We keep on truckin': Trends in freight energy use and carbon emissions in 10 IEA countries

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Abstract

Based on a bottom-up approach relying on national authoritative data, we compare trends in the structure of freight use (heavy truck, light truck, rail, and water), its energy use, and associated CO_2 emissions across ten member countries of International Energy Agency (IEA) from the earliest year of data availability to 2007-2008. The cross-country comparison of the freight transportation sector indicates that CO_2 emissions (on a per capita basis) span a wide range and have developed in a fashion heavily dependent on local needs and without full knowledge or coordination with policies and practices in other countries. Over the last two decades, the effect of freight transport activity (measured in tonne-km) on CO_2 emissions has decreased or virtually remained the same in most of the countries, helped by the ongoing shift in the structure of the economy, while the effects of energy intensity (mainly improvement in trucking energy use) and modal structure (shift towards trucking away from rail and water) have become relatively important. This suggests that major opportunities for freight CO_2 emissions reduction in developed economies will arise from better management of freight energy intensity (mainly for trucking) and transition toward less energy intensive modes.

Introduction

Despite its being overlooked in most energy and greenhouse gas discussions, the freight transport is actually one of the most rapidly growing sectors of the economy, with faster growth than that of passenger travel. Because of its almost complete domination by business-driven activity, freight cannot be considered with the same tools as passenger transportation, whose energy use and emissions are dominated by private automobiles. Recently, however, national authorities have begun to pay separate attention to freight, in particular because of bottlenecks in roads, ports, and even rails (Macarewicz et al., 2010; Eddington, 2006; Canadian report; DOT Freight outlook).

With recent focus on freight, Schipper et al. (1997), Schipper and Marie-Lilliu (1999) and Kamakate & Schipper (2009) provided broad international perspectives on the importance of the freight sector to both transport and total CO_2 emissions. McKinnon (2007) has provided a great deal of information on the nature of trucking in the UK, while Sorrell et al. (2010) have applied a broader orientation to related freight emissions to overall GDP, the role of manufacturing and other goods and materials in the GDP, and the separation of markets, length of haul, tonnes hauled, etc. This approach is important, but is beyond the scope of the present work because of data problems. Still, the conclusion from all of these investigations is that freight energy use and CO_2 emissions have risen faster than those of passenger travel for a variety of reasons, which will be elucidated below.

Table 1 shows the emissions from passenger and freight transport by mode for selected OECD countries in 1973, 1990, and 2008 (or 2007), as well as the change in the share of freight emissions. Except for Japan, the freight emissions and their proportions to total transport emissions have steadily. To fully understand this trend and to devise energy and climate policy that addresses it, it is critical to understand major

Table 1. Passenger and freight carbon emissions and the share of freight emissions for selected OECD countries.

Country	Passenger Emissions [MtC]				Freight Emissions [MtC]			Freight Emissions Share [%]
	Car	Bus	Rail	Air	Truck	Rail	Water	
USA1973	218.5	2.3	1.2	21.6	56.2	11.7	7.0	24%
USA1990	233.3	3.3	1.3	34.1	94.7	8.8	6.6	29%
USA2008	300.0	3.6	1.5	39.0	127.6	11.0	5.5	30%
JPN1973	11.8	1.1	2.2	1.0	13.2	0.6	2.8	51%
JPN1990	25.9	1.3	2.4	2.2	24.2	0.2	2.3	46%
JPN2008	34.4	1.2	2.6	3.4	21.4	0.2	1.8	36%
UK1973	12.8	0.8	2.8	0.2	5.3	0.4	1.0	29%
UK1990	19.0	1.0	3.8	0.3	8.9	0.2	1.2	30%
UK2007	20.5	1.7	4.0	0.4	10.9	0.3	1.4	32%
AUS1973	5.6	0.1	0.4	1.1	2.2	0.3	1.0	32%
AUS1990	9.4	0.3	0.2	1.0	4.2	0.7	0.5	33%
AUS2007	11.3	0.4	0.3	1.7	6.7	0.9	0.4	37%
FRA1990	16.6	0.6	0.2	0.5	10.0	0.2	0.1	36%
FRA2008	18.2	0.6	0.2	0.4	12.9	0.1	0.1	40%

(Source: our bottom-up estimation)

drivers of freight CO_2 emissions for countries with varying economic, geographical, and transport system characteristics.

Methodology

DECOMPOSITION

In this paper, we take the ASIF approach to describe the change in CO_2 emissions (Schipper, et al., 2000). It interprets each country's transport CO_2 emissions as a combined effect of the four factors: 'A' connotes total transport activity (in tonne-km or passenger-km), 'S' gives the modal shares, 'I' gives the energy intensity of each mode (in MJ/tonne-km or MJ/passenger-km) and 'F' gives the CO_2 content of the fuel (in g/MJ). The detailed description of the methodology can be found in Schipper et al. (1997) and Kamakate and Schipper (2009).

In the ASIF formulation, each factor encapsulates a subset of influences beyond the quantity it stands for: The activity effect 'A' reflects the changes in the size and structure of an economy; and the structure effect 'S' reflects the changes in the modal choice of the system's users—based on the price of freight transport service or specialized service needs—and its interaction with transportation system planning. The intensity effect 'I' represents a wide range of more fundamental causes, including the changes in the technology of transport modes, the regulation of their fuel efficiencies, and the efficiency of transportation system operation (congestion, freight loading, and industry practices). The fuel mix effect 'F' reflects the changes in individuals' fuel and technology choices to fulfill their specific modes of freight transport demand—which is influenced by the prices of fuels and technologies—and environmental concerns and regulations. The key advantage of the ASIF approach is that it forces the analyst to understand freight (or travel) from the bottom up of the structure of freight use. For instance, in the ASIF formulation, an overall reduction in energy intensity might lead to lower fuel use and emissions per tonne-km, while shifts towards energy-intensive trucking and air freight could raise emissions, as in the case for almost every country studied. The reward for our data-intensive approach is an in depth view of how each component and each mode has evolved over time in multiplying together to yield freight emissions. The same power applies to international comparisons.

