

Life Cycle Energy and Environmental Assessment of Aluminum-Intensive Vehicle Design

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ABSTRACT

Advanced lightweight materials are increasingly being incorporated into new vehicle designs by automakers to enhance performance and assist in complying with increasing requirements of corporate average fuel economy standards. To assess the primary energy and carbon dioxide equivalent (CO_2e) implications of vehicle designs utilizing these materials, this study examines the potential life cycle impacts of two lightweight material alternative vehicle designs, i.e., steel and aluminum of a typical passenger vehicle operated today in North America.

LCA for three common alternative lightweight vehicle designs are evaluated: current production ("Baseline"), an advanced high strength steel and aluminum design ("LWSV"), and an aluminum-intensive design (AIV). This study focuses on body-in-white and closures since these are the largest automotive systems by weight accounting for approximately 40% of total curb weight of a typical passenger vehicle. Secondary mass savings resulting from body lightweighting are considered for the vehicles' engine, driveline and suspension.

A "cradle-to-cradle" life cycle assessment (LCA) was conducted for these three vehicle material alternatives. LCA methodology for this study included material production, mill semi-fabrication, vehicle use phase operation, and end-of-life recycling. This study followed international standards ISO 14040:2006 [1] and ISO 14044:2006 [2], consistent with the automotive LCA guidance document currently being developed [3].

Vehicle use phase mass reduction was found to account for over 90% of total vehicle life cycle energy and CO_2e emissions. The AIV design achieved mass reduction of 25% (versus baseline) resulting in reductions in total life cycle primary energy consumption by 20% and CO_2e emissions by 17%. Overall, the AIV design showed the best breakeven vehicle mileage from both primary energy consumption and climate change perspectives.

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INTRODUCTION

Federal regulations defining minimum Corporate Average Fuel Economy (CAFE) and consumer demand for increased fuel economy are encouraging OEMs to pursue weight reduction alternatives for vehicle structures. In that effort, lightweight materials, which includes advanced high strength steel and aluminum, have become an increasingly important consideration in future vehicle body engineering. Industry and technical experts have projected that by 2050, there is the potential to reduce the weight of light-duty vehicles by 20 to 50% [4, 5, 6, 7].

Latest comprehensive automotive materials study published by Ducker [8] indicates use of high strength steels and aluminum is increasing rapidly. For instance, new North American vehicles' average aluminum content increased from 202

pounds in 1995 to 343 pounds in model year 2012. That study forecast aluminum content in new vehicles will increase to an average of 550 pounds by 2025.

A number of LCA studies have been conducted to quantify the environmental impacts of lightweighting ground transportation vehicles. One such study is the Magnesium Front End Research and Development (MFERD) project under the sponsorship of Natural Resources Canada, Beijing University and the US Department of Energy [9]. In that study, a life cycle assessment (LCA) compared the energy and potential environmental impacts of advanced magnesium- and aluminum-based front end structures for a 2007 GM Cadillac CTS using the production steel structure as a baseline. The aluminum lightweight design showed the lowest life cycle energy and global warming potential impacts and the most favorable breakeven vehicle mileage.

In preparing its Environmental Impact Statement for the 2017-2025 CAFE Standard, the National Highway Traffic Safety Administration (NHTSA) reviewed a number of LCA studies evaluating environmental impacts of automotive component light-weighting. NHTSA concluded "...reductions in energy use and GHG emissions during the use stage of vehicles through high strength steel and aluminum material substitution exceed the increased energy use and GHG emissions needed to manufacture these lightweight materials at the vehicle production stage." [10]

Prior LCA studies have not isolated material substitution from other vehicle and component design changes. This study was designed to provide a clearer understanding of LCA impact of lightweight materials on a vehicle structure engineered to meet OEM production requirements for NVH, stiffness, safety, performance and durability. The proven body structure currently in production has been used as the basic body structure for the reduced mass body designs. Reduced mass designs were optimized for material grade and gauge using proven design optimization tools. Secondary mass reductions (engine, driveline, suspension) are based on engineering evaluation of practical mass reductions resulting from reduction of body system mass.

