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Lightweighting shipping containers: Life cycle impacts on multimodal freight transportation

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ABSTRACT

Freight transportation by truck, train, and ship accounts for 5% of the United States' annual energy consumption (U.S. Energy Information Administration, 2017a). Much of this freight is transported in shipping containers. Lightweighting containers is an unexplored strategy to decrease energy and GHG emissions. We evaluate life cycle fuel savings and environmental performance of lightweighting scenarios applied to a forty-foot (12.2 meters) container transported by ship, train, and truck. Use phase burdens for both conventional and lightweighted containers (steel reduction, substitution with aluminum, or substitution with high tensile steel) were compared to life cycle burdens. The study scope ranged from the transportation of one container 100 km to the lifetime movement of the global container fleet on ships. Case studies demonstrated the impact of lightweighting on typical multimodal freight deliveries to the United States. GREET 1 and 2 (Argonne National Laboratory, 2016a,b) were used to estimate the total fuel cycle burdens associated with use phase fuel consumption. Fuel consumption was determined using modal Fuel Reduction Values (FRV), which relate mass reduction to fuel reduction. A lifetime reduction of 21% in the fuel required to transport a container, and 1.4% in the total fuel required to move the vehicles, cargo, and containers can be achieved. It was determined that a 10% reduction in mass of the system will result in a fuel reduction ranging from 2% to 8.4%, depending on the mode. Globally, container lightweighting can reduce energy demand by 3.6 EJ and GHG emissions by 300 million tonnes CO_2e over a 15-year lifetime.

1. Introduction

The transportation sector accounted for 29% of the United States' energy consumption in 2016 (U.S. Energy Information Administration, 2017a), with truck, train, and ship freight movement accounting for over 20% of this consumption (28 quads). Freight transportation relies primarily on fossil fuels, resulting in release of greenhouse gases (GHG), which are known for their negative environmental effects (Davis et al., 2016; Ramanathan and Feng, 2009; U.S. EPA, 2017). Lightweighting offers an opportunity to reduce fuel, energy, and emissions during transportation, as the lighter the vessel, the less fuel required to move it. 90% of non-bulk cargo worldwide is transported by containers, with the total world container fleet estimated at 35 million TEU (Twenty-foot

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Nomenclature

A	rolling resistance (journal bearing, rolling, and track resistances)
a	acceleration
B	higher order rolling resistance and mechanical rotational losses (flange friction, flange impact, rail rolling friction)
C	aerodynamic losses (head wind pressure, rear drag, skin resistance, and yaw angle of wind tunnels)
$D_{all\ vessels}$	total distance traveled by all vessels on route
D_{haul}	average trip distance per haul
Dst	duty cycle distance
D_{total}	distance one ship travels on route
FC	overall fuel consumption
FC_{acc}	fuel consumption driven by accessory loading
FC_{aero}	fuel consumption driven by aerodynamic resistance
FC_{conv}	fuel consumption of a conventional vehicle
FC_f	fuel consumption driven by mechanical losses due to engine friction and pumping
FC_{full}	fuel consumption for a fully loaded container
FC_l	fuel consumption driven by miscellaneous powertrain losses
FC_{LW}	fuel consumption of a lightweighted vehicle
FC_M	fuel consumption driven by the transportation of mass
FC_{7MT}	fuel consumption for a container loaded to 7 metric tonnes on a truck or train
FRV	Fuel Reduction Value
H_f	fuel lower heating value
M	mass
M_{full}	mass of a fully loaded container
M_{7MT}	mass of a container loaded to 7 metric tonnes on a truck or train
N_{hauls}	number of hauls
η_i	engine efficiency
η_t	transmissions efficiency
$N_{vessels}$	number of vessels on shipping route
R	train running resistance
$S_{cruising}$	cruising speed of a ship
t	time
T_{haul}	total time needed in hours to complete a haul
v	speed of vehicle
γ	all non-mass related terms

Equivalent Units) (Castonguay, 2009; Theofanis and Boile, 2009). The potential savings that can be achieved through lightweighting are significant, since a large amount of fuel is required to transport containers over their lifetimes.

The goal of this study was to model the life cycle reduction in energy and GHG emissions that are possible by lightweighting shipping containers. Fuel savings implications were examined for both the U.S. and global container fleets, as well as two typical multimodal trips.

U.S. government agencies regularly collect data on energy and emissions from the freight transportation sector including GHG inventories by economic sector, transportation-specific information such as modal energy intensity, and annual freight transportation energy demand and emissions, broken down by mode and fuel types (Davis et al., 2016; U.S. DOT, 2017; U.S. EPA, 2015). Many studies that model energy demand base estimates of freight transportation energy consumption on national tonne-km data, or use these as an input to predictive models (Pietzcker et al., 2014; Ramanathan, 2000; Schipper et al., 1997; Zhang et al., 2009). Cargo volume can also be used to model energy demand, generally in the form of TEU or TEU-mile (Winebrake et al., 2008). These cargo-related metrics will not demonstrate the impact of container mass on fuel consumption, so instead of basing calculations on national energy demand, the impacts of lightweighting need to be calculated for an individual container, and then scaled up to estimate the nationwide effect of lightweighting.

Energy intensity is a metric used to allocate on a unit mass basis the energy consumed to transport a payload. An example set of units is liters of fuel/100 tonne-km. When transporting people, liters/passenger-km is used. Analysis of energy intensity trends can be used to estimate future consumption. Energy intensity studies are in agreement that trucks are the most energy intensive mode. Modal distribution and vehicle and cargo mass influence intensity, as increased truck mode share increases intensity, and increased cargo mass decreases intensity (Kamakaté and Schipper, 2009; McKinnon, 1999). Chester and Horvath demonstrated the influence of total mass on energy and emission intensity for a high-speed passenger train, noting that higher occupancy results in lower energy intensity (Chester and Horvath, 2010). Recent energy intensity research has focused primarily on the truck mode, so work on other modes is necessary to ensure a more comprehensive understanding of modal energy intensities.

Lightweighting is an approach with potential to reduce freight transportation energy and emissions. Multiple studies have identified lightweighting strategies for freight transportation, with an emphasis on the truck mode, most likely due to its relatively higher energy intensity. These studies indicate that fuel savings can range from 6% to 20% based on the lightweighting strategy employed and the mode considered (Ang-Olson and Schroeer, 2002; Galos et al., 2015; Hubbard and Beck, 2016; Odhams et al., 2010; Prucz et al., 2013; U.S. EPA, 2016). Some studies model fuel consumption based on anticipated drive cycles (Galos et al., 2015; Odhams et al., 2010). This is a better approach for estimating fuel savings from mass reduction than simply using a rule-of-thumb estimation, because it also accounts for other, non-mass related components such as aerodynamic drag and friction. Fuel consumption models can be used to estimate a modal Fuel Reduction Value (FRV). This quantity estimates the reduction in fuel use resulting from a vehicle mass reduction and has been extensively studied for cars and light duty trucks (Kim et al., 2015; Kim and Wallington, 2013). The use of fuel consumption models to derive an FRV is an innovative development in the estimation of fuel savings, as in the past, fuel demand for the freight sector was based on aggregate tonne-kilometer data. FRVs also enable a bottom-up calculation approach, in which we estimate the potential fuel, energy, and emissions savings that are achievable through the lightweighting of a single shipping container, and then scale up the savings to represent the savings possible if we lightweight all containers in the United States or globally.