Decomposing road freight energy use in the UK

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Abstract

UK GDP increased by 43.3% between 1989 and 2004, but energy consumption for road freight is estimated to have increased by only 6.3% Applying the techniques of decomposition analysis we estimate the relative contribution of ten variables (termed 'key ratios') plus GDP to the change in road freight energy use. The results are best interpreted as an estimate of the percentage growth in energy consumption that would have resulted from the change in the relevant key ratio (e.g. length of haul) had the other ratios remained unchanged. The results demonstrate that the main factor contributing to the decoupling of UK road freight energy consumption from GDP was the decline in the value of domestically manufactured goods relative to GDP. Over the period 1989-2004 this largely offset the effect of increases in GDP on road freight energy consumption. While the decline in domestic manufacturing was to some extent displaced by increases in imports, the net effect of these supply factors, together with shifts in the commodity mix, has been to reduce UK road freight energy consumption by 30.1% KOKO. The net effect on global carbon dioxide (CO_2) emissions is likely to be somewhat less beneficial, since many freight movements associated with the manufacture of imported goods have simply been displaced to other countries.

Introduction

The contribution of freight transport to climate change is substantial and growing. Globally, freight transport accounts for one third of transport energy consumption and around 8% of total energy-related carbon dioxide (CO_2) emissions. The bulk of these emissions derive from heavy goods vehicles (HGVs), which in most countries account for the majority of freight activity. In the UK, for example, HGVs account for more than 95% of goods moved (tonne kilometres), 24% of road fuel use, 22% of transport CO_2 emissions and 5% of total CO_2 emissions.

Despite this, freight transport has been relatively neglected in terms of both climate policy and the associated policy research. Policy initiatives to restrain the growth in energy use and carbon emissions from this sector (e.g. the UK Sustainable Distribution Strategy) have been both limited and ineffective, while policy research has focused disproportionately upon passenger transport. Both the European Union and the UK have the stated goal of decoupling various measures of road freight activity from GDP, but this has generally been interpreted as relative rather than absolute decoupling - implying that energy use and carbon emissions could continue to increase, even if the objective was met.

Freight activity is driven by complex and interlinked trends in production, trade, distribution and retail, including income growth, wider sourcing of products, increased specialisation, 'just-in-time' distribution and increasing concentration of manufacturing and stockholding. The corresponding impact on energy use and carbon emissions is mediated by parallel trends in logistics, vehicle technology and the management of transport resources, including factors such as the size, fuel efficiency and average load factor of vehicles. Some of these trends have led to greater energy use in this sector over recent years, while others have encouraged reductions in energy use. If the growth in carbon emissions from freight transport is to be halted and reversed, the nature and relative importance of these trends needs to be better understood.

This paper contributes to that end by quantifying the relative contribution of eleven variables to the change in UK road freight energy use over the period 1989-2004. The paper uses decomposition analysis, which has only previously been applied to freight transport at a relatively aggregate level (Greening, et al., 1999; Lakshmanan and Han, 1997; Schipper, et al., 1992), However, freight transport researchers have developed similar but less formal techniques at a more disaggregated level using the notion of *key ratios* (McKinnon, 2007; Netherlands Economic Institute, 1997). For example, the ratio of the 'goods moved' by freight vehicles (tonne kilometres) to the 'goods lifted' by freight vehicles (tonnes lifted) represents one such key ratio (the average length of haul). This paper brings these two approaches together by conducting a formal decomposition analysis of energy use for UK road freight transport using ten individual 'key ratios' plus GDP. The only other study we are aware of that uses this approach is Kveiborg and Fosgerau (2007), who decompose road freight vehicle kilometres in Denmark using eleven key ratios.

The paper is structured as follows: Section 2 introduces the key ratios, summarises some relevant trends and explains how the Log Mean Divisia Index (LMDI) method of decomposition analysis was applied to road freight data for the UK. Section 3 outlines and interprets the results of this analysis, including the trends for individual commodity groups and vehicle types. Section 4 summarises the factors contributing to the relative decoupling of UK road freight energy consumption from GDP and highlights some policy implications.

Definitions and trends

This study identifies the relative contribution of ten key ratios plus GDP to the change in UK road freight energy use over the period 1989 to 2004[1]. The analysis is confined to energy use by heavy goods vehicles (HGVs) which have a gross vehicle weight exceeding 3.5 tonnes. These account for approximately 80% of goods lifted (tonnes) and 95% of goods moved (tonne kilometres) by road in the UK. Freight transport by light goods vehicles (<3.5 tonnes) is excluded owing to inadequate data, although this represents a hidden and growing source of freight transport. Each key ratio is formed from two key quantities (Tables 1 and 2). The first three ratios in the Table 2 are relevant to the supply of goods in the UK economy while the remainder are relevant to the transport of those goods. The key ratios are defined for each year (t) and several are disaggregated by commodity group (c) and/or vehicle type (k). If each key ratio remained unchanged over time then the overall relationship between GDP and road freight energy consumption should also remain unchanged. But in practice there will be changes in these ratios, brought about through either change in the relative importance of each commodity and/or vehicle type or changes in the key ratios for each individual commodity and/or vehicle type.

During the period 1989 to 2004, energy consumption for road freight in the UK is estimated to have increased by only 6.3% while UK GDP increased by 43.3%, implying that the aggregate energy intensity of UK road freight fell by 25.8% (Figure 1). During this period, therefore, the UK achieved relative but not absolute decoupling of road freight energy consumption from GDP. Figure 2 compares the trends in GDP to those of four other measures of road freight activity, namely: road tonnes lifted (*TLIFT*), road tonnes moved (*TKM*), loaded distance travelled (*VKM*) and total distance travelled (*VKMT*). Since total distance travelled did not increase as fast as either road tonnes moved or loaded distance travelled, trends in the composition and use of the vehicle fleet appear to have partly offset the factors encouraging the intensification of freight transport. Also, all of these measures of road freight activity are estimated to have increased by more than road freight energy consumption.[2]

The 'energy intensity' key ratio is defined as the energy use per vehicle kilometre (Table 2). But energy intensity may also be defined in other ways, such as the energy use per road tonne kilometre (*EI_TKM*), total tonnes lifted (*EI_MLIFT*), road tonnes lifted (*EI_TLIFT*), £ of goods supplied (*EI_MANT*) or £ of GDP (*EI_GDP*) – with the latter being the measure that is relevant to decoupling. Figure 3 compares the estimated trends in each of these measures over the period 1989 to 2004. This shows how the shift towards larger vehicles has reduced the energy use per tonne kilometre by more (12.7%) than the energy use per vehicle kilometre (2.5%). However, energy use per road tonne lifted fell by only 1.9% and a modal shift towards road freight led to a 1.0% increase in energy intensity when measured on the basis of tonnes lifted on all modes. On the basis of the total value of goods supplied, energy intensity increased by 7.6%, but when measured on the basis of GDP, road freight energy intensity fell by 25.8%. This suggests that it is the shift from manufacturing to services within the UK, rather than changes in the freight transport sector, that has played the dominant role in decoupling UK road freight energy consumption from GDP.

