits.

About the Author

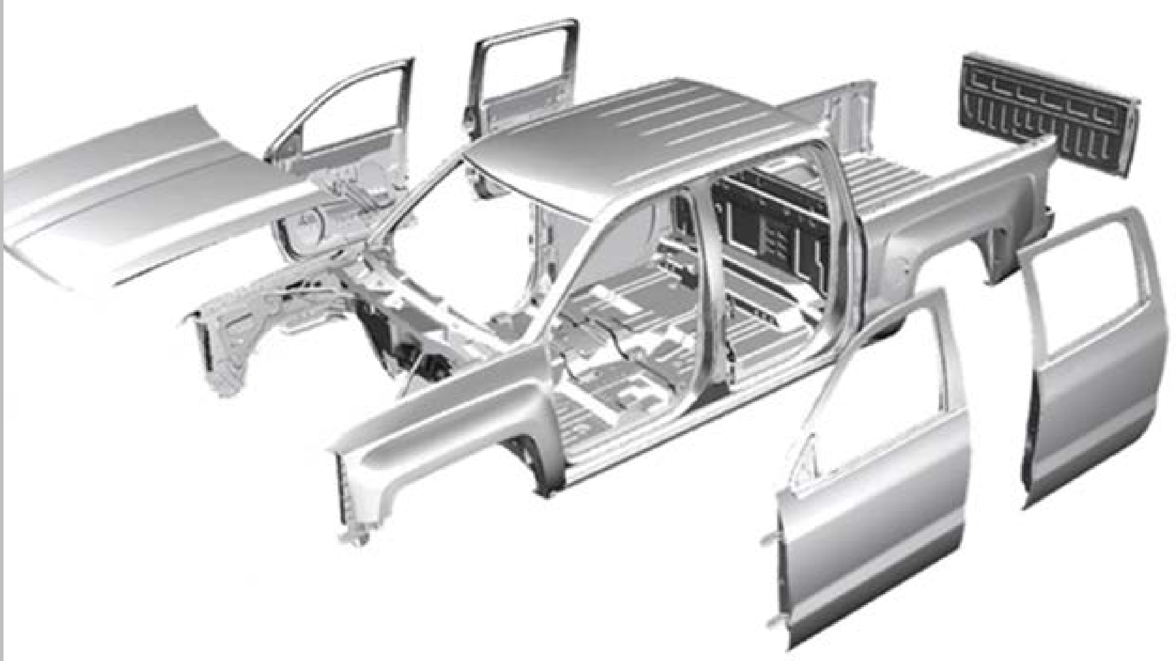
Lindita Bushi holds a doctoral engineering degree in Life Cycle Assessment from the University of Erlangen-Nürnberg, Germany. With over 17 years of international LCA consulting experience, Dr. Bushi has conducted numerous ISO 14044 conformant LCAs in an effort to drive and determine the sustainability environmental benefits of industrial processes, products, and services. Her LCA consulting experience extends to a large number of sectors (metals, automotive, building, energy, transport, and recycling). Dr. Bushi has over 10 years of experience in LCA of lightweighting materials and processes. She has extensive multi-national experience working with industrial clients, academia, and joint government-industry programs and taskforces. Since 2004, she has worked for the Athena Sustainable Materials Institute as a Senior Research Associate (http://www.athenasmi.org/about-asmi/team/).

Dr. Bushi is a member of Canadian ISO/TC 207/SC5 on Life Cycle Assessment and the Chair of Canadian ISO/TC 207/SC3 on Environmental Labelling. She is a recognized individual verifier within the International EPD® System and a member of the American Center for LCA (ACLCA) committee for Product Category Rules (PCRs) in LCA. Dr. Bushi has also conducted and co-authored numerous carbon footprint projects over the past ten years according to ISO 14064, WRI GHG Protocols and British PAS 2050:2008.

Dr. Bushi is proficient in the most widely used LCA software platforms such as SimaPro and familiar with GaBi and Umberto. She has developed professional training courses in LCA, environmental management systems and environmental policy, organized international conferences, and published a number of academic papers and journal articles. Dr. Bushi guest lectures in LCA and automotive lightweighting as part of the Master's of Engineering Leadership in Applied Science program at the University of British Columbia (UBC).

From 2012 to 2014, Dr. Bushi served as the Executive of the Development Technical Group for the CSA Group LCA Guidance for Auto Parts (http://shop.csa.ca/en/canada/life-cycle-assessment/spe-14040-14/invt/27036702014).

Photo courtesy (front and back covers): EDAG Inc. 2017



LCA Report:

Comparative LCA Study of EDAG Silverado Body Lightweighting as per ISO 14040/44 LCA Standards and CSA Group LCA Guidance Document for Auto Parts, August 2018.

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