

We keep on truckin': Trends in freight energy use and carbon emissions in 11 IEA countries[☆]

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ABSTRACT

Based on detailed national and international data on freight transportation, we analyze trends in freight CO₂ emissions in 11 IEA countries from the earliest year of data availability to 2007–2010. The cross-country comparison of the freight transportation sector indicates that per capita CO₂ emissions span a wide range and are mostly determined by local needs without full knowledge or coordination with policies and practices in other countries. Over the last several decades, while many developed countries have experienced decreased coupling between total freight activity (measured in tonne-km) and income, no major indication of decreased coupling between trucking and income was found. Rather, the coupling has been strengthened in many countries due to a continued increase in the share of trucking in total freight activity. The energy intensity of trucking has exhibited very large variation among the countries, and its recent international trends are mixed, providing greater challenges to reduce freight CO₂ emissions. Modal shift toward rail away from truck presents a sizeable opportunity to reduce freight CO₂ emissions, although the potential gain varies widely among the countries.

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1. Introduction

Although transport usually appears as a broad category in the analysis of energy use, it is rarely, if ever, analyzed further by freight versus passenger services. As a result, the freight transport sector has often been overlooked in energy and greenhouse gas discussions. This is unfortunate, as freight transport has been growing more rapidly than passenger transport, and the trend is likely to continue in the future (IPCC, 2007). Freight transport is shaped by complex and interrelated changes in production and consumption of goods driven by income growth and attendant supply chain characteristics that are influenced by increasing specialization and sourcing of products (Lehtonen, 2008; McKinnon, 2008). Thus freight differs from passenger transportation, where energy use and emissions are mainly generated by private automobiles. Recently, however, as the appreciation of the

role of the transport sector in energy use improves, national authorities have begun to pay separate attention to freight, particularly because of bottlenecks in roads, ports, and even railways (Macarewicz et al., 2010; Eddington, 2006).

With the increasing focus on freight transportation in energy studies, the literature has offered broad international perspectives. Schipper et al. (1997), Schipper and Marie-Lilliu (1999) and Kamakate and Schipper (2009) all demonstrated the significance of the freight sector to both transport and total CO₂ emissions. McKinnon (2008) identified a series of potential measures to moderate the growth in freight-related CO₂ emissions in an international context. At the national level, McKinnon (2007) provided a great deal of information on the nature of trucking in the UK, and Sorrell et al. (in press) have provided a broader orientation to relate 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 detailed structure-based approach may be important but is beyond the scope of the present work because of data issues.

Still, the conclusion from the previous literature is that, in many developed countries, the significance of freight energy demand and CO₂ emissions within the transportation sector has steadily grown. Fig. 1 illustrates passenger and freight CO₂ emissions in selected industrialized economies. It indicates that the growth of freight emissions has generally been faster than

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¹ The authors deeply regret that Lee Schipper died from pancreatic cancer just after he had been able to comment on the first draft of this paper. We have attempted to make changes that were discussed in the first draft and accept full responsibility for any errors that have been introduced since his participation.

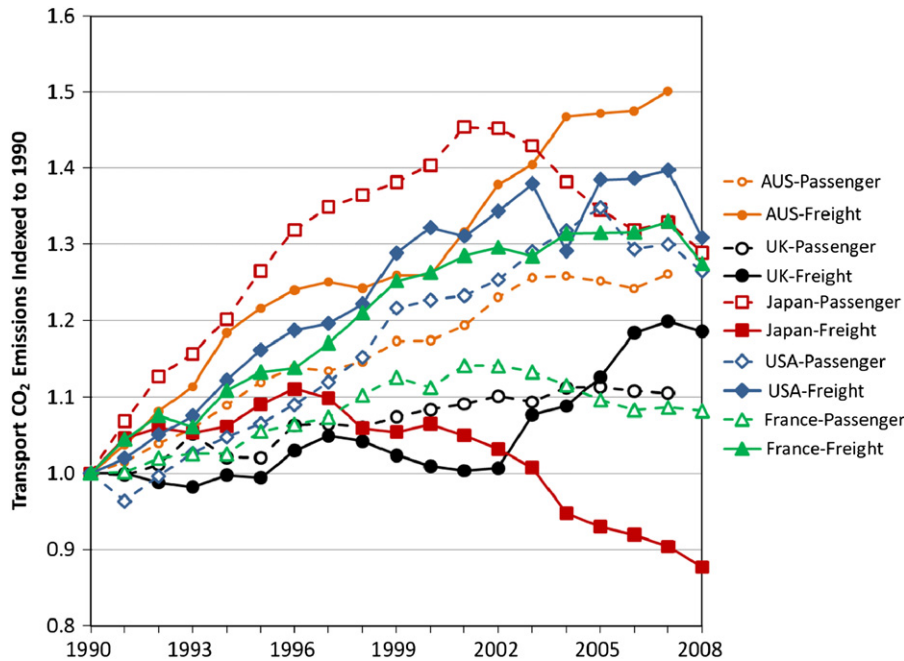


Fig. 1. Passenger and freight CO₂ emissions for selected industrialized countries indexed to 1990.

(Source: Passenger transport emissions from the dataset used in Millard-Ball and Schipper (2011) and freight transport emissions from our own calculation.)

that of passenger emissions with the exception of Japan, whose CO₂ emissions started to decrease, and there is substantial variation in the growth rate among the countries.

This study explores the questions of why freight emissions have continued to increase in many developed countries, why the growth rate of freight emissions has varied among them, and what might be learned by investigating and comparing trends and performance of their freight transport sectors. To address these research questions, it has been essential to identify and interpret major drivers of freight CO₂ emissions and their changes based on the best available information on the freight sector, preferably from countries with varying economic, geographical, and transport system characteristics. This approach offers insights into the development of freight transport policies that help reduce energy consumption and attendant CO₂ emissions, ranging from local freight logistics management and freight infrastructure planning to energy and climate mitigation policies.

This research develops the earlier analysis by Kamakate and Schipper on trucking energy use (Kamakate and Schipper, 2009), by offering more general insights applicable in a broader context. The present study separates the activity of light trucks from that of heavy and medium trucks, for which tonne-km data are mostly available, incorporates six more countries—one big country (Canada), four European countries (Germany, Sweden, Denmark, and Spain), and one rapidly developing Asian country (South Korea)—and captures more recent trends through 2007 or 2010, reflecting the continued rise in income and fuel prices. Also importantly, rail freight energy use and emissions, which have not been scrutinized in earlier studies, were systematically analyzed in this study, helped by methodological advancements in estimating freight-only rail energy demand and incorporating system-wide CO₂ emissions associated with railway electricity demand.

This study confirms that there is no indication of a shift from trucking as the dominant mode of freight transport toward more energy efficient modes. Rather, trucking continued to grow faster than rail and water freight in most of the IEA countries represented, putting upward pressure on freight energy demand and

attendant CO₂ emissions, which is consistent with the earlier studies (Schipper et al., 1997; Kamakate and Schipper, 2009). Not surprisingly, the energy intensity of trucking remains much higher than other freight modes and varies widely across the countries due to variations in vehicle size and the utilization of vehicle capacity (IEA, 2007b; McKinnon, 2008; Kamakate and Schipper, 2009). Our study reveals that no international consistency exists in the trends of trucking energy intensities over the recent two decades with virtually no change from the similarly mixed trends observed between 1973 and 1992 (Schipper et al., 1997). That is, the freight sector in many of the countries has yet to be optimized, but instead has developed without full knowledge or coordination with policies and practices in other countries. It was also found that the developed countries, except for the two less developed economies (Spain and Korea), have experienced modest degrees of decoupling between total freight activity and income and a slow-down in the growth of total freight demand over the last two decades, helped by the steady transition in economic structure and decreased dependency on rail and water freight. This study, however, points to the fact that there is no major indication of decoupling of trucking volume from income in any of the countries. This suggests that the linkage between total freight activity and income might be strengthened again in the future, given the universal trends of globalization, outsourcing, and vertical disintegration of production operations (McKinnon, 2008). Another important finding is that, despite sizeable variations in rail electrification and system-wide emissions related to electricity production and delivery, shifting toward rail away from trucking could still provide significant opportunities to reduce CO₂ emissions in the freight sector in all of the countries represented, and perhaps in other developed countries as well.

The remainder of the paper is structured as follows. Section 2 details our research approach by identifying several methodological issues. Section 3 discusses the three sets of results emerging from the analyses: overall freight energy consumption, trucking sector energy consumption, and rail freight energy consumption. Concluding remarks are presented in Section 4.

2. Methodology

2.1. Data coverage

This study covers 11 IEA countries: the U.S., Canada, Japan, France, the UK, Australia, Germany, South Korea, Sweden, Denmark, and Spain—that is, six European countries, two Asian countries, and three other large countries (the U.S., Australia, and Canada). Although these eleven countries represent a heterogeneous mix of geographical and socioeconomic characteristics and are only a part of the total IEA population, we believe their trends in the transportation sector have been generally representative of the world's developed economies: over the last three decades, transportation energy use (passenger and freight combined) in these eleven countries has steadily accounted for more than 80% of total transportation energy use in OECD countries (IEA, 2007b).