Methodology

Trends in energy consumption are frequently expressed as the product of two or more factors. For example, the energy consumption of an industrial sector (E_i) could be expressed as the product of the economic output (A_i) and energy intensity (E_i) of that sector ($I_i=E_i/A_i$). Total industrial energy consumption is then given by:

1. A longer time series would be desirable, but inconsistencies in the UK Input Output tables make it difficult to extend the analysis to before 1989. The analysis may subsequently be updated to include more recent years, but the 2005 changes in the format of UK freight statistics may create some discontinuities. Also, such updating is far from straightforward since there are numerous gaps and inconsistencies in the relevant time series and a great deal of effort is required to estimate the missing data - see Sorrell et al. (2008).

2. These conclusions are sensitive to the estimates of the proportion of total UK road freight activity that is undertaken by foreign-registered vehicles. Together with road freight activity in Northern Ireland, we estimate that this now accounts for one tenth of total UK road-tonne kilometres. Since the main data source on UK road freight only reports activity by GB-registered vehicles in Great Britain, it gives a misleading indication of the actual level of UK road freight activity. However, given the paucity of data on activity by foreign-registered vehicles, our estimates are subject to considerable uncertainty and may best be considered as an upper bound. However, this uncertainty does not affect our estimates of key ratios such as the average length of haul.

Table 1. Key quantities

Acronym	Definition	Measure
GDP_t	UK gross domestic product	£
$MAND_{ct}$	Value of domestically produced manufactured goods, broken down by commodity group	£
$MANT_{ct}$	Value of the total supply of manufactured goods, broken down by commodity group	£
$MLIFT_{ct}$	Weight of goods lifted by all modes of freight transport	Tonnes
$TLIFT_{ckt}$	Weight of goods lifted by HGVs	Tonnes
TKM_{ckt}	Weight of goods moved by HGVs	Tonne-km
VKM_{ckt}	Distance driven in loaded HGVs	Vehicle-km
$VKMT_{ckt}$	Distance driven in loaded and unloaded HGVs	Vehicle-km
$FUEL_{ckt}$	Estimated energy consumption by HGVs	Litres of fuel

Table 2 Key ratios (calculated from key quantities)

Acronym	Definition	Interpretation	Measure
$DOMMAN_t$	$\frac{MAND_t}{GDP_t}$	*Domestic manufacturing share*: ratio of the value of domestically produced manufactured goods to UK GDP (a measure of the economic importance of manufactured goods)	Fraction (<=1)
$CSHARE_{ct}$	$\frac{MAND_{ct}}{MAND_t}$	*Commodity share*: share of commodity group *c* in the total value of domestically produced manufactured goods (a measure of the economic importance of commodity group *c*)	Fraction (<=1)
$IDOMSHARE_{ct}$	$\frac{MANT_{ct}}{MAND_{ct}}$	*Inverse domestic commodity share*: inverse measure of the share of domestic production of commodity group *c* in the total UK supply of commodity group *c* (an inverse measure of the importance of domestic manufacturing for group *c*)	Fraction (>=1)
$FINT_{ct}$	$\frac{MLIFT_{ct}}{MANT_{ct}}$	*Freight intensity*: ratio of the tonnes lifted of commodity *c* onto all modes of freight transport to the value of the UK supply of commodity *c* (a measure of the 'freight intensity' of that commodity)	Tonnes lifted/£
$ROAD_{ct}$	$\frac{TLIFT_{ct}}{MLIFT_{ct}}$	*Road share*: share of tonnes lifted for commodity group *c* that are taken by HGV	Fraction (<=1)
$VSIZE_{ckt}$	$\frac{TLIFT_{ckt}}{TLIFT_{ct}}$	*Vehicle share*: share of HGV tonnes lifted for commodity group *c* that are taken by vehicle type *k*	Fraction (<=1)
LOH_{ckt}	$\frac{TKM_{ckt}}{TLIFT_{ckt}}$	*Length of haul*: average length of haul for commodity group *c* in vehicle type *k*	km
ILF_{ckt}	$\frac{VKM_{ckt}}{TKM_{ckt}}$	*Inverse payload weight*: an inverse measure of the average payload weight for commodity group *c* in vehicle type *k*	1/tonnes
$ERUN_{ckt}$	$\frac{VKMT_{ckt}}{VKM_{ckt}}$	*Empty running*: ratio of total vehicle km to loaded vehicle km for commodity group *c* in vehicle type *k* (a measure of the importance of 'empty running')	Ratio (>=1)
$EINT_{ckt}$	$\frac{FUEL_{ckt}}{VKMT_{ckt}}$	*Energy intensity*: ratio of energy consumption to total vehicle km for vehicle type *k* carrying commodity group *c*	litres per kilometre

