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The impact of scale on energy intensity in freight transportation

Michael Gucwa *, Andreas Schäfer

Precourt Energy Efficiency Center, Stanford University, Yang and Yamazaki Environment and Energy Building, Room 326, 473 Via Ortega, Stanford, CA 94305-4205, United States

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ABSTRACT

This paper analyzes energy intensities of ships, diesel–fuelled railways, trucks, and aircraft, using publicly available data. The analysis suggests that differences in operation, not technology, explain most of the variation in energy intensity within and across modes. Among the operational characteristics, most important is the amount of cargo weight transported per vehicle and therefore the scale of the respective transportation system. It is found that each mode has a characteristic envelope in an average energy intensity versus average cargo weight diagram, and estimates of the elasticities of energy intensity with respect to load size are made.

1. Introduction

The rising share of higher value commodities and the associated need for fast and on-time deliveries have continued to gradually shift the relative importance away from waterways and railways toward trucks and aircraft. Mainly because of their higher speed and smaller carrying capacity, the shift toward transportation modes accommodating increasingly high-value goods is accompanied by a strong increase in the average energy intensity of the freight transportation system, all other factors equal.

At the same time, mode-specific energy intensities may continue to change due to adjustments in technology and operations (when referring to operations, we also include the choice of the size of the vehicle, i.e., fleet planning). While economic forces are likely to continue to push technologies toward higher levels of energy efficiency, thus reducing the weighted average freight transportation energy intensity, the impact of changes in operational practices is less clear. For example, a more pronounced use of smaller trucks due to supply chain changes, an economic shift away from heavy-engineering, and increased levels of services would lead to an increase in the average energy intensity of the truck fleet and possibly more than compensate any reductions due to improvements in technology. The combined effect of changes in technology and operations could therefore lead to a rise in average truck energy intensity, thus amplifying the increase in the average energy intensity of the freight transportation system due to the above-discussed increase in the relative importance of trucks and aircraft. To better understand the potential for such changes in mode-specific energy intensity, this paper analyzes the dependence of modal energy intensities on vehicle operating conditions.

Our study is along the lines of the US Congressional Budget Office (1982) report that sought to quantify the fundamental factors affecting energy intensity of major transportation modes. Instead of using commodity as a categorical explanatory variable for energy intensity, however, we use a proxy, the weight of freight loaded per ship, locomotive, truck, or aircraft. The continuous variable, cargo mass, offers the advantage of being directly comparable for all transport modes.

* Corresponding author. Tel.: +1 6507144459.
E-mail address: mgucwa@stanford.edu (M. Gucwa).

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2. Basic physics

We define energy intensity as energy use per revenue tonne-km (E/RTK)[1] which can be expressed as the product of energy use per vehicle-km travelled (E/VKT) and the inverse, distance-weighted, average carried load per vehicle (RTK/VKT) – a factor we refer to as scale variable. The latter, in turn, is the product of vehicle capacity ($RTK_{available}$/VKT) and freight load factor (RTK/$RTK_{available}$). Eq. (1) describes this identity. The expressions of energy use per VKT for each of the modes are given in Eq. (2) and can be derived from two fundamental principles of physics, i.e., the equation of motion and the conservation of energy.

$$\frac{E}{RTK} = \frac{E}{VKT} \cdot \frac{VKT}{RTK} = \frac{E}{VKT} \cdot \frac{VKT}{RTK_{available}} \cdot \frac{RTK_{available}}{RTK} \tag{1}$$

with

$$\begin{aligned}
\frac{E}{VKT} &= \frac{1}{VKT} \cdot \int_0^{VKT} \frac{1}{\eta}\left[\frac{\rho_w}{2}V^2 c_T A_s + m\dot{V} + \frac{\rho_A}{2}V^2 c_D A\right]dx \quad &\text{(Ships)}\\
&= \frac{1}{VKT} \cdot \int_0^{VKT} \frac{1}{\eta}\left[mgC_R + m\dot{V} + \frac{\rho_A}{2}V^2 c_D A\right]dx \quad &\text{(Railways)}\\
&= \frac{1}{VKT} \cdot \int_0^{VKT} \frac{1}{\eta}\left[mgC_R + m\dot{V} + \frac{\rho_A}{2}V^2 c_D A\right]dx \quad &\text{(Trucks)}\\
&= \frac{1}{\eta}\left[\frac{g}{L/D}\,\frac{m_F}{\ln\frac{m_0}{m_0 - m_F}}\right] \quad &\text{(Aircraft)}
\end{aligned}$$

