A Holistic Analysis of Passenger Travel Energy and Greenhouse Gas Intensities

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Abstract. Transportation is a major energy consumer and emitter of greenhouse gases (GHGs). Exploring the opportunities for energy savings and GHG emissions reductions requires understanding transportation energy or GHG intensity, which is defined as energy use or GHG emissions per unit activity, here passenger-km travelled. This aggregate indicator quantifies the amount of energy required or GHGs emitted to provide a generic transportation service. Here we show that the range of observed energy and GHG-intensities of major transportation modes is remarkably similar and that occupancy explains about 70-90% of the variation around the mean; only the remaining 10-30% are explained by differences in trip distances and other factors, such as technology and operating conditions. Whereas average occupancy levels differ vastly, they translate into roughly similar levels of energy and GHG intensity for nearly all major transportation modes.

Main. Nearly all studies exploring the energy or GHG intensity of transport systems across modes or countries focus on only averages per mode—whether as a basis for modal comparisons at a given point in time [1-5], cross-country comparisons of its longitudinal development for specific transportation modes [6,7], or as a key performance indicator in benchmarking studies [8]. However, because these intensities are determined by the employed technology, operational characteristics, traffic conditions, and other factors, their value, or a comparison thereof, cannot be easily interpreted in the absence of these determinants, unless we understand their influence on energy and GHG intensity. Yet, there does not seem to exist any systematic analysis of the key factors affecting energy and GHG intensities of passenger transport modes. Only one recent freight study explained the energy intensity of major modes by the amount of cargo transported per vehicle, vehicle speed, engine technology, and other factors [9].

To fill this gap, this study identifies the key determinants of energy and GHG intensities for the four major modes of passenger travel, i.e., light-duty vehicles, buses, railroads, and aircraft. Whereas existing approaches simply (and wrongly) concluded that passenger aircraft are the most energy- and GHG-intensive mode, followed by first automobiles and then buses or railways, typically visualized by a simple bar chart [1-5], the more systematic approach pursued here yields a characteristic trajectory of energy and GHG intensity versus vehicle occupancy for each transport mode. These trajectories enable a more robust analysis of the energy and environmental performance of competing transportation modes.

Energy Intensity and the Square-Cube Law

A good starting point is the definition of energy intensity, here the ratio between energy use (E) and passenger-km travelled (PKT), that is, E/PKT. This expression can be easily expanded to energy use per vehicle-km travelled (E/VKT) divided by vehicle occupancy (PKT/VKT), i.e., the distance-weighted number of passengers per vehicle. Vehicle occupancy, in turn, is the product of load factor (the average number of passengers per seat, i.e., PKT per available seat-km [ASK]) and vehicle capacity (the average number of seats per vehicle, i.e., ASK/VKT). The inverse relationship between energy intensity and the load factor is intuitive. The more passengers are accommodated in a vehicle, the larger the denominator of energy intensity. Although the additional weight from the larger number of passengers increases E/VKT too, the rise in PKT/VKT is always larger, thus leading to a net decline in energy intensity. In contrast, the inverse relationship between energy intensity and vehicle capacity is a consequence of the square-cube law. The latter states that an increase in the size of a body causes its volume to rise more strongly than its surface area (that is, cube versus square). Because the aerodynamic drag is partly surface area-related, the drag per unit volume or seat capacity declines with increasing size. Guided by the same principle, larger and more powerful heat engines, required for larger vehicles, are more energy-efficient than their smaller counterparts, as the surface-related losses of friction and heat transfer are smaller in relation to the volume-related power output. Hence, as with the load factor, growing vehicle size translates into lower energy intensity.