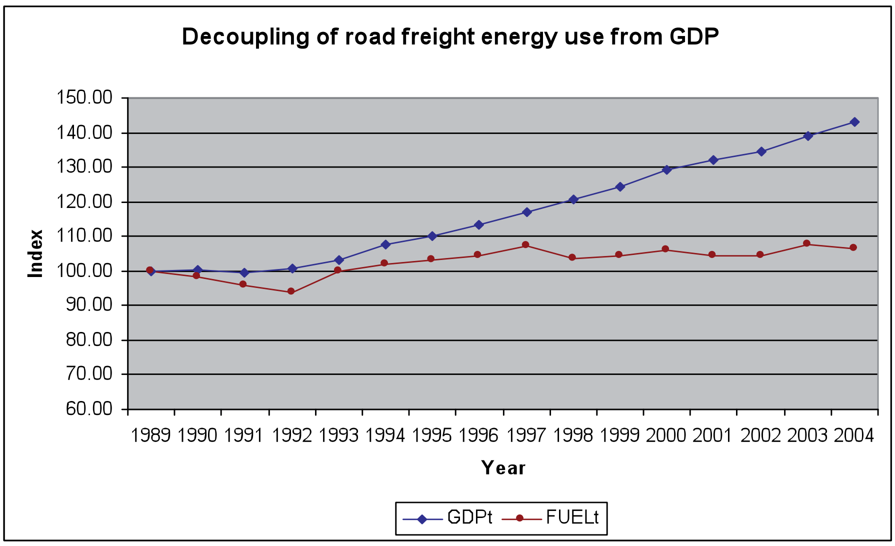

Figure 1. Decoupling of UK road freight energy use from GDP

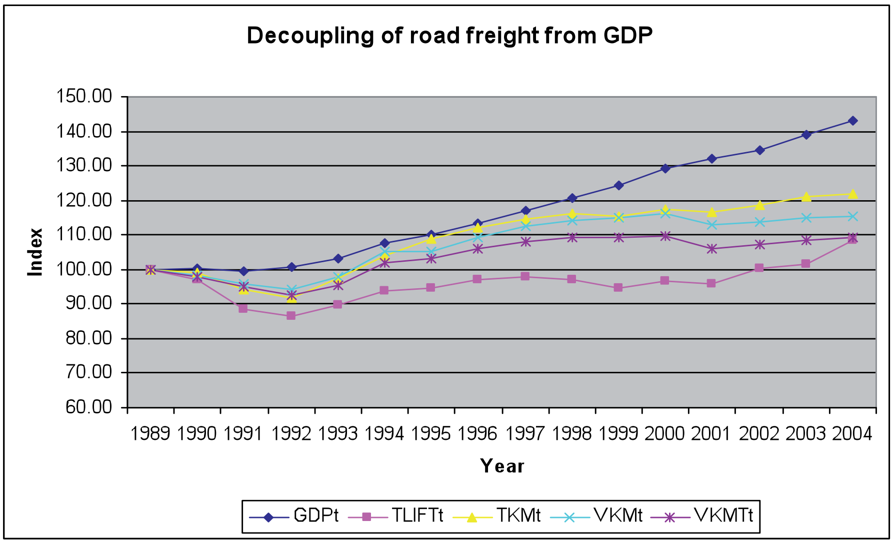

Figure 2. Summary of UK road freight decoupling trends - indexed change 1989-2004

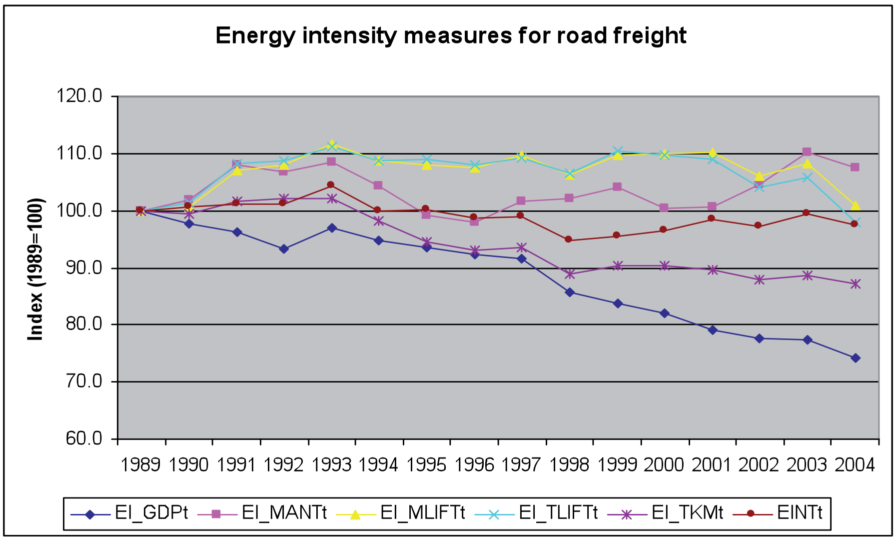

Figure 3. Measures of UK road freight energy intensity - indexed change 1989-2004

$$E = \sum_i E_i = \sum_i A_i I_i$$

If we express the share of total industrial output (A) for each sector as $S_i = A_i / A$, this can be rewritten as $E = \sum_i A S_i I_i$. The A, S_i and I_i terms are often referred to as *activity*, *structure* and *intensity* respectively. However, these terms are less appropriate when more than three factors are employed.

The objective of decomposition analysis is to quantify how changes in each of the right-hand side factors (A, S_i and I_i) have contributed to the overall change in the explained variable (E). For example, how much has changes in energy intensity (I) contributed to the measured change in energy consumption (E)? A *multiplicative* decomposition expresses the ratio of energy consumption at the end of the period to that at the beginning ($D^t_{TOT} = E^t / E^0$) as the product of comparable ratios for each of the right-hand side variables.

$$D^t_{TOT} = E^t / E^0 = D^t_A D^t_S D^t_I \qquad (1)$$

Here, each D^t_x is an estimate of the ratio of energy consumption in year t to that in year 0 that has resulted from the corresponding change in the relevant variable (x) over that period. So for example, D^t_A represents the estimated ratio of E_t to E_0 that has resulted from the change in total industrial output. Typically, some of the D^t_x will be greater than unity and others less than unity. So for example, increases in energy consumption as a result of increases in total industrial output ($D^t_A > 1.0$) may be partially or wholly offset by reductions in energy consumption as a result of reductions in energy intensity ($D^t_I < 1.0$). A variety of methodological approaches are available to estimate the D^t_x terms (Ang, 2004). This study uses the Log Mean Divisia Index (LMDI), which is increasingly becoming the preferred approach thanks to its flexibility and theoretical consistency (Ang, 2004a).

We begin by expressing the total energy consumption of truck type k carrying commodity group c in year t as the product of the key ratios:

$$FUEL_{ckt} = GDP_t \frac{MAND_t}{GDP_t}\frac{MAND_{ct}}{MAND_t}\frac{MANT_{ct}}{MAND_{ct}}\frac{MLIFT_{ct}}{MANT_{ct}}$$
$$\frac{TLIFT_{ct}}{MLIFT_{ct}}\frac{TLIFT_{ckt}}{TLIFT_{ct}}\frac{TKM_{ckt}}{TLIFT_{ckt}}\frac{VKM_{ckt}}{TKM_{ckt}}\frac{VKMT_{ckt}}{VKM_{ckt}}\frac{FUEL_{ckt}}{VKMT_{ckt}} \quad (2)$$

This may be rewritten as:

$$FUEL_{ckt} = GDP_t DOMMAN_t CSHARE_{ct} IDOMSHARE_{ct}$$
$$FINT_{ct} ROAD_{ct} VSIZE_{ckt} LOH_{ckt} ILF_{ckt} ERUN_{ckt} EINT_{ckt} \quad (3)$$

Total energy consumption in year t is then:

$$FUEL_t = \sum_{ck} FUEL_{ckt} \quad (4)$$

Using the multiplicative form of the LMDI, the ratio of total energy consumption in year T ($FUEL^T$) to that at the beginning of the period ($FUEL^1$) is given by:

$$D_{TOT}^T = \frac{FUEL^T}{FUEL^1} \quad (5)$$

This may be expressed as a product of the decomposition factors:

$$D_{TOT}^T = D_{GDP}^T D_{DOMMAN}^T D_{CSHARE}^T D_{IDOMSHARE}^T D_{FINT}^T$$
$$D_{ROAD}^T D_{VSIZE}^T D_{LOH}^T D_{ILF}^T D_{ERUN}^T D_{EINT}^T \quad (6)$$