Baseline vehicle is modeled after a current production mid-size crossover sport utility vehicle based on a Toyota Venza. This vehicle is representative of a nominal North American vehicle based on mass (1,711 Kg), material utilization (65% steel (36 % mild steel, 29 % HSS), 9 % Aluminum), fuel economy (24 Label MPG), powertrain (V-6 FI) and performance (0-60 MPH 6.2 sec.).

Lightweight steel vehicle (LWSV) [11] and aluminum intensive vehicle (AIV) bodies were designed and optimized by EDAG Engineering. EDAG is a widely recognized and respected automotive design services organization supporting automotive OEM and Tier 1 suppliers globally. Optimized LWSV body utilized 85% HSS and AHSS for body-in-white (BIW) with aluminum fenders, hood and lift gate. Optimized AIV body design [12] was developed by EDAG using the same structural optimization models used for the LWSV.

LCA FRAMEWORK

Goal of this LCA study is to compare environmental performance of three mid-size crossover sport utility vehicle designs based on a popular vehicle driven today in North America. The three vehicle designs are: current production (Baseline) and two alternative lightweight material designs: an advanced high strength steel design (LWSV) and an aluminum-intensive design (AIV). Assessment is based on the recent automotive guidance document establishing the requirements for assessment of the environmental performance of autoparts [3]. Guidance includes criteria for the identification of product category and the framework for performing the underlying life cycle assessment according to ISO 14040 series. Assumptions utilized in this LCA framework for vehicle mileage, drive cycle,

mass savings effects on fuel economy, data sources and allocation of recycling are consistent with the guidance document.

The functional unit is the transportation service provided by the three SUV versions built and driven for 250,000 km in North America. The 250,000 Km useful life assumption is consistent with latest NHTSA average vehicle lifetimes studies [13].

The reduced mass body design alternatives were engineered to meet all NHTSA and IIHS 5-star safety criteria and to match stiffness; noise, vibration, and harshness (NVH) performance; and durability of the baseline vehicle. Reduced mass body alternatives retained the proven fundamental architecture of the baseline production vehicle. Body of the Light Weight Steel Vehicle (LWSV) was optimized making maximum practical use of high strength (HSS) and advanced high strength steels (AHSS) and aluminum. The Aluminum Intensive Vehicle (AIV) body is optimized utilizing currently available automotive aluminum alloys.

Scope of the study is limited to North America. Latest North America life cycle inventory (LCI) data are used for both steel and aluminum. The Steel LCI data [14] contained ferrous scrap input with varying amount for four different types of conventional steel, but no LCA distinctions were made between conventional steels and high strength steels such as advanced high strength steel and ultrahigh strength steels.

Aluminum LCI data is based on primary aluminum production for North America from the International Aluminum Institute and semi-fabrication of aluminum rolled sheet and extrusions from the latest Aluminum Association LCI study [15]. It was assumed that the impacts of different aluminum alloys have minimal impacts from an overall life cycle perspective. Primary aluminum ingot production data reflects the 95:5 share of "Pre-baked" vs. "Soderberg" electrolysis production technology currently operating in North America and the self-generation and contractual supply (75% hydropower) of North American electricity consumed for primary aluminum electrolysis. Data is representative of the production-weighted average data for North America. All production steps associated with producing semi-fabricated rolled, extruded, and cast aluminum have been included such as mining of bauxite, the production of aluminum oxide, and the smelting and casting of primary aluminum.

Environmental impacts considered are total primary energy in terms of cumulative energy demand from Ecoinvent 1.02 and global warming potentials based on TRACI 2.1 Version 1.00. TRACI is the Tool for the Reduction and Assessment of Chemical and other environmental Impacts and is a midpoint-oriented LCIA methodology developed by the U.S. Environmental Protection Agency specifically for the US using input parameters consistent with US locations.

PRODUCT SYSTEM

Baseline vehicle used in this study is a production mid-size sport utility vehicle modeled after the Toyota Venza. This vehicle is representative of a nominal North American vehicle based on size, weight, fuel economy, performance, materials and powertrain (conventional internal combustion). Body structure of this vehicle has known durability and NVH characteristics and proven safety performance in NHTSA ("Top rated") and IIHS ("5 Star") safety testing. Baseline vehicle body materials (Body-in-white and closures) are typical of a current North American vehicle at 55% Mild Steel (MS), 45% High Strength Steel (HSS).