Modal Comparison

The inverse relationship between vehicle occupancy and energy or GHG intensity is depicted in Figures 1 and 2 for light-duty vehicles, buses, commuter railways, and fixed-wing aircraft. The double-logarithmic scale linearizes the hyperbolic decline in energy and GHG-intensity with rising vehicle occupancy. Jointly, the modal trajectories stretch over two to nearly three orders of magnitude in occupancy levels, yielding almost similar differences in energy and GHG intensity. Even for individual modes, differences in vehicle occupancy can cause changes in energy and GHG intensity of up to one order of magnitude. On an aggregate fleet level, light-duty vehicles, urban buses, commuter railways, and commercial aircraft experience average energy intensities between 1 and 10 MJ/passenger-km (MJ/pkm), despite operating in different markets (local, regional, and intercity) and at different speeds. At the extreme, commercial aircraft operate at speeds that are about 10 times as high compared to other modes of intercity travel. Yet their two to nearly three orders of magnitude higher occupancy level yields a range of energy intensities similar to those of urban buses, commuter and intercity railways, and light-duty vehicles. (In contrast, owing to their low occupancy, business jets experience the highest levels of energy and GHG intensities). The similarity of the range of commercial aircraft average energy and GHG intensities with those of other passenger modes is in contrast to the freight transportation system, where dedicated freighter aircraft are unable to more strongly exploit the scale (tonnes per vehicle) and thus experience one to three orders of magnitude higher intensities than railroads and water vessels [9]. Intercity buses experience energy intensities below 1 MJ/pkm, mainly as a consequence of their relatively high occupancy and steady speed which results in reduced acceleration losses.

Some of the occupancy levels of light-duty vehicles and buses are below unity, a condition that leads to especially high energy and GHG intensities. These very low vehicle occupancies can be attributed to the high share of non-revenue-generating VKT, which is 60% for taxis [10], 40% for ridesharing [11], 8-33% for single occupancy simulation study-based automated vehicles (AVs) or 2-20% for shared AVs [12-16].

[Figs. 1, 2]

Energy and GHG intensities by mode also differ due to other variables, the impact of which is reflected by differences of typically up to a factor of two at a given occupancy level. Figure 3 depicts the dependency of energy intensity on the average trip distance (ATD). The latter ranges from a few hundred meters for light-duty vehicles to around 7,000 km for aircraft operating in domestic US traffic. Because light-duty vehicles experience higher occupancy levels with growing travel distance (due to the increasing share of vacation-related and thus more social trips) and because longer average trip distances translate into more steady speeds and less acceleration losses (due to the larger share of highway-driving), their energy intensity tends to decline with increasing trip distance. In contrast, the energy intensity – trip distance relationship for public surface modes is comparatively weak. In air transportation, energy intensity declines with longer average trip distance, as the longer cruise stage is less energy intensive than take-off and climb. However, at a distance of around 2,000 km, average energy intensity starts to increase again because of the weight penalty associated with the extra fuel required for longer distances.

[Fig. 3]

Explaining Energy Intensity

The data displayed in Figures 1 and 3 can be used to explain the energy intensity of transport modes. In addition to regressing energy intensity over vehicle occupancy and average travel distance, regional differences can be measured by indicator variables (see Methods). The results of our statistical analysis show that vehicle occupancy alone explains about 70-90% of the variation around the mean energy intensity of all examined transport modes (see SI). Depending on the mode, a significant part of the remaining 10-30% is explained by trip distance. The remaining unexplained variability is then due to different technology and operating conditions not explicitly captured by the variables employed here. The regression analysis also indicates that a 10% increase in average vehicle occupancy leads to a 6-9% reduction in energy intensity, dependent on the mode—the decline in energy intensity due to higher occupancy alone is partially offset by the simultaneous increase in E/VKT. Thus, all trajectories in Figures 1 and 2 decline at a slightly lower than 1:1 ratio, that is, evolving at an angle slightly greater than 135°. (See also extended data figures 1-4). In comparison, the trip distance elasticity is significantly smaller—a 10% increase in trip distance leads to an only 0.1-2% decline in energy intensity, dependent on the mode. Although longer-distance trips lead to slightly lower average energy intensities, the impact on total trip-related energy use is small due to the direct relationship with trip distance.

Our statistical analysis also suggests that regional differences matter for average energy intensity levels. Light-duty vehicles operating in European countries (here France, Germany, Great Britain, Switzerland) experience a 40% lower energy intensity than those operating in Canada on average, everything else equal. This difference can be attributed to the roughly one segment smaller vehicle size of European vehicles compared to their North American counterparts [17]. Similarly, urban and regional buses operating in European cities, Swedish regions, and Taiwanese provinces experience a 19, 32, and 40% lower energy intensity compared to their US counterparts on average, after controlling for occupancy level and average travel distance. These country differences in energy intensity are in part due to differences in traffic flows (which also depend on the existence of dedicated bus lanes), technology characteristics defining driving resistances (such as vehicle weight) and drivetrain efficiency, the use of air conditioning, and other factors. Our results also show that diesel railways operating in North-Eastern and North-Western India are 38% more energy intensive than those in the US, at identical occupancy and travel distance. This could be a result in part due to mountainous terrain, resulting in larger driving resistances. Moreover, business jets and widebody aircraft consume around 100% and 70% more energy per Revenue Passenger Kilometer (RPK) than narrowbody aircraft at the occupancy levels and stage lengths observed in the data set.