In Eq. (2), η corresponds to the propulsion or drivetrain efficiency (for aircraft the overall efficiency, i.e., the product of thermal, propulsive, and combustion efficiency), g to the acceleration due to gravity, V to the vehicle speed, $\dot{V}$ to vehicle acceleration, m to the vehicle mass (including payload), c_T to the resistance coefficient (the sum of the coefficients of viscous resistance, wave-making resistance, and a correlation allowance between these two resistances), c_R to the rolling resistance coefficient (with different values for railways and trucks), A_s to the wetted surface area of the submerged hull, ρ_w to the density of water, ρ_A to the density of air, c_D to the aerodynamic drag coefficient of the respective vehicle, A to the cross-sectional area of the vehicle, L/D to the lift-to-drag ratio of the aircraft, m_F to the mass of aircraft fuel, and m_0 to the mass of the aircraft at take-off.

Basic physics implies that energy intensity declines with increasing scale, i.e., increasing vehicle capacity ($RTK_{available}$/VKT) and increasing freight load factor (RTK/$RTK_{available}$). The inverse relationship between energy intensity and vehicle capacity can be attributed to the square-cube law. This principle implies that as an object grows, its volume increases at a faster rate than its surface area, i.e., with the cube of the multiplier as compared to the square. As shown in Eq. (2), the resistance terms of the three surface transportation modes scale linearly with the exposed surface area, such as the wetted surface for viscous resistance in ships or the cross sectional area in the case of air resistance. If the projected shape of the vehicle is roughly rectangular, its capacity will grow at the cube of a length dimension while the exposed surface area will only grow at the square, i.e., the square-cube law. Therefore the air resistance or water viscous resistance per unit of cargo mass will decrease. An additional reduction in energy intensity for a given load factor results from the rising share of cargo to vehicle weight with growing vehicle size. For example, light trucks can carry a cargo mass between 8% and 33% of their empty weight, a range that increases to between 125% and 200% for tractor-trailer combinations (National Academy of Sciences, 2010).

While an increase in a surface vehicle's carrying capacity causes energy intensity for a given load factor to decline, aircraft energy intensity seems to be invariant to alterations in size. Poll (2011) using data from existing commercial passenger aircraft, argues that no obvious dependency exists between aircraft scale and the mass of its structure and other equipment, except fuel required, to support a single passenger. This is because the carrying capacity of an aircraft is determined by the lift force, which is proportional to the wing area, i.e., the square of a linear dimension.

In addition to vehicle capacity, energy intensity declines with rising freight load factor (RTK/$RTK_{available}$). Freight ships, freight railways, and heavy trucks operate at a roughly constant speed ($\dot{V} \cong 0$) for a large fraction of their voyage. Under such conditions, a larger payload mass influences energy use mainly through the larger wetted area (A_s) of loaded ships and the higher rolling resistance of loaded railways and trucks. Although the higher payload mass increases E/VKT, it reduces the inverse scale variable VKT/RTK more strongly, thus resulting in an overall decline of E/RTK. A similar effect can be shown to exist for aircraft.

3. Data

The critical variables are VKT (ship-km, locomotive-km, truck-km, or aircraft-km), RTK, and mode-specific energy use. Obtaining an internally consistent set of these data is often challenging.

[1] Revenue is included to restrict the term to those tonne kilometers generated that earn revenue for the operator. It precludes capital movements that are necessary for the operator but do not move paid cargo, i.e. back-hauls, ballast, or empty containers. The energy variable (E), however, includes these non-revenue generating activities.

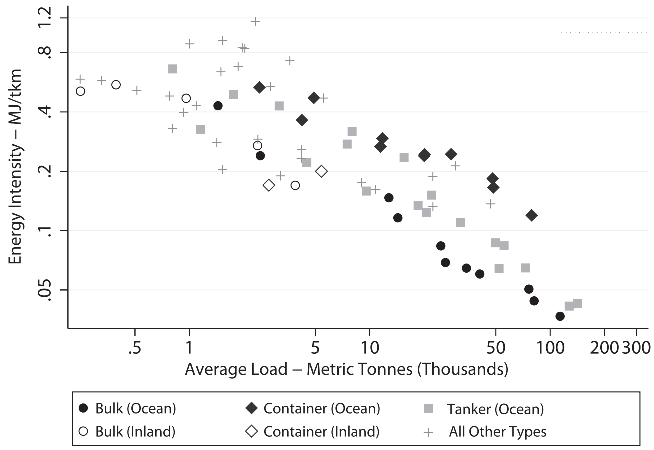

Fig. 1. Energy intensity versus average load for shipping and waterways.