The ASIF approach has been applied to both travel and freight by Schipper and co-workers (Schipper, et al., 1997; Kamakate & Schipper, 2009; Eom & Schipper, 2010) and other analysts. For most countries, there are four freight transport modes—rail, air, domestic water-borne (i.e., sea, lake, and river) and trucking. Trucking can be further split into heavy and medium truck tonne-km and light trucks, for which a measure of tonne-km may not exist, but whose fuel use may be significant compared to heavy trucks. In contrast to Kamakate and Schipper (2009), we separate light truck fuel and vehicle activity from that of heavy and medium trucks, for which tonne-km data are available. More importantly, the present study incorporates five more countries—four European countries (Germany, Sweden, Denmark, and Spain) and one rapidly developing Asian country (South Korea)—and captures more recent trends through 2007 or 2008, reflecting the continued rise in income and fuel prices.

DATA

This study covers 10 IEA countries: the U.S., Japan, France, the U.K., Australia, Germany, South Korea, Sweden, Denmark, and Spain—that is, six European countries, two Asian countries, and two other big countries (the U.S. and Australia). Although these ten countries represent a range of geographical and socio-economic heterogeneities under the constraint of data availability, we believe their trends in the transportation sector have been representative of those of all developed economies in the world: over the last three decades, transportation energy use (passenger and freight combined) in these ten countries has steadily accounted for about 80-83 % of total transportation energy use in OECD countries (IEA 2007).

The data used in this study mostly come from authoritative national energy and transportation statistics for the transportation sector. The data used in this study include annual energy use (PJ) by four freight transport modes—heavy (and medium) truck, light truck, rail, and water—each mode's energy consumption by fuel type, freight activity (tonne-km), distance carried (vehicle-km), and load factors (ton/vehicle), as well as other socioeconomic indicators such as population, GDP, and sector-wise GDP value added. For trucking, we include both own-account and for-hire trucking. Activity and energy consumption of trucks passing through a country where they are not registered are excluded, whereas registered freight carried to a port for export (or from a port for import) is included. All rail freight, including transit, is included, but all freight between countries by sea or air is excluded. We also do not consider pipeline transport due to the limited data availability.

In many cases, one or more types of information were not reported, or only limited time-series information were available. For example, light trucking activity (tonne-km) data is partly available or not available at all (the U.S., Australia, Germany, Denmark, Sweden, and Spain) or not available but derivable from load factor data (South Korea). Where needed, we applied the load factor of 0.7 (tonne/vehicle) to construct light trucking activity from carried distance, which is available for all of the ten countries. Because in all of the countries light trucking activity only covers a small portion of total national freight activity, changes in the assumed load factor only have small effects on total freight activity and its energy intensity and virtually no effect on the decomposition trends. Note also that, in this study, we only analyzed the Germany data after 1991 to properly represent the country's entire freight transportation sector: we used DIW (Deutsches Institut fur Wirtschaftsforschung) report covering from 1994 through 2008, as well as Verkehr in Zahlen database, which provide combined statistics for West and East Germany between 1991 and 1994 and those for united Germany thereafter.

Another major issue was to separate freight related energy use from railway energy use, which is often reported in aggregate. There were countries with detailed rail energy split for entire data years (South Korea, Denmark, and the U.S.), those with detailed energy split for a part of the years (Sweden, Germany, Australia, France, and the U.K.), and those with energy split only into freight and passenger transport (Japan). For the U.S., we used rail diesel and electricity consumption by use estimated by ORNL (ORNL, 2009). For Germany, we obtained detailed energy split by use between 1995 and 2008 from Deutschebahn and applied the energy use shares for diesel and electricity for the years before. For France, specific weight ratios (gross-tonne-km/tonne-km for freight and gross-tonne-km/passenger-km for passenger) reported by UIC (Union Internationale des Chemins de fer) were used to calculate diesel and electricity energy consumption by use; for Spain and Sweden, we employed the same method with the use of interpolation for several missing years (for Sweden, SIKA's detailed energy split was used since 2000). For Australia, Apelbaum Consulting's detailed rail energy analyses were used and, for missing years, the energy shares were interpolated. Due to the absence of data, the U.K.'s rail energy was split based on our reasoned judgment based on reports from RSSB (Rail Safety and Standards Board). For Japan, rail energy consumption by use, reported by the Ministry of Land Transport and Infrastructure, was applied to split both diesel and electricity into freight and passenger uses.

Results and Discussions

FREIGHT ENERGY USE AND CARBON EMISSIONS

Figure 1 illustrates the development of per capita CO_2 emissions from the freight transport sector with respect to per capita GDP in the 10 IEA countries examined in this paper. The countries' per capita CO_2 emissions span a wide range even at the same income level, and the U.S., Australia, and Spain have shown distinctively higher emissions than the other countries. South Korea, Denmark, Sweden, France, Germany have steadily increased their emissions over the last two decades, resulting in Denmark's recent emissions being comparable to Australia's emissions in the 1970s. For the rest of the countries, while not very strong, it has been the trend that per capita freight CO_2 emissions increase with income, except for the U.K. and Australia, whose emissions temporarily decreased in the 1980s and 1990s, respectively, and for Japan with steadily decreasing emissions since the mid 1990s, which was the combined effect of the moderation of freight transport activity and the shift of road freight towards heavier trucking.

To explain this considerable heterogeneity in freight CO_2 emission across the countries, we begin by discussing the trend of freight transport activity for the countries. The level of freight transport service delivered to one country, usually represented by tonne-kilometers, may depend on the country's economic structure, geographic characteristics, geo-economic distribution, and the volume of international trade. We illustrate in Figure 2 the countries' development in per capita ton-kilometers with respect to per capita GDP (PPP basis) from the earliest year of data availability to 2007–2008.