Reduced mass body alternatives retained the proven fundamental architecture of the baseline production vehicle. Alternative body (body-in-white and closures) models were engineered to meet all NHTSA and IIHS safety criteria and to match stiffness, NVH performance and durability of the baseline vehicle. Body of the LWSV was optimized making maximum practical use of high strength and advanced high strength steels for BIW and aluminum for closures (11). Aluminum Intensive Vehicle (AIV) body design was developed utilizing currently available automotive aluminum materials using structural optimization models developed for the LWSV (12).

Three different reference flows of total vehicle mass were established for defining the functional unit: baseline (1711 kg), LWSV (1453 kg), AIV (1290 kg). Table 1 gives an overview of the different technologies and composition for the three vehicle designs.

Focus of this study is LCA implications of mass optimization of iron, steel and aluminum in vehicle design. Light weight designs evaluated in this study resulted in shifts in iron, steel and aluminum content. Base vehicle has a combined iron and steel content of 1138 kg. and aluminum content of 157 kg. The remaining 573 kg mass of other materials (glass, plastic, fiber) are assumed to be the same under both lightweight scenarios and not impacted by primary or secondary mass reductions of LWSV or AIV designs. The LWSV makes extensive use of high strength and advanced high strength steels for BIW and aluminum for closures. AIV body in white includes aluminum sheet, extrusions and cast suspension nodes. Both the LWSV and AIV models include secondary mass reductions of aluminum engine, transmission, and wheels.

The AIV design offers 25% vehicle weight reduction through the use of 459 kg of aluminum, about three times more than the baseline vehicle. Structural optimization of body-in-white and closures for both LWSV and AIV result in secondary mass reductions in aluminum engine, driveline and wheel components. Use of aluminum suspension towers provided a significantly higher level of total vehicle mass savings. Iron content is estimated to be significantly reduced in LWSV and AIV designs due predominantly to conversion of suspension and steering components to aluminum.

Table 1. Description of Vehicle Designs

Scenario/Material	Baseline	LWSV	AIV
Cast Iron	127	49	49
Steel (kg)	1011	794	366
Pickled Hot Rolled (SP)	242	181	172
Electro-Galvanized (BIW, SP)	684	344	138
Hot-Dip Galvanized (BIW, SP)	59	45	34
Engg. Steel (Other)	27	224	22
Aluminum (kg)	157	194	459
Sheet	12	55	296
Cast	128	125	125
Extrusion	17	14	38
Total New Component Weight (kg)	1295	1037	874
Vehicle Weight (kg)	1711	1453	1290

VEHICLE "IN USE" PHASE

Use phase is a critical aspect of the life cycle of vehicle and generally dominates the environmental impact [16]. Nominal lifetime for the vehicle is assumed to be 250,000 km consistent with the study by NHSTA [13].

Use stage LCA impacts for LWSV and AIV are based on mass-induced fuel consumption for a steel baseline vehicle adjusted for mass-induced fuel savings. All assessments include powertrain modifications to achieve baseline vehicle performance. Mass-induced fuel consumption changes (decrease/increase) with powertrain adaptation discussed by Koffler et al. 2010 [17] have been adopted in a recent autopart life cycle assessment [9].

The total life cycle mass-induced fuel consumption change is estimated as follows:

$$C_{A,n} = (m_{part,n} - m_{part,b}) \times VA \times LTDD$$

$C_{A,n}$ = the total life cycle mass-induced fuel change (decrease/ or increase) of new autoparts designs in liters

$m_{part,n}$ = mass in kg of new design autoparts(i.e., 1037 kg LWSV, 874 kg AIV)

$m_{part,b}$ = mass in kg of baseline autoparts (baseline, replaced with the new design), i.e., 1295 kg

VA = mass-induced fuel consumption reduction value with powertrain adaptation, in l/(100km·100kg) (0.38l/100km.100 kg for naturally aspirated engine [17])

LTDD = baseline life-time driving distance (250,000 km)

Mass of parts considered in the analysis include all primary and other affected secondary parts such as engine, transmission and suspension. Mass-induced fuel consumption reduction value is estimated based on the fuel economy established with EPA FTP-75 (55% city and 45% highway).