3.1. Shipping

We consider both marine and inland water systems. Due to the large size of vessels, and the long distances involved, ocean shipping accounts for the vast majority of waterborne RTK. We use the energy intensity estimates from the International Maritime Organization (Buhaug et al., 2009), supplemented by those from the France's Ministère De L'Écologie, Du Développement Durable, Des Transports Et Du Logement (2009).

For inland waterway transportation we use data from the Netherlands (Schilperoord, 2004) and France (TL and Associés, 2006). The Schilperoord report combines engine and propulsion efficiencies, resistance coefficients from detailed ship data, and utilization information to estimate energy intensity. TL & Associés survey vessel operators to obtain ship characteristics, utilization information, and fuel consumption.

Depending on a ship's capacity, average load factor, and speed, ship energy intensity in our data set varies between 0.04 and 0.55 MJ/tkm. While the capacity across the vessels ranges over three orders of magnitude (bulk inland waterway carrier versus ocean tanker), it is still one to two orders within one ship type. In contrast, the variability of the average load factor is significantly smaller. Ocean vessels operate at average load factors of 50 to 70%, whereas inland waterway ships have large average loads of around 70%, with the exception of inland container vessels that operate at almost full capacity. Most of the variation in the scale variable (RTK/VKT), therefore, is due to differences in vessel size rather than load factors.

Fig. 1 illustrates the decline of energy intensity with increasing ship size, for two classes of inland waterways (empty symbols) and three classes of ocean vessels (full symbols). The figure's log–log scale transforms the otherwise hyperbolic relationship to straight-line trajectories. Although the inverse energy intensity – scale relationship applies to all types of vessels, there is significant variability at a given load. This spread can be attributed to both basic physics and operational practices, captured by the right-hand-side terms in Eq. (2). For example, for a given amount of payload and thus cargo ship size, inland waterways require lower energy inputs per tonne-km than ocean vessels, due to the lower hull resistance and speed of operation. Similar differences exist for ocean ships. Container ships experience the highest energy intensity at a given average load carried. This can be attributed at least in part to these vessels' high speed, which is around 40–70% higher compared to bulk ships.

3.2. Railways

Although railway operations and energy use are generally well documented, the easily accessible figures include RTK, tonnes transported, and aggregate (passenger and freight) railway energy use. Unfortunately, data describing freight locomotive-km and freight train energy use are only available for a few countries. Ideally, these figures should be complemented with additional operational indicators such as average train speeds (an important variable in Eq. (1)), which can help explain differences in energy intensities across countries. We collected a limited number of internally consistent data sets of the above described key freight train-related variables-RTK, locomotive-km (the VKT equivalent), energy use, and average train speeds. This includes data for Canada (Statistics Canada, 1995–2009), India (Government of India, 2005–2006, 2009–2010), and the US (Association of American Railroads, 1988–2011). We also include three data points for Uruguay by combining energy intensity data from the Latin American Railway Association (Asociación Latinoamericana de Ferrocarriles, 2012) with RTK per locomotive-km data from the Statistical Yearbook (Instituto Nacional de Estadística, 2011). The energy intensity data was verified with independent estimates by (Rossi et al., 2007; Sbroiavacca et al., 2008). Unfortunately, no average train speeds were available. Energy intensity data published by the Asociación Latinoamericana de Ferrocarriles was also complemented with estimates of RTK per locomotive-km for Cuba (Oficina Nacional de Estadísticas, 2010) and Venezuela (Ferrominera