Where:

$$D_x^T = \exp\left[\sum_{kc} w_{kc}^T \bullet \ln\left(\frac{x_{kc}^T}{x_{kc}^1}\right)\right] \quad (7)$$

Where *x* represents a key ratio such as *CSHARE* and the weights (w_{kc}^T) are formed from the logarithmic mean of the initial and final share of energy consumption by each combination of vehicle type (*k*) and commodity group (*c*). Using $L(a,b)$ to denote logarithmic mean ($L(a,b) = (a-b)/\ln a - \ln b$), the formula for the weight terms is:

$$w_{kc}^T = \frac{L(FUEL_{kc}^T, FUEL_{kc}^1)}{L(FUEL^T, FUEL^1)} \quad (8)$$

The above formulae suggest that to examine the change in UK road freight energy use over the period 1989 to 2004 we simply need data for 1989 (*t=1*) and 2004 (*t=T*). However, the results of such a *period-wise* decomposition are sensitive to the choice of base year and final year and do not show how the effects of the decomposed factors have evolved over time. Hence, where annual data is available, it is preferable to conduct a *time-series* decomposition where the *annual* change in energy use is decomposed. Using D_x^t to represent the multiplicative decomposition coefficient for the period *t-1* to *t*, the relevant formula is:

$$D_x^t = \exp\left[\sum_{kc} \frac{L(FUEL_{kc}^t, FUEL_{kc}^{t-1})}{L(FUEL^t, FUEL^{t-1})} \bullet \ln\left(\frac{x_{kc}^t}{x_{kc}^{t-1}}\right)\right] \quad (9)$$

Period-wise coefficients can then be derived from the results of the time-series analysis for any relevant time period. For example, for the period *t=1* to *t=T*, the period-wise coefficients may be calculated from:

$$\Delta D_x^T = \prod_{t=2,T} D_x^t \quad (10)$$

The above formulae allow the change in total energy consumption over the period to be decomposed. But the decomposition framework also allows the change in energy consumption for individual subgroups to be decomposed. In particular, we can decompose the change in energy consumption for each commodity group (*c*) or each vehicle type (*k*). For example, in the case of individual commodity groups (*c*), the relevant time-series formulae are:

$$D_{TOT_c}^t = \frac{FUEL_c^t}{FUEL_c^{t-1}} \quad (11)$$

$$D_{TOT_c}^t = D_{GDP_c}^t D_{DOMMAN_c}^t D_{CSHARE_c}^t D_{IDOMSHARE_c}^t D_{FINT_c}^t$$
$$D_{ROAD_c}^t D_{VSIZE_c}^t D_{LOH_c}^t D_{ILF_c}^t D_{ERUN_c}^t D_{EINT_c}^t \quad (12)$$

Where:

$$D_{x_c}^t = \exp\left[\sum_k \frac{L(FUEL_{kc}^t, FUEL_{kc}^{t-1})}{L(FUEL_c^t, FUEL_c^{t-1})} * \ln\left(\frac{x_{kc}^t}{x_{kc}^{t-1}}\right)\right] \quad (13)$$

We construct the following three decomposition analyses:

Top level: time-series of D_x^t, allowing a decomposition of total fuel consumption ($\Delta FUEL^t$).

Commodity level: time-series estimates of $D_{x_c}^t$ allowing a decomposition of fuel consumption by commodity group ($\Delta FUEL_c^t$).

Vehicle level: time-series estimates of $D_{x_k}^t$ allowing a decomposition of fuel consumption by vehicle type ($\Delta FUEL_k^t$).

ENDOGENEITY

Decomposition analysis has difficulties in accommodating 'endogenous variables' – that is, variables whose values are determined by the values of one or more of the other right-hand-side variables within the decomposition equation (as compared to exogenous variables whose values are independent of the other right-hand-side variables). So for example, the value of the freight intensity key ratio ($FINT_{ct}$) depends upon the proportion of goods which are imported and therefore upon the value of the key ratio $IDOMSHARE_{ct}$.

The problems created by endogenous variables may be expected to depend on the number of variables used within the decomposition equation. If the decomposition is relatively straightforward (e.g. just two terms, structure and intensity) the problem may reasonably be overlooked - at least for analysis over relatively short time periods. But as the number of variables increases, the correlation and interdependence between those variables may be expected to increase. This is the challenge faced in the present analysis, where a total of ten key ratios are employed. Examples of interdependence include the following:

- A positive correlation between energy intensity ($EINT_{ckt}$) and length of haul (LOH_{ckt}), with energy efficiency tending to be better on longer trips.

- A positive correlation between freight intensity ($FINT_{ct}$) and the share of road freight ($ROAD_{ct}$), with freight intensity tending to be higher for commodities carried largely by road;
- a positive correlation between length of haul (LOH_{ckt}) and average payload weight (LF_{ckt}) with vehicles on longer trips tending to carry heavier loads;
- a negative correlation between the contribution of domestic manufacturing to UK GDP ($DOMMAN_t$) and the of the share of domestic production in the total UK supply of manufactured goods ($IDOMSHARE_t$), with increases in imports frequently being associated with reductions in domestic production;
- a negative correlation between the share of domestic production in the total UK supply of a particular commodity ($IDOMSHARE_{ct}$) and the freight intensity of that commodity ($FINT_{ct}$), with increases in imports frequently being associated with reductions in freight intensity.

The last two are particularly important and complicate the interpretation of the results. For example, we would expect a £ of domestically produced goods to generate more freight transport than a £ of imported goods because domestic production requires intermediate flows of raw materials, components and subassemblies, while imports simply require the transport of the final good. An increase in the relative importance of imports for a particular commodity will be indicated by an increase in the key ratio IDOMSHAREct and should in principle lead to a reduction in energy consumption for freight transport in the UK. However, this reduction will not be measured by the corresponding decomposition coefficient DIDOMSHARE. Instead, DIDOMSHARE may be interpreted as an estimate of the increase in energy consumption that results from the increase in imports, independent of any changes in the other key ratios. This includes the key ratio DOMMANt and hence implies that the domestic production of that commodity remains unchanged. As a result, an increase in the relative importance of imports for a particular commodity will lead to a positive value for $D_{IDOMSHARE_c}$ – implying an increase in energy consumption. At the same time, an increase in the relative importance of imports for that commodity should lead to a reduction in the DOMMANt key ratio and hence a negative value for DDOMMAN – implying a reduction in energy consumption. The net effect may be estimated from the product of the two.

DATA SOURCES

The data required for the above analysis was obtained from several UK and international sources, described in Sorrell *et al.* (2008). Inevitably, these form an incomplete picture, with a number of important gaps and omissions where additional tabulations and/or estimation is required. The greatest uncertainty is associated with the estimates of tonnes lifted by all modes by commodity group ($MLIFT_{ct}$) and vehicle kilometres by commodity group and vehicle type ($VKMT_{ckt}$). The procedure for deriving estimates of these and other values is described in detail in Sorrell *et al.* (2008).

