Life cycle assessment-based selection of a sustainable lightweight automotive engine hood design

Xin Sun¹ · Jingru Liu² · Bin Lu² · Peng Zhang¹ · Mingnan Zhao¹

Received: 19 April 2016 / Accepted: 15 December 2016 / Published online: 20 January 2017
© Springer-Verlag Berlin Heidelberg 2017

Abstract

Purpose This study presents a life cycle assessment (LCA)-based sustainable and lightweight automotive engine hood design and compares the life cycle energy consumption and potential environmental impacts of a steel (baseline) automotive engine hood with three types of lightweight design: advanced high strength steel (AHSS), aluminum, and carbon fiber.

Methods A “cradle-to-grave” LCA including the production, use, and end-of-life stages is conducted in accordance with the ISO 14040/14044 standards. Onsite data collected by Chinese automotive companies in 2015 are used in the assessment. The Cumulative Energy Demand v1.09 method is applied to evaluate cumulative energy demand (CED), and the International Panel on Climate Change 2013 100a method is used to estimate global warming potential (GWP 100a).

Results and discussion Among the different lightweight designs for the engine hood, the aluminum design is the most sustainable and has the lowest CED and GWP (100a) from a life cycle perspective, which is based on a lifetime driving distance of approximately 150,000 km. In addition, the AHSS design is also sustainable and lightweight. The carbon fiber design results in higher CED and GWP (100a) values than the steel (baseline) design during the life cycle but results

in the largest CED and GWP (100a) savings through waste material recycling. The AHSS design exhibits the best break-even distance based on CED and GWP (100a) within 150,000 km.

Conclusions Sensitivity analysis results show that the lifetime driving distance and material recycling rate have the largest impacts on the overall CEDs and GWPs of the three lightweight designs.

Keywords Automotive engine hood · Environmental impacts · Fuel consumption · Fuel reduction · Life cycle assessment · Lightweight design

1 Introduction

In response to increasingly stringent fuel economy and tailpipe emission regulations, several approaches have been used by automotive manufacturers to reduce vehicle fuel consumption and tailpipe emissions, such as reducing the rolling resistance coefficient (Liu et al. 2011), introducing alternative fuel systems (Ashnani et al. 2015), improving drive train efficiency (Gao et al. 2015), and reducing vehicle weight (Helms and Lambrecht 2007). Lightweight automotive designs that reduce vehicle weight are considered as one of the most important solutions for improving fuel economy and reducing harmful emissions (Cui et al. 2011; Zhou et al. 2015). New types of lightweight materials, including advanced high strength steel (AHSS), aluminum, and composite materials, are increasingly being used in automotive bodies. For example, the body of the Novel Jun contains 50% high strength steel, the body of the Audi A8 is made of aluminum, and the new BMW7 is constructed using a carbon core design.

Although fuel consumption and tailpipe emissions during the driving stage can be reduced by using new types of

Responsible editor: Wulf-Peter Schmidt

✉ Jingru Liu
liujingru@rcees.ac.cn

¹ China Automotive Technology and Research Center, Tianjin 300300, China

² State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

lightweight materials, these lightweight materials may also consume more energy and produce more environmental emissions during other life phases than traditional steel materials (Liu et al. 2012; Witik et al. 2011). Lightweight designs could lead to higher environmental impacts over its lifespan than traditional designs from the life cycle point of view (Dubreuil et al. 2010; Kampe 2001; Liu et al. 2012; Mayyas et al. 2012; Saur et al. 2000). Current fuel economy and tailpipe emission standards and regulations ignore the environmental performance of other vehicle life phases and do not ensure overall pollution reductions in the life cycle of a vehicle. Therefore, the environmental and potential impacts of other vehicle life cycle aspects should be evaluated for policy-making and automotive research and development.

LCA has been proposed as a method for compiling and evaluating the inputs, outputs, and potential environmental impacts of a product throughout its life cycle (ISO 2006). LCAs account for all phases of a vehicle's lifespan and provide a more comprehensive picture of a vehicle's environmental impact. Combined with other product life cycle technologies such as life cycle costing (LCC) and life cycle optimization (LCO), LCA toolkit provides new opportunities for manufacturing companies to create innovative, sustainable products based on optimized life cycle performance (Mayyas et al. 2012). Therefore, recommendations have been made by the European Union's Committee on the Environment and the Environmental Protection Agency of the United States to consider full LCAs for post-2020 and post-2025 fuel economy and tailpipe emission regulations, respectively. However, fuel economy and tailpipe emission regulations related to LCA have not been implemented or recommended in China until now.