The data used in this study mostly come from authoritative national and international energy and transportation statistics.² The data include annual energy consumption (PJ) by four freight transport modes—heavy (and medium) truck, light truck, rail, and water—each mode's energy use by fuel type, freight activity (tonne-km), distances driven (vehicle-km), and load factors (tonne/vehicle), as well as other socioeconomic indicators such as population, GDP, and sector-wise GDP value added. The socioeconomic indicators are from OECD National Accounts, as represented by real 2000 local currency converted to 2000 USD at purchasing power parity. For trucking, we have attempted to include both own-account and for-hire trucking. All rail freight, including fossil fuel freight, is included, but all freight between countries by sea is excluded. Domestic air freight transport and pipeline transport are not included due to limited availability of reliable data and, in the case of air freight transport, due to their relatively small contribution to the entire sector.³

2.2. Trucking and water freight data

Data sources and assumptions for trucking and water freight are detailed in [Appendix](#). In many instances, the authors' reasoned judgment and personal communications with national experts were made to fill out missing data categories, to reconcile alternative data sources, and to interpolate for missing years. For example, light trucking activity (tonne-km) data is either partly available or not available at all in some countries (the U.S., Australia, Germany, Denmark, Sweden, and Spain): in others, it is not directly available but is derivable from load factor data (South Korea). Wherever needed, we applied an average load of 0.7 t/vehicle trip to construct light trucking activity from carried

² Despite the availability of international statistics, we draw mostly on national energy and transportation statistics because they provide detailed, internally-consistent freight transport and energy information. For instance, IEA energy balance provides transport energy consumption for the countries, but passenger and freight transport are not reported separately. OECD reports freight activity data but the coverage and definition of activity is not consistent with ours. ODYSSEE energy efficiency database for Europe provides detailed freight energy consumption and activity data by freight mode with varying time coverage. However, the process by which national data are reported and treated in ODYSSEE is not clear, particularly for rail freight energy, trucking energy, and trucking activity data, although in several necessary cases we used the database to complement our national-level data. As such, we did not attempt to compare our numbers with the international database, and such database comparison analysis would be beyond the scope of this study.

³ Available data indicate that domestic air freight accounts for less than 5% of total freight energy consumption and less than 1% of total freight activity in 2007 in all of the countries examined. Data for pipeline transport energy consumption, however, span a wider range with the highest share of around 20% in Canada and nearly zero shares in European countries.

distance, which is available for all of the countries. Because light trucking activity only covers a small portion of total national freight tonne-km, changes in the assumed load factor only have small effects on total freight activity and its overall energy intensity and have virtually no effect on the decomposition trends.

We acknowledge that there are uncertainties and reporting inconsistencies in the allocation of trucking activity and fuel consumption. In countries with little or no international traffic (e.g., Japan, the UK, Australia, and South Korea) the reported trucking fuel consumption matches well with trucking activity. In many of the other countries with international traffic, however, trucking activity (domestic and international) and fuel consumption are reported based on vehicle registration, so that transport activity and fuel consumption of trucks passing through a country where they are not registered are excluded. The exception is for Denmark, Spain, and Sweden, where fuel consumption of foreign trucks are not separated from the data. Thus, our sample study necessarily underestimates overall trucking activity in Europe (by excluding foreign transit), so that trucking energy intensities of the European countries under consideration might not be well suited for direct comparison, although their trends over time may still be valid. Because we estimated CO₂ emissions from disaggregated mode-based fuel consumption data, the allocation of emissions follows that of fuel consumption.

Note also that this study employs German dataset since 1991 to properly represent the country's entire freight transportation sector. We used DIW (Deutsches Institut für 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. It should be also noted that Canadian data used in this study have a degree of uncertainty because of the absence of compatible estimates of tonne-km and vehicle-km for heavy trucking and a lack of data on own-account trucking and domestic shipping fuel consumption. To estimate heavy trucking activity in Canada, we followed the approach taken by [Lawson \(2009\)](#), utilizing the average load of heavy trucking from 2006 National Roadside Trucking Surveys and the average fuel consumption rate from the Mobile Greenhouse Gas Emissions Model. We also extrapolated Canadian own-account trucking activity based on the U.S. ratio of for-hire to own-account trucking and Canadian shipping energy consumption based on the U.S. shipping energy intensity, assuming that the two countries' trends are largely similar.⁴

2.3. Rail freight data

A major challenge regarding rail freight data is to distinguish freight related energy consumption from passenger usage in the aggregate railway energy consumption—both diesel and electricity. The data available for analyzing rail freight energy use vary significantly by country. For the purposes of this paper, the basic determinant of rail energy use is the gross tonne-km (the weight of cargo plus the tare weight of the freight wagons—the total weight of the train—moved one kilometer), which is the best proxy for actual work done in moving cargo and thus has the most direct relationship with energy consumption.⁵ With very

⁴ We acknowledge that the data for trucking in Canada are especially approximate and potentially subject to a wider margin of error than for the other countries. Nevertheless, we felt it was useful to try to include Canada because it helps illustrate the difference between continental or semi-continental countries—U.S., Australia and Canada—and other developed economies.

⁵ In practice, a number of variables affect energy consumption. The dominant factor is total train weight, which we use here. Other factors, such as train length,

few exceptions, which were estimated by extrapolation between years, rail freight net tonne-km (cargo weight moved one km) are available by country and by railway for all years: in many cases, gross tonne-km on the same basis were also available. Where gross tonne-km data were not available, gross tonne-km were estimated from the ratio of gross tonne-km to net tonne-km from prior or later years. This is a reasonable approach since the ratio of gross train weight to net cargo weight is determined by the equipment fleet in service and operating practices, both of which change only slowly in any given country. Beyond the estimation of gross tonne-km, countries fall into various levels of detail in energy use data, although some form of aggregate energy use data for railways is available for most countries.

In the U.S., all but a small percentage of rail freight traffic (tonne-km) is moved by Class I freight railroads,⁶ and all freight traction power is diesel. In addition, U.S. Class I railroads report fuel consumption to the regulator (the Surface Transportation Board), so an accurate⁷ series of rail freight traffic and energy consumption data by type of fuel going back to the early years of the 20th century is available. Canadian Railways report similar data to Transport Canada and the Railway Association of Canada, so that, with a few minor gaps that were extrapolated, Canadian railway freight energy data (all diesel) are also complete and accurate.

Australian rail freight data are taken from data developed by Applebaum Consulting. In this case, only net tonne-km are available for all years, and energy use is available for a limited number of years. In addition, electric traction became more significant in later years. Freight energy consumption was separated from total rail energy consumption using the ratios of energy to net tonne-km for diesel and electricity, and relative shares of electricity versus diesel were extrapolated in the gap years. Neither of these should introduce significant variability since Australian freight technology is similar to that of the U.S. and Canada, where gross to net ratios fell by only about 10% during the period 1970–2009, and since electric traction never amounted or more than about 1% of total freight energy use.

Freight rail energy calculations for the remaining countries (Japan, Korea, France, Germany, UK, Sweden, Spain, and Denmark) are necessarily more approximate. The most reliable data source for these countries is the “International Railway Statistics” (Schedules 42, 51, 61 and 81) published by the International Union of Railways (UIC) in Paris.⁸ In some cases (Korea), other national data have been used to supplement the UIC data. In many European cases, with the advent of the E.U. requirement that infrastructure be separated from operations, some data from operators have been lost and the consistency of the entire dataset

(footnote continued)

curvature, gradient, and speed, can also have an effect. For the most part, within any given national rail system, these parameters can be averaged into gross train weight and thus into gross tonne-km. See, for instance, AREA Part 2 on Train Performance (AREA, 1996). See also, FRA (2009) and Lindgren and Sorenson (2005) for discussions of the basic drivers of rail energy use.

⁶ “Class I Railroads” are the largest U.S. freight railroads. In 2008, Class I included all railroads with a gross revenue of more than US\$ 401.8 annually.

⁷ Because U.S. (and Canadian) railway data are used for public reporting, tax calculations and regulatory proceedings, they are prepared under accounting principles and are as “accurate” as the large numbers involved permit.

⁸ Schedule 81 of the report requests railways to split their energy use by freight versus passenger and, within freight, by electricity versus diesel. Unfortunately, this Schedule has only been available in later years and not all railways have completed it in all years. Some railways (UK and France) have never completed it in its entirety and it is rare that complete information for all railways is available in any given year. Earlier UIC statistics (“Statistics Digest” from 1971 to 1984) do give useful information about traffic and total energy consumption by type of fuel for many railways, which permitted an earlier anchor point for extrapolation over the entire time period.

over time has suffered. Germany is a difficult case since there were two countries (and two railways) prior to 1994. Data for the two railways prior to 1994 have been combined directly and averages computed, but since the railways were disparate in their traffic and technology, the value of the average is weakened.

Accepting these caveats, we estimated total rail freight energy use by type of traction by: (1) using either actual gross tonne-km where available or estimated gross tonne-km (from net tonne-km) where necessary to develop the railway’s total freight gross tonne-km; (2) using available data and trends, estimate the split of total gross tonne-km as between diesel and electric traction; and (3) using the available data on the ratio of energy use/gross tonne-km by type of traction and employing reasonable estimates of these ratios for years in which there are gaps in the data. Data become sparse or less comparable for the E.U. and Asian railways before about 1990 in most of these countries, so while the estimates for 1990 to 2008 are reasonable, the potential error in our estimates before 1990 grows accordingly. As far as we know, this approach to estimating rail freight energy consumption by energy source across a series of countries has not been attempted before. The next step, in a following paper, will be to apply a similar approach to rail passenger energy consumption by energy source, and to extend the analysis to several major railway systems (Russia, China, and India) that we were not able to include in the current publication.

In addition, we attempted to properly examine CO₂ emissions from the freight transportation sector and thus to identify potential opportunities of decarbonizing the sector. For non-electricity fuels, we applied 2006 IPCC guidelines of emissions factors for mobile combustion to freight fuel consumption (IPCC, 2006). The power sector emissions attributed to rail electricity consumption that each country reports pose a complication. Here, we identified a set of primary fuels and their supplies to deliver one unit of electricity to the rail sector, based on detailed national energy balances published by IEA (2010). The primary fuel consumption includes fuel inputs for power generation and fuel shares to generate electricity out of combined heat and power systems (CHP), adjusted for the energy industry’s own use of electricity and delivery losses. The set of fuel consumption data collectively constitutes the primary energy equivalent of delivered electricity, and CO₂ emissions of rail electricity were accounted for by multiplying it with the emissions factors for stationary combustion in the 2006 IPCC guidelines (IPCC, 2006).