Discussion

Figures 1 and 2 suggest that the range in observed energy and GHG intensities of most passenger transportation modes is surprisingly similar, irrespective of the vast differences in operating characteristics. Within the range in energy intensities, the key factor affecting a specific energy intensity level is not technology but rooted on individual travel and industry behavior, that is, vehicle occupancy. Whereas the average occupancy levels of light-duty vehicles, urban and intercity buses, railways, and aircraft differ vastly, they translate into roughly similar levels of energy and GHG intensity for most transport modes. The roughly similar levels of energy intensities for railways, aircraft and more efficient household vehicles in intercity travel implies that the key determinant of trip-related energy use and GHG emissions by mode is travel distance. Because aircraft operate over the longest distances (see Fig. 3), they typically experience by far the highest trip-based energy use and GHG emissions per person.

The trajectories shown in Figures 1-3 are based on multiple data sources. Whereas the energy and GHG intensities of urban and regional buses, railways and aircraft are derived from fuel consumption and passenger records, the Australian and US intercity bus data points represent only estimates. The reliance on estimates is still larger for light-duty vehicles, as only the Canadian and Costa Rican data points represent measurements—all others are based on calculations from national government agencies. In addition, the aggregation level among data sources differs widely, ranging from individual (household) level for US light-duty vehicles to operator-specific data of US bus and railroad companies. Whereas these differences don't affect the general validity of the relationships shown in Figures 1-3, they would influence the typical ranges of energy and GHG intensities around the mean and are thus not pursued further.

Figures 1 and 2 also show that intercity buses are the least energy and GHG-intensive mode, a result that is consistent with other studies, e.g., [1,4]. Yet, identifying a clear “winner” is problematic, as the quality of the transportation service, that is, PKT, differs markedly across modes. For example, light-duty vehicles offer more convenience, better comfort and higher speed than intercity buses but at a three-fold energy and GHG intensity level. At the extreme, aircraft have a five-times higher energy intensity and a ten-times higher GHG intensity than intercity buses, but operate at ten-times the average speed. Moreover, an intercity bus would experience roughly the three-fold energy intensity under urban traffic and occupancy conditions.

Implications

Due to its paramount importance, vehicle occupancy alone could be used to carry out first-order estimates of a transport modes’ energy intensity. This determinant’s significance also implies that future changes in occupancy will affect energy and GHG intensity. Industry behavior aims at maximizing profits and thus occupancy levels of commercial transport modes. For example, the economic viability of aircraft is measured in terms of “minimum load factor requirements” for a given seat capacity [17]. In contrast, the utility maximization behavior of consumers could lead to lower occupancy levels. Already in the past, light-duty vehicle occupancy in the US and other industrialized countries has declined due to rising car ownership and use, which in turn was driven by several factors, ranging from income growth to the increasing participation of women in the labor force [18], thus leading to higher energy intensity levels. The advent of automated light-duty vehicles, either individually owned or through private use within a sharing economy, could lead to another systemic drop in occupancy levels and thus to a further increase in energy intensity. As shown in Figure 1, automated vehicles, if not shared, will experience average occupancy levels well below 1 pkm/vkm, due to empty trips between passenger drop-off and pick-up and searching for a parking spot. This could lead to an even tripling in light-duty vehicle energy intensity, an increase that would be difficult to compensate by fuel-saving technology. In the absence of transport policy interventions that aim at increasing vehicle occupancy, the increase in GHG emissions due to a possible trend towards ever higher energy intensities in light-duty vehicle travel could be reduced most effectively through electrification of passenger transport technologies in combination with a reduction of the GHG intensity of electricity.

Our analysis relates to only internal combustion engine vehicles. Although electrification could lead to different absolute levels of (primary) energy intensity, the basic physics underlying the trajectories are similar and thus the relative energy intensities between electrically propelled modes would broadly remain unchanged.