Several LCA studies have been conducted which considered both the environmental impacts of the entire automotive material selection and auto part design processes. Saur et al. (2000) provided an example of an LCA for an automobile fender design. Five candidate material scenarios were analyzed based on 11 environmental metrics to rank their sustainability relative to a baseline steel fender. Saur et al. (2000) used the subjective scores of experts and the public for each sustainability metric, which added uncertainty to the sustainability results. The results of Saur et al. showed that polypropylene (PP)/ethylene-propylene-diene copolymer (EPDM) was the most sustainable material, followed by steel and aluminum. Mayyas et al. (2012) implemented an LCA-based approach to assess the performances of different materials during a vehicle's body-in-white production stage. It was found that aluminum- and magnesium-intensive structures consumed less energy over a vehicle lifespan of approximately 200,000 miles. Steel and AHSS were ranked highest in terms of energy savings and CO₂ emissions when the lifetime was decreased to approximately 50,000 miles. Liu et al. (2012) estimated and analyzed the life cycle

environmental impacts of automotive engine hoods made of aluminum alloy and composite plastic. The results showed that aluminum has a lower life cycle environmental impact than composite plastic because aluminum hoods result in lower gasoline consumption during the servicing phase. Dubreuil et al. (2010) conducted an LCA study to compare the energy consumption and potential environmental impacts of advanced magnesium-based front end parts of GM-Cadillac CTSS, which have a steel structure with an aluminum front end, as an alternate light structure scenario. It was found that the aluminum design exhibited the best break-even distance from energy use and climate change perspectives within the lifespan of the vehicle.

However, the methods that these researchers used to estimate mass-induced fuel consumption and changes over vehicle lifespans are not comparable and have high uncertainties. For example, different fuel economy estimation methods related to vehicle weight were used by Hakamada et al. (2007), Mayyas et al. (2012), and Liu et al. (2012). The incremental methods were applied by Dubreuil et al. (2010) and Ding et al. (2015), in which the lifetime vehicle fuel consumption is assumed based on secondary weight savings and changes in fuel consumption are assumed directly related to changes in component and vehicle weight. In the study of Dubreuil et al. (2010), the fuel savings will be 507 and 289 L for the magnesium (weight reduction of 37.2 kg) and aluminum (weight reduction of 21.2 kg) front end designs, respectively, over the lifespan service distance of 200,000 km. In the study of Ding et al. (2015), the vehicle was found to avoid 1447 to 1590 L of gasoline consumption if the six steel parts were replaced by aluminum over the vehicle's life cycle driving of 200,000 km. The incremental method results in the overestimation of fuel savings for lightweight vehicles.

Koffler (Koffler and Zahller 2012a; Koffler and Zahller 2012b) performed an LCA study on behalf of the American Chemistry Council (ACC) to compare the life cycle performances of polymers and metals used in automotive assist steps and bolsters. The results of Koffler et al., which were expressed by a net negative value compared to the baseline, show that lightweight plastic products outperform metal products regarding their GWP and primary energy demand. Koffler et al. calculated life cycle fuel savings due to lightweight design assuming a vehicle lifetime mileage of 150,000 miles based on the methodology described by Koffler and Rohde-Brandenburger (2010). The method used by Koffler and Rohde-Brandenburger (2010) to estimate mass-induced fuel consumption and vehicle lifespan changes has been widely recognized and cited by the Canadian Standards Association Group for conducting LCA of auto parts incorporating weight changes due to material composition, manufacturing technology, or part geometry (CSA Group 2014; Dubreuil et al. 2012; Koffler and Zahller 2012a; Koffler and Zahller 2012b).

In this paper, the method proposed by Koffler and Rohde-Brandenburger (2010) is used to estimate the mass-induced fuel consumption and its variations to determine and compare the life cycle energy consumption and potential environmental impacts of different automotive engine hood designs. The main objective of this paper is to apply an LCA method to serve as a quantitative analysis tool for sustainable engine hood design aimed at reducing a vehicle's life cycle energy consumption and environmental impacts.

2 Life cycle assessment model

2.1 Goals and scope

This study aims to put forward an LCA-based sustainable lightweight automotive engine hood design by comparing the life cycle energy consumption and potential environmental impacts of steel (baseline) automotive engine hoods with the life cycle energy consumption and potential environmental impacts of three types of lightweight automotive engine hoods: AHSS, aluminum, and carbon fiber.

The functional unit selected for this research is the transportation service of an engine hood used in a passenger car over its lifetime of 150,000 km. In this study, a conventional, steel-stamped engine hood, for a typical compact passenger car (curb weight of 1325 kg) is considered as a baseline model. The reference flow of the steel engine hood design is 17.06 kg. Because the lightweight designs weigh less, they consume less fuel during the use stage while maintaining the same functional performance. From onsite investigations of Chinese automotive companies and literature reviews (Wang et al. 2006; Zhou et al. 2015; Zhu et al. 2011), the following reference flows of the three lightweight designs were established: 13.60 kg for AHSS, 10.93 kg for aluminum alloy, and 10.40 kg for carbon fiber, representing weight reduction percentages of 20.31, 35.94, and 39.06%, respectively, compared to the baseline. Relevant parameters associated with the four types of engine hood designs are shown in Table 1.

