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Effect of mass on multimodal fuel consumption in moving people and freight in the U.S.

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ABSTRACT

The United States transportation sector consumes 5 billion barrels of petroleum annually to move people and freight around the country by car, truck, train, ship and aircraft, emitting significant greenhouse gases in the process. Making the transportation system more sustainable by reducing these emissions and increasing the efficiency of this multimodal system can be achieved through several vehicle-centric strategies. We focus here on one of these strategies – reducing vehicle mass – and on collecting and developing a set of physics-based expressions to describe the effect of vehicle mass reduction on fuel consumption across transportation modes in the U.S. These expressions allow analysts to estimate fuel savings resulting from vehicle mass reductions (termed fuel reduction value, FRV), across modes, without resorting to specialized software or extensive modeling efforts, and to evaluate greenhouse gas emission and cost implications of these fuel savings. We describe how FRV differs from fuel intensity (FI) and how to properly use both of these metrics, and we provide a method to adjust FI based on mass changes and FRV. Based on this work, we estimate that a 10% vehicle mass reduction (assuming constant payload mass) results in a 2% improvement in fuel consumption for trains and light, medium, and heavy trucks, 4% for buses, and 7% for aircraft. When a 10% vehicle mass reduction is offset by an increase in an equivalent mass of payload, fuel intensity (fuel used per unit mass of payload) increases from 6% to 23%, with the largest increase being for aircraft.

1. Introduction

The transportation sector of the United States uses 70% of U.S. petroleum consumption (about 5 billion barrels per year), which amounts to 28% of total U.S. annual energy consumption (ORNL, 2018b). This energy enables the movement of both people and freight. However, the combustion of petroleum generates fossil carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions. Reducing GHG emissions has become an imperative that has resulted in major regulatory policies, such as automobile GHG emission standards developed by the Environmental Protection Agency-EPA (USEPA and USDOT, 2012). Emission reductions are needed from all modes of transportation including cars, light duty trucks, medium and heavy duty trucks, railroads, buses, aircraft, and ships. There are several vehicle-centric ways to achieve reduced fuel consumption (FC, in units of gal/100 mi) and resultant carbon emissions from the transportation sector, including more efficient conventional vehicle powertrains, advanced powertrains, and reduced-mass (or lightweighted) vehicles. The latter option is the focus of this paper.

Not including impacts from construction and maintenance of transportation infrastructure, over 85% of life cycle energy

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consumption and greenhouse gas emissions of (internal combustion) cars and light duty trucks arise from use-phase fuel consumption (Sullivan et al., 1998; ANL-Argonne National Laboratory, n.d.-a; Chester and Horvath, 2009). There are a number of factors responsible for vehicle fuel consumption including friction between the system and its environment (e.g., rolling resistance, aerodynamic and hydrodynamic drag), power source and transmission inefficiencies, type of power source, usage patterns, and vehicle mass (M – short tons). Vehicle mass M is the sum of vehicle curb mass (M_c) and payload mass (M_{pyld}), which is payload and/or passengers. Gross vehicle mass, M_{gv}, is the maximum value that M can have for a given vehicle and is specified by the manufacturer. Because the lightweighted (reduced mass) version of a vehicle uses less fuel than its heavier counterpart over the same distance, manufacturers, especially those making cars and light duty trucks, often consider mass reductions as a way to reduce vehicle FC.

As part of ongoing efforts to reduce FC, numerous studies have been conducted on vehicle lightweighting (e.g., Koffler and Rohde-Brandenburger, 2010; Keoleian and Sullivan, 2012; Lewis et al., 2014; Kim and Wallington, 2016; Mayyas et al., 2017). These life cycle assessment studies address mostly cars and LDTs with various powertrains, including internal combustion engine (ICE) vehicles (both spark and compression ignited), hybrid electric vehicles (HEV), battery electric vehicles (BEV), and plug-in electric vehicles (PHEV).