2.4. Decomposing CO₂ emissions

CO₂ emissions are the result of numerous direct and indirect driving forces. They can be reduced to a smaller set of broad factors using IPAT-type analyses as examined by many environmental impact studies (Kaya, 1990; Cramer, 1998). The IPAT equation represents the environmental impact (*I*) as the product of three terms: population (*P*), affluence (*A*), and Technology (*T*). While the IPAT formulation may serve useful diagnostic purposes, its weakness is that it employs only one-dimensional variables. In place of this, Schipper et al. (2000) suggested the ASIF approach, which interprets each country’s transport CO₂ emissions as a combined effect of four multi-dimensional 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 CO₂ 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 changes in the size and structure of an economy. 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 changes in the technology of transport modes, regulation of their fuel efficiencies, and the efficiency of transportation system operation (congestion, freight loading, and industry practices). The fuel mix effect 'F' reflects 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. As such, total CO₂ emissions at time *t* can be expressed as follows:

$$\text{Emissions}_t = A_t \sum_i \left(S_{i,t} I_{i,t} \sum_j F_{i,j,t} \right) = \text{GDP}_t \frac{A_t}{\text{GDP}_t} \sum_i \left(S_{i,t} I_{i,t} \sum_j F_{i,j,t} \right)$$

where subscript *i* and *j* represent the type of transportation mode and its fuel choice, respectively. We further decomposed the activity effect into the effect of GDP and the effect of activity intensity of GDP (i.e., the demand for transport per dollar of GDP). However, due to the absence of detailed commodity flow surveys for the countries, these GDP-related effects are aggregate, not freight mode specific.

Like the IPAT formulation, the *ASIF* approach can effectively illustrate the consequences of the multiplicative relationship between its driving forces with each driving force amplifying changes in the others. For example, while a given reduction in energy intensity may have only a small effect on per capita CO₂ emissions in a developed country with already stabilized freight transport demand, it may have a substantial effect in a developing country with rapidly growing freight transport demand. Note however that the key advantage of the *ASIF* approach is that it forces the analyst to understand freight (or passenger travel) from the bottom up, beginning from the structure of freight use. For instance, in the *ASIF* formulation, an overall reduction in energy intensity might lead to less fuel use and emissions per tonne-km; at the same time shifting towards energy-intensive trucking and air freight could raise emissions, as in the case for almost every country studied. Other decomposition approaches without using both modal structure/activity data and energy intensities fail to describe changes in total transport emissions arising from structural and intensity changes (see, for example, Timilsina and Shrestha (2009)). 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.

Limitations of the *ASIF* approach include the fact that, as several decomposition studies in a broader context suggest, the level of aggregation of a variety of factors may affect the results of the analysis (Lutz, 1994), and that each aggregate factor may not be independent of the others (DeCanio, 1992), potentially due to the presence of other more fundamental drivers. Therefore, results based on an *ASIF* analysis cannot always be directly translated into the priorities of policy intervention. Rather, the goal is to gain descriptive insights into the relative significance of 'A,' 'S,' 'I,' and 'F' factors in a *ceteris paribus* condition for a given period of time, which might be used to identify potential areas of improvement. An international comparison of *ASIF* results may partly address limitations of a single country analysis, possibly offering richer, comparative insights into the extent to which a certain *ASIF* factor for a country under consideration might improve or deteriorate with or without policy intervention.

The *ASIF* approach has been applied to both travel and freight by Schipper et al. (Schipper et al., 1997; Kamakate and

Schipper, 2009; Eom and 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 trucks 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, incorporate the data of six more countries through most recent year available, and fully investigate the trends in freight CO₂ emissions by estimating freight rail energy consumption and attendant system-wide emissions.

3. Results

3.1. Freight energy use and carbon emissions

The eleven IEA countries' freight CO₂ emissions per capita have spanned a very wide range even at the same income level, and the U.S., Australia, Canada, and Spain have shown distinctively high per capita emissions (Fig. 2). Note that, as will be discussed, Spain's per capita emissions are much higher than the other European countries because it relies predominantly on trucking that is calculated to be more energy intensive than average European trucking. In addition to this considerable heterogeneity in freight CO₂ emissions, in nearly all cases, the emissions have steadily increased with income, suggesting that increased income per capita is associated with increased freight activity and increased energy consumption. A few noticeable exceptions include the UK and Australia, whose emissions temporarily decreased in the 1980s and 1990s, as well as Japan with steadily decreasing emissions since the mid-1990s, as a result of the moderation of freight transport activity and the shift of road freight towards heavier trucking (Kamakate and Schipper, 2009).

The considerable heterogeneity in freight CO₂ emission across the IEA countries is to some extent explained by the large difference in freight transport activity (tonne-kilometers) among the countries (Fig. 3). Even income effect controlled, per capita freight transport activity varies widely across the countries. This is because one country's freight transport activity depends on a variety of other important factors, including economic structure and its relationship with freight transport as a derived

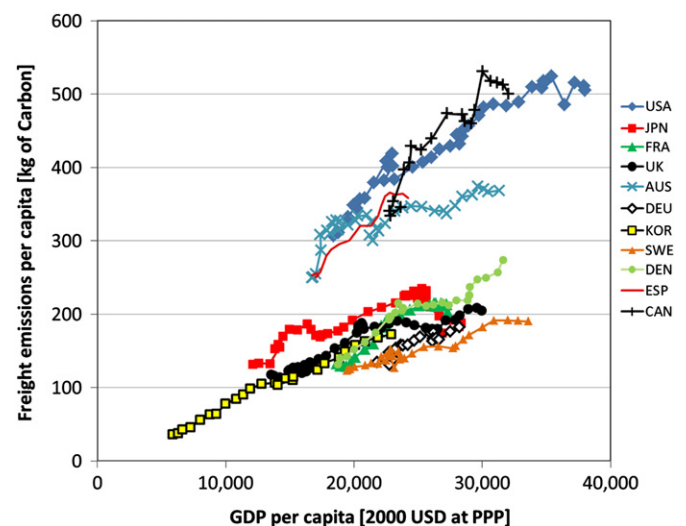


Fig. 2. Freight carbon emissions per capita vs. GDP per capita.

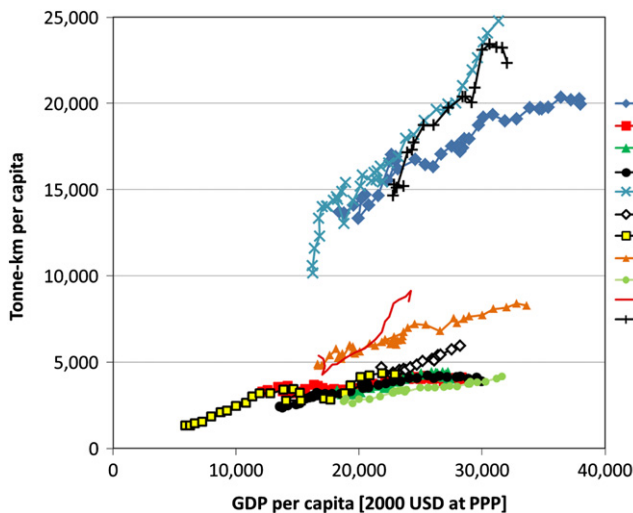


Fig. 3. Tonne-km per capita vs. GDP per capita.

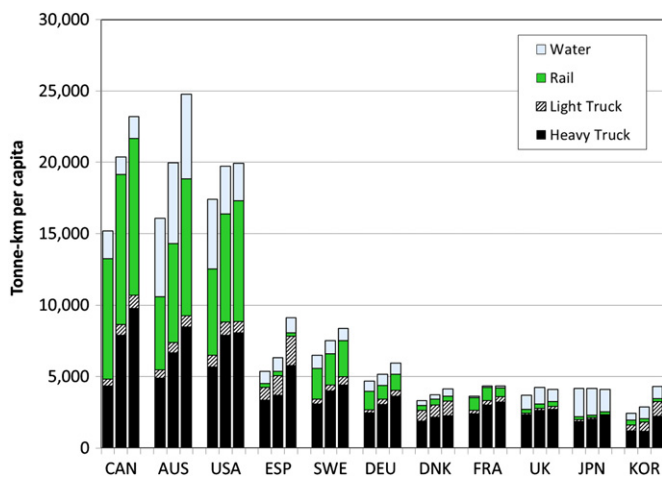


Fig. 4. Tonne-km per capita and modal shares in 1990, 2000, and 2007.

demand, geographic characteristics of production and consumption and attendant supply chain, and the volume of international trade.

The eleven IEA countries can be classified into three groups, depending on the recent level of per capita freight transport activity (Fig. 3) and its modal shares (Fig. 4), which also varies across the countries. The first group of countries, the U.S., Canada, and Australia, exhibits particularly higher activity than the other countries, probably due to greater geographical scale and higher share of fossil fuel freight (Schewel and Schipper, 2011). In particular, 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, relatively more economically viable. Indeed, in the U.S. Canada, and Australia, rail and water transport have accounted for more than half of total freight transport activity, which made their trucking shares the lowest among the eleven IEA countries (Fig. 4). Based on the statistical analysis of year-1989 freight volumes, Bennathan et al. (1992) also found that country area dominates the explanation of rail freight activity. Note that international transit freight is not included in European countries' activities, which should have made their numbers even smaller than the other countries'

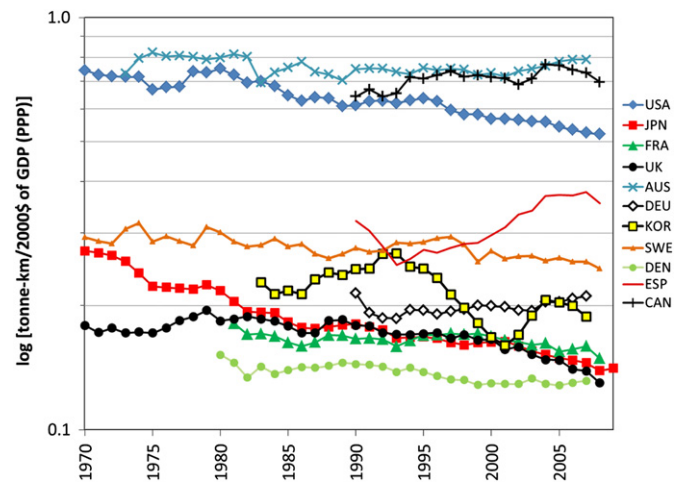


Fig. 5. Comparison of the freight activity intensity of GDP.

numbers.⁹ The second group consists of Spain, Sweden, Germany, France, and Denmark, all of which are not as big as the first group countries and share some portion of the borders with their trading partners. These countries show modest levels of total freight transport activity, and small shares of rail and water transport, except for Sweden exhibiting a relatively higher share of rail freight activity due to its intensive iron ore freight in the northern part of the country. The last group of countries—the UK, Japan, and South Korea—exhibit the lowest level of per capita trucking transport and relatively high shares of water transport. This may be because these countries have little, if any, border sharing with other countries, thus relatively small cross-border trucking. Yet, the actual trucking tonne-km in the UK is likely to be a little higher than the reported because of its exclusion of the traffic through the Channel Tunnel and the ferries. It should also be noted that, in all of the countries represented, the trucking shares have continued to increase, perhaps driven by increased demands for faster shipping of final and intermediate products.

