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Life cycle assessment and cost analysis of hybrid fiber-reinforced engine beauty cover in comparison with glass fiber-reinforced counterpart

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ABSTRACT

Life cycle assessment is a useful tool that helps to quantify the ecological impact of a product. It also enables us to compare two products. Regardless of its weaknesses, this tool is by far one of the best methods introduced and is one of the most complicated techniques available for environmental assessment. While the benefit of using bio-based materials instead of synthetic materials is well known, to date very few studies are available comparing the two products. The aim of this paper is to compare a currently available car engine beauty cover with a hybrid bio-based cover. This study's results show that the new hybrid materials not only perform better in terms of emissions during car operation (because of the fuel savings resulting from lightweighting), but that their production and end of life is also environmentally benign. A cost analysis of the two types of engine covers shows that the new hybrid materials are a good substitute for current materials because their manufacture costs half that of current materials.

1. Introduction

Lightweighting is an important topic for improving fuel consumption and reducing emissions in the automotive and aviation industries. It is well known that the amount of fuel consumption is proportional to vehicle weight. On average, each reduction in a car's weight of 10% can save up to 8% on fuel consumption. (Stans and Bos, 2007; Van den Brink and Van Wee, 2001). Lightweighting is more valuable in the front of the vehicle, especially the engine area, because of the necessary balanced ratio of front-to-rear weight distribution (Wordley and Saunders, 2006; Woods and Jawad, 2000). Another important concept in lightweighting is secondary weight reduction, also known as "mass decompounding," (Verbrugge et al., 2009) the principle by which a lighter car can have a smaller engine with no decrease in performance, in comparison with the original car. A very good demonstration of this fact is the MMLV project (Bushi et al., 2015). Most emission reductions are due to the use phase cycle or driving phase of the lighter car; however, using bio-based materials could also be a better choice in the production and disposal phase; it may even cost less than current materials.

A recent study on a grille shutter housing made of three different composites (glass fiber-reinforced composites (30%), cellulose fiber-reinforced composite (30%), and kenaf fiber composite (40%)) showed that using cellulose fiber to reinforce the part is 39.5 MJ less energy-intense than using glass fiber counterparts (Boland et al., 2014).

Some important research on the subject of LCA for lightweight materials took place in the late 1990s. In one of the earliest studies of this kind, researchers compared hemp fiber-reinforced side panels with acrylonitrile-butadiene-styrene (ABS) side panels. These researchers compared the LCA of the two parts and reported that production of the part made of hemp fiber-reinforced composite required 59 MJ, which was more than 55% less energy-intensive than production with ABS thermoplastic materials. The only major drawback was the amount of NOx released: although the release was still less for the hemp fiber parts, the emissions were not as good as expected (Wötzel et al., 1999). Similarly, another study on hemp fiber demonstrated comparable results for bus body components (Schmehl et al., 2008). Das (2011) compared a carbon-fiber floor pan with a steel floor pan and showed that carbon fiber was not better than steel; however, he argued that changing the source of the carbon fiber to lignin would help the fabrication of the carbon fiber to be less energy-intensive. Like the previously mentioned researchers, Das also reported that regardless of the composition and source of the carbon fiber, steel performs better both in terms of NOx emissions and human health (Das, 2011). Existing research also reflects the trend toward replacing conventional materials with their bio-based equivalents: for example, Luz et al. (2010) replaced talc with sugarcane in an interior aesthetic and found a decrease of 4.5% in the energy required for production. The same year, Alves et al. (2010) replaced glass fiber with jute fiber to produce the structural front bonnet for an off-road vehicle; results indicated that although the

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production phase did not favor jute fiber, the use phase compensate for that and the whole life cycle did favor the jute fiber.

In addition to these materials, researchers tried out many different bio-based materials as substitutes for conventional materials. Some of these materials included flax, wood paneling, coconut fiber, cotton fiber, cellulose fiber, foams, kenaf, cork, sawdust, lignin, and agricultural residues (Diener and Siehler, 1999; Çinar, 2005; Finkbeiner and Hoffmann, 2006; Birat et al., 2015; Faruk et al., 2014; Boland et al., 2014; La Rosa et al., 2014; Nourbakhsh and Ashori, 2010; Najafi et al., 2006; Boland et al., 2015).

This study's objective is to perform a life cycle assessment and production cost analysis of an engine beauty cover made of two different composite materials: namely, glass fiber-reinforced polyamide composites and hybrid cellulose-and-carbon fiber-reinforced polypropylene composites which were developed at the Center for Biocomposites and Biomaterials Processing, University of Toronto's Faculty of Forestry (CBBP). The study covers the comparison from cradle to grave, ignoring automobile use phase and its fuel savings.

2. Methodology

2.1. Life cycle assessment

Life cycle assessment (LCA) is a robust process (well-defined by ISO standard family 1404X) to calculate the effects of processes, products, and services on our planet. It is even possible to directly compare products, processes, and services (International Organization for Standardization, 2006a). According to ISO standards, the LCA has four distinct stages: 1) goal and scope definition, including the description of the system boundaries and functional units that determine what the system includes and what is ignored, what processes are backgrounded, and so on; 2) inventory analysis; 3) impact assessment; and 4) interpretation.

The goal of this study is to compare the emissions from the current glass fiber-reinforced engine beauty cover with its hybrid cellulose/carbon fiber-reinforced counterpart during the production phase and up to the end of life, which, in North America, is usually in a landfill.

2.1.1. System boundary

The scope of this research is cradle to grave, starting with the extraction of the necessary materials, such as the growth of the tree used for natural fiber, extraction and refinery of oil for material and energy, extraction and processing of natural gases, extraction of coal, and other energy sources such as renewable and nuclear power. It follows these processes all the way to emission and landfill. Figs. 1 and 2 show the system boundaries and processes in the life cycle of bio-based and conventional engine covers.

2.1.2. Functional unit and scope definition

This study's functional unit is an engine beauty cover that will cover a generic V6 engine of a Ford SUV/pickup truck to provide cosmetic appeal, isolate the heat from the engine, and reduce noises. The cover will be expected to last for 25 years or 290,000 km, whichever comes first. The reference flow for the current research is one fiber-reinforced plastic engine beauty cover that could be either hybrid or glass fiber-based, injection-molded, and estimated to have a life span of over 290,000 km or 25 years. This part will be shredded and sent to a landfill after its life span. The total volume for the part is 957.98 cm^3, with fiber content evaluated based on weight. A unit composed of 30 wt% (glass fiber and mica group minerals mix) is assumed to perform similarly to one of 30 wt% (cellulose fiber and carbon fiber hybrid) (Table 1). Both compounds contain up to 5% proprietary materials (excluded from our calculations), and both compounds meet the manufacturer's minimum standard requirements.

2.1.3. Method, assumption, and impact limitations

This study included only unit processes that contribute more than 1% to system total flows of mass, primary energy, and environmental pollutants. It excluded fuel consumption during the product's use phase, which has been reviewed elsewhere (Akhshik et al., 2017). This LCA study will follow only the landfill scenario for the end of the product's life; this is the most common practice for the plastic composite parts in North America (Stagner et al., 2013; Miller et al., 2014). We assume that the engine beauty covers were sent to the assembly plant with the average mileage of the real distances.

Both engine beauty covers contain up to 5% proprietary additives, which we have excluded from our calculations. Avoided burdens method was used for the calculation of the recycled materials like the one in the polyamide (20%).

For modelling the impacts, we used US EPA TRACI 2.1 for both engine beauty covers. Data categories were both primary and secondary, selected based on impacts as indicated by TRACI (Bare, 2012) and also based on the availability of data in the databases. We collected landfill data from the European generic database and confirmed those using Canadian sources. All other secondary data came from OpenLCA (GreenDelta GmbH, Germany 2014), SimaPro (PRéConsultants, The Netherlands 2015), Gabi (Think step, Germany 2015), GREET (Argonnenational lab, 2015), and NREL (NREL, 2012) databases. For the calculations, wherever no data were available for North America, we used European data.

This study did not consider the environmental impact of cardboard manufacturing, recycling, and packaging because most auto manufacturers and the OEMs recycle their cardboard efficiently. The study also excluded part reuse because it did not fall within the 1% criteria.

The electricity calculated for the energy consumption was based on the average Ontario electricity grid mix during the year 2016. We calculated all prices in the cost analysis in Canadian dollars and converted them to US dollars using a conversion rate of 1.2:1. Manufacturing energy costs, was estimated based on the addition of the prices for each sources of the energy that was used for manufacturing the part. For the purpose of these calculations the available energy prices in KWh were used. Materials cost was calculated for making 1 million parts per year, based on the actual quotes from the material producers. This includes the produced scraps and the material loss due to the manufacturing, shipping and handling. Processing and transportation cost, for both parts, were rounded up to 1 USD for both types of the parts. This includes injection molding machine rate, labor and transportation of parts and materials between the gates.

2.1.4. Transportation and logistics data

We calculated all the transportation and the logistics data based on the actual distances between gates unless mentioned elsewhere; the total transportation data for the main materials follow:

For the current materials, minerals traveling for 1400 km by truck and all other materials (including minerals) will travel for 1260 km to the OEM gate. For each 1 kg of mineral sent to the compounder, 5 kg of composite materials will be sent to the OEM by train. The engine beauty covers are shipped by truck to the assembly plant, which has on average distance of 1134 km.

For the hybrid materials, the carbon fiber is traveling for 1258 km by truck, and the pulp travels for 500 km by ship and truck, as Table 2 shows.

2.1.5. Multi-functionality and allocation

We have encountered only one multifunctionality in the production of the hybrid engine beauty cover. The wood fiber production was either a by-product of the construction wood or pulp and paper. Moreover, for the plastic production, according to the databases, an allocation appears to exist for the portion of the flow of the mass. We use the avoided burden approach to avoid recalculations for polyamide recycling.