Methods

Based upon Figure 1, equation 1 relates energy intensity (E/PKT) to vehicle occupancy (PKT/VKT) and the average trip distance (ATD).

$$\frac{E}{PKT} = \beta_0 \cdot \left(\frac{PKT}{VKT}\right)^{\beta_1} \cdot ATD^{\beta_2} \cdot \varepsilon \qquad (1)$$

In addition, energy intensity is affected by operating conditions, technology and size of aircraft and light-duty vehicles (which may differ across countries), here measured by a dummy variable (*I*). Eqn 4 shows the resulting regression equation in log-linear form.

$$ln\left(\frac{E}{PKT}\right) = \beta_0 + \beta_1\, ln\left(\frac{PKT}{VKT}\right) + \beta_2\, ln(ATD) + \sum_{n=3}^{N} \beta_n\, I_n + \varepsilon \qquad (2)$$

Table SI-1 in the SI reports the detailed regression results. In summary, occupancy alone explains about 70-90% of the variation around the mean energy intensity of all examined transport modes. A significant part of the remaining 10-30% is explained by trip distance and other factors, such as technology and operating conditions. The remaining unexplained variability is then due to different technology and operating conditions not explicitly captured with the variables employed here.

Data Availability

All the data were derived from public databases. The datasets used in the analysis have been deposited on a publicly accessible repository and are freely available. (ADD URL)

Competing Interests

The authors declare no competing interests.

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Contributions

A.W.S. led the data collection, data analysis and the preparation of the manuscript. S.Y. contributed to the data collection, data analysis and the preparation of the manuscript.

