Applied Energy 126 (2014) 13–20

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Vehicle lightweighting vs. electrification: Life cycle energy and GHG emissions results for diverse powertrain vehicles

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HIGHLIGHTS

- We modeled life cycle energy and greenhouse gas (GHG) emissions from diverse powertrain vehicles.
- Lightweight versions of the vehicle models were compared against baseline models.
- Maximum energy and GHG emissions occur with aluminum vs. advanced high strength steel.
- Design harmonization method shows 0.2–0.3 kg of support required per 1 kg powertrain mass increase.

ARTICLE INFO

Article history:
Received 3 November 2013
Received in revised form 11 February 2014
Accepted 14 March 2014
Available online 22 April 2014

Keywords:
Lightweight vehicles
Electrification
Life cycle analysis
Design harmonization
Greenhouse gas emissions
Energy

ABSTRACT

This work assesses the potential of electrified vehicles and mass reduction to reduce life cycle energy and greenhouse gas (GHG) emissions. Life cycle assessment (LCA) is used to account for processes upstream and downstream of the vehicle operation, thereby incorporating regional variation of energy and GHG emissions due to electricity production and distinct energy and GHG emissions due to conventional and lightweight materials. Design harmonization methods developed in previous work are applied to create baseline and lightweight vehicle models of an internal combustion vehicle (ICV), hybrid electric vehicle (HEV) and plug-in hybrid electric vehicle (PHEV). Thus, each vehicle is designed to be functionally equivalent and incorporate the structural support required for heavier powertrains. Lightweight vehicles are designed using body-in-white (BIW) mass reduction scenarios with aluminum and advanced/high strength steel (A/HSS). For the mass reduction scenarios considered in this work, results indicate that the greatest life cycle energy and GHG emissions reductions occur when steel is replaced by aluminum. However, since A/HSS requires less energy to produce as compared to aluminum, the energy and GHG reductions per unit mass removed is greatest for A/HSS. Results of the design harmonization modeling method show that 0.2–0.3 kg of structural support is required per unit increase in powertrain mass, thus extending previous methods.

1. Introduction

Lightweight materials and vehicle electrification are gaining popularity in the US light-duty vehicle fleet and have the potential to reduce life cycle energy and greenhouse gas (GHG) emissions from the transportation sector [1,2]. However, some lightweight materials, such as aluminum and carbon fiber, require more energy to produce than conventional materials and vehicle electrification requires electricity from the grid, which varies based on energy source [3–10]. Life cycle assessment (LCA) is a useful tool to determine the impact of these technologies since it not only evaluates the vehicle use phase, but also the processes required for producing vehicle materials and fuels and end-of-life vehicle management [11].

Abbreviations: A/HSS, advanced/high strength steel; AER, all-electric range; ANL, Argonne National Laboratory; BIW, body-in-white; CAFE, Corporate Average Fuel Economy; CD, charge depleting; CS, charge sustaining; EPA, Environmental Protection Agency; FTW, front track width; GHG, greenhouse gas; HEV, hybrid electric vehicle; HSS, high strength steel; HWFET, Highway Fuel Economy Test; ICV, internal combustion vehicle; LCA, life cycle assessment; MPG, miles per gallon; MPGe, miles per gallon equivalent; NERC, North American Electric Reliability Corporation; NHTSA, National Highway Traffic Safety Administration; PHEV, plug-in hybrid electric vehicle; TTW, tank-to-wheel; TVLC, total vehicle life cycle; UDDS, Urban Dynamometer Driving Schedule; UF, utility factor; VMT, vehicle miles traveled; WTT, well-to-tank.

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http://dx.doi.org/10.1016/j.apenergy.2014.03.023
0306-2619/

Since automotive trends indicate that aluminum and advanced/high strength steels (A/HSS) are steadily increasing within the vehicle fleet composition, the impact of these lightweight materials on life cycle energy and GHG emissions should be assessed [12]. Previous work has determined that the energy and GHG emissions of primary aluminum are significantly higher than steel, primarily due to the energy intensive process of reducing alumina to aluminum [3,5]. However, by recycling aluminum, this process is eliminated and the energy required in production is more similar to steel [5]. Due to its high electricity demand, the GHG emissions intensity of aluminum has a large variability based on production location and allocation methods [5,13]. On the other hand, the production of A/HSS is less dependent on electricity and requires little to no additional energy as compared to conventional steel. This is because steel is strengthened mainly by alloying elements or thermally treating the metal, which are reported by the steel industry to be less than 5% of the overall production impacts [14,15].

Previous work relating to mass reduction potentials of aluminum and A/HSS have focused on possible reductions in the body-in-white (BIW), as the body is generally the heaviest part of the vehicle [16]. For instance, a recent study sponsored by the National Highway Traffic Safety Administration (NHTSA) evaluated the maximum mass reductions possible for the Honda Accord and found that the baseline BIW mass, which is already 48% HSS, could be reduced by 22% with AHSS and 35% with an aluminum-intensive design [17]. On the other hand, The Aluminum Association found that the BIW mass of the Toyota Venza could be reduced by 42% from the baseline BIW, comprised of HSS and AHSS [18]. Also, WorldAutoSteel used topology optimization in their FutureSteelVehicle design and found that the mass of a baseline HSS and AHSS BIW could be reduced by 35% if higher strength steels were used [19]. While the studies sponsored by the aluminum and steel industries likely reflect their respective business interests, they provide insight regarding the projected capabilities of the materials based on optimistic assumptions [18,19].