The decomposition analysis combines data on the supply of goods, obtained primarily from the UK Input-Output tables, and the transport of goods, obtained from the Continuing Survey of Road Goods Transport (CSRGT) and the Transport Statistics Great Britain (TSGB). Since fuel consumption for road freight not separately identified in the UK energy statistics, it is estimated instead from the energy intensity and vehicle kilometre data in the CSRGT. Both the CSRGT and the TSGB are confined to Great Britain, which means that they exclude Northern Ireland. Hence, the available data on the supply of goods refers to the UK, while that on freight transport refers solely to Great Britain. The supply and transport of goods within Northern Ireland forms a relatively small proportion of the UK total, but this proportion has changed over time.[3]

An additional problem is that the CSRGT data is confined to the activities of HGVs registered within Great Britain. But some of the activities of HGVs in the UK may be undertaken by vehicles registered in other European countries. The latter may represent a small part of total UK vehicle activity, but this proportion has changed over time. Indeed, foreign-registered vehicles appear to be capturing an increasing proportion of the UK freight market (McKinnon, 2007)

The decomposition analysis needs to have a consistent geographic and vehicle coverage throughout. To achieve this, we need to add estimates of the transport of goods within Northern Ireland to the transport data (giving a UK coverage) and add estimates of vehicle activity by HGVs registered in other European countries to those recorded by the CSRGT (giving an all HGV coverage).

Some data on vehicle activity in Northern Ireland is available from the Department for Regional Development, Northern Ireland (DfRD, 2005), while some data on the activity of foreign-registered vehicles is available from the UK Department for Transport (DfT, 2004 and Eurostat (Pasi, 2007). But these data sources are sparse and may be subject to considerable error given the small size of the relevant surveys. Our chosen approach is to use this data to *adjust* the estimates of vehicle activity provided by the CSRGT to produce a set of estimates for the activity of all HGVs within the UK. However, we emphasise that these adjustments are subject to considerable uncertainty. The process involves estimating a time-series of multipliers that are used to convert estimates of the activity by GB-registered HGVs in GB (i.e. CSRGT data) into estimates of the activity of all HGVs within the UK (Sorrell *et al.*, 2008) The adjustment factors vary from year to year, but are assumed to be identical for each commodity (*c*) and vehicle (*k*) category. Also, the *same* adjustment is applied to the data on goods lifted, goods moved, loaded vehicle kilometres and total vehicle kilometres. This means that, while the key quantities *TLIFT*, *TKM*, *VKM* and *VKMT* are adjusted, the corresponding key ratios (*VSIZE*, *LOH*, *ILF*, *ERUN* and *EINT*) remain *unaffected* (i.e. they take the same values as implied by the CSRGT for each commodity and vehicle type). The process is slightly different for goods lifted by all modes ($MLIFT_t$) since only the portion of this which relates to road transport needs to be adjusted. In the absence of these adjustments, goods moved (*TKM*) in Great Britain are estimated to have changed little since 1998 - implying an absolute decoupling from GDP growth. In contrast, once these adjustments are made, goods moved are estimated to have increased

3. We estimate that Northern Ireland now accounts for around 3% of tonnes lifted by HGVs in the UK.

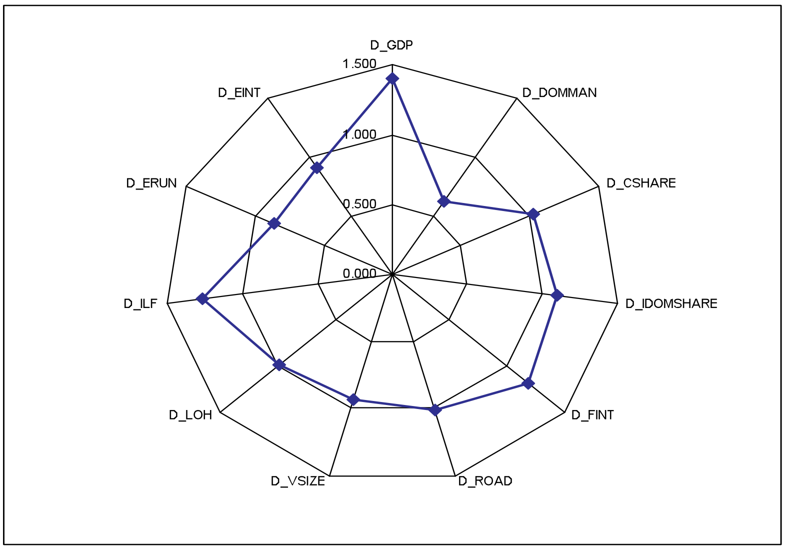

Figure 4 Period-wise multiplicative decomposition of total UK road freight energy consumption.

Table 3. Period-wise multiplicative decomposition of total UK road freight energy consumption.

Key ratio	Multiplicative decomposition results (D_x^T)	Multiplicative results – $D_x^T - 1.0$ (%)
GDP	1.43	43.3
Domestic manufacturing share (*DOMMAN*)	0.619	-38.1
Commodity share (*CSHARE*)	1.028	2.8
Inverse domestic share (*IDOMSHARE*)	1.098	9.8
Freight intensity (*FINT*)	1.188	18.8
Road share (*ROAD*)	1.008	0.8
Vehicle share (*VSIZE*)	0.930	-7.0
Length of haul (*LOH*)	0.984	-1.6
Inverse payload weight (*ILF*)	1.261	26.1
Empty running (*ERUN*)	0.859	-14.1
Energy intensity (*EINT*)	0.914	-8.6
Total	**1.063**	**6.3**

by 4.7% since 1998, implying only a relative decoupling. The bulk of the difference results from the increasing proportion of goods carried by foreign registered vehicles.

Results

PERIOD-WISE DECOMPOSITION OF TOTAL ROAD FREIGHT ENERGY CONSUMPTION

Figure 4 and Table 3 illustrate the results of the multiplicative decomposition of total road freight energy consumption for the period 1989 to 2004. Each D_x^T is an estimate of the ratio of energy consumption in year 2004 to that in 1989 that has resulted from the corresponding change in the relevant key ratio (x) over that period. If this coefficient exceeds unity, the key ratio has contributed to an *increase* in road freight energy consumption - and vice versa.

It is estimated that, ceteris paribus, the growth in GDP between 1989 and 2004 would have increased road freight energy consumption by 43.3%. In practice, however, road freight energy consumption is estimated to have increased by only 6.3%. The results show that the main factor contributing to the decoupling of energy consumption from GDP was the decline in the value of domestically manufactured goods relative to GDP (D^T_{DOMMAN}). This reflects the declining importance of manufacturing to the UK economy. It is estimated that the fall in the value of domestically manufactured goods relative to GDP reduced the aggregate energy intensity of road freight (i.e. $FUEL_t/GDP_t$) by 38.1% over this period.