The entire life cycle of the engine hood was considered in this LCA to estimate energy consumption and environmental emissions. The system boundaries are shown in Fig. 1. The three stages investigated were the production, use, and end-of-life stages.

The processes in which raw materials were transported to engine hood production sites and materials were transported from the engine hood site to recycling and waste treatment plants were investigated. For each life cycle process, the raw materials, energy consumption, road transport requirements, and direct emissions were considered. The manufacturing of capital equipment, such as onsite structures, machinery, and other infrastructure, was not considered.

2.2 Methods and database

This study was conducted based on the principles of the ISO 14040 series of standards for LCA (ISO 2006). The SimaPro 8 software suite was used as a support tool to establish the LCA model and perform the assessment.

The RCEES 2012 database, a local Chinese life cycle inventory database developed by the Research Center for Eco-Environmental Sciences of the Chinese Academy of Sciences based on SimaPro software, was used in the analysis. It includes more than 1000 units and processes, such as transportation and waste treatment and metal, mineral, plastic, water, chemical, fuel, and energy production (Liu et al. 2015; Sun et al. 2014; Yang et al. 2015).

2.3 Life cycle inventory analysis

2.3.1 Production stage

The production processes associated with engine hoods include the production of raw materials; manufacturing the semi-finished product, alloy, plastic, and composite materials; and fabricating the engine hood. As shown in Table 2, the LCA and manufacturing processes during the production stages for the four types of engine hood designs are sourced from onsite investigations of Chinese automotive companies in 2015. According to the onsite surveys, pollutant emissions during the engine hood production stage are not considered because they account for less than 1% of the total pollutant emissions during the life cycle of the engine hood.

This study considers potential variations associated with primary mass changes (PMCs) and secondary mass changes (SMCs). PMCs occur in auto parts due to changes in material composition. SMCs occur in other auto parts due to PMCs. It is assumed that the SMC rate is 30% of the PMCs for all lightweight designs and that all of the SMC materials are steel.

Material, energy, and resource consumption and the pollutant emissions associated with 1 kg carbon fiber reinforced polymer matrix composite material (CFRP) production were obtained from Das (2011) based on a model of the textile-grade precursor to polyacrylonitrile (PAN) carbon fiber combined with sheet molding compound manufacturing technology. Polyester has been considered as the matrix material in this study. Major input materials necessary during sheet molding compound film production include polyvinyl acetate (as the low shrink additive), zinc stearate (mold release agent), and magnesium oxide (as thickener), along with the carbon fiber (29% by weight) and polyester resin with comonomer (63% by weight). In total, 21.051 kWh of electricity and 8.859 kg of natural gas are consumed during the production stage for 1 kg PAN sheet molding compound carbon fiber. Background material (steel, AHSS, aluminum, and chemicals) and energy (water, electricity, and natural gas) data were

Table 1 Relevant parameters associated with the four engine hood designs

Parameter information	Unit	Steel (baseline)	AHSS	Aluminum	Carbon fiber
Engine hood weight	kg	17.06	13.60	10.93	10.40
Engine hood weight reduction	kg	N/A	3.47	6.13	6.67
Engine hood weight reduction percentage	N/A	N/A	20.31%	35.94%	39.06%
Bend rigidity	N.mm ⁻¹	5.28	5.21	5.09	17.09
Lateral bend rigidity	N.mm ⁻¹	37.04	39.22	33.33	68.97
Torsion rigidity	N.mm ⁻¹	76.92	76.92	90.91	100.00
First step of modality	Hz	30.50	34.40	39.40	36.60

acquired from RCEES 2012 (Liu et al. 2015; Sun et al. 2014; Yang et al. 2015) (Table 3).

2.3.2 Use stage

According to the onsite survey, the fuel consumption of the steel (baseline) vehicle is 5.90 L/100 km. Exhaust gas emissions from the use stage are based on site-test that are shown in Table 4 for the steel (baseline) design.

In this study, the Koffler et al. method (Koffler and Rohde-Brandenburger 2010) is used to estimate the mass-induced fuel consumption of the steel (baseline) vehicle (without powertrain adaptation), and the mass-induced fuel change (with powertrain adaptation) is estimated to achieve equal

driving performance compared to the reference steel (baseline) vehicle. To quantify the vehicle fuel consumption, the EPA-combined fuel economy (EPA CFE)-[55% city (FTP-75)/45% highway (HWFET)] driving cycle (EPA 2016) is considered.