Figure 2 indicates that, even income effect controlled, per capita freight transport activity varies widely across the countries. These countries can be classified into three groups, depending on the recent levels of per capita freight transport activity. The first group of countries, the U.S. and Australia, exhibits particularly higher activity than the other countries, perhaps due to the greater geographical coverage or a higher share of fossil fuel freight (Schewel & Schipper, 2011). Such geographical characteristics would require a longer haul distance to fulfill domestic and global goods transaction, which would make bigger, increasing-returns-to-scale modes, such as rail, water, and air transport, economically viable. Indeed, as Figure 3 indicates, in the U.S. and Australia, rail and water transport have accounted for more than half of total freight transport activity. The second group consists of Spain, Sweden, Germany, France, and Denmark, all of which are not as big as the first group and sharing some portion of the borders with their trading partners; these countries show medium levels of freight transport activity. Sweden has a relatively higher share of rail due to its iron ore freight. For the rest of the countries—the U.K., Japan, and South Korea—per capita trucking transport is in the lowest level, and the share of water transport is relatively high. This is because they have little, if any, border

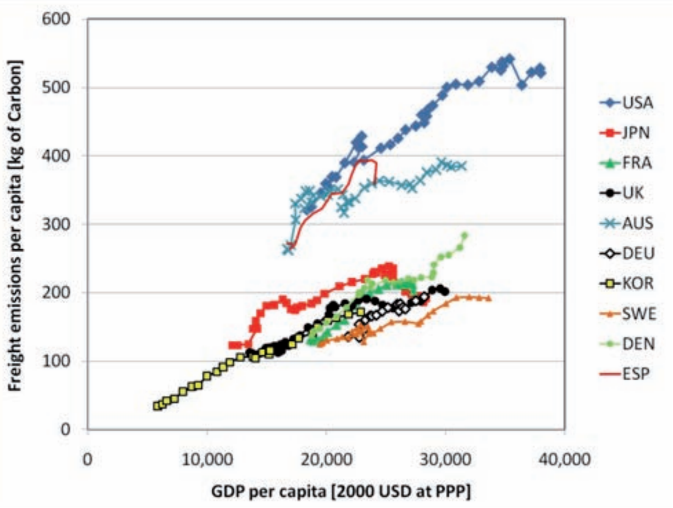

Figure 1. Freight carbon emissions per capita vs. GDP per capita.

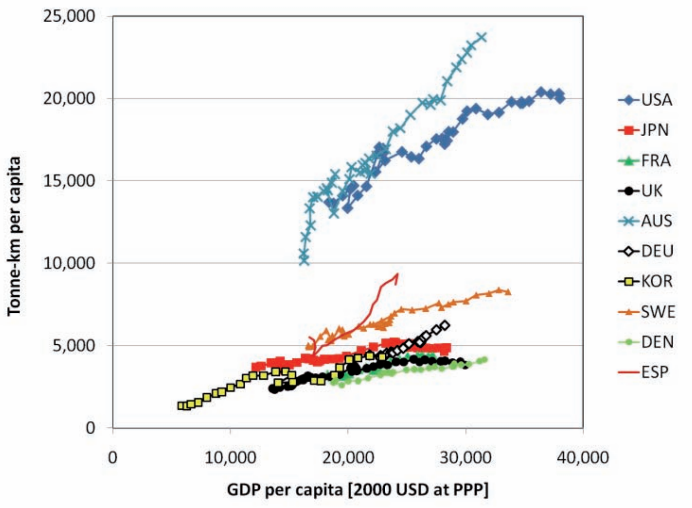

Figure 2. Tonne-km per capita vs. GDP per capita.

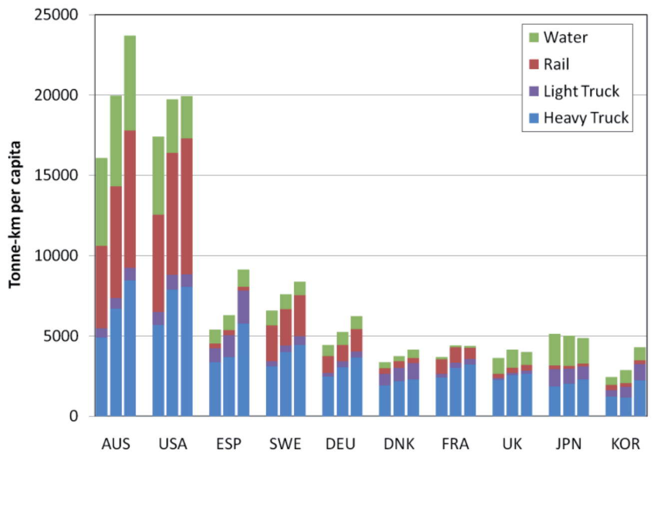

Figure 3. Tonne-km per capita and modal shares in 1990, 2000, and 2007.

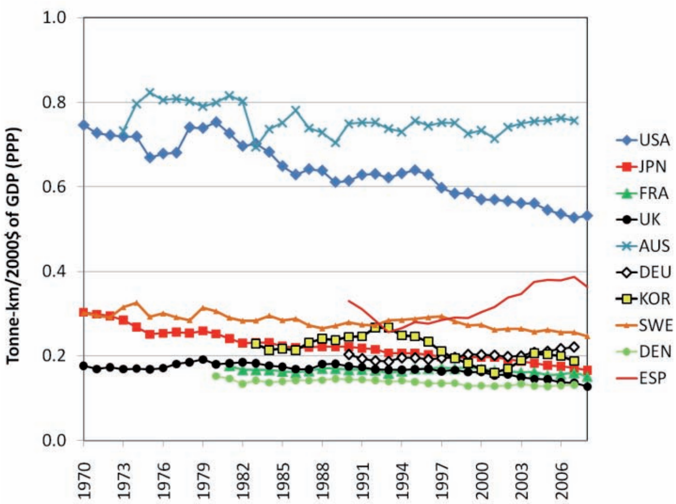

Figure 4. Comparison of the freight activity intensity of GDP.

sharing with other countries, thus relatively small cross-border trucking: In the U.K., the actual trucking tonne-km may be higher than the reported because it excludes the traffic through the Channel Tunnel and the ferries.