Figures

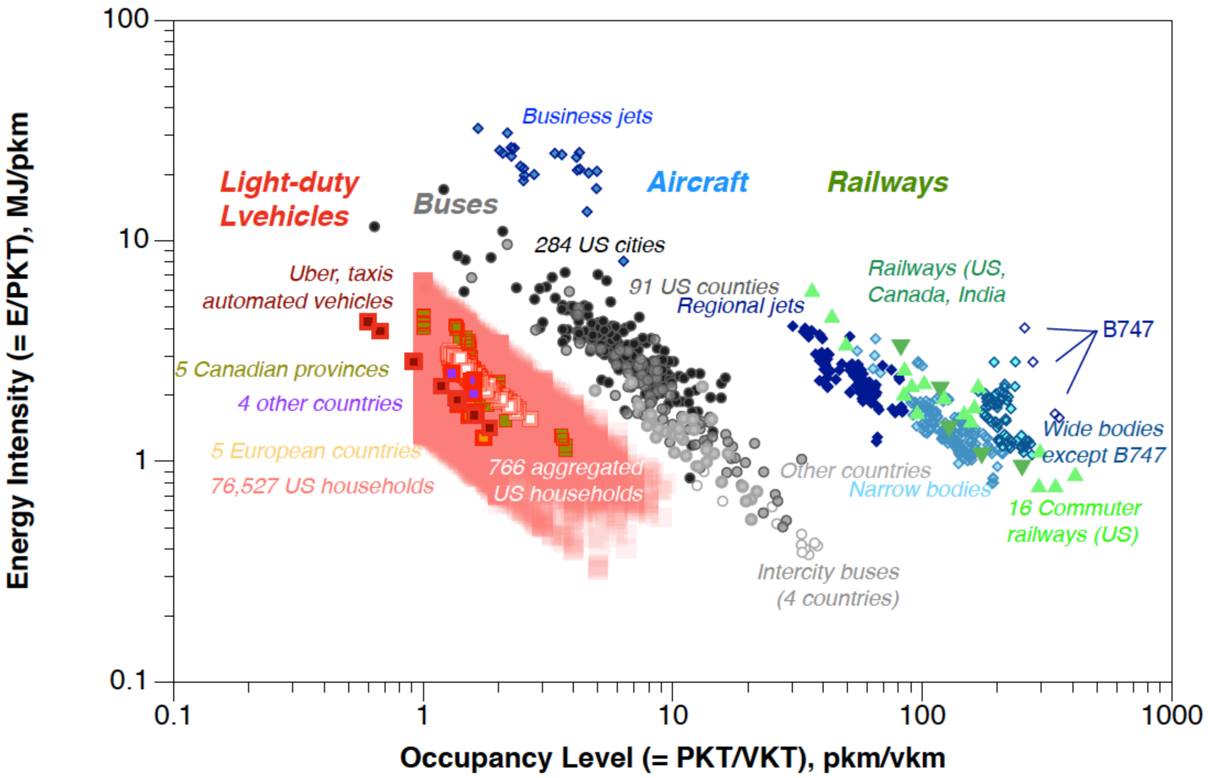

Figure 1 Energy intensity versus vehicle occupancy for light-duty vehicles, buses, railways, and fixed-wing aircraft. See the SI for a description of the data. On an aggregate level, most modes experience energy intensities of 1-10 MJ/pkm. However, the energy intensity of variants operating in special market segments can differ by nearly two orders of magnitude, ranging from 0.4-0.8 MJ/pkm for intercity buses to 20-30 MJ/pkm for business jets. The energy intensities of light-duty vehicles in four other countries (Australia, Canada, Costa-Rica, Japan, South-Korea), and the US evolve along roughly the same trajectory; the smaller-sized vehicles operating in four European countries (France, Germany, Great Britain, Switzerland) are aligned

with a less energy-intensive path. Energy use per PKT of buses operating in US cities and counties are higher compared to those operating elsewhere. The trajectories of aircraft and railways seem to overlap, despite vastly different levels of speed. Only petroleum-fueled transport systems are shown to ensure comparability. The SI shows that diesel locomotive and electric locomotive propelled trains evolve along a similar trajectory.

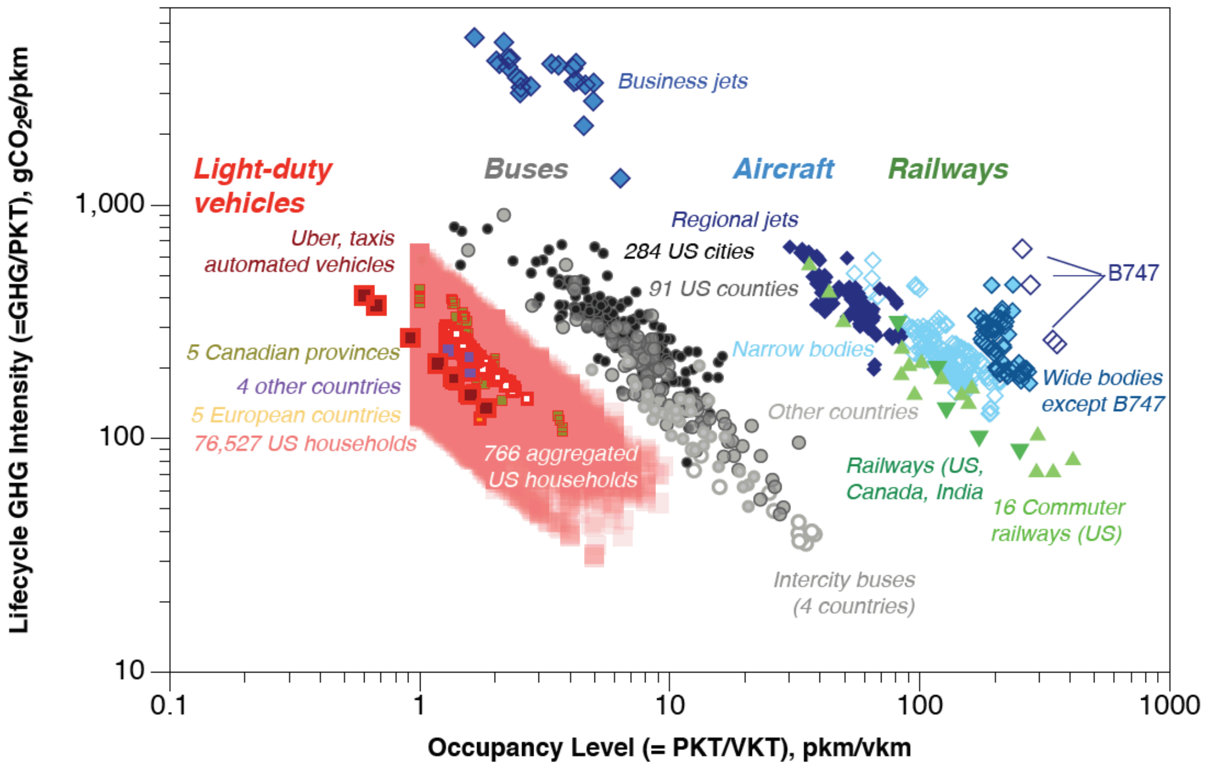

Figure 2 Lifecycle GHG intensity versus vehicle occupancy for light-duty vehicles, buses, railways, and fixed-wing aircraft from Figure 1. The warming impact of aviation is assumed to be twice that of CO_2 alone, if excluding the highly uncertain effect of contrail-induced cirrus clouds [20], thus leading a higher aircraft GHG intensity compared to other modes. The well-to-tank GHG emissions, which include non-CO_2 greenhouse gases, are described in the SI. Only petroleum-fueled transport systems are shown to ensure comparability. The GHG emission factors (well-to-wheel) are based on the GREET1_2017 model [19]. See the SI for a description of the data.