The total mass-induced energy demand (W_{sum}) in the EPA's combined fuel economy formula is calculated as follows (Koffler and Rohde-Brandenburger 2010):

$$W_{sum} = W_R \times (1 - d) + W_A = m \times ((1 - d) \times g \times f_R \times C_{WR} + C_{WA})$$

where

W_R = work required to overcome the rolling resistance;

W_A = work required to overcome the acceleration resistance;

Fig. 1 System boundaries of the automotive engine hood life cycle

Table 2 Life cycle inventory and manufacturing processes of the production stage for four engine hood designs

Category	Subcategory	Unit	Steel (baseline)	AHSS	Aluminum	Carbon fiber
Materials	Steel	kg	24.76	0.00	0.00	0.00
	AHSS	kg	0.00	19.42	0.00	0.00
	Aluminum alloy	kg	0.00	0.00	18.22	0.00
	Carbon fiber	kg	0.00	0.00	0.00	13.86
	Steel (SMCs)	kg	0.00	−1.04	−1.84	−2.00
Energy and resource	Water	kg	0.00	0.00	67.68	0.00
	Electricity	kWh	2.65	2.65	25.54	25.51
Process scraps	Waste steel	kg	7.70	5.83	0.00	0.00
	Waste aluminum	kg	0.00	0.00	7.29	0.00
	Waste carbon fiber	kg	0.00	0.00	0.00	3.47
Manufacturing processes	N/A	N/A	Blanking and stamping, welding, adhesive bonding, flanging	Blanking and stamping, welding, adhesive bonding, flanging	Extrusion, casting, stamping, adhesive bonding, flanging	Sheet molding compound film production, compression molding, adhesive bonding, flanging

m = curb weight of the steel (baseline) vehicle (1325 kg);
 d = share of deceleration phases in the driving cycle in % (17%) based on the EPA CFE (55% city/45% highway) (Dubreuil et al. 2012);

g = gravitational constant, m/s^2 ;

f_R = rolling resistance coefficient (dimensionless);

C_{WR} = characteristic value (17,198 m) for the EPA CFE (55% city/45% highway) (Koffler and Rohde-Brandenburger 2010); and

C_{WA} = characteristic value ($2221 \text{ m}^2/s^2$) for the EPA CFE (55% city/45% highway) (Koffler and Rohde-Brandenburger 2010).

For 100 km and 100 kg, the mass-induced energy demand is

$W_{sum(100kg, 100km)} = \left(\frac{100km}{17.176 \text{ km}}\right) \times 100kg \times ((1-17\%) \times 9.81 \frac{m}{s^2} \times 0.01 \times 17,198m + 2,221m^2) = 2.1 \text{ MJ}$. The mass-induced fuel consumption, $V_{100 \text{ kg, EPA CFE}}$, for naturally aspirated gasoline engines is calculated as follows:

$$\begin{aligned}
 &= W_{sum(100kg, 100km)} \times 1.05 \times \eta_{diff, g} \\
 V_{100kg} &= 2.1 \text{ MJ} \times 1.05 \times 0.073 \text{ l/MJ} \\
 &= 0.161 \frac{l}{100kg * 100km}
 \end{aligned}$$

where

$\eta_{diff, g}$ = differential efficiency of a naturally aspirated gasoline engine (0.073 l/MJ) and

% = losses in the automatic transmission (conservative assumption) (Koffler and Zahller 2012a; Koffler and Zahller 2012b).

Multiple simulations of drivetrain adaptations have produced fuel reduction values 1.9 to 3.0 times higher than the values without additional drivetrain adaptations (average gasoline = 2.37) (Koffler and Rohde-Brandenburger 2010). F_{cp} , the mass-induced fuel change potential of the auto part and with powertrain adaptations to maintain the vehicle dynamics before and after changes in weight, is calculated as follows:

$$\begin{aligned}
 F_{CP} &= 2.37 \times 0.161 \frac{l}{100kg * 100km} \\
 &= 0.38 \frac{l}{100kg * 100km}
 \end{aligned}$$

The total life cycle mass-induced fuel change (C) of the lightweight design (assuming powertrain adaptation) is calculated as follows:

$$C = \Delta m \times F_{CP} \times LTDD_V$$

where Δm = mass changes of the auto part (kg), including the PMCs Δm_p and SMCs Δm_s . It is assumed that the SMC rate is 30% of the PMCs of the lightweight designs.

LTDDV is the baseline vehicle lifetime driving distance (150,000 km).