Interestingly, despite some fluctuations, the IEA countries have experienced overall decreases in freight activity per dollar of GDP—which we call the freight activity intensity of GDP¹⁰—suggesting modest degrees of decoupling between total freight activity and GDP (Fig. 5). Two noticeable exceptions are Spain and Korea, both of which are later in the stages of economic development than the others.¹¹ However, this may largely be the unintended outcome of various economic trends rather than the deliberate result of policy (Sorrell et al., in press). We expect that the trend in the freight activity intensity of GDP is associated with the shift in the structure of an economy: the less the economy requires freight transport to produce a unit of output, the less will be the freight activity intensity of GDP. Even without a counterbalancing increase in value added per unit of goods delivered or sizeable improvement in freight logistics, shrinkage of the industrial sector generally leads to a decline of the freight activity intensity of GDP, that is, increased decoupling of freight activity from economic activity, which has been the case in many of the countries, particularly in the U.S. and Japan.

⁹ We speculate that other large, semi-continental countries (Russia, China, and India) would fall into this grouping, and earlier analysis (Thompson, 2002) has supported this hypothesis.

¹⁰ Each country's freight activity intensity of GDP is equivalent to the slope of the country's freight activity-income plot in Fig. 3.

¹¹ Eurostat (2005) also points out that in Spain the decoupling has occurred in the opposite direction with freight activity growth exceeding its economic growth.

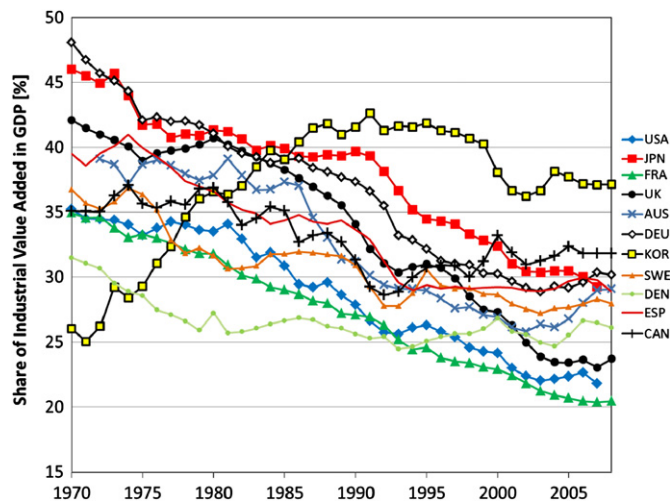


Fig. 6. Changes in the share of industrial value added in GDP. (Source: World Bank.)

Indeed, we found that the changes in the freight activity intensity of GDP have largely been associated with changes in the composition of economic sectors, particularly of the industrial sector as represented by the share of industrial value added in GDP (Fig. 6).¹² In the U.S., Japan, and the UK, the period of continued decline in freight activity intensity of GDP roughly corresponds to the period of the steady decrease in the share of industrial value added in GDP, although pipeline transportation is excluded from the freight activity numbers. Several other countries, including Spain, Canada, 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 or even increase thereafter: this period overlaps with Spain industry's job generation after the 1990–1994 recession, Canada's sluggish productivity growth after the 1990–1992 recession, and Germany's structural adjustment with the incorporation of East Germany. South Korea's distinctive trend in freight activity intensity is also consistent with its dramatic change in the economic structure. The country's freight activity intensity gradually rose until the early 1990s, when it started to decline (Fig. 5). This corresponds to the economy's rapid economic development based on heavy and chemical industries until the mid-1990s, followed by a structural shift reinforced by the 1997 Asian Financial Crisis. The structural change reversed the continued increase in the industrial share of GDP (Fig. 6).

These findings imply that, at the national level, as the economy's reliance on the production of material goods decreases mainly due to increased off-shoring occurring in many of the developed countries, the linkage of freight transport activity with GDP might be loosened, possibly lowering freight transport activity demanded by the economy and its associated CO₂ emissions. From the perspective 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 may ripple through multiple economies, potentially with larger consequences than the economy's foregone transport activity might suggest. Helm et al. (2007), for example, point out that UK official greenhouse gas emissions have decreased by 15%, whereas consumption-based emissions, which includes emissions from bunker fuel used to

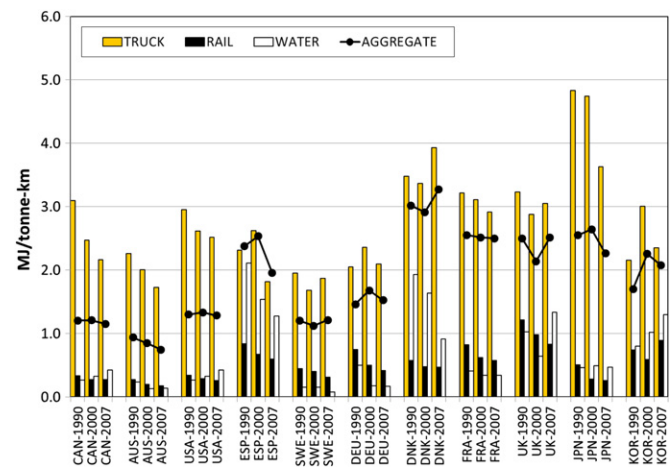


Fig. 7. Freight energy intensity by mode (primary energy for electricity included).

deliver international transport services and imported goods, have increased by 19% over the same period. 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 CO₂ emissions, particularly when regional heterogeneities in freight transport requirement and fuel utilization intensity come into play (Davis and Caldeira, 2010).

Just as the trend in freight transport activity is of critical importance to the sector's CO₂ emissions, so is the energy required to deliver a given amount of freight transport demand. Three points are worth making regarding the energy intensity of freight transport (MJ/tonne-km). First, in all of the countries represented, trucking has undoubtedly the highest energy intensity among the alternative modes, and its energy intensity varies substantially across the countries (Fig. 7). This is consistent with the earlier international comparison studies including Schipper et al. (1997) and IEA (2009). These studies related the variation in trucking energy intensity to vehicle size and vehicle utilization. Also, despite several fluctuations over time, trucking energy intensity has generally been lowest in Australia, Sweden, and Germany, and has been highest in Denmark, and Japan. Note that although Danish heavy trucking is as efficient as that of Germany, it presents relatively high overall trucking energy intensity because of its high share of light trucking,¹³ relatively low load factor, and, to a lesser extent, the inclusion of fuel purchased by foreign trucks in the reported data. Also, despite some improvement over the last several decades, Japan remains the most energy intensive because its trucks are smaller in size than trucks in other countries (Kamakate and Schipper, 2009).

Second, substantial cross-country variation is also observed in the energy intensities of rail and water transport (Fig. 7). Rail freight transport has been most energy efficient in the U.S., Canada, and Australia, and water freight transport has been most energy efficient in Australia and Sweden. Spain, Denmark, the UK, and Korea have had noticeably higher levels of water freight energy intensity, possibly reflecting some inefficiency in water freight logistics and utilization.

Third, in aggregate, countries with the most energy intensive freight transport sector have been those with relatively energy intensive trucking sector and with relatively low shares of rail and

¹² Here, the industrial value added includes gross product from manufacturing, mining, construction, utility sectors, which usually requires freight transportation of raw, intermediate, and final products in its supply chains.

¹³ Our calculated share of light truck tonne-km to total truck tonne-km in Denmark agrees with the share of 36% reported in Mathiesen et al. (2012), which is the highest among the European countries examined in this study.

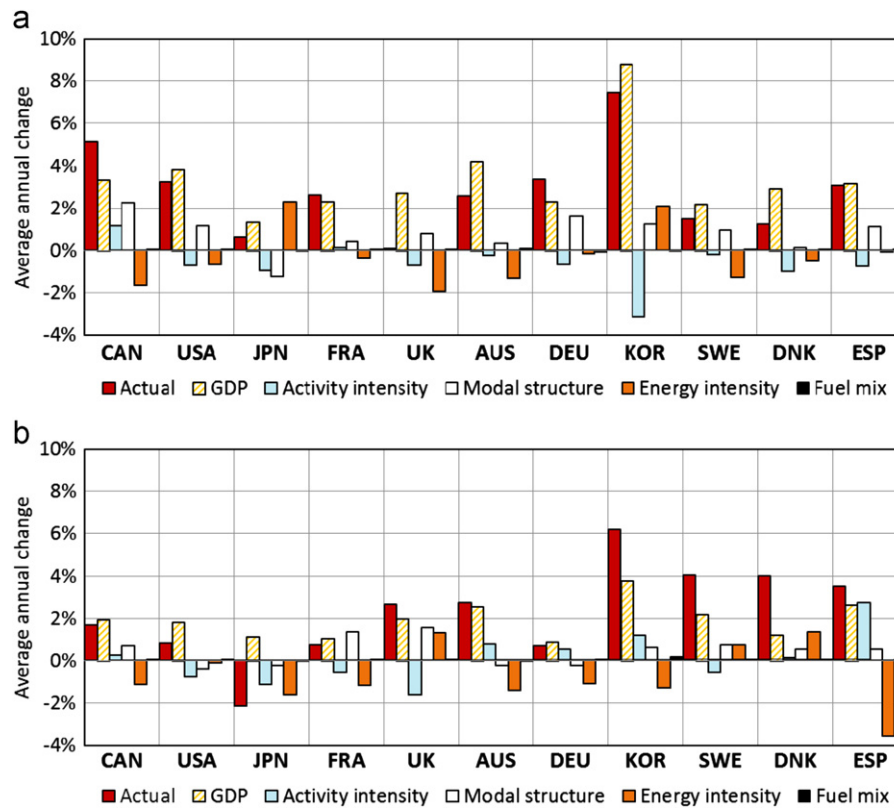


Fig. 8. Laspeyres decomposition of freight CO₂ emissions (1990–2000 and 2000–2007). (a) Decomposition of CO₂ emissions change between 1990–2000 and (b) decomposition of CO₂ emissions change between 2000–2007.

water transport (Fig. 7). Denmark is an example, whereas the opposite cases include Australia and Sweden. Also importantly, the trends in aggregate energy intensity over time generally followed the trends in trucking energy intensity, except for the cases in Canada, the U.S., and France, where trucking as a share of total freight transport activity has increased substantially over the last two decades (Fig. 4).