The ten countries exhibit significant differences not only in their freight transport activity but also in freight transport activity per dollar of GDP, which we call the freight activity intensity of GDP. The freight activity intensity of GDP is shown in Figure 4—each plot is equivalent to the time-series of the slope of its corresponding country's curve in Figure 2. Similar to the cross-country ordering in the levels of per capita freight transport activity, the freight activity intensity of GDP has been most pronounced in the U.S. and Australia, followed by Spain and Sweden, and then by the other countries. This indicates that countries with currently higher levels of per capita freight transport activity tend to be those with historically higher freight activity intensity of GDP, perhaps due to their distinctive geographical and geo-economic characteristics or a high share of coal, iron ore, and other basic commodities. Canada behaves similarly, but is not shown because of a lack of data on tonne-km of own-account trucking and fuel use for domestic shipping, but the trends are similar to those of the U.S. and Australia (Schipper et al., 1998)

Many of the ten countries have experienced sizeable changes in freight activity intensity of GDP, although such within-country changes are smaller than the variation across the countries (Figure 4). The within-country change in the freight activity intensity of GDP is in a large part attributable to the shift in the structure of an economy: the less the economy requires freight transport for a given unit of production, the less will be the freight activity intensity of GDP. Without a counterbalancing increase in value added per unit of goods delivered or sizeable improvement in freight logistics, shrinkage of the industrial sector would lead to a decline of the freight activity intensity of GDP, which in fact has been the case for many of the countries, particularly in the U.S. and Japan.

Figure 5 presents the changes in the share of industrial value added in GDP for the ten countries: here, the industrial value added includes gross product from manufacturing, mining, construction, electric, water, and gas sectors. It indicates that, in the U.S. and Japan, the period of the rapid decline in the freight activity intensity coincides with the steady decrease in the share

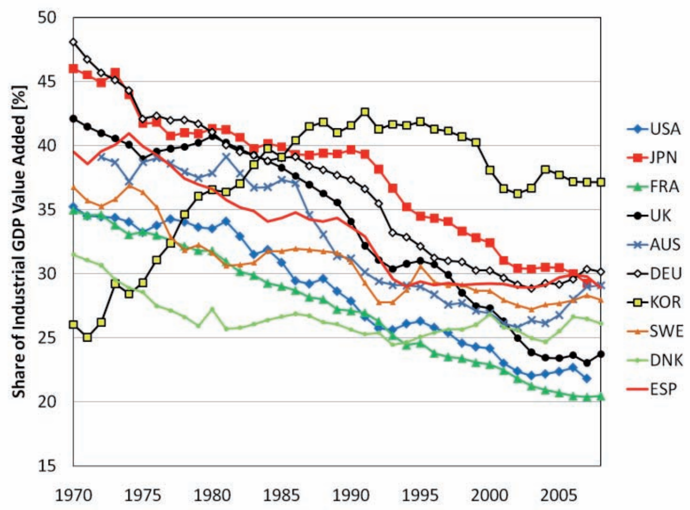

Figure 5. Changes in the share of industrial value added in GDP (Source: World Bank).

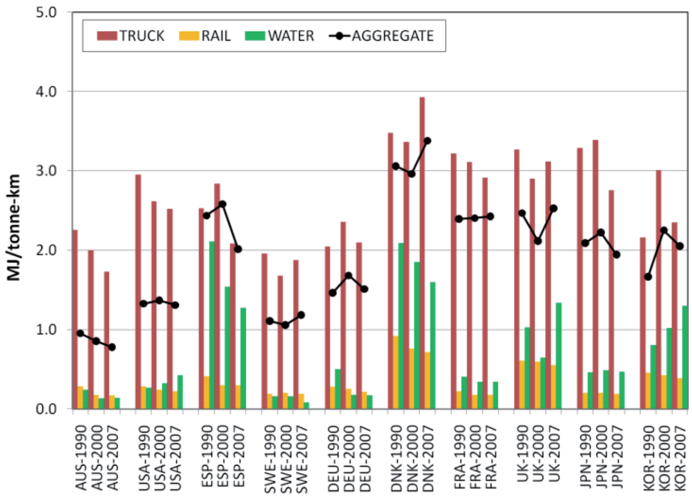

Figure 6. Freight energy intensity by mode.

of industrial value added in GDP, although pipeline transportation is excluded from the freight activity. In contrast, several countries, including Spain and Germany, have experienced increases in freight activity intensity since the mid-1990s, as previously decreasing industrial share of GDP started to remain nearly unchanged thereafter. This was probably due to Spain industry's job generation after the 1990-1994 economic recession and Germany's structural adjustment with the incorporation of East Germany. The case is somewhat mixed for South Korea: the freight activity intensity gradually rose until the mid-1990s, when it started to decline thereafter. This corresponds to the economy's remarkable development based on heavy and chemical industries until mid-1990s, followed by the structural shift that reversed the continued increase in the industrial share of GDP (Figure 5), partly reinforced by the 1997 Asian Financial Crisis. In most of the countries except for South Korea, the similar trend was observed also for the combined share of the industrial and agricultural sectors combined, which are usually freight transport intensive: in South Korea, unlike the trend of the industrial share only, the combined share has steadily declined (not shown). Seen from the fact that South Korea's share of agricultural value added in GDP has also rapidly declined from as much as 30 % in 1970 to 2 % in 2008, it seems that the country's agricultural sector, primarily run by local light trucks, has had far lower freight activity intensity than its industrial sector counterpart.

These findings suggest that, at a national level, as the structure of an economy changes, the linkage of freight transport activity with GDP might be reduced, possibly lowering freight transport activity demanded by the economy and its associated CO_2 emissions. In terms of global freight transport activity, however, this may not be the case. Due to global trade, the effects of a structural shift of one economy will ripple through multiple economies, potentially with larger consequences than the economy's avoided transport activity might suggest. Above all, ongoing transformation of the global economy, driven either by differences in factor prices and technology across countries or by their monetary policies and trade barriers, might lead to a major shift in global freight CO_2 emissions particularly when regional heterogeneities in freight transport requirement and fuel utilization intensity come into play (Davis & Caldeira, 2010).

Just as the trends in freight transport activity are important in determining CO_2 emissions from the freight transport sector, so is the energy required to meet the freight transport demand. Figure 6 presents the modal energy intensity and aggregated energy intensity in the ten countries in 1990, 2000, and 2007. In terms of aggregated energy intensity of freight transport, Australia, Sweden, Germany, and the U.S. have been the lowest among the countries. In all countries, trucking required the highest energy per tonne-kilometer among the freight modes, although its level varied considerably across countries: Schipper et al. (1997) linked this variation to truck size and degree of capacity utilization. While there were many fluctuations in trucking energy intensity, trucking energy intensity has been the lowest in Australia, Sweden, and Germany, and has been the highest in Denmark. Even greater variability across the countries is observed in the energy intensity of rail and water transport. Rail freight transport in Australia, the U.S., Sweden, Germany, France, and Japan has been least energy intensive among the countries; and water freight transport in Australia and Sweden has been least energy intensive. Denmark, Spain, and the U.K. have had noticeably higher levels of rail or water energy intensity, possibly reflecting some inefficiencies in rail and water logistics or freight transport system as a whole in these countries.

Having discussed the international trends in freight transport activity and modal energy intensity, we now investigate the consequences of the multiplicative relationship between the four factors of freight CO_2 emissions—activity, structure, intensity, and fuel mix—over the last two decades or so. Figure 7(a) shows an actual average annual percentage change in CO_2 emissions between 1990 and 2000, as well as hypothetical average annual percentage changes representing consequences if only one of the factors had changed during the same period; and Figure 7(b) presents the same calculation for the period between 2000 and 2007. Note that in the activity effect is further decomposed into the GDP effect and the activity-intensity-of-GDP effect to illustrate their relative significance in affecting the effect of freight transport activity; however, due to the ab-

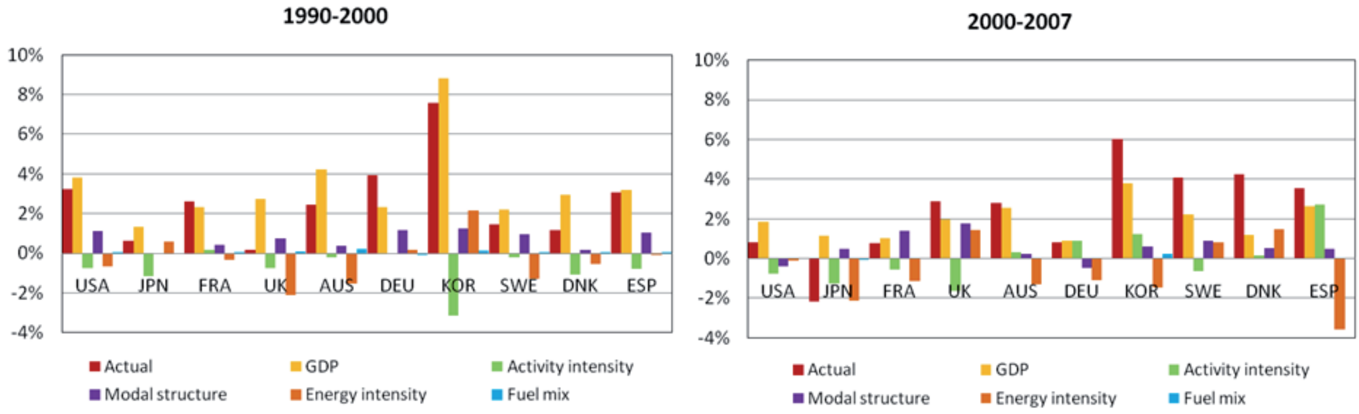

Figure 7a and b. Decomposition of changes in freight CO_2 emissions (1990–2000 and 2000–2007).

sence of detailed commodity flow surveys for the countries, the GDP effect is aggregate, not freight mode specific. Therefore, we now have five factors of freight CO_2 emissions—GDP, activity intensity, modal structure, energy intensity, and fuel mix.

Several important points should be made with regard to the decomposition analysis. First, total CO_2 emissions have all increased in each period, except for Japan after 2000, and the rate of increase varied considerably across the countries, mainly due to their differences in the effects of the first four factors—the rates of change in GDP, activity intensity of GDP, modal structure, and energy intensity. The effect of fuel mix on CO_2 emissions changes was minimal. This is because diesel is the dominant fuel for freight transport with the share of rail electricity being small for most countries. This finding suggests that if a large-scale, lower CO_2 substitute for diesel were available the fuel mix effect could have a significant impact on future emissions.

Second, while in most of the countries, the increasing GDP effect has tended to moderate over time, the effect was not great enough to offset the intensification of freight activity (tonne-km/$ of GDP) in South Korea, Spain, and Germany, so that these countries had higher activity effect (tonne-km) between 2000 and 2007 than before, mainly driving up their freight CO_2 emissions between 2000 and 2007. This is consistent with the findings from Figure 4.

Third, falling energy intensity between 1990 and 2000 put downward pressure on CO_2 emissions in the U.K., Australia, and Sweden, and between 2000 and 2007, it did so in a greater number of countries including Japan, France, Australia, Germany, South Korea, and Spain. In the U.K., Sweden, and Denmark, however, increases in CO_2 emissions have become even faster between 2000 and 2007 as their aggregate energy intensities did start to increase. The energy intensification was driven mainly by the increases in the energy intensity of heavy trucks in those countries.

The last important point is that, in many of the countries, the changes in modal structure have put upward pressure on CO_2 emissions over the last two decades or so, and it indeed has been the major driver of increases in emissions in France and the U.K. between 2000 and 2007: in these countries, overall trucking has rapidly supplanted other freight transport modes. The two small exceptions are the U.S. and Germany in the 2000s, where favorable changes in modal structure partly offset increases in CO_2 emissions: these countries exhibited moderation in the rate of modal shift toward trucking and even slight gains in the share of rail freight since 2000, resulting in lower emissions than they would otherwise have experienced.

Overall, over the last two decades while the rate of increase in the activity effect (the combination of the GDP effect and the activity intensity effect) has decreased or virtually remained the same in most of the countries except for South Korea and Spain, the effects of energy intensity and modal structure have become relatively important in determining the sector's CO_2 emissions, particularly in Japan, France, the U.K., and Denmark. This implies that if the moderating activity trend continues in the IEA countries, major opportunities for freight CO_2 emissions reduction may arise increasingly from the management of the intensity and structure of the freight transportation sector. Greater regulatory attention to transportation system planning and practices may be required than ever before in the developed world. Note that, in the E.U., the rail system has been operated mostly for passenger service, not freight (Sweden is a possible exception). As a result, the opportunity to carry more freight on E.U. railways may be limited by total capacity and passenger usage, although the separation of infrastructure from rail operations becoming common in the E.U. may promote maximizing the total benefits from the use of rail infrastructure by both passenger and freight. Also, the rise of high speed rail with its separate tracks may liberate capacity for slower freight services.

TRUCKING ENERGY USE

To properly identify the intensity- and structure-related opportunities for CO_2 emissions reductions, it would be essential to take a closer look at the trend of trucking, which has remained accountable for more than 85 % of total freight CO_2 emissions from the ten IEA countries' freight transportation sector over the last two decades. We illustrate in Figure 8 the international trends in tonne-km of trucks (heavy and light trucks combined) per dollar of GDP (PPP basis). The figure indicates that while the trucking intensity of GDP varies widely across the countries, the variation is not as great as in the case of total freight activity intensity (Figure 4). It seems that non-income effects, perhaps arising from the differences in geographical characteristics and geo-economic distribution, have had greater significance in non-trucking activities—rail, water, and air freight transport—than in trucking.

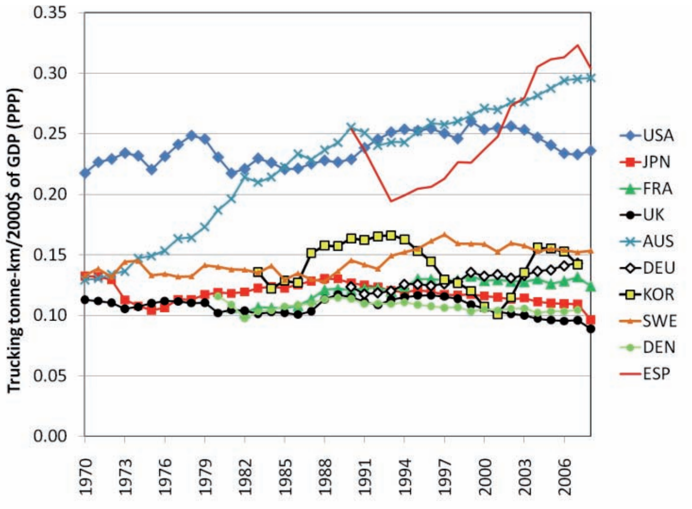

Figure 8. Trucking intensity of GDP.

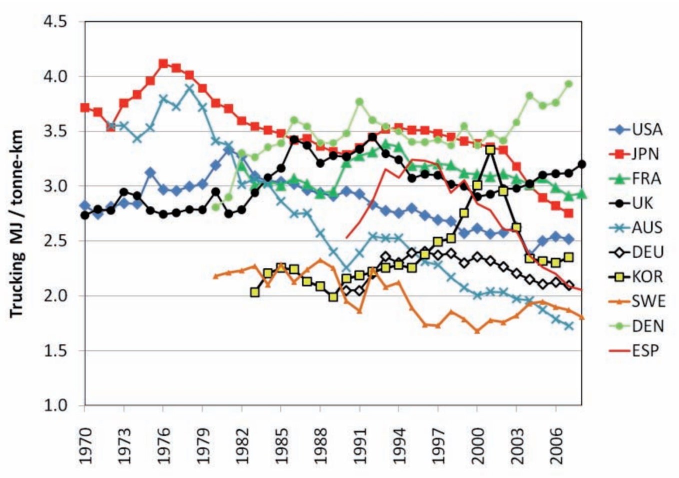

Figure 9. Energy intensity of trucking (heavy and light trucks aggregated).

A comparison of the trucking intensity of GDP (Figure 8) and the total freight activity intensity of GDP (Figure 4) also reveals that their cross-country orderings are somewhat different. This is because of the cross-country differences in the share of trucking activity to total freight activity. Spain, in particular, became among the highest in terms of trucking intensity because of its heavier dependence on trucking, now accounting for as much as about 85 % of the total freight activity.

Even more importantly, at a national level, the trends in the trucking intensity are somewhat different from those in total freight activity intensity. In particular, the U.S., Australia, and France, all of which had largely non-increasing total freight activity intensity, now exhibit the overall increases in trucking intensity (Figure 8). That is, while the countries' structural change in the economy over the last three decades, as represented by increasingly less dependence on industrial value added, have led to the growth in trucking activity that was faster than the percentage increase in GDP, their growth in total freight activity was not as fast as the percentage increase in GDP. This is largely because the countries' demand for rail and water freight transport did not grow as much as trucking due to the ongoing modal shift toward trucking away from rail freight. Particularly in large countries, rail haulage is closely associated with shipments of energy, grains, and raw materials (Schewel & Schipper, 2011; Schipper et al. 2000 (for Australia); and Schipper et al., 1994 (for Sweden)). With fossil fuels accounting for nearly half of all US rail tonne-km, the future of these fuels in a CO_2 constrained world will have a bigger impact on future rail demand. However, in some of the other countries examined, including Japan, Sweden, Denmark, and the U.K., the trucking intensity of GDP has remained the same or even declined in the recent past (Figure 8), and the shares of rail and water freight activities did not grow at all (Figure 3). To summarize, although the ongoing structural change in the economy is likely to result in the decoupling of the growth in rail and water freight demand from the growth in GDP, it may not necessarily translate into the decoupling of the growth in trucking.

Trucking energy intensity has varied considerably across and even within the countries, which is illustrated in Figure 9. This variability reflects differences and changes in the average size of truck, freight load, haulage, fuel prices, and technical and operational efficiencies (IEA, 2007; Thompson, 2009). The next two figures explore the trends in energy intensity of heavy trucks, which account for the most part of trucking, in terms of the three key factors affecting the energy intensity: load factor, fuel intensity, and average fuel price. Figure 10 compares the load factor (tonne/vehicle) and fuel intensity (MJ/vehicle-km) of heavy trucks in 1990, 2000, and 2007, and Figure 11 compares the average fuel price ($2,000/liter) and energy intensity (MJ/tonne-km) of heavy trucks in the same years. As with the energy intensity, load factor, fuel intensity, and average fuel price span wide ranges. The differences in fuel intensity reflect differences in fleet mix within heavy trucks, their technical efficiency, or road conditions. For instance, Japan has the smallest trucks, even exclusive of mini and small trucks, and thus exhibits the lowest level of fuel intensity and the highest level of energy intensity.

Figure 9 indicates that Australia has experienced the greatest reduction in trucking energy intensity over the last three decades, related to the steadily increasing use of heavy long haul trucks. It may not be a coincidence that Australia had remarkable increases in the load factor of heavy trucks over the last two or three decades (Figure 10). Sweden and Germany have consistently been among the lowest in trucking energy intensity with relatively large truck shipments of raw and manufactured products (Figure 11). At the other extreme are the U.K. Japan, France, which have shown the highest trucking energy intensities due to their short hauls or low load factors (the U.K. and Japan) or relatively high fuel intensity (France).

Despite these variations, it has been the overall trend that trucking energy intensity remained largely the same or declined over time in many of the countries examined, mainly driven by the increases in load factor. Yet, the fuel intensity had no noticeable impact or even put upward pressure on trucking energy intensity in those countries. However, the energy intensity trend is reversed in Denmark, South Korea, and Spain: trucking energy intensity in Denmark has increased over the last two decades; South Korea and Spain experienced temporary energy intensification in the 1990s (Figure 9). In the case of Denmark, the rapidly increasing heavy trucking fuel inten-

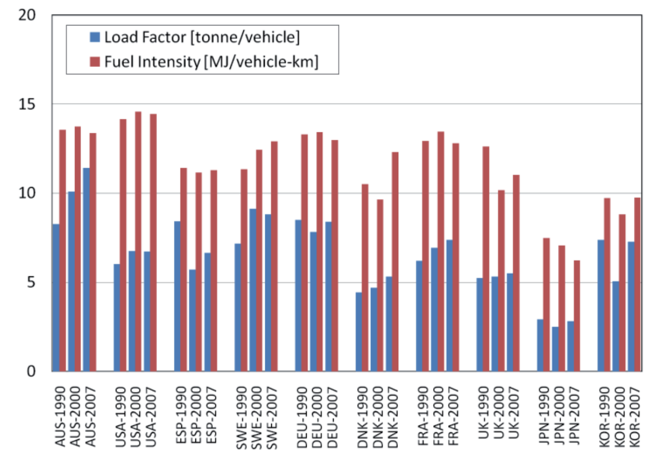

Figure 10. Load factor and fuel intensity of heavy trucks in 1990, 2000, and 2007.

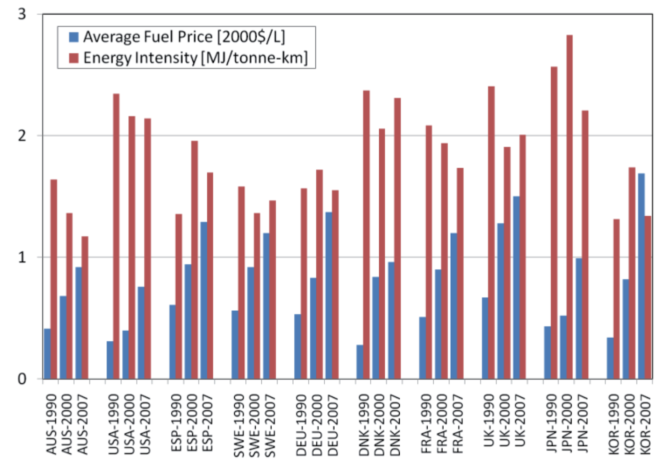

Figure 11. Average fuel price and energy intensity of heavy trucks in 1990, 2000, and 2007.

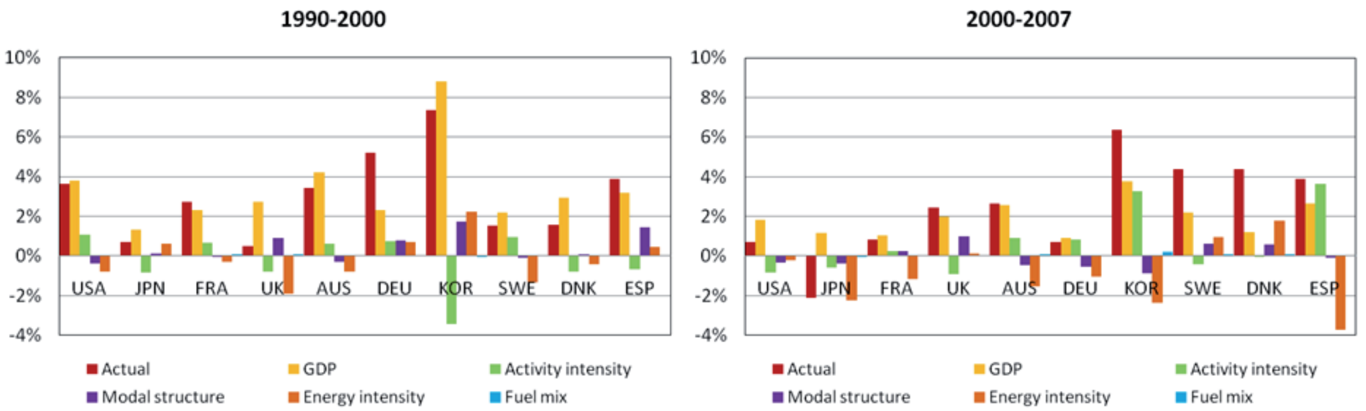

Figure 12a and b. Decomposition of changes in trucking CO_2 emissions (1990–2000 and 2000–2007).

sity (Figure 10), due to the increasing share of heavier fleets on road may have contributed to the energy intensification. In the case of South Korea, the period of trucking energy intensification well matches with the time when the substantial reduction in load factor of heavy trucks occurred. Not coincidentally, the structure of the economy started to shift toward service-based economy in the 1990s and the Asian Financial Crisis occurred in 1997, which also drastically changed the country's structure of passenger transport (Eom and Schipper, 2010).

The effect of fuel price may have played a major part in lowering energy intensity in several countries. Figure 11 indicates that, in the 2000s, heavy trucking energy intensities in Japan, Germany, Spain, and South Korea started to fall or declined more rapidly than before; we found that, during the same period, these countries had experienced unprecedented increases in fuel prices. Whether each country's heavy trucking energy intensity increases or declines over time is largely correlated with the growth rate in the price of trucking fuel (mostly automotive diesel): with a faster growth in the fuel price, a decline in energy intensity is more likely, whereas, with a slower growth, an increase in energy intensity is more likely—The t-value test between 5-year moving average of annual growth rates in the price and the energy intensity suggested that no correlation hypothesis can be rejected at the significance level of 1 % for Japan, Germany, Denmark, and Spain and at 10 % for Canada and the U.K. The above findings collectively suggest that the price effects in Japan, Germany, and Spain may have promoted the increases in the freight load in the 2000s, which ultimately resulted in the recent declines in trucking energy intensities.

To better understand the international trends in trucking CO_2 emissions, we now investigate the consequences of the multiplicative relationship between activity, modal structure, energy intensity, and fuel mix within the trucking sector by splitting trucks into two modes, heavy trucks (over 3.5 tonne of load capacity) and light trucks (below 3.5 tonne). Again, the activity effect is further decomposed into the GDP effect and the activity intensity-of-GDP effect, both of which are in aggregate, not truck mode specific. Figure 12(a) shows the actual average annual percentage change in trucking CO_2 emissions between 1990 and 2000, as well as hypothetical average annual percentage changes if only one of the five factors had changed during the same period; and Figure 12(b) presents the same results for the period between 2000 and 2007.

Trucking CO_2 emissions have all increased in both periods, except for Japan between 2000 and 2007; and the rate of the increase varied considerably, mainly due to differences in the rates of the changes in GDP, activity intensity, and energy intensity. In South Korea and Spain, the previously decreasing trucking intensity started to increase in the latter period, playing a major part in raising trucking CO_2 emissions in the 2000s, as is the case of the decomposition of total freight CO_2 emissions. The growth rates of the trucking CO_2 emissions and the energy intensity effect are virtually the same as those of the total freight CO_2 emissions and the freight energy intensity effect shown in Figure 7, suggesting that the trucking sector has been largely responsible for the energy intensity changes of the entire freight transportation sector.

The change in modal structure had small effects in many of the countries, except for South Korea and Spain, and the effect of fuel mix (mostly from gasoline to diesel in light trucks) has been negligible. During the 1990s, the shifts in modal structure towards light trucks put upward pressure on CO_2 emissions in several countries including the U.K., Germany, South Korea, and Spain, but, since 2000, the trend has been weakened or even reversed, particularly in Germany, South Korea, and Spain, resulting in lower emissions than they would otherwise.

Overall, as in the case of the decomposition of total freight CO_2 emissions, in most of the countries, the effect of trucking activity (the GDP effect and the activity intensity effect combined) has declined or virtually remained the same over the last two decades or so, which made the energy intensity effect, and to a lesser extent the modal structure effect, relatively important in determining trucking CO_2 emissions—The exceptions are South Korea and Spain, whose effects of trucking intensity of GDP still remain important. For these countries, improvement in freight logistics and management would help reduce trucking CO_2 emissions for those countries. Given the continued moderation in trucking activity in the other countries, major opportunities for the reduction in trucking CO_2 emissions, and more broadly total freight CO_2 emissions, may come from the management of the intensity and structure of the trucking sector.

Summary and Conclusion

Over the last three decades, per capita energy use for freight transport and associated CO_2 emissions have continued to increase in most of the ten IEA countries examined in this study, although they took wide ranging emissions pathways even at the same income level. Using national authoritative data starting from as early as 1970 extending to 2007-2008, we decomposed each country's freight CO_2 emissions as the combined effect of freight service demand (GDP and freight transport intensity of GDP), the modal choice of the freight system users, the energy requirement for the freight modes, and their fuel mix.

We found that although freight activity is still coupled with GDP growth, the countries have had substantially different freight activity intensity of GDP, depending on their geographical coverage and border sharing with trading partners, which might limit the extent to which the coupling can be loosened in the future. The positive indication is that, many of the countries have experienced sizeable reductions in the freight transport intensity, helped by the ongoing shift in the structure of the economy toward the service sector away from the industrial sector. The structural shift among developed economies may continue to put downward pressure on freight transport requirement per unit of output and its associated CO_2 emissions at least at the country level. However, this might not be the case at the global level, in which the structural shift would ripple through multiple economies with regional heterogeneities in freight transport requirement and energy intensity.

In all countries, trucking has dominated other freight modes in terms of freight activity, energy use, and associated CO_2 emissions. Trucking has had the highest energy intensity among the freight modes; and it exhibited large variability across the countries, suggesting that overall handling of truck freight or road traffic management is yet to be optimized. Despite this, trucking energy intensity has fallen in four of the ten countries examined partly due to increased load factor and improvement in vehicle fuel efficiency. The trend in trucking energy intensity is largely correlated with the change in fuel price, the role of which is worthy of more detailed study.

Taken together, over the last two decades, the effect of freight transport activity on CO_2 emissions has decreased or virtually remained the same in most of the countries, while the effects of energy intensity (mainly improvement in trucking energy use) and modal structure (shift towards trucking away from rail and water) have become relatively important. In the case of trucking, accounting for about 85 % of freight CO_2 emissions in the ten IEA countries, the effect of trucking activity has also moderated during the same period, which made the energy intensity effect (mostly negative), and to a lesser extent the modal structure effect, relatively important in determining CO_2 emissions. If such moderating activity trends continue in developed countries, major opportunities for freight CO_2 emissions reduction are likely to come from better management of the intensity and structure of the freight transport system.

In most of the countries, the share of rail and water freight transport has been relatively small and continued to decline because of the ongoing modal shift toward trucking, which is generally more energy (and carbon) intensive. It is well advised to implement integrated resource planning of the freight transport system, which may range from broad-based policies promoting more even modal shares or better siting of industry facilities relative to where the goods are delivered and demanded to mode-specific instruments such as a carbon tax imposed on freight transport fuel or better utilization of passenger rail infrastructure for freight transport.

In this study, we did not investigate the implications that electrification and bio-fuel consumption in trucking might have for CO_2 emissions reduction in the freight transportation sector. Also, the full fuel cycle impact of rail electrification has not been assessed, although it may offset energy savings (and CO_2 reductions) associated with the freight modal shift toward rail and its electrification. Depending upon the energy and carbon intensities of the power system, the countries may have different interpretations of increased rail use and its electrification. Future research would address these issues.

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