Table 3 CED, GWP per kg of material production (from cradle-to-gate)

Impact category	Unit	Steel-baseline	AHSS	Aluminum	Carbon fiber
GWP(100a)	kgCO ₂ e	2.44	2.96	16.76	34.60
CED	MJ	24.41	49.76	157.59	1106.62

Table 4 Exhaust gas emissions in the use stage of the steel (baseline) vehicle

Pollutants	Value (g/km)
CO	0.257
NMHC	0.033
NOx	0.023
CH ₄	0.004
CO ₂	142.00

When including SMCs (assuming powertrain adaptation), the maximum total life cycle mass-induced fuel change of a vehicle due to auto part PMCs is

$$\begin{aligned}
 C &= (\Delta m_p + \Delta m_s) \times F_{CP} \times LTDD_V \\
 &= 1.3 \Delta m_1 \times \frac{0.38l}{100} \text{ kg} \times 100 \text{ km} \times 150,000 \text{ km} \\
 &= 7.41 \Delta m_1 (l)
 \end{aligned}$$

Based on the method above, the use stage model parameters associated with four types of engine hood designs are shown in Table 5. Due to the mass-induced fuel change during a vehicle life cycle, CO₂ emission is assumed to change at the same rate during the vehicle use stage. Background gasoline extraction and production data were acquired from RCEES 2012 (Liu et al. 2015; Sun et al. 2014; Yang et al. 2015).

2.3.3 End-of-life stage

In this study, it is assumed that 95% of the vehicles are collected, dismantled, shredded, and sorted at the end-of-life stage and that the metal recycling rate is 95% for steel and AHSS, and 90% for aluminum. Waste steel and AHSS are recycled to avoid primary steel production, and waste aluminum is recycled to avoid primary aluminum production. Waste materials that cannot be recycled are treated as solid waste according to the waste treatment scenario specified in RCEES 2012.

Two technologies have been proposed for recycling carbon fiber reinforced plastics (CFRPs), mechanical recycling, and fiber reclamation (Pimenta and Pinho 2011). Fiber reclamation

processes are particularly suitable for CFRPs and include pyrolysis, oxidation in a fluidized bed, and other chemical recycling processes. Pyrolysis is a widespread and commercial-scale recycling process that is used for CFRPs (Oliveux et al. 2015; Pimenta and Pinho 2011).

Pyrolysis is a thermal recycling process that decomposes matrices at approximately 400 to 600 °C according to their thermal properties to recover fibers. In this process, thermal decomposition is conducted in an inert environment or controlled atmosphere with a low proportion of oxygen to prevent the oxidation of fibers. Rapid gasification might be necessary after the principal step for cleaning the fibers of char due to resin decomposition. The gas fraction produced from matrix decomposition can be condensed and reused as a fuel or burned to recover heat (Vo Dong et al. 2015).

In this study, the pyrolysis process is used as a CFRP recycling method. Pyrolysis requires approximately 30 MJ/kg of energy (Witik et al. 2013), and the recycling rate of waste carbon fiber is 90%. Recycled carbon fibers have properties that are comparable to the properties of virgin carbon fibers produced from PAN and can be used to replace virgin carbon fibers (Das 2011; Oliveux et al. 2015).

2.4 Life cycle impact analysis

The Cumulative Energy Demand v1.09 method (Frischknecht 2003) is used to evaluate the CED, which is expressed in GJ. The CED is the sum of all energy sources, including the natural non-renewable and renewable resources extracted directly from the Earth. Non-renewable energy comes from sources that will run out or cannot be replenished on human timescales and include fossil fuels (oil, coal, and natural gas) and nuclear energy. Renewable energy is generally defined as energy from resources that are naturally replenished on human timescales, such as wind, solar, geothermal, water, and biomass. IPCC 2013 GWP (100a) is a method developed by the Intergovernmental Panel on Climate Change that focuses on the impacts of the GWP over 100 years and is one of the most accepted methods for calculating GWP (IPCC 2013), which is measured in kg of CO₂-e.

Table 5 Use stage model parameters for four engine hood designs

Parameter information	Steel (baseline)	AHSS	Aluminum	Carbon fiber
Vehicle curb weight (kg)	1325.00	1320.49	1312.52	1303.86
Engine hood weight (kg)	17.06	13.60	10.93	10.40
Powertrain resizing	N/A	Yes	Yes	Yes
Primary mass reduction (kg)	N/A	3.47	6.13	6.67
Secondary mass change rate	N/A	30%	30%	30%
Total mass reduction (kg)	N/A	4.51	7.97	8.66
Lifetime driving distance (km)	150,000	150,000	150,000	150,000
Life cycle fuel savings (l)	N/A	25.68	45.44	49.39

Table 6 Life cycle, CED, GWP, and selected air emissions for four engine hood designs