Either mathematical models or empirical FC vs. vehicle mass correlations are required to assess the impact of mass reduction on a vehicle's FC. There are sophisticated computer modeling tools used by vehicle designers for simulating the impact of mass reductions on vehicle performance factors such as FC, gradeability, and 0–60 acceleration time. All vehicle manufacturers have such modeling tools in-house (e.g., CVSP – Corporate Vehicle Simulation Program) and the public has the Autonomie tool (formerly the Powertrain Systems Analysis Toolkit-PSAT) (ANL-Argonne National Laboratory, n.d.-b). However, there are many cost, energy, emissions, policy, and life cycle analysts within the regulatory, academic, NGO, and environmental communities who lack access or the desire to use such tools due to their proprietary nature, cost, or sophistication. They too have an interest in the FC, cost, and emissions tradeoffs associated with a vehicle mass reduction and would benefit from an alternative approach, especially one like we present here that familiarizes them with the simple physics underlying the mass dependence of vehicle FC. Examples of previous studies that have used simplified methods to evaluate the energy and emissions benefits of vehicle lightweighting are provided in the review by (Kim and Wallington, 2013a).

The mass dependence of vehicle FC is an important quantity for estimating the merit of a vehicle lightweighting initiative. For cars and light duty trucks (LDTs), this quantity is termed the fuel reduction value – FRV (Lynne, 1998; Koffler and Rohde-Brandenburger, 2010). FRV is fundamentally dependent on three factors: vehicle energy efficiency, rolling resistance, and duty cycle (speed vs. time profile). The greater part of FRV is determined by duty cycle for a given class of vehicle, with energy efficiency and rolling resistance of different vehicles within a class contributing variation about that FRV (Nam and Giannelli, 2005; Helms and Kräck, 2016). Fortunately, physics-based models have been developed to quantify all the components of vehicle fuel consumption listed above, including that of vehicle mass (Kim and Wallington, 2013b), from which vehicle FC, FRV, and fuel intensity (F_{int} = FC/M_{pyld}, in gal/100 ton-mi) are readily computed. In fact, the computer modeling tools mentioned above are physics-based models and they incorporate many vehicle and duty cycle variables and account for dependences among them. An additional development (Kim and Wallington, 2013b) is the use of vehicle certification data (USEPA, n.d.-a) for estimating FRVs, thus making it possible to compute FRVs for a wide range of cars and LDTs listed in government databases over many years.

The physics-based equations developed for light duty vehicles also apply to all other wheeled vehicles, though core parameters such as rolling resistance, aerodynamic drag, and engine, transmission, and miscellaneous losses for these heavier duty vehicles are unique to each of them. However, a few reports (Delorme et al., 2009; Nylund and Erkkila, 2005) provide enough information to allow determination of FC and FRV values for Class 6 and Class 8 trucks, city buses, and LDTs using a simplified form of the basic equations. Basic models have also been developed for estimating FRVs of trains (Davis, 1926) and aircraft (Spakovszky, n.d.). However, computing FC and FRV for ships is more complicated due to a number of factors. Alternatives to simple models for ships include both numerical (American Bureau of Shipping, 2013) and regression (empirical) (Holtrop and Mennen, 1982) methods.

Our purpose here is to develop and assemble a set of simple physics-based fuel consumption equations, henceforth denoted as the FCE Set, for estimating FC, FRV and F_{int} values of the following transportation modes operating in the U.S.: cars, LDT, medium and heavy duty trucks, trains, buses, and commercial high altitude jet aircraft. Electric passenger trains were excluded due their energy consumption being only 0.2% of the U.S. transportation total. These equations are used to estimate the impact of two weight reduction scenarios on FC and F_{int} for each transportation mode. Each equation contains an FRV that is representative of its transportation mode. The impact of the vehicle duty cycle and other factors on FRV are discussed. Sources of data are identified for determining FRV and other terms in the equations. Where sufficient data permit, we compare FRVs computed from experimental and simulation sources for cars and heavy duty trucks. Due to the absence of an analytical expression for mass dependence of FC for tankers and container ships, values of FC, F_{int}, and FRVs developed here are based on values from the literature. Analytical expressions for FC, F_{int}, and FRV are available for high altitude commercial jet aircraft and are used to calculate values presented here. Finally, computed FC and F_{int} values are compared to values from the literature. Our FCE Set provides analysts an alternative approach for estimating fuel consumption impacts of mass reduction across modes in transportation vehicles while also providing a physics-based understanding of this relationship without the need for sophisticated or costly computer models.

2. Methods

The metric of key interest here is FRV (in gal/100 ton-mi), which is formally defined as

$$\text{FRV} = \Delta\text{FC}/\Delta\text{M} \tag{1}$$