The declining importance of domestically manufactured goods was in part offset by an increase in the share of imports in total goods supply ($D^T_{IDOMSHARE}$). The growth in imported goods is estimated to have increased energy consumption for freight transport by 9.8% relative to 1989. However, this is not the same as the actual change in energy consumption associated with the increase in imports, since such a shift would also have contributed to changes in other key ratios such as such as the domestic manufacturing share ($DOMMAN_t$) and aggregate freight intensity ($FINT_t$).

The net effect of the decline in the value of domestically manufactured goods relative to GDP, shifts in the mix of domestically produced commodities and the increase in the share of imports can be estimated from the product of D^T_{DOMMAN}, D^T_{CSHARE} and $D^T_{IDOMSHARE}$. This suggests that, in combination, they reduced aggregate energy consumption by 30.1%. In other words, changes in the value (relative to GDP), composition and source of manufactured goods have made a major contribution to the decoupling of UK road freight energy consumption from GDP.

The other factors contributing to decoupling of road freight energy consumption from GDP are estimated to be the reduction in empty running (-14.1%), the reduction in energy use per vehicle kilometre (-8.6%), the shift towards larger vehicles (-7.0%*)* and changes in the average length of haul (-1.6%). The latter appears surprising, since increases in the average length of haul have been a major contributor to the increase in road freight energy consumption in the past (Netherlands Economic Institute, 1997) and the fleet average length of haul (LOH_t) is estimated to have increased by 12.3% between 1989 and 2004. However, trends in the fleet average length of haul include the effect of changes in the mix of vehicles (notably the shift towards >33 tonne articulated vehicles) which in the decomposition analysis is measured separately by D^T_{VSIZE}. Closer inspection reveals that between 1989 and 2004 there was a reduction in the average length of haul for two categories of rigid vehicle and the largest category of articulated vehicle. Since the latter accounts for a substantial fraction of both total goods moved and total road freight energy consumption it is likely to be largely responsible for the negative contribution of this key ratio to the aggregate change in energy consumption. The net effect of shifts in the vehicle mix and changes in the length of haul can be estimated from the product of D^T_{VSIZE} and D^T_{LOH}. This suggests that, in combination, they reduced aggregate energy consumption by 8.5%.

The factors acting against a decoupling of road freight energy consumption from GDP are estimated to be: reductions in the average payload weight (26.1%), increases in freight intensity (18.8%), shifts in the mix of domestically produced commodities (2.8%) and a modal shift (in terms of goods lifted) towards road (0.8%). Again, the first result appears surprising since the fleet average payload weight (*LFt*) is estimated to have increased by 5.5% over this period, but closer inspection reveals that the average payload weight fell for each individual category of vehicle. The net effect of the shift towards larger vehicles and the reduction in average payload weight for each category of vehicle can be estimated from the product of D^T_{VSIZE} and D^T_{ILF}. This suggests that, in combination, they increased aggregate energy consumption by 17.3%. In other words, in terms of their effect upon energy consumption, the shift towards larger vehicles was insufficient to compensate for the reduction in average payload weight for each category of vehicle - despite leading to an increase in average payload weight for the fleet as a whole.

Freight intensity may in principle be decomposed into the product of two variables, namely: *value density* (the ratio of the value of goods to their weight in £/tonne) and *handling factor* (the ratio of the tonnes lifted onto all modes of transport to the tonnes supplied). In principle, lower value density goods should generate more tonnes lifted, although higher value goods may be associated with more tonne or vehicle kilometres per unit of value. Handling factor is often considered to be crude measure of the number of links in the supply chain and varies widely from one commodity to another. Unfortunately, the available data does not permit an accurate estimation of these important variables, owing to the difficulties in estimating the weight of goods supplied (Sorrell *et al.*, 2007). The estimated contribution from changes in freight intensity is substantial (18.8%) and suggests either that handling factors have increased or that value densities have fallen for individual commodities. This is independent of any shifts in the mix of domestically produced commodities (D^T_{CSHARE}), the impact of which is estimated to have been relatively small (2.8%). While fleet average freight intensity ($FINT_t$) is estimated to have increased by only 5.3% over this period, the trends in freight intensity vary widely between commodity groups, with a particularly large increase for food and drink products. The aggregate results suggest that the freight intensity of commodities with a large ratio of energy consumption to tonnes lifted has increased by more than the average.

The net effect of shifts in the commodity mix, increases in imports and changes in freight intensity can be estimated from the product of D^T_{CSHARE}, $D^T_{IDOMSHARE}$ and D^T_{FINT}. This suggests that, in combination, they increased aggregate energy consumption by 34.0%. In contrast, while a greater proportion of goods lifted are now carried by road, this appears to have had only a small impact (0.8%) on total road freight energy consumption.

It helpful to simplify the decomposition of energy consumption into the product of three factors, as follows:

$$D^T_{TOT} = D^T_{SUPP} D^T_{FINT} D^T_{TRANS} \tag{14}$$

Where:

$$D^T_{SUPP} = D^T_{GDP} D^T_{DOMMAN} D^T_{CSHARE} D^T_{IDOMSHARE} \tag{15}$$

And:

$$D^T_{TRANS} = D^T_{ROAD} D^T_{VSIZE} D^T_{LOH} D^T_{ILF} D^T_{ERUN} D^T_{EINT} \tag{16}$$

Here, D^T_{SUPP} is a measure of the effect of factors relevant to the supply of goods in the UK economy; D^T_{FINT} is a measure of the effect of factors relevant to freight intensity; and D^T_{TRANS} is a measure of the effect of factors relevant to the ratio of energy consumption to total goods lifted, which includes the mix of vehicles and the manner in which they are used. The results suggest that factors relevant to the supply of goods (D^T_{SUPP}) contributed a 2.1% reduction in energy consumption for freight transport, factors relevant to freight intensity (D^T_{FINT}) contributed an 18.8% increase in energy consumption and factors relevant to the transport of those goods (D^T_{TRANS}) contributed an 8.6% reduction in energy consumption. Overall, the effect of the increase in freight intensity outweighed the combined effect of both the factors relevant to the supply of goods and changes in the way those goods were transported, leading to a net increase in energy consumption for road freight over this period. This suggests that either reductions in the value densities or increases in the handling factor of commodities with a high ratio of energy consumption to road tonnes lifted have played an

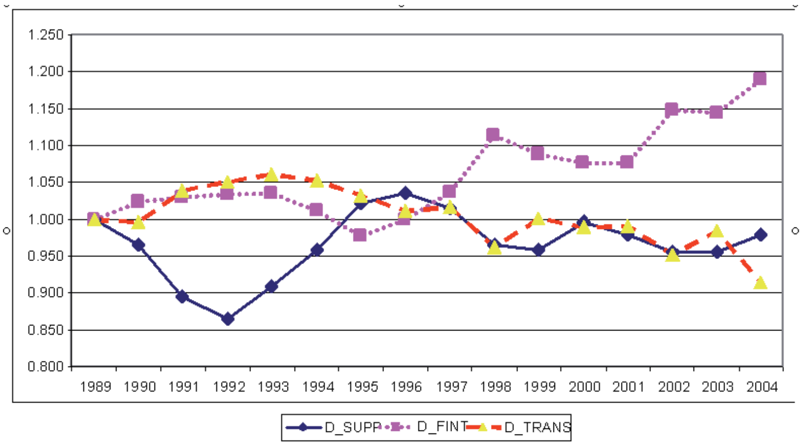

Figure 5. Three-factor time-series multiplicative decomposition of energy consumption.