Life cycle stage	CED (GJ)	GWP(100a) (kgCO ₂ e)	SO ₂ (kg)	NO _x (kg)	NM VOC (kg)
AHSS (13.60 kg)					
Production	0.37	−1.64	−0.14	−0.12	0.00
Use	−1.30	−72.78	−0.04	−0.04	0.00
End-of-life	0.06	6.74	0.03	0.02	0.00
Total	−0.86	−67.68	−0.16	−0.15	0.00
Aluminum (10.93 kg)					
Production	1.51	165.17	0.58	0.51	0.05
Use	−2.29	−128.61	−0.08	−0.07	0.00
End-of-life	−1.24	−125.47	−0.41	−0.38	−0.04
Total	−2.02	−88.91	0.09	0.06	0.00
Carbon fiber (10.40 kg)					
Production	14.02	458.82	2.08	1.85	0.79
Use	−2.49	−139.75	−0.08	−0.08	0.00
End-of-life	−9.19	−271.76	−1.33	−1.25	−0.08
Total	2.34	47.31	0.67	0.52	0.71
Steel-baseline (17.06 kg)					
Production	0.49	46.74	0.17	0.10	0.00
Use	446.06	25,071.66	14.67	17.28	5.33
End-of-life	−0.31	−33.22	−0.13	−0.07	0.00
Total	446.24	25,085.18	14.70	17.30	5.33

3 Results and discussion

3.1 Life cycle assessment results

Table 6 shows life cycle assessment results, based on total net changes (differential values) in cradle-to-grave CED, GWP (100a), and selected air emissions of the three lightweight engine hoods compared with the steel-baseline (absolute values).

Figures 2 and 3 show the CED and GWP (100a) values associated with the three types of lightweight engine hood

designs throughout their life cycles. The carbon fiber design has the largest positive CED and GWP (100a) impacts during the production stage and the largest negative impacts during the use and end-of-life stages, followed by the aluminum hood designs. Carbon fiber and aluminum are energy-intensive materials that require more energy consumption and produce more greenhouse gas (GHG) emissions during the production stage compared with steel. Recycling of these materials during the end-of-life stage can offset a large portion of energy consumption and GHG emissions associated with primary production. However, all these three kinds of candidate materials,

Fig. 2 Comparison of the life cycle cumulative energy demands of three lightweight engine hood design

Fig. 3 Comparison of the life cycle global warming potentials (100a) of three lightweight engine hood designs

carbon fiber, followed by aluminum and AHSS, could reduce vehicle energy consumption and GHG emissions compared to steel engine hoods based on a 150,000-km lifetime service distance because they reduce fuel consumption during the vehicle use stage.

Based on the entire life cycle, the aluminum engine hood achieves the largest reduction in total CED and GWP, followed by the AHSS hood. In addition, the carbon fiber engine hood increases the total CED and GWP compared with the steel (baseline) engine hood.

In order to accurately depict the overall net decrease or increase of the potential environmental impacts due to the lightweight designs, it is recommended that the life cycle impacts be structured according to the production, use, and end-of-life stages (see Figs. 4 and 5).

Two important pieces of information can be derived from this chart: the break-even distance (km) and the overall net

decrease or increase of the potential environmental impacts due to each lightweight design, respectively.

Figure 4 depicts the overall net decrease or increase in potential environmental impacts associated with CED due to lightweight designs. A negative slope indicates a decrease in fuel consumption due to the lightweight design and represents a net decrease in CED over the vehicle's driving distance for each lightweight design.

The CED break-even distance for AHSS compared to the steel (baseline) design is 43,063 km. This means that a net CED benefit will be achieved with using the AHSS design after the break-even distance. The CED break-even distance for the aluminum design is 98,992 km, which is higher than the break-even distance of the AHSS design. In comparison, carbon fiber design does not have a CED break-even point within 150,000 km due to high energy consumption during the carbon fiber engine hood production process. Based on the

Fig. 4 Cumulative energy demand with driving distance for three lightweight engine hood designs

Fig. 5 Global warming potential (100a) compared with driving distance for three lightweight engine hood designs

current state of technology and a vehicle lifetime of 150,000 km, the aluminum design exhibits a better net energy profile than the AHSS design. The carbon fiber design displays the worst CED performance.

Figure 5 illustrates the overall net decrease or increase in the potential environmental impact associated with GWP (100a) due to lightweight designs. The AHSS design has a net GWP (100a) advantage over the steel (baseline) design in the production stage (0 km). The aluminum and carbon fiber designs both do not have CED break-even points within 150,000 km because of the large amounts of GHG emissions during the production stages, especially for carbon fiber design.

In conclusion, the aluminum design is the most sustainable lightweight design because it resulted in the largest overall net decrease of the CED and GWP (100a) values compared to the steel (baseline) over the vehicle lifetime of 150,000 km. In addition, the AHSS design is another sustainable lightweight design and exhibits the best break-even distance on the CED and GWP (100a) within 150,000 km. The carbon fiber design

resulted in overall net increase of the CED and GWP (100a) values compared with the steel (baseline) design over the investigated life cycle.

3.2 Sensitivity analysis

A sensitivity analysis is conducted to examine the effects of varying several LCA parameters on the overall life cycle impacts of the lightweight hoods. A single factor sensitivity analysis method is used to analyze three proposed parameters: lifetime service distance, material recycling rate, and secondary mass change rate. The proposed percent changes of all factors are based on changing values (10% of their nominal values). The results are shown in Table 6.