Having discussed the international trends in freight transport activity and energy intensity, we now investigate the consequences of the multiplicative relationship between the factors of freight CO₂ emissions—activity, structure, intensity, and fuel mix—over the last two decades or so. Fig. 8(a) shows an actual average annual percentage change in CO₂ 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 Fig. 8(b) presents the same calculation conducted for the period between 2000 and 2007. Note that the activity effect is further decomposed into the GDP effect and the activity-intensity-of-GDP effect to illustrate their relative influences on the change in CO₂ emissions. In sum, we now have five factors contributing actual change in freight CO₂ emissions—GDP, activity intensity, modal structure, energy intensity, and fuel mix.

Four important points should be made with regard to the decomposition analysis. First, total CO₂ emissions have all increased in both periods—except for Japan in the 2000s—and the rate of increase varied considerably among 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 CO₂ emissions changes was minimal. This is because diesel is still the dominant fuel for all of the freight transport modes, particularly for trucking, and the electrification of rail freight does not

necessarily reduce CO₂ emissions. This finding suggests that if a large-scale, lower CO₂ substitute for diesel were available, the fuel mix effect could have a significant impact on future emissions. Broader use of dedicated commercial bioenergy would contribute to decarbonizing the sector (Luckow et al., 2010).

Second, in most of the countries represented, economic growth has slowed down over the last two decades, and the coupling between GDP and freight volume has been loosened, resulting in the moderation in the growth of freight activity. Yet, in Spain and Korea, the moderation in GDP growth over the last two decades, combined with the improvement in energy intensity, was not great enough to offset the intensification of freight activity (tonne-km/\$ of GDP) in the later period (2000–2007). As a result, the increases in freight CO₂ emissions remain strong, which is consistent with the findings from Fig. 5. Spain's rapid population growth particularly in the 2000s and Korea's economic recovery after the Asian Financial Crisis may partly explain the trend.

Third, while declining energy intensity in the 1990s had put downward pressure on CO₂ emissions in Canada, the UK, Australia, and Sweden, it did so in a greater number of countries in the 2000s such as Canada, Japan, France, Australia, Germany, South Korea, and Spain. That is, the increases in GDP in these countries would have led to even greater CO₂ emissions growth if the corresponding reductions in freight energy intensity had not occurred. However, in the UK, Sweden, and Denmark, increases in CO₂ emissions have become even faster in the 2000s as their aggregate energy intensities did start to rise. The intensification in freight energy use was driven mainly by the increases in the energy intensity of heavy trucking in those countries (Fig. 7).

The last important point is that, in many of the countries, the changes in modal structure toward trucking have put upward pressure on CO₂ emissions over the last two decades. Increased trucking indeed has been the major driver of increases in

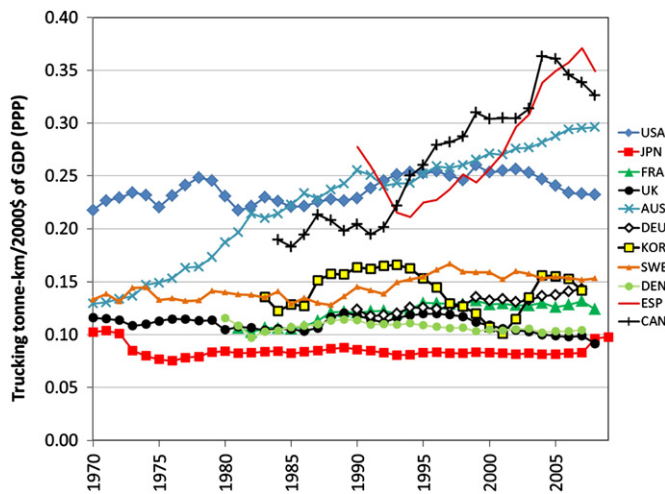


Fig. 9. Trucking intensity of GDP (heavy and light trucking combined).

emissions, particularly in Canada and Germany during the 1990s and in France and the UK since 2000: in these countries, overall trucking has rapidly supplanted rail and water transport. The three modest exceptions are the U.S., Australia, and Germany in the 2000s, where moderate changes in modal structure partly offset increases in CO₂ 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.¹⁴

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 slowed 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 CO₂ emissions. This implies that if the moderating activity trend continues in the IEA countries, major opportunities for freight CO₂ emissions reduction will increasingly arise from the improvement of the energy intensity and modal structure planning in the freight transportation sector.

3.2. Trucking energy use and carbon emissions

To properly identify the intensity- and structure-related opportunities for CO₂ 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 CO₂ emissions from the ten IEA countries' freight transportation sector over the last two decades.

Not surprisingly, the trucking intensity of GDP varies widely across the countries and has fluctuated considerably within the countries (Fig. 9). A comparison of the trucking intensity of GDP (Fig. 9) with the total freight activity intensity of GDP (Fig. 5) offers several insights into the significance and characteristics of trucking in the freight transport sector in the eleven IEA countries.

First, the variation in the trucking intensity of GDP across the countries is not as great as the case of total freight activity intensity, and their cross-country orderings are also different. It appears that non-income effects, perhaps coming from the differences in geographical coverage and attendant supply chain characteristics, have had less influence on trucking activities than

on non-trucking activities—rail and water transport (Bennathan et al., 1992). This is consistent with the above finding that the larger countries tend to have relatively larger shares of rail and water freight activity than the others. Another interesting finding is that Spain, which distinguishes itself from the larger countries in terms of total freight intensity of GDP, now became comparable to them in terms of the trucking intensity. This is because of Spain's heavy reliance on trucking, currently accounting for as much as about 85% of total freight activity.¹⁵

Even more importantly, no major indication of decoupling was found between GDP and trucking activity in most of the countries.¹⁶ National-level trends in the trucking intensity of GDP are even reversed from those in total freight activity intensity of GDP in several countries. In particular, Canada, Australia, and, to a lesser degree, the U.S., all of which had largely non-increasing total freight activity intensity, now exhibit the overall increases in the trucking intensity (Fig. 9)—note that in the U.S. rail activity intensity increased at the same time, counterbalancing the decrease in water activity intensity. The indication is that, over the last several decades, these large countries have intensified the use of trucking as the major mode to fulfill the demand for freight service. With the change in the structure of the economies, rail and water freight transport did not grow as fast as it might, while the demand for trucking increased far more rapidly. Rail haulage may not continue to increase in these countries because of its close association with shipments of energy, raw materials, and grains (Schewel and Schipper, 2011; Schipper et al., 2000—for Australia; Schipper et al., 1994—for Sweden), although the rapid growth of long-haul containerized traffic on the U.S. may partially offset a traffic shift to trucking that would otherwise have occurred. In the U.S., with fossil fuels accounting for nearly half of all US rail freight activity, the future of these fuels particularly in a CO₂ constrained world may have an even bigger impact on the future of rail freight demand. All of these suggest that, although the ongoing structural shift and potential CO₂ mitigation policies in the developed economies are likely to result in the decoupling of the growth in rail and water freight demand from the growth of GDP, they may not necessarily translate into the decoupling of the growth in trucking demand.

Like the trends in trucking intensity of GDP, trucking energy intensity has varied considerably across and within the countries (Fig. 10). Such variability was also pointed out by earlier studies by Kamakate and Schipper (2009) and Schipper et al. (1997), and it reflects differences and changes in the average size of truck, freight load, haulage, fuel prices, and technical and operational efficiencies (Schipper et al. 1997; IEA, 2007a; Thompson, 2009).

Interestingly, no agreement was found in the trends of trucking energy intensities among the countries over the last two decades (Fig. 10)—Denmark, the UK, Sweden, South Korea, and Spain have experienced steady or temporary increases in trucking energy intensities over the last two decades, while the other countries have generally had steady improvement.¹⁷ This is

¹⁵ One possibly unrecognized cause of Spain's heavy reliance on trucking is that the Spanish railway system has a different gauge than the rest of the E.U., so international rail freight has been significantly hindered.

¹⁶ Some steady decreases in trucking intensity of GDP were found in Denmark and the UK. The trend in Denmark is mainly attributable to improved logistics (Kveiborg and Fosgerau, 2007), and the trend in the UK may be due to the structural shift in the economy (Sorrell et al., 2010).

¹⁷ South Korea and Spain have experienced temporary energy intensification in the 1990s. In the case of South Korea, the period of trucking energy intensification matches well with the time when the substantial reduction in load factor of heavy trucks occurred (see Fig. 11). Not coincidentally, in the early 1990s, the structure of the Korean economy started to shift toward a service-based economy, and in 1997 the Asian Financial Crisis occurred, which also drastically changed the country's structure of passenger transport (Eom and Schipper, 2010).