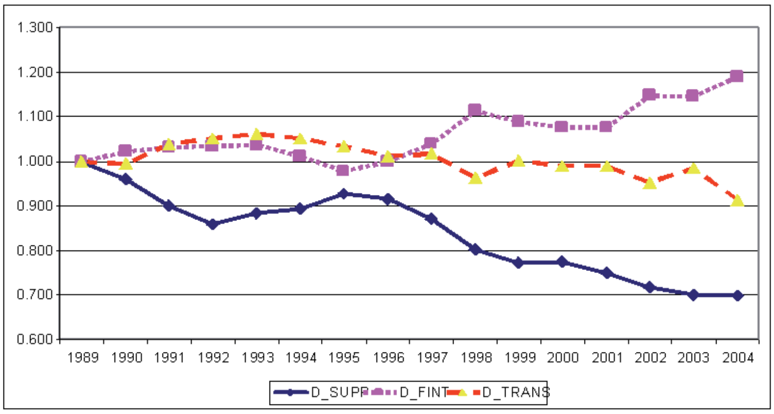

Figure 6. Three-factor time-series multiplicative decomposition of energy intensity.

important role. Unfortunately, the available data does not allow us to determine the relative importance of these two variables with any confidence. However, while energy consumption for road freight has increased overall, the rate of increase is much less than that for GDP owing to an aggregate 25.8% reduction in road freight energy intensity.

TIME-SERIES DECOMPOSITION OF TOTAL ROAD FREIGHT ENERGY CONSUMPTION

The use of time-series decomposition makes it is possible to track the contribution of each key ratio over time. With ten key ratios, it is helpful to examine the trends by using the more simplified decomposition given by Equation 14. Figure 5 illustrates the estimated contribution of factors relevant to the supply of goods (D^T_{SUPP}), the freight intensity of those goods (D^T_{FINT}) and the transport of those goods (D^T_{TRANS}) to the change in road freight energy consumption over the period 1989 to 2004. Figure 6 does the same for the change in aggregate road freight energy intensity.

It is notable that the contribution of these variables has not followed a smooth trend. In the case of factors relevant to the supply of goods (D^T_{SUPP}), the recession in the early 1990s contributed to a large reduction in road freight energy consumption, but this trend was reversed between 1992 and 1996. Since 1996, these factors have acted to reduce the aggregate energy intensity of road freight. In contrast, factors relevant to the transport of goods (D^T_{TRANS}) acted to increase road freight energy intensity in the early 1990s, but since 2000 they have reduced energy intensity. Factors relevant to freight intensity are estimated to have increased aggregate energy intensity by more than 20% since 1995, with half of this increase occurring since 2000.

DECOMPOSITION OF ROAD FREIGHT ENERGY CONSUMPTION BY COMMODITY AND VEHICLE TYPE

Decomposition analysis can also be used to examine the relative contribution of different factors to the change in road freight energy consumption for each commodity group. As an illustration, Figure 7 shows the period-wise results for food and drink products. Comparison with Figure 4 shows that increases in freight intensity were relatively more important for food and drink products than for freight transport overall - i.e. there were greater changes in handling factors and/or value densities for food and drink products than for commodities overall. It is possible that increases in the amount of packaging used for food products may have played a role.

Table 4 summarises the period-wise results for each commodity group using the simplified, three-factor decomposition of energy consumption introduced above. To highlight departures from the aggregate trends, Table 5 summarises the percentage difference between the results for each commod-

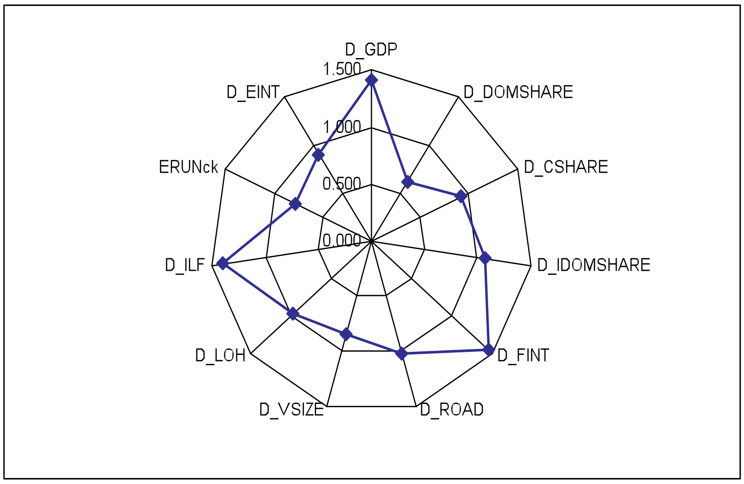

Figure 7. Period-wise multiplicative decomposition of energy consumption for food and drink products.

Table 4. Three factor, period-wise multiplicative decomposition of energy consumption by commodity group.

Commodity group	D_{SUPP}	D_{FINT}	D_{TRANS}	D_{TOT}
Food, drink and tobacco	0.864	1.443	0.825	**1.029**
Wood, timber and cork	0.854	1.798	0.877	**1.346**
Crude minerals	1.026	0.916	0.821	**0.771**
Ores	3.098	0.324	0.894	**0.897**
Crude materials	0.697	1.729	1.774	**2.139**
Coal and Coke	0.936	0.468	0.621	**0.272**
Building materials	0.862	1.140	1.346	**1.322**
Iron and steel products	0.674	1.082	0.997	**0.728**
Fertiliser	0.970	0.473	0.891	**0.409**
Petrol and petroleum products	1.375	0.860	0.432	**0.512**
Chemicals	1.215	0.711	0.993	**0.858**
Other metal products n.e.s	0.989	1.038	1.113	**1.142**
Machinery and transport equipment	1.106	1.098	1.114	**1.353**
Miscellaneous manufactures	0.957	1.399	0.849	**1.136**
Miscellaneous articles	1.203	1.002	1.093	**1.318**
Aggregate results	**0.979**	**1.188**	**0.914**	**1.063**

ity group and those for aggregate energy consumption (i.e. $100*(D^T_{x_c} - D^T_x)/D^T_x$).