The sensitivity analysis results show that lifetime service distance has a considerably impact on the total CEDs and GWPs (100a) (Table 7). The sensitivity value in overall GWP (100a) is related to the engine hood weight, with lighter hoods corresponding with more variable lifetime driving distance impacts. Lighter engine hoods have lower overall GWPs

Table 7 Sensitivity analysis results for some LCA parameters

Parameter	AHSS		Aluminum		Carbon fiber	
	CED	GWP	CED	GWP	CED	GWP
Lifetime driving distance						
+10%	+15.04%	+10.75%	+11.32%	+14.46%	-10.63%	-29.54%
-10%	-15.04%	-10.75%	-11.32%	-14.46%	+10.63%	+29.54%
Material recycling rate						
+10%	+5.05%	+6.43%	+13.45%	+30.98%	-56.79%	-87.86%
-10%	-5.05%	-6.43%	-13.45%	-30.98%	+56.79%	+87.86%
Secondary mass change rate						
+10%	+0.29%	+0.38%	+0.22%	+0.51%	-0.21%	-1.03%
-10%	-0.29%	-0.38%	-0.22%	-0.51%	+0.21%	+1.03%

(100a) compared to heavier engine hoods because the total life cycle GWP (100a) depends on the amount of gasoline required to travel a proposed distance.

Material recycling rate has strong effects on the total overall CED and GWP of aluminum and, particularly, carbon fiber hoods. A +10% change in the waste carbon fiber material recycling rate impacts the CED and GWP by −56.79 and −87.86%, respectively, based on the carbon fiber engine hood design. The AHSS engine hood design slightly affects the overall CED and GWP (100a) when the recycling rate is changed. Notably, a high recycling rate should be a fundamental requirement for energy-intensive materials (such as aluminum and carbon fiber) which could offset their energy consumption and GHG emissions during the production stage.

The secondary mass change rate has very small impact on the overall CEDs and GWPs (100a) of the lightweight designs.

4 Conclusions

This paper presents an LCA-based method for CED and GWP (100a) analyses associated with the selection of sustainable materials for vehicle engine hoods. The proposed method was used to evaluate the life cycle environmental performance of different materials, namely, steel (baseline), AHSS, aluminum, and carbon fiber. Results show that the aluminum design has the lowest CED and GWP (100a) values over the lifespan of the vehicle, which is assumed to be approximately 150,000 km. The AHSS design is another sustainable lightweight design choice. The carbon fiber design results in higher life cycle CED and GWP (100a) values compared to the steel (baseline) design.

This study also presents a set of CED and GWP values which clearly illustrate the energy consumption and GHG emissions during the different life stages of engine hoods made from different materials. Additionally, a sensitivity analysis is performed to examine the effects of changing some LCA parameters on overall CED and GWP. The sensitivity analysis results show that lifetime service distance and material recycling rate have large impacts on the overall CEDs and GWPs (100a) of the three lightweight designs.

This study provides additional information for sustainable lightweight engine hood designs, which are useful for the automotive industry because lightweight engine hoods can reduce vehicle life cycle energy consumption and GHG emissions. Moreover, this study may provide constructive information for introduction of fuel economy and tailpipe emission standards and regulations from a life cycle perspective.