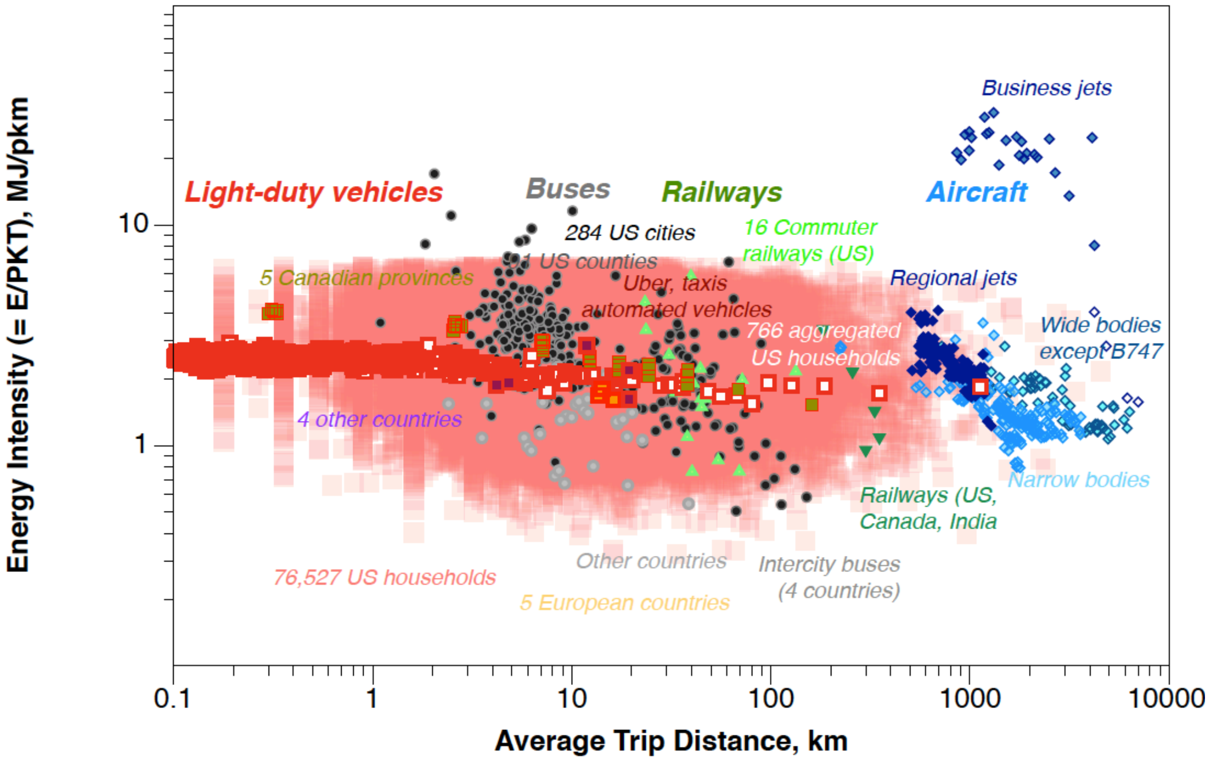

Figure 3 Energy intensity versus average trip distance for the transport modes in Figures 1 and 2. Longer trip distances generally lead to lower energy intensity, all other factors equal. In surface transportation, longer trip distances relate to higher vehicle occupancies, more elevated average speeds, and smoother driving (and thus reduced acceleration losses). In air transportation, longer average trip distances translate into a longer cruise stage, which is less energy intensive than take-off and climb. Hence, average energy intensity declines with rising trip distance before it starts to increase again because of the weight penalty of the extra fuel required for longer distances. No trip distance data was available for intercity buses. See the SI for a description of the data.