Commodities for which energy consumption has increased by more than the average include wood, timber and cork, crude materials, building materials and miscellaneous products; while commodities which energy consumption has increased by less than the average include coal and coke, chemicals, fertiliser and petroleum products. However, the commodity groups differ widely in their contribution to total energy consumption. For example, food and drink products account for around one quarter of total road freight energy consumption, while coal and coke products account for only 0.4%. The trends for some commodities therefore have a substantially greater influence on total energy consumption than the trends for others.

It is notable that increases in freight intensity have played an important role in increasing energy consumption for crude materials, food and drink products and miscellaneous manufacturers, while for most other commodities trends in freight intensity have acted to reduce energy consumption. It is also notable that transport related factors have reduced the energy consumption associated with transporting food and drink products and miscellaneous manufactures, but have increased the energy consumption associated with the transport of miscellaneous articles and building materials. These factors relate largely to the organisation of the logistics system and the efficient use of vehicles. Note that the results for ores are not considered to be robust, although the quantities are involved are extremely small in both value and weight terms.

In a similar manner, it is possible to examine the relative contribution of different factors to the change in energy consumption for each vehicle type. Table 6 summarises the results for each vehicle type using the simplified, three-factor decomposition of energy consumption introduced above. To highlight departures from the aggregate trends, Table 7 illustrates the percentage difference between the results for each commodity group and those for aggregate energy consumption (i.e. $100*(D^T_{x_k} - D^T_x)/D^T_x$).

Factors relevant to the supply of goods and freight intensity have a broadly similar impact on the energy consumption used by each category of freight vehicle. The differences between cat-

Table 5. Three factor, period-wise multiplicative decomposition of energy consumption by commodity group – percentage difference from aggregate results.

Commodity group	D_{SUPP}	D_{FINT}	D_{TRANS}	% of total energy consumption 2004
Food, drink and tobacco	-11.8	21.5	-9.7	26.65
Wood, timber and cork	-12.8	51.4	-4.1	1.95
Crude minerals	4.8	-22.9	-10.2	4.45
Ores	216.3	-72.8	-2.2	0.54
Crude materials	-28.8	45.6	94.2	2.36
Coal and Coke	-4.4	-60.6	-32.0	0.36
Building materials	-12.0	-4.0	47.3	6.38
Iron and steel products	-31.2	-8.9	9.1	2.78
Fertiliser	-1.0	-60.2	-2.5	0.22
Petrol and petroleum products	40.4	-27.6	-52.7	2.55
Chemicals	24.1	-40.2	8.7	3.81
Other metal products n.e.s	1.0	-12.6	21.8	1.89
Machinery and transport equipment	13.0	-7.6	21.9	7.60
Miscellaneous manufactures	-2.3	17.7	-7.1	23.35
Miscellaneous articles	22.9	-15.6	19.6	15.09

Table 6. Three factor, period-wise multiplicative decomposition of energy consumption by vehicle type.

Vehicle type	D_{SUPP}	D_{FINT}	D_{TRANS}	D_{TOT}
Rigids 3.5-7.5	0.993	1.211	1.026	**1.234**
Rigids 7.5-17	0.987	1.208	0.321	**0.383**
Rigids 17-25	0.992	1.152	1.123	**1.283**
Rigids >25	0.997	1.119	1.811	**2.019**
Artics 3.5-33	0.992	1.249	0.263	**0.326**
Artics >33	0.958	1.204	1.439	**1.660**
Aggregate results	**0.979**	**1.188**	**0.914**	**1.063**

Table 7. Three factor, period-wise multiplicative decomposition of energy consumption by vehicle type - percentage difference from aggregate results.

Vehicle type	D_{SUPP}	D_{FINT}	D_{TRANS}	% of total energy consumption 2004
Rigids 3.5-7.5	**1.40**	1.95	12.23	15.1
Rigids 7.5-17	**0.73**	1.68	-64.86	9.9
Rigids 17-25	**1.29**	-3.01	22.82	8.9
Rigids >25	**1.76**	-5.84	98.21	16.9
Artics 3.5-33	**1.26**	5.16	-71.17	7.2
Artics >33	**-2.16**	1.36	57.47	62.8

Table 8. Percentage change in road freight energy consumption that would have resulted from each factor acting individually

Key ratio	% change
Gross domestic product (GDP)	40.2
Domestic manufacturing share: ratio of the value of domestically produced manufactured goods to UK GDP	-38.1
Commodity share: share of commodity group *c* in total value of domestically produced manufactured goods	2.8
Inverse domestic commodity share: inverse share of domestic production of commodity group *c* in the total UK supply of commodity group *c*	9.8
Freight intensity: ratio of tonnes lifted of commodity *c* onto all modes of freight transport to value of UK supply of commodity *c*	18.8
Road share: share of tonnes lifted for commodity group *c* that are taken by HGV	0.8
Vehicle share: share of HGV tonnes lifted for commodity group *c* that are taken by vehicle type *k*	-7.0
Length of haul: average length of haul for commodity group *c* in vehicle type *k*	-1.6
Inverse payload weight: inverse of the average payload weight for commodity group *c* in vehicle type *k*	26.1
Empty running: ratio of total vehicle km to loaded vehicle km for commodity group *c* in vehicle type *k*	-14.1
Energy intensity: ratio of energy use per vehicle km for vehicle type *k* carrying commodity group *c*	-8.6
Total	**6.3**

egories result largely from the transport related variables and in particular the relative share of goods lifted taken by each vehicle type as represented by ($D^T_{VSIZE_k}$). It is notable that reductions in the average payload weight ($D^T_{ILF_k}$) have increased energy consumption by rigid vehicles by proportionally more than they have for articulated vehicles. Reductions in the amount of empty running ($D^T_{ERUN_k}$) have reduced energy consumption for all types of vehicle, but particularly for the largest categories of rigid vehicles. The impact of improvements in fuel use per vehicle kilometre ($D^T_{EINT_k}$) have been greater for articulated vehicles. A particularly notable finding is that changes in the average length of haul have reduced the energy consumption for articulated vehicles, but increased the energy consumption for rigid vehicles. One possible explanation is a centralisation of local distribution centres, leading to an increase in the average length of haul for the smaller rigid vehicles used for local distribution.

Discussion

The results of the aggregate decomposition are summarised again in Table 8.

The results demonstrate that the main factor contributing to the decoupling of UK road freight energy consumption from GDP was the decline in the value of domestically manufactured goods relative to GDP. Over the period 1989-2004, this largely offset the effect of increases in GDP on road freight energy consumption. While the decline in domestic manufacturing was to some extent displaced by increases in imports, the net effect of these supply factors, together with shifts in the commodity mix, has been to reduