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Critical factors affecting life cycle assessments of material choice for vehicle mass reduction

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1. Introduction

1.1. *Vehicle mass reduction*

New greenhouse gas (GHG) standards for cars and light trucks are taking effect for model year 2017, progressing towards an anticipated sales weighted average level of 173 g/mile CO_2 for model year 2025, and fuel economy standards increasing each year to the Corporate Average Fuel Economy (CAFE) target of 51.4 mpg fleet-wide by 2025 (for a projected vehicle sales mix). As a result, vehicle manufacturers are looking for solutions that can meet these goals without sacrificing marketable vehicle attributes (Nehuis et al., 2014; U.S. EPA, 2012a, 2014). Reducing mass enables vehicles to operate more efficiently during the use phase because energy demands (e.g., acceleration, rolling friction) on the powertrain are reduced. This reduction in mass can have major benefits on the total life-cycle impacts of vehicles because the current use phase accounts for 84–88% of the total life-cycle energy consumption and GHG emissions for conventional light-duty vehicles. Comparatively, the manufacturing contributes approximately 4–7% of the energy consumption over the life of a light-duty vehicle (Keoleian and Sullivan, 2012; Mcauley, 2003; Sullivan and Cobas-Flores, 2001; Sullivan et al., 1998). Because of this dominant contribution of impacts from the use phase, mass reduction efforts and other use-phase efficiency measures provide an effective means to reduce the total life-cycle impacts. However, the share of life-cycle impacts between the production and use phase for vehicles is likely to shift away from the use phase with increasing efficiency and with reduced light-duty vehicle GHG emissions standards, as shown in the example comparison in Fig. 1.

Vehicle mass reduction is an effective method to improve vehicle operating efficiency and reduce both fuel consumption and CO_2 emissions by reducing vehicle road loads. In some instances, vehicle mass reduction can be used to offset mass gained through the use of other technologies, such as the weight of additional battery capacity needed for vehicle electrification. Computer-aided design has enabled engineers to make significant gains in recent years through the use of structural optimization models and dynamic vehicle crash models that have contributed to increased safety and vehicle mass reduction by reducing the overall materials required within the structure of the vehicle (Das, 2014a; Nehuis et al., 2014). With optimization of the vehicle body structure and geometry now being an inherent step in the design of a new vehicle, further vehicle mass reduction must be accomplished by expanding the suite of materials utilized in vehicle construction through targeted efforts based on specific material properties, forming technologies, and integration into complete vehicle designs (Mayyas et al., 2012a; Modaresi et al., 2014). The primary contributors to a vehicle's weight and the focus of most mass reduction efforts are the components that make up the body-in-white (BIW) (the stage in automotive design and manufacturing where a vehicle's body components have been welded together to form a structure) and closures, which are primarily metal in most current light-duty vehicles (Caffrey et al., 2015).

Some materials perform better than others for certain vehicle applications based on the current range of characteristics of a particular metal, metal alloy, or composite. This range of characteristics is highlighted by the progression of conventional steels to

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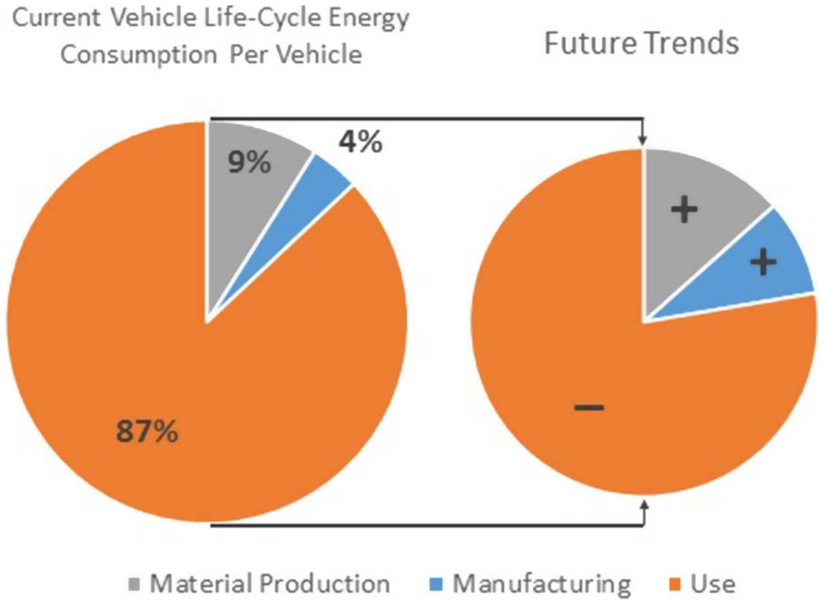