¹⁴ The moderation in the modal shift toward trucking in the U.S., as well as its gain in rail share, is partly attributed to the deregulation of the freight transportation market that occurred in 1981 and its broader impacts on the competitive position of rail versus trucking.

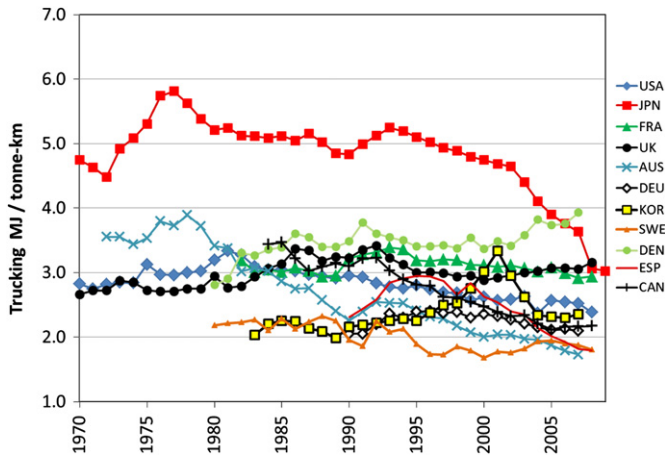


Fig. 10. Energy intensity of trucking (heavy and light trucking combined).

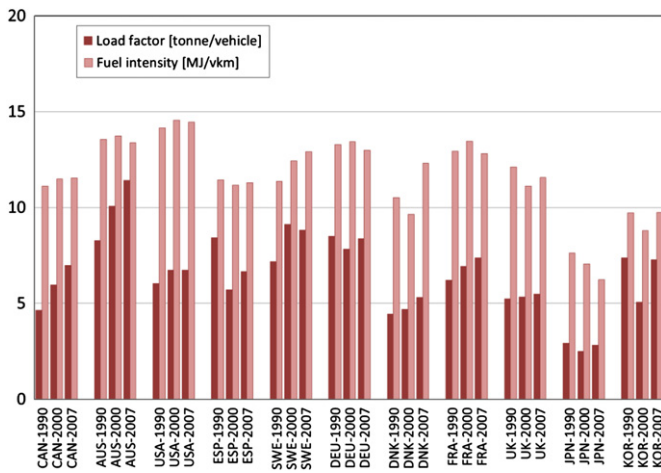


Fig. 11. Load factor and fuel intensity of heavy trucking in 1990, 2000, and 2007.

surprising because the same mixed trends in international trucking energy intensities were pointed out by Schipper et al. (1997) based on earlier data of 10 IEA countries covering between 1973 and 1992, and, since then, despite steady improvements in trucks' technical efficiency and global restructuring of the sector, the mixed trends still persist.¹⁸

To help understand the trends in trucking energy intensity, we discuss the changes in two major indicators related to heavy trucks, which account for the most part of overall trucking: load factor (tonne/vehicle) and fuel intensity (MJ/vehicle-km). Similar to the energy intensity of heavy trucking, load factor and fuel intensity have spanned wide ranges (Fig. 11). The differences in fuel intensity reflect differences in fleet mix within heavy trucks, their technical efficiency, or road conditions.

In fact, the difference in actual fuel efficiencies has been only a small part of the energy intensity equation. Vehicle size, the shares of capacity carried, and empty hauling may have been even more important (McKinnon et al., 2003; McKinnon, 2008). For instance, the Japanese trucking sector has been most energy intensive because its trucks are lightly loaded and small in size, even exclusive of mini and small trucks (Kamakate and Schipper, 2009). This made the country's trucking fuel intensity the lowest

¹⁸ Global average trucking energy intensity estimated by IEA (2009) reports slow but steady improvements between 1995 and 2005, perhaps driven by the improvement in energy efficiency in countries with major trucking volume.

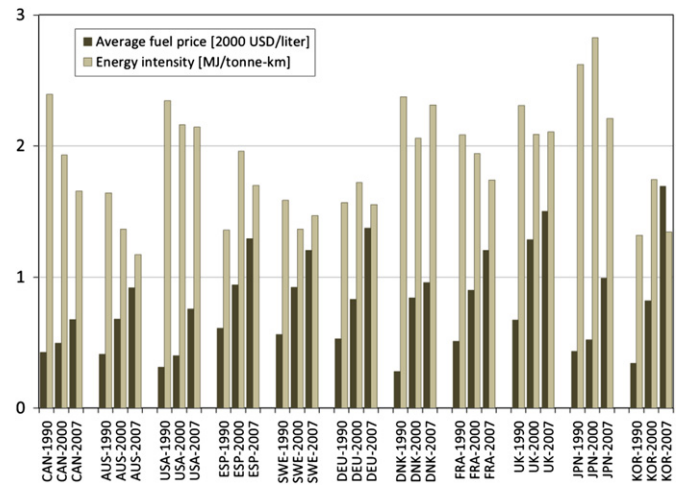


Fig. 12. Average fuel price and energy intensity of heavy trucking in 1990, 2000, and 2007.

(Fig. 10 and Fig. 11). Aside the issue of potential overestimation of trucking energy consumption, Denmark has energy intensive trucking sector because its large share of light trucking perhaps because the country has relatively low diesel price (Schipper et al., 1993), its heavy trucks are on average characterized by relatively low load factor and low payload weight (IEA, 2009), and it has very little domestic long haulage (Schipper and Marie-Lilliu, 1999). The most notable case is Australia, which has experienced pronounced reduction in trucking energy intensity over the last three decades, helped by increasingly intensive and efficient use of very heavy long haul trucks, so called 'road trains.' It is not a coincidence that Australia's heavy trucks became increasingly more loaded without an increase in fuel intensity. Sweden and Germany have consistently been among the lowest in trucking energy intensity because of the heavy and efficient truck shipments of raw and manufactured products.

Fuel price might have played a critical role in affecting trucking energy intensity by promoting utilization of vehicle capacity. During the 2000s, for example, heavy trucking energy intensities in Japan, Germany, Spain, and South Korea started to fall or declined more rapidly than ever before. Over the same period, these countries had experienced unprecedented increases in fuel prices (Fig. 12). It turned out that whether each country's heavy trucking energy intensity increases or decreases in a given time period is largely correlated with its 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 trucking energy intensity indicated that the "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 UK. These findings suggest that the recent price effects in Japan, Germany, and Spain may have promoted improvements in trucking energy intensities in the 2000s, including the increases in trucking load factor. It should be noted however that the change in trucking fuel price has not been large enough to dictate changes in modal share in the countries examined, although we lack a full understanding of price elasticity for both individual modes and cross-modal substitution. A few exceptional studies on this subject also suggest that a major increase in oil price is not sufficient to force a modal shift toward rail (Beuthe et al., 2001; Schade et al., 2008).

Another important driver that probably contributed to an improvement in trucking energy efficiency is the liberalization of the trucking

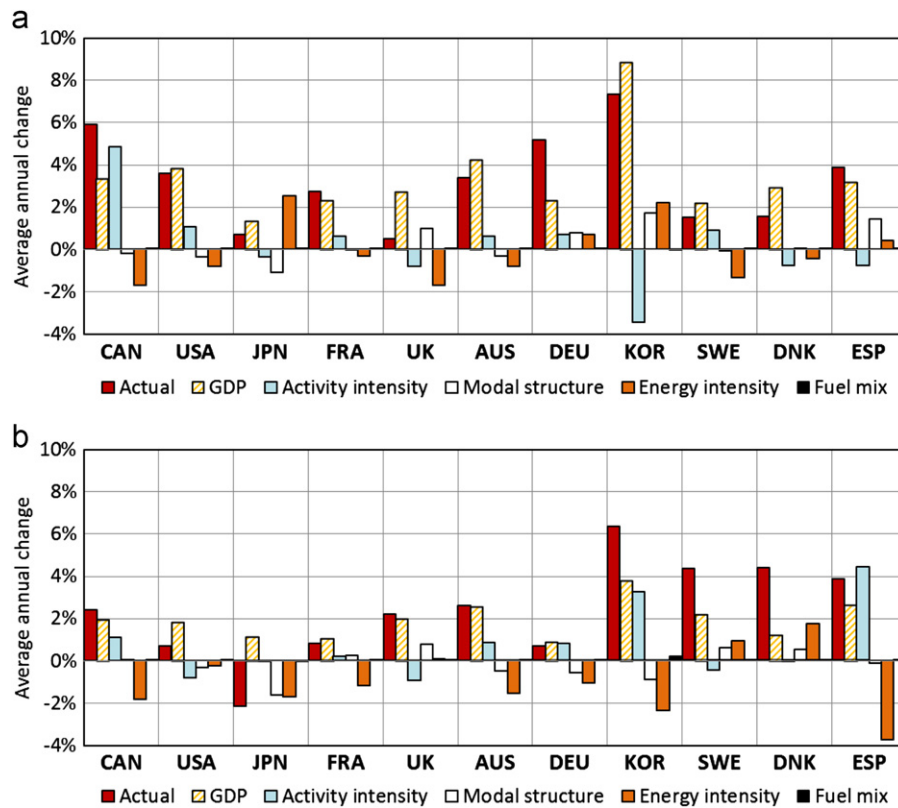


Fig. 13. Laspeyres decomposition of trucking CO₂ emissions between 1990–2000 and 2000–2007. (a) Decomposition of CO₂ emissions change between 1990–2000 and (b) decomposition of CO₂ emissions change between 2000–2007.

industry—in Europe during 1990s (the creation of a single market coupled with deregulation) and the reforms in non-European countries during 1980s and 1990s. These reforms have promoted competition between trucking companies, while lowering freight rates and improving productivity (Boylaud and Nicoletti, 2001).

To better understand the international trends in trucking CO₂ 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 t of load capacity) and light trucks (below 3.5 t). 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. Fig. 13(a) shows the actual average annual percentage change in trucking CO₂ 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 Fig. 13(b) presents the same results for the period between 2000 and 2007.