References

- Ashnani MHM, Miremadi T, Johari A, Danekar A (2015) Environmental impact of alternative fuels and vehicle technologies: a life cycle assessment perspective. *Por Environ Sci* 30:205–210
- CSA Group (2014) Guidelines for conducting LCA of auto parts incorporating weight changes due to material composition, manufacturing technology, or part geometry vol SPE-14040-14. Canadian Standards Association Group, Canada
- Cui X, Zhang H, Wang S, Zhang L, Ko J (2011) Design of lightweight multi-material automotive bodies using new material performance indices of thin-walled beams for the material selection with crash-worthiness consideration. *Mater Design* 32:815–821
- Das S (2011) Life cycle assessment of carbon fiber-reinforced polymer composites. *Int J Life Cycle Assess* 16:268–282
- Ding N, Gao F, Wang Z, Yang J (2015) Life cycle energy and greenhouse gas emissions of automobiles using aluminum in China. *J Ind Ecol* 20:818–827
- Dubreuil A, Bushi I, Das S, Tharumarajah A, Gong X (2010) A Comparative Life Cycle Assessment of Magnesium Front End Autoparts. *SAE Technical Papers* 01 doi:10.4271/2010-01-0275
- Dubreuil A, Bushi I, Das S, Tharumarajah A, Gong X (2012) A Comparative Life Cycle Assessment of Magnesium Front End Autoparts. *SAE Technical Papers* 01 doi:10.4271/2012-01-2325
- EPA (2016) EPA's FTP-75 and HWFET driving cycles. <http://www.dieselnet.com/standards/cycles/hwfet.html>. Accessed 2.24 2016
- Frischknecht R, Jungbluth N et al (2003) Implementation of life cycle impact assessment methods. Final report ecoinvent 2000, Swiss Centre for LCI. Duebendorf, CH. www.ecoinvent.ch
- Gao Z et al (2015) Drive cycle simulation of high efficiency combustions on fuel economy and exhaust properties in light-duty vehicles. *Appl Energ* 157:762–776
- Hakamada M, Furuta T, Chino Y, Chen Y, Kusuda H, Mabuchi M (2007) Life cycle inventory study on magnesium alloy substitution in vehicles. *Energy* 32:1352–1360
- Helms H, Lambrecht U (2007) The potential contribution of lightweighting to reduce transport energy consumption. *Int J Life Cycle Assess* 12:58–64
- IPCC (2013) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA
- ISO (2006) ISO 14040: 2006 environmental management-life cycle assessment-principles and framework. International Organization for Standardization, Geneva
- Kampe S (2001) Incorporating Green Engineering in Materials Selection and Design. In: 2001 Green Engineering Conference: Sustainable and Environmentally-Conscious Engineering, Roanoke, Virginia. Virginia Tech's College of Engineering and the U.S. Environmental Protection Agency
- Koffler C, Rohde-Brandenburger K (2010) On the calculation of fuel savings through lightweight design in automotive life cycle assessments. *Int J Life Cycle Assess* 15:128–135
- Koffler C, Zahller M (2012a) Life cycle assessment of polymers in an automotive assist step, prepared for: American Chemistry Council. PE INTERNATIONAL, USA
- Koffler C, Zahller M (2012b) Life cycle assessment of polymers in an automotive bolster, prepared for: American Chemistry Council. PE INTERNATIONAL, Inc., USA
- Liu Q, Chen Q, Yang J (2011) The Impact of Tire Rolling Resistance on the Fuel Economy of Vehicle. *AUTOMOB PARTS*:77–80 doi:10.3969/j.issn.1674-1986.2011.08.029
- Liu Z et al (2015) Targeted opportunities to address the climate-trade dilemma in China. *Nature Clim Change* advance online publication. doi:10.1038/nclimate2800

- Liu ZF, Wang J, Zhang L, Bao H (2012) Life cycle assessment of automotive engine hoods made of aluminum alloy and glass mat reinforced thermoplastic. *J Hefei Univ Tech* 35:433–438
- Mayyas AT, Qattawi A, Mayyas AR, Omar MA (2012) Life cycle assessment-based selection for a sustainable lightweight body-in-white design. *Energy* 39:412–425
- Oliveux G, Dandy LO, Leeke GA (2015) Current status of recycling of fibre reinforced polymers: review of technologies, reuse and resulting properties. *Prog Mater Sci* 72:61–99
- Pimenta S, Pinho ST (2011) Recycling carbon fibre reinforced polymers for structural applications: technology review and market outlook. *Waste Manag* 31:378–392
- Saur K, Fava JA, Spatari S (2000) Life cycle engineering case study: automobile fender designs. *Environ Prog* 19:72–82
- Sun X, Liu J, Yang D, Lv B (2014) The carbon footprint of household air-conditioners and its key influence factors. *Acta Scien Circum* 34: 1054–1060
- Vo Dong PA, Azzaro-Pantel C, Boix M, Jacquemin L, Domenech S (2015) Modelling of Environmental Impacts and Economic Benefits of Fibre Reinforced Polymers Composite Recycling Pathways. In: Krist V, Gernaey JKH, Rafiqul G (eds) *Computer Aided Chemical Engineering*, vol Volume 37. Elsevier, pp 2009–2014. doi:10.1016/B978-0-444-63576-1.50029-7
- Wang H, Gao W, Pan L, Liu C (2006) Lightweight structure of engine hood. *J Tongji Univ (Natural Science)* 34:1098–1103
- Witik RA, Payet J, Michaud V, Ludwig C, Manson J-AE (2011) Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. *Cosmos Part A-Appl S* 42:1694–1709
- Witik RA, Teuscher R, Michaud V, Ludwig C, Manson J-AE (2013) Carbon fibre reinforced composite waste: an environmental assessment of recycling, energy recovery and landfilling. *Compos Part A-Appl S* 49:89–99
- Yang D, Liu J, Yang J, Ding N (2015) Life-cycle assessment of China's multi-crystalline silicon photovoltaic modules considering international trade. *J Clean Prod* 94:35–45
- Zhou J, Wang F, Wan X (2015) Optimal design and experimental investigations of Aluminium sheet for lightweight of car hood. *Mater Today: Prog* 2:5029–5036
- Zhu P, Meng J, Yu M, Feng Q, Zhou QW (2011) Lightweight design and Formability analysis of saloon car aluminum-alloy engine hood. *CNN J Highway Transp* 24:113–120