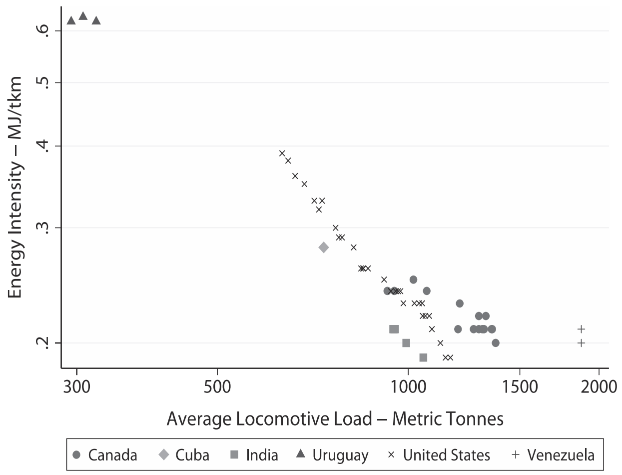

Fig. 2. Energy intensity versus average load carried per diesel locomotive for six countries.

Orinoco, 2012). Statistics from other countries were excluded due to lack of sufficient data or implausible values for energy use.

A final limitation is that our analysis only includes diesel–fuelled trains. This restriction is for practical reasons, given the petroleum dependence of all other modes examined (ships, trucks, and aircraft) with similar upstream energy use. Therefore, a comparison of final energy use alone provides an unbiased picture of the relative performance of these modes, assuming that differences in upstream energy use between gasoline, diesel fuel, jet fuel, and heavy oils are negligible in light of the precision of the data describing modal energy intensities. While diesel trains represent all freight trains in Canada, Cuba, Uruguay, the US, and Venezuela, they accounted for around 36% of all freight train RTK by Indian State Railways in 2009/10.

Depending upon mainly the scale variable (the ratio of RTK and locomotive-km) and the average speed, railway energy intensity ranges between 0.20 and 0.73 MJ/tkm in our data set. As with waterways, the variation of the average load factor is small when using the same definition in comparison to the average amount of cargo transported per locomotive.[2]

Fig. 2 illustrates the linearized decline in railway energy intensity with increasing scale variable for Canada, Cuba, India, Uruguay, the US, and Venezuela over the mean load carried per locomotive, i.e., RTK divided by locomotive-km. Because freight trains can have multiple locomotives, we divide the net RTK by the locomotive-km instead of train-km. The data points of Canada, Cuba, India, Uruguay, the US, and Venezuela evolve within one narrow, downward-sloped envelope. The historical decline in energy intensity was partly because of a shift toward heavier loads per locomotive.

Because of differences in cargo density, different commodities will lead to variation in the scale variable. While trains carrying high-density iron ore experience a high ratio of RTK/locomotive-km and thus a lower energy intensity (the Venezuelan data points in Fig. 2), the scale variable is smaller for lower-density commodities such as manufactured goods, which – in line with the Congressional Budget Office report (US Congressional Budget Office, 1982) – automatically leads to higher energy intensities.

The country trajectories do not show changes in energy intensity because of changes in payload alone, since they are also influenced by changes in technology and operational characteristics, such as train speeds and composition. In fact, these technology and operational variables can explain differences in energy intensity at a given level of the scale variable, such as the lower energy intensity of Indian freight trains compared to those operating in the US and Canada. Indian freight trains operate at speeds below 25 km/h, which is about 25% below that of their US counterparts. Canadian freight trains operate at about 20% higher average speeds than US freight railways, which helps explain their higher energy intensity compared to US railroads. Of course, differences in carloads, locomotive technology, speed profiles, terrain, and other factors may also have contributed to the slightly higher energy intensity of Canadian railroads.

3.3. Trucks

While many statistical data books report truck RTK, significantly less sources also provide figures describing the associated VKT and energy use. Our data set includes a 1958 survey from Canada (Motor Vehicle Manufacturers Association of the United States, 1960) and more recent survey-based figures (1998–2007, 2010) from Australia (Australian Bureau of Statistics, 2000–2010). A hybrid of vehicle use surveys and fuel balances is the basis for a 1940 estimate of trucks operating in rural areas of the US (Barger, 1951). All other country data appear to result from balances of aggregate transportation and energy

[2] The load factors for Canada and India are based on the ratio of empty car kilometers versus loaded car kilometers, whereas that of especially the US railroads is based on the ratio of RTK and available RTK.

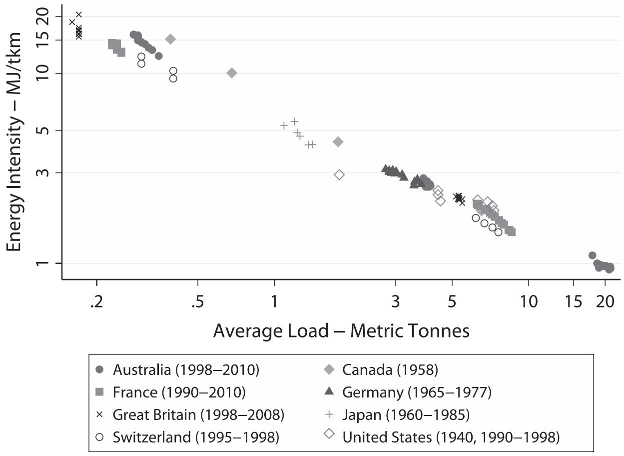

Fig. 3. Energy intensity versus average load carried per truck for eight countries.

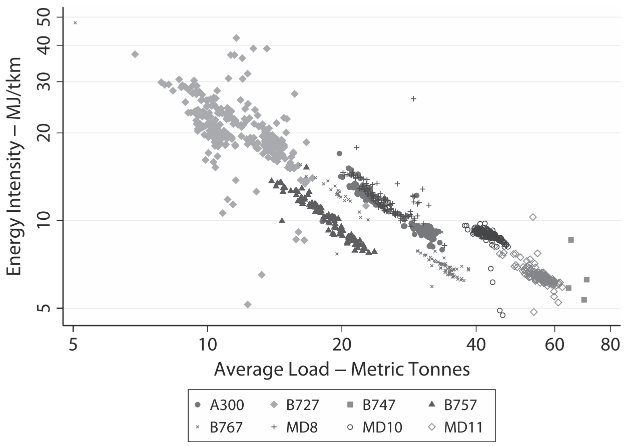

Fig. 4. Aircraft energy intensity versus average load for the aircraft types generating most tonne-kilometers operated by US carriers for 1991 to 2010. *Note*: Only data points with greater than 2000 departures are displayed.

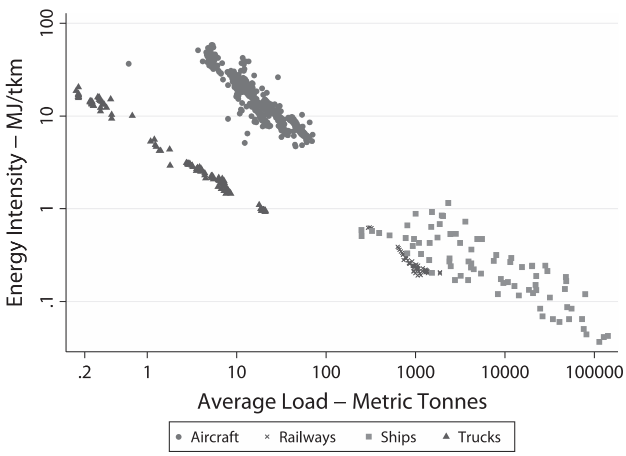

Fig. 5. Energy intensity of freight transportation modes over the average carried load per vehicle.

use data, potentially supported by surveys and model simulations. These include 1990–2010 data for France (Commissariat Général au Dévelopment Durable, 2011), 1965–1977 data for West Germany (Deutsches Institut für Wirtschaftsforschung (DIW), 1987), 1976 and 1998–2008 data for Great-Britain (Department for Transport, 1986, 2010), 1960–1985 data in 5-year time steps for Japan (Ministry of Internal Affairs, 1965–2011), 1995–1998 data for Switzerland (Bundesamt für Statistik, 2002), and 1990–1998 figures for intercity trucks operating in the US (Davis, 1993–2000). Although the available time series data are significantly longer for Germany and Japan, they exclude "own-account" RTK after 1977 in Germany and aggregate "light motor vehicle" energy use to those of trucks after 1985 in Japan.

Depending upon mainly the scale variable (the ratio of RTK and VKT) and the type of engine, truck energy intensity in our data set varies between 1.3 and 16 MJ/tkm. As with the other surface transportation modes, the Australian data suggests that the variation of the average load factor is very small in comparison to vehicle size (unfortunately, no other load factor related data is available, but related studies confirm similar numbers in the order of 60–70% (World Bank, no date)). Therefore, most of the variation in the scale variable can be attributed to differences in vehicle size.

Fig. 3 depicts the linearized reciprocal relationship between truck energy intensity (E/RTK) and the scale variable (RTK/VKT) for all eight countries. Energy intensity is around 15 MJ/tkm for light trucks and vans but declines with rising RTK/VKT to around 1 MJ/tkm for heavy trucks. The latter carry around 100 times the weight of cargo as light trucks.

Because of the strong dependence on trucks size, differences in average truck energy intensity between countries can primarily be attributed to differences in the fleet composition. On the one extreme, the large share of light trucks in the 1985 Japanese truck fleet, manifested by an average payload carried of 1.4 tonnes per vehicle, has resulted in an energy intensity of about 4.2 MJ/tkm. On the other extreme, the comparatively larger Australian trucks, carrying an average of 4.7 tonnes per vehicle in 2010, consumed roughly half as much energy per tonne-km. These two values confine the range of national average fleet characteristics. Such differences in national truck fleet composition likely result from differences in the economy and infrastructure investment.

3.4. Aircraft

Data are taken from US Air Carrier Traffic and Capacity Statistics by Aircraft Type (US Department of Transportation, 2010). It presents quarterly summary statistics provided by US carriers for 1991 to 2011 compiled by aircraft type/configuration, carrier entities (geographic regions in which a carrier operates), and service class. The relevant data fields include aircraft RTK, departures, and the fuel consumed. The data set includes international as well as domestic operations but is limited to carriers based in the US. We consider only dedicated freight aircraft, reducing the data set to 6486 data points over 20 years. Doing so allows for direct attribution of fuel usage towards freight transportation, but misses an important market for airfreight in the belly of passenger aircraft (dedicated air freight accounts for 32% of the tonne kilometers recorded in the data set in 2010). By neglecting the lower energy intensity belly freight transportation, the focus on dedicated airfreight would lead to an overestimate of the system-wide airfreight transportation energy intensity.

Depending on the scale variable (RTK per aircraft km), aircraft stage length, and aircraft type, energy intensity in our data set ranges from approximately 3 to 49 MJ/tkm. Unlike the surface transportation modes discussed earlier, the variation in the scale variable (RTK/VKT) can be explained by both differences in aircraft capacity ($RTK_{available}$/VKT) and the load factor (RTK/$RTK_{available}$) to a similar extent.

The linearized relationship between the scale variable and energy intensity is shown in Fig. 4 for eight aircraft types. Short-haul narrow-body aircraft such as the Boeing 727 experience the highest energy intensity, whereas long-haul, wide-body aircraft such as the Boeing 747 require the least amount of energy per tonne-km. These differences in energy intensity across aircraft types can be attributed largely to technological progress that occurred over time and operating characteristics, i.e., stage length. The energy-intensive take-off and climb stages account for a comparatively large share of the flight profile in a short-distance mission, typically smaller aircraft, whereas they can become negligible over longer stage lengths, generally by larger aircraft.

3.5. Comparison of modes

Fig. 5 combines the modal freight transportation energy intensities, providing scale relationships for ships, railways, trucks, and aircraft on a double logarithmic scale. Overall, energy intensity spreads by a factor of a thousand, while the average amount of cargo transported has a range of six orders of magnitude. As with individual freight transport modes, those transportation systems operating at the smallest scale account for the greatest level of energy intensity, whereas those exploiting scale to the largest extent account for the lowest amount of energy used per tonne-km. All data points seem to broadly evolve within one envelope, which is confined by trucks and railways at the lower limit and aircraft and container ships at the upper.

A more careful comparison of the individual trajectories reveals that the generally lowest energy intensity of ships results from their very large scale, as manifested by their-compared to railways-higher energy intensity at a given payload, e.g., 1000 tonnes. This does not come as a surprise in light of the lowest possible (wheel-on-rail based) rolling resistance of trains compared to a ship's hull resistance (see Eq. (2)). Similarly, the compared-to-trucks higher energy intensity of dedicated freight aircraft mainly results from their roughly 10 times higher speed of operation. Other reasons include a significantly

Table 1
Coefficients for the mode and data set specific controls that only appear in one model.

	Ships	Railways	Trucks	Aircraft
Scale parameter (Γ)	-0.589^{***}	-0.910^{***}	-0.591^{***}	
Load factor (Λ)				-0.690^{a***}
Time (τ)	Not available	Not estimated	-0.001	0.002^{*}
Log(speed) (γ)	1.416^{***}	0.413^{***}	Not available	Not available
Constant (C)	-1.051^{**}	3.398^{***}	2.089^{***}	5.441^{***}
Sample size	64	52	135	6,486
Adjusted R^2	0.953	0.905	0.997	0.812

[a] For aircraft we report only the scale effect resulting for load factor ($RTK/RTK_{available}$).
[*] Significant at 10% levels.
[**] Significant at 5% levels.
[***] Significant at 1% levels.

smaller share of the payload-to-maximum take-off weight of dedicated freight aircraft of less than 30% compared to the payload weight to gross vehicle weight for heavy trucks which is about 67%.

4. Estimation of scale elasticities

As an increase in payload mass causes energy intensity to decline, the slopes of all modal trajectories are negative. Yet, the decline in energy intensity was also caused by other factors than increasing scale, most importantly fuel efficiency improvements. The latter can be expected to have especially contributed to the declining energy intensity trajectory of aircraft, given the strong historical decline of energy use per RTK of new aircraft. To separate the impact of changes in the components of scale from other effects, using $\Gamma = RTK_{available}/VKT$ for vehicle capacity and $\Lambda = RTK/RTK_{available}$ for load factor, we specify the following fixed-effect models for energy intensity in log-linear form

$$\text{Ships} \quad log\left(\frac{E}{RTK}\right)_i = C + \beta \cdot log(\Gamma)_i + \gamma \cdot log(\text{average speed})_i + D^{class} \cdot \text{class}_i + \in_i \tag{3a}$$

$$\text{Railways} \quad log\left(\frac{E}{RTK}\right)_{i,t} = C + \beta \cdot log(\Gamma)_{i,t} + \gamma \cdot log(\text{average speed})_{i,t} + \in_{i,t} \tag{3b}$$

$$\text{Trucks} \quad \log\left(\frac{E}{RTK}\right)_{i,t} = C + \beta \cdot \log(\Gamma)_{i,t} + \tau \cdot t + \delta \cdot (\%\ \text{diesel})_{i,t} + D^{country} \cdot \text{country}_i + \in_{i,t} \tag{3c}$$

$$\text{Aircraft} \quad log\left(\frac{E}{RTK}\right)_{i,t} = C + \alpha \cdot \text{model}_{year} + \tau \cdot t + \phi \cdot log(\Lambda)_{i,t} + \sigma \cdot log(\text{stage})_{i,t} + D^{carrier} \cdot carrier_i + \varepsilon_{i,t} \tag{3d}$$

The truck and aircraft regression equations include a time trend, which captures changes in energy intensity due to factors other than those specified on the right-hand-side of Eq. (2). These terms include fuel efficiency improvements but also operational changes other than changes in payload capacity and vehicle speed. Eq. (3a), for ships, does not include a time trend because of the cross-sectional nature of our data, and nor does Eq. (3b), for freight trains, due to high levels of collinearity with load size per locomotive. In addition, where possible, control variables differentiate between the use of the vehicle, technology characteristics, or specific country conditions. Heteroskedasticity is allowed for by using a robust estimate of variance.[3]

Table 1 reports key results of estimating Eqs. (3a–d). For each mode the coefficient for average load carried (β) is significant and negative in value, implying increasing returns to scale. According to the regression output, rail is most responsive to changes in scale (here mainly represented by an increase in vehicle capacity), having an estimated elasticity of -0.9. This value implies that for every 1% increase in the RTK per locomotive, the energy intensity of rail freight transportation declines by 0.9%. This can be attributed to the very low rolling resistance of steel wheel on steel rail, the dominant driving resistance of freight trains operating in the countries examined here. Shipping and trucking are statistically indistinguishable in terms of their scale elasticity; for every 1% increase in truck or ship RTK, energy intensity declines by an estimated 0.6%. Finally aircraft have an estimated load-factor related scale elasticity of -0.69. If transported over longer stage lengths (within the range observed in our data set), aircraft energy intensity declines further, as indicated by the coefficient for stage length (σ), -0.44.

Both ships and railways allow the inclusion of average operation speed in the regression equation. Unfortunately, only four countries include information about average railway operation speed: Canada, Cuba, India, and the US. The model including speed was estimated only with these four countries, and the coefficient on log speed (γ was estimated at 0.41. For ships the coefficient γ is estimated to be 1.42. That ships have higher elasticity for speed is consistent with the higher

[3] The databases were not assembled by randomly selecting country data points and thus the estimated coefficients could be biased but, given that the data are determined by basic physics, this is unlikely.

water resistance as opposed to rolling resistance. Where the data permit, additional controls were included. In the case of shipping, there are controls for each ship class, although only the coefficients for fuel tankers are significant. The coefficients imply, that all else being equal, crude oil tankers exhibit 1% higher energy intensity, liquefied gas tankers an extra 39%, and products tankers 56% when compared to other classes.

In the case of trucks, diesel engine-propelled vehicles are 28% less energy intensive than all gasoline fleets, all else being equal. A few countries stand out in terms of energy intensity as well. For a given size and fuel type, the energy intensity of Japan's truck fleet is 20% lower than that of the US, possibly, in part, because of higher fuel taxes in Japan (International Energy Agency, 2011).

While the airfreight data from the US Department of Transportation does not allow for inter-country comparison, the data includes a rich set of covariates. The inclusion of a unique aircraft code makes it possible to associate each data point with a specific aircraft variant. While this does not provide us with the actual age of each aircraft, it does allow the data to be associated to an overall model vintage, providing some measure of the technological age of the data point. The coefficient for model introduction year implies that each year of technological improvement and aircraft design leads to a 1.4% reduction in energy intensity. This result is roughly consistent with the industry rule of thumb of a 1% per year fuel efficiency improvement of new aircraft models over the last few decades with less drastic reductions in aircraft energy intensity (Morrell and Dray, 2009). The year the measurement took place, τ, is included to account for other trends not captured by the model year, i.e., performance degradation with age and unobserved operational changes. This implies a 0.2% annual energy intensity increase that corresponds with industry data (Morrell and Dray, 2009). Finally, the data include information on the carrier responsible for a given data point, allowing for carrier effects. The two largest operators of dedicated freight aircraft, FedEx and UPS use 26% and 19% less energy per revenue tonne-km than the aggregate of the rest of the US freight fleet.

5. Conclusions

Modal energy intensities in isolation of other metrics do not convey a meaningful description of the energy use characteristics of a transportation system. Because of the influence of operational characteristics on transport system energy use, understanding freight transportation energy intensities requires taking additional variables into account. Important in this context is the scale of the transportation system in terms of the average amount of cargo mass transported per vehicle; a variable correlated with vehicle size and load factor. Due to the correlation between energy intensity and scale, differences in country level energy intensities are largely determined by the composition of the surface and air vehicle fleets, and not by technology. Other important determinants are mode-specific and include ship and railway speeds, the share of diesel engine trucks, and aircraft-related operational and vintage-related variables.

Because of the influence of scale on the energy intensity of surface transportation modes, a straightforward approach to reduce energy use is to exploit this effect through the design of larger transportation systems, increasing the load factor of existing transportation, and shifting to systems that operate at larger scale. While each of these three options offers opportunities to increase scale, they also present challenges. Designing ever-larger transportation systems, for example, will encounter diminishing returns with respect to energy savings. These are reflected by the nature of the hyperbolic relationship between energy intensity and transport system scale. Because scale parameters differ by mode, any increase in scale needed to reduce energy intensity by a given amount varies. Our analysis finds that an increase in cargo capacity of a transportation system by 10% leads to a roughly 8.3% reduction in rail energy intensity and to a 5.5% reduction in truck and shipping energy intensity.

An increase in load factors would represent the most straightforward way of reducing freight transport energy intensity, as no modifications would be required. However, this strategy can be challenging because of asymmetric trade flows and the need for increasingly specialized vehicles. For aircraft, our estimates show that an increase in load-factor by 10% would reduce energy intensity by 6.4%.

Finally, the enhanced use of transportation systems operating at a larger scale is already limited because higher value commodities require service characteristics that may be difficult to match by waterways and railroads. In addition, in cases where a substitution of e.g. railways and ships for trucks seems possible, it is not clear that significant reductions in energy intensity can be achieved, as energy intensities of these three modes converge for similar types of cargo and thus similar levels of scale variables.

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