We found that the countries' trucking CO₂ emissions have all increased in both periods, except for Japan in the 2000s (Fig. 13). Yet, the rate of the increase in CO₂ emissions varied considerably, mainly due to differences in the rates of the changes in GDP, activity intensity, modal structure, and energy intensity. Also, among them, the growth rates of the trucking CO₂ emissions and the energy intensity effect are virtually the same as those of the total freight CO₂ emissions and the freight energy intensity effect shown in Fig. 13, confirming that the trucking sector has been largely responsible for the energy intensity changes of the entire freight transportation sector.

While in all of the countries, the growth in trucking CO₂ emissions has moderated over the last two decades because of the slow-down in economic growth, in many countries it involved an intensification of trucking activity in relation to GDP

(Figs. 9 and 13). Particularly in South Korea and Spain, the previously decreasing trucking intensity of GDP has started to increase in the 2000s, mainly contributing to the increases in trucking CO₂ emissions in the latter period, as is the case of the decomposition of total freight CO₂ emissions (Fig. 8). In these countries, improvements in supply chain to reduce average handling factor and average length of haul would help reduce trucking CO₂ emissions. The effect of fuel mix (mostly from gasoline to diesel in light trucks) has been negligible, and the effect of energy intensity is mixed as indicated by Fig. 10. The shifts in modal structure towards light trucks during the 1990s put upward pressure on CO₂ emissions in several countries including the UK, Germany, South Korea, and Spain; but, since 2000, the trend has been weakened or even reversed, resulting in lower emissions than they would otherwise.

Overall, in all of the countries, economic growth has moderated, which made the contributions of the activity intensity of GDP, trucking energy intensity, and, to a lesser extent, modal structure relatively important in determining the future of CO₂ emissions. The above finding suggests that major opportunities for the reduction in trucking CO₂ emissions, and more broadly total freight CO₂ emissions, may come from reducing the dependency of the economy on trucking, improving the utilization of vehicle capacity, and promoting a shift to heavier trucks. This would require coordinated regulatory intervention and economic incentives to transform how goods are produced, handled, and delivered to consumers, although consumer preference for 'just-in-time' delivery may continue to pose major challenges.

3.3. Railway Energy Use

Rail freight transport requires special attention because of the presence of electricity demand that is derived from other primary

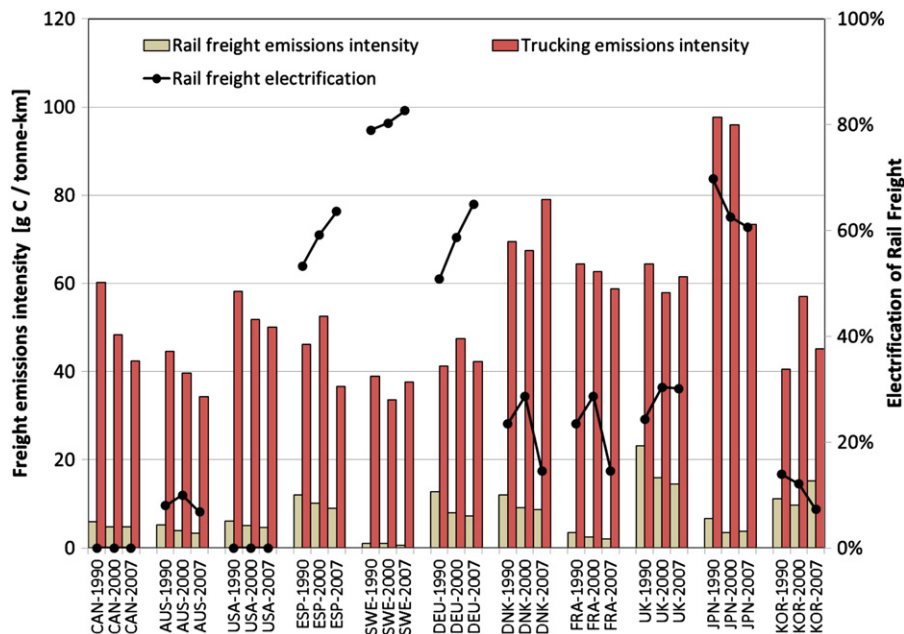


Fig. 14. Emissions intensities of rail and truck freight and electricity shares in rail freight energy.

sources. A reduction in the overall energy intensity of rail freight [MJ/tonne-km] may come either from improvement in rail freight operations or, in some instances, from electrification of the sector away from diesel, depending on the fuel mix and efficiency of the power sector. Rail electrification can lead to an efficiency gain of around 15% on a life-cycle basis due to lower energy losses in power generation than in ICEs and the opportunity of using regenerative braking and minimizing idling (IEA, 2009). Similarly, any change in the carbon intensity of rail freight [gC/tonne-km] can be made either by the change in the energy intensity of rail freight [MJ/tonne-km] or by the change in the carbon emissions per energy consumed [gC/MJ], both of which are somewhat responsive to the degree of electrification in rail freight.

Comparing carbon emissions intensity of rail freight [gC/tonne-km] with the share of electricity use to total rail freight energy gives a sense of how carbon-intensive the rail freight sector is and what rail electrification has done for the sector's CO₂ emissions (Fig. 14). Note that the carbon emissions of rail freight include both its direct diesel emissions and a portion of power sector emissions attributed to rail freight electricity demand.

Our life-cycle analysis of emission intensities of rail and truck freight indicates that there is a significant opportunity of reducing total freight CO₂ emissions by shifting toward rail away from trucking in all of the countries, although its potential magnitude varies substantially (Fig. 14). Potential CO₂ reductions from the modal shift essentially depend on the relative energy intensity of rail freight transport to trucking and the relative carbon coefficient of rail freight fuel to trucking fuel—the relative carbon coefficient is determined by the levels of electrification in rail freight and carbon emissions associated with producing and delivering electricity. For example, Japan presents the greatest opportunity because of its inefficiency in trucking combined with the relatively high degree of rail electrification, although Japan may have the least potential for shifting traffic because of the dominance of passenger traffic on the railways (and the Shinkansen system carries no freight at all). Modal switch toward rail would also help France and Sweden further reduce freight CO₂ emissions. This is because their rail freight sector is least carbon intensive owing to the high degrees of rail electrification coupled with the least carbon intensive power sector—the countries' rail

freight has relied mainly on electricity that is delivered predominantly by nuclear and hydro power. Germany and South Korea, however, would not gain as much because of their relatively high levels of rail emissions intensities and modest levels of trucking emissions intensities. This effect will be magnified in Germany if the current plans to close nuclear generation are carried out.

In most of the countries represented—except for South Korea and Japan in the 2000s—total rail emissions intensity has decreased over the last two decades (Fig. 14). This change may have been driven by the improvement in rail freight logistics or, in a few cases, by rail electrification coupled with cleaner power sector. The continued electrification in France and Sweden, in particular, would make their rail freight sector even more energy-efficient and less carbon-intensive.

However, several countries where the rail freight sector is energy-efficient from the final energy point of view, owing to their high rail electrification, turned out to be relatively carbon-intensive because of their high carbon coefficient of electricity (Fig. 14). These countries include Spain and Germany.¹⁹ Although continued electrification of the sector, combined with improvement in rail freight logistics, has put downward pressure on its carbon intensity over the last two decades, drastic reduction in the sector's carbon intensity is not likely to occur until the power sector is decarbonized at the same time. Countries with both energy- and carbon-intensive rail freight sector include the UK and, to a lesser extent, Denmark and South Korea. Further rail electrification in these countries might decrease energy intensity of rail freight, but not as much in terms of the carbon intensity of rail freight because of the power sector's heavy reliance on fossil fuels.

There is a paradox involved in rail freight efficiency. "More than one-third of all the world's CO₂ emissions from energy production and consumption come from carbon-based fuels (principally coal) hauled by railways. By comparison, if all of the world's railway coal traffic were shifted to trucks, the total world emission of CO₂ would increase by slightly more than 2%. There is

¹⁹ According to our calculation based on detailed national energy balances published by IEA (2010), about 180 kg and 130 kg of CO₂ are emitted to deliver 1 GJ of end-use electricity in Germany and Spain, respectively, which is higher than railway diesel's carbon coefficient of 74.1 kg/GJ used by IPCC.

thus a dilemma posed by the fact that railways' very energy efficiency facilitates the transport of fuels that add to the GHG challenge." (Thompson, 2010) This means that other technologies, especially carbon capture and sequestration may ultimately have a major effect on transport GHG emissions.

To summarize, electrification helps reduce energy intensity of rail freight (MJ/tonne-km) by displacing less-efficient diesel use, but it may also increase carbon intensity of energy (gC/MJ) because of carbon-intensive power generation in many of the industrialized countries. In this sense, Canada might benefit more from rail electrification than the U.S. because of Canada's much cleaner power sector that relies mainly on hydro and nuclear power. Possible introduction of an economy-wide carbon policy in the future, which leads to less carbon-intensive power generation and more costly diesel supply, might further reduce CO₂ emissions from rail freight, not only by accelerating the sector's electrification but also by promoting the modal shift toward cleaner rail freight away from diesel-based trucking.

4. Conclusions and policy insights

Over the last three decades, per capita energy demand for freight transport and the associated CO₂ emissions have continued to increase in nearly all of the IEA countries examined in this study, except for Japan. The countries also have taken wide ranging emissions pathways even at the same income level. Using national authoritative data starting from as early as 1970 extending to 2007–2010, we decomposed each country's freight CO₂ emissions as the combined effect of freight service demand—GDP and freight activity 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 the relationship between total freight volume and income has been substantially different among the eleven countries, depending upon more fundamental factors such as geographical coverage, economic structure, and foreign trade. The positive indication is that, over the last decades, many of the IEA countries represented have experienced decreased coupling between total freight volume and income. This was made possible by the ongoing structural shift in the economy away from the industrial sector and its decreased dependency on rail and water freight. Despite fundamental economy dynamics that might limit the extent to which the coupling can be loosened in the future, it is expected that the structural shift among developed economies may continue to put downward pressure on freight transport requirement per unit of economic output and potentially on its attendant CO₂ emissions at least at the country level. Yet, this might not be the case at the global level, in which the structural shift would ripple through multiple countries characterized by less efficient conditions of supply chain and energy and carbon intensities.