The fuel economy improvements that result from vehicle mass reductions have been shown to be a function of the powertrain architecture [20–23]. For instance, a study by An et al. found that the benefit of mass reduction is less for a hybrid electric vehicle (HEV) as compared to an internal combustion vehicle (ICV) [20]. This is due to the fact that HEVs are able to capture kinetic energy through regenerative braking and eliminate engine idling, a significant source of efficiency losses for ICVs [20]. Previous work has also shown that powertrain re-sizing has a significant impact on fuel economy improvements, particularly for ICVs due to the fact that smaller engines enable operation in a higher load regime where efficiency is greatly increased [22,23].

Previous vehicle LCAs have demonstrated the tradeoffs between increased emissions during the material production phase and decreased emissions during vehicle use for aluminum and HSS lightweight vehicles [3–5]. For instance, Kim et al. compared aluminum and HSS in a life cycle model, assuming various levels of vehicle mass reduction using each material (11–23% with aluminum and 6–11% with HSS) [3]. For the range of mass reduction scenarios considered, the GHG emissions payback period is 4–10 years for aluminum and 1–4 years with HSS. However, if secondary aluminum is used in a low GHG grid region, the payback period is reduced to 1–2 years. Results by Das show similar results, as the higher production energy and emissions of primary aluminum outweighs the lower energy consumption during vehicle use [4]. Ultimately, the life cycle benefits of using aluminum as a lightweight vehicle material are highly dependent on the amount of aluminum that is recycled, while the impact of HSS relies primarily on the amount of mass it is able to reduce from the vehicle [3,4].

In addition to evaluating the impact of mass reduction, previous LCAs have compared the impact of conventional vs. electrified vehicles and found that results are highly dependent on assumptions regarding the source of electricity [6–9]. For example, a study by Argonne National Laboratory (ANL) found that the emissions for the PHEV ranged from 90% lower than the baseline ICV in the region with the least dependence on fossil fuels to 10% higher in the region dominated by coal [6]. Also, MacPherson et al. also demonstrated the sensitivity of GHG emissions for plug-in electric vehicles by evaluating the impact of electric grid region. They found that life cycle GHG emissions could change by more than 100 gCO_2/mi-eq for a PHEV and 150 gCO_2/mi-eq for a BEV depending on the GHG intensity of the grid [24].

While previous LCAs provide valuable insight to the life cycle impacts of lightweight materials and electrification, the vehicle models used have assumed either a constant glider for all powertrains or a fixed increase in structural mass per increase in powertrain weight [6–8]. Since previous work has not developed equivalent vehicle models for diverse powertrains, comparisons between the vehicles may have a bias towards one powertrain technology over another. The objective of this work is to assess the potential of aluminum and A/HSS to reduce life cycle energy and GHG emissions from conventional and electrified vehicles with the vehicle design harmonization techniques described in previous work. Accordingly, the life cycle impacts of a baseline ICV, HEV, and PHEV with a 10-mile all-electric range (AER), PHEV-10, are evaluated in a LCA and evaluated against lightweight versions of these vehicles. Baseline vehicles are designed according to previous work (using the aggregated method) and lightweight vehicles are modeled assuming that the baseline BIW can be re-designed using aluminum or A/HSS. Also, it is assumed that secondary mass reductions, or the mass change due to subsystem (including powertrain) resizing, are implemented to the vehicle design in an early stage and can provide further mass reductions. The impact of mass reduction on fuel economy is determined individually for each vehicle, thereby capturing the differences due to powertrain architecture. Lastly, vehicle-cycle energy and GHG emissions are determined and scenario analyses are used to determine the impact of a range of material production and electricity energy and GHG intensities, including a closed-loop recycling scenario. To assess the impact of using the design harmonization method as compared to previous approaches, life cycle results are also obtained using the constant glider and structural mass multiplier methods and evaluated against the current method.

2. Method

The life cycle evaluation of vehicles with diverse powertrains is conducted according to the design harmonization algorithm shown in Fig. 1. The current work evaluates vehicle mass, powertrain component sizes and the material composition of a baseline and lightweight ICV, HEV and PHEV-10 (hereafter referred to simply as "PHEV").

2.1. Baseline vehicle models

Vehicle mass is determined with regression analysis of vehicle teardown data using front track width (FTW) and powertrain mass as predictor variables for vehicle mass. Then, component sizes are determined based on performance criteria, such as acceleration time, gradeability and AER. Lastly, the material composition of the vehicle is found based on vehicle teardown data of a representative ICV and powertrain-specific components for a HEV and PHEV. The vehicles modeled are all compact, 5-passenger vehicles, comparable to the Toyota Corolla, Prius and Plug-in Prius. (Refer to previous work for more detailed descriptions on the method and results for baseline vehicle models.)