Fig. 1. Energy consumption for material production, manufacturing, and use for a light-duty vehicle now and trends for the future. Total life-cycle energy use will decrease as the proportion of impacts for the material production and manufacturing phases are expected to increase and the use-phase impacts are expected to decrease. This is the expected trend with substitutions of more intensive but lighter materials such as aluminum alloys or carbon fiber replacing less intensive but heavier materials such as mild steel. Stronger, higher strength steels are also expected to displace mild steels by reducing total volumes required. Values for the current chart are a simplified breakdown based on Keoleian and Sullivan (2012), Sullivan and Cobas-Flores (2001), and Sullivan et al. (1998).

steels with higher tensile strength such as high-strength steels (HSSs) and advanced high-strength steels (AHSSs). AHSS refers to multiphase steels which may contain combinations of martensite, bainite, and retained austenite phases and having tensile strength in excess of 500 MPa. AHSS is further broken down into even higher tensile strength categories that include ultra-high-strength steels (UHSSs) and gigapascal (GPa) steels (i.e., steels with greater than 1 GPa tensile strength) (World Auto Steel, 2016). The higher strength steels can offset conventional steel within a structure by using less material in the same applications. Additionally, each material may have many different methods of forming that can make it more or less appropriate for a specific application (Nehuis et al., 2014). Component specific material selection allows for significant vehicle mass reduction through material replacement and design optimization as well as multi-material design which often integrates a number of previously separate components into one piece. This sort of component integration can be used to reduce both component mass and the finished cost of the component, thus improving the cost-effectiveness for CO_2 reduction.

Fig. 2 illustrates the typical vehicle-based material composition based on curb weight (the full weight of the vehicle including consumables such as fuel, but excluding passengers and cargo) for 2010 and 2013, with an overall decrease of 20 kg (1.1%) over three years. Fig. 2 also shows a specific example of the 2013 Ford Fusion, which has 1560 kg of mass and is made up of nearly half the steel and iron, five times as much AHSS/UHSS, and approximately the same amount of aluminum as the 2013 average. In 2015, a collaborative effort between the U.S. Department of Energy (DOE), Ford Motor Company and Magna International completed a holistic vehicle mass reduction study in which they reduced the weight of a 2013 Ford Fusion. The resulting lightweight concept vehicle design (designated Mach 1) reached a target 23.5% mass reduction. The Mach 1, as shown in Fig. 2, has a nearly threefold increase of aluminum and a decrease of 4.5 times the amount of AHSS/UHSS with a small amount of magnesium being included and a reduction of the steel and iron content by 34%. Aluminum alloy parts were used in the body, interior, chassis, and powertrain. This was achieved through the use of castings, extrusions, stampings, and forgings (Bushi et al., 2015).

Vehicle designs implementing mass reduction must also fulfill multiple design constraints, which include attaining manufacturer-designated safety targets, cost targets, functional targets, component durability targets, and noise-vibration-harshness (NVH) targets, which can take a higher priority than fuel efficiency and emissions reductions. According to Nehuis et al., the trend of increasing vehicle weight "was stopped by developing new vehicle concepts and by using lightweight materials (light metals, high-strength steel and fiber-reinforced plastics) intensively" (Nehuis et al., 2014).

Fig. 3 shows the changes in light-duty vehicle weight, fuel economy, and horsepower over the last 40 years. Vehicle weight stopped increasing starting in approximately 2004 and remained static while horsepower and, to an even greater extent, fuel economy continued to increase. Because reducing the mass of a vehicle increases the power-to-weight ratio, efforts seeking to address the new efficiency standards may be able to reduce powertrain output requirements to achieve equivalent or even improved performance characteristics compared to existing vehicles while reducing the mass even further (Kelly et al., 2015).