Nevertheless, our analyses indicate that the recent development of trucking sector and its energy demand indeed pose major challenges to slowing and even reversing the growth in freight CO₂ emissions. No major indication of loosened coupling between trucking volume and GDP was found over the last several decades; in fact, the coupling has been strengthened in many of them. The share of trucking in total freight activity continued to increase in most of the countries. On top of this, the energy intensity of trucking, which is much higher than those of other modes, has presented very large variation among the countries, and their overall trends are still mixed, suggesting that overall handling of truck freight or road traffic management is yet to be optimized. Because of the simple dominance of trucking in freight transport, similar variation and mixed trends in the energy intensity of overall freight sector were observed from the

countries. The suggestion is that loosening the coupling between trucking and economic growth and improving trucking energy efficiency must be an essential part of strategies to reduce freight CO₂ emissions. Streamlining the supply chain and better utilizing vehicle capacity would help decarbonize the sector, although increasing demand for final and intermediate products in a 'just-in-time' manner would, to some extent, offset the gains. In the longer term, broader use of dedicated commercial bio-energy would make a sizeable difference as well.

Modal shift toward rail freight away from trucking presents a substantial opportunity to reduce freight CO₂ emissions in the developed countries represented in this study, although the potential gain varies widely among them. Although rapid modal shift is not likely in the short term, given the rail infrastructure requirement and the existing investment in infrastructure and vehicles, worsening road congestion occurring in many of the countries could promote this transition. 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 severely limited by existing rail capacity and passenger usage (Vassallo and Fagan, 2005). In this regard, the separation of infrastructure from rail operations that is mandated in the E.U. may help maximize the total benefits from the use of rail infrastructure, and the rise of high-speed rail on its separate tracks may also to some extent liberate capacity for slower freight services. Nevertheless, any effective longer-term policy to promote rail freight in the E.U. would have to be matched by major capacity investment programs and would probably not be able to attain modal shares as high as those observed in the U.S. and Canada. This study also indicates that electrification of rail freight transport itself may not necessarily reduce CO₂ emissions. This is because the inherently higher efficiency of electric power train over diesel locomotive is partly offset by delivery losses and, given inefficient, carbon-intensive power generation, also by increased carbon intensity of overall rail energy use.

In the long term, countries may be well advised to review their transport policies to remove any barriers to improving transport energy efficiency, including more efficient and balanced freight transport planning, removal of adverse regulation (the transport deregulation in the early 1980s in the U.S. both promoted a shift from road to rail and freed the railroads to invest in more efficient technology), and fuel tax policies. In addition, countries should contemplate other tools, such as concessioning or privatization of the rail freight sector, which improve the institutional incentives for efficient and market-driven operation. Countries could also consider broad-based policy arrangements, such as promoting better siting of industry facilities and freight infrastructure, that account for where goods are delivered and demanded. Also the implementation of an aggressive carbon policy that influences the choice of energy-efficient freight transport modes may also be useful. With this said, we should also recognize that existing transport energy tax policies add a great deal of "noise" to what might otherwise be a straightforward calculation. As wide variations in existing diesel and gasoline prices among a number of countries suggest (GTZ, 2008), any reasonable carbon tax on fuels would be far smaller than current fuel taxes that are imposed primarily to generate general revenues rather than to finance transport facilities. The desired impact of realistic carbon taxes on fuel may be lost in the noise of other revenue generating tax policies.

Appendix

This appendix details data sources and major assumptions made for the individual countries explored in this paper. The data

used in this study mostly come from official transportation and energy statistics or other authoritative sources. The key data include annual energy consumption by four freight transport modes—heavy truck, light truck, rail, and water—each mode's energy consumption by fuel type, freight activity (tonne-km), distances driven (vehicle-km), and load factors (ton/vehicle). In many cases, the authors' reasoned judgment and personal communications with national experts were made to fill out missing data categories, to reconcile alternative data sources, and to interpolate for missing years. Occasionally, we also employed the dataset presented in Schipper et al. (1997) and Kamakate and Schipper (2009). In addition, most of the rail freight data come from either national railway sources, or from the International Union of Railways.

Australia: Trucking energy consumption by mode from Apelbaum Consulting's Australian Transport Facts (2009) complemented by ABARE's Australian Energy Consumption (2008) (<http://abare.gov.au>); Domestic water freight energy consumption calculated based on Australian Energy Consumption (2008) complemented by Australian Transport Facts (2009); Trucking and shipping activities by mode and recent year estimates from Freight Measurement and Modeling in Australia (2006) published by the Bureau of Transport and Regional Economics.

Canada: Light and medium-heavy trucking (below 14.9 t) energy consumption, fuel consumption rate, and freight activities by fuel back to 1990 all from the Office of Energy Efficiency (OEE) of Natural Resources Canada (business trucking only); Very heavy trucking (over 14.9 t) activity from OEE and its distances driven calculated based on an assumed average load of 14.74 taken from 2006 National Roadside Trucking Surveys; Heavy trucking fuel consumption derived by assuming an average fuel consumption rate of 46.88 l/1000 km taken from the Mobile Greenhouse Gas Emissions Model; Own-account trucking activities calculated by multiplying OEE's trucking activities with the multiplier of 0.3 and its fuel consumption derived by assuming the same freight energy intensities for a given truck class; Domestic water freight activities from North American Transportation Statistics Database (<http://nats.sct.gob.mx/nats/>) and its fuel consumption derived by assuming the U.S. domestic water freight energy intensity.

Denmark: Heavy trucking energy consumption, fuel consumption rate, and freight activity by mode and fuel from the Danish Road Directorate's database, complemented by Odyssee Energy Efficiency Indicators (<http://www.odyssee-indicators.org>) and Danish Energy Agency's Energy Statistics (2009); Light truck fuel consumption from Odyssee Indicators and light truck activity from vehicle-km data from Danish Road Directorate's database with an assumed load factor of 0.7 (t/veh); Domestic water freight energy consumption has some degree of uncertainty. It was derived from the Energy Statistics' aggregated shipping fuel consumption splitted into passenger and freight uses based on the ratio from a detailed consumption dataset published by Danish Energy Agency in 1992; Domestic water freight activity from StatBank Denmark (<http://www.statbank.dk>).

France: Trucking energy consumption, fuel consumption rate, and freight activity by mode and fuel, as well as water freight energy consumption, all from the detailed dataset from *Le Bilan de la Circulation* (2010) published by the Ministère des Equipments; Domestic water freight activity from Odyssee Indicators.

Germany: Trucking energy consumption and fuel consumption rate by mode and fuel from various *Wochenbericht* published by Deutsches Institut für Wirtschaftsforschung (DIW) and from communication with a DIW staff; Heavy trucking activity from *Verkehr in Zahlen* published by DIW and light trucking activity from *Wochenbericht's* distance traveled multiplied by an

assumed load factor of 0.7 (t/veh); Water freight energy consumption and activity all from *Verkehr in Zahlen*.

Japan: Trucking energy consumption, fuel consumption rate, and freight activity by mode and fuel all from Road Transportation Statistics Yearbook (various years) published by the Ministry of Land Transport and Infrastructure; Domestic water freight energy consumption and freight activity from the database of Energy Data Modeling Center.

South Korea: Trucking and water freight energy consumption, fuel consumption rate, and freight activity by mode and fuel all from Korean Energy Consumption Survey (KECS), which has been conducted every three years since 1983 by the Korean Energy Economics Institute; Interpolation was made for missing years between KECS survey years, complemented by the Statistical Yearbooks (various years) published by the Ministry of Land, Transport, and Marine Affairs; For more details, see Eom and Schipper (2010).

Spain: Trucking and water freight energy consumption, fuel consumption rate, and freight activity by mode and fuel primarily from the 2009 Anuario Estadístico of Spain's Ministerio de Fomento, complemented by data in "Lostransportes, las infraestructuras y los Servicios Postales," a comprehensive annual report for the transportation industry also published by the Ministerio de Fomento; Trucks are divided into light and heavy trucks based on "Encuesta Permanente de Transporte de Mercancías por Carretera" for heavy trucking activity and IDEA (Spanish Energy Efficiency Agency) for light trucking vehicle distance; For more details, see Mendiluce and Schipper (2011).

Sweden: Freight energy and activity data for historical years tabulated by Schipper and Price (1994); Heavy trucking activity from the Central Bureau of Statistics (SCB); Trucking energy consumption by mode and fuel calculated based on Road Transport CO₂ emissions obtained from Energimyndigheten, complemented by Odyssee Indicators; Trucking vehicle distance by mode from Körsträckor dataset published by Statens Institute for Kommunikations Analyser (SIKA); Light trucking activity calculated based on an assumed load factor of 0.7 (t/veh); Water freight activity from SCB and water energy consumption from Statens Energimyndighet's reports, *Transportsektorns Energivändning*, and its interpolates.

United Kingdom: Trucking vehicle-km and activity by mode from Department for Transport's Transport Statistics Great Britain (2009) adjusted by the population ratio of the UK to Great Britain; Trucking energy consumption by mode and fuel from Energy Consumption in the UK (2009) published by Department of Energy and Climate Change; Water freight activity from the Transport Statistics and its energy consumption from the Energy Consumption in the UK with the assumption of domestic shipping energy all used by water freight.

United States: Trucking energy consumption, vehicle-km, and freight activity by mode from the Oak Ridge Transportation Energy Data Book (various years) and the National Transportation Statistics published by the Bureau of Transportation Statistics; Light trucking activity calculated based on an assumed load factor of 0.7 (t/veh); Light trucking data interpolation for missing years based on Truck (Vehicle) Inventory and Utilization Survey available on the U.S. Census Bureau; For more details, see Schipper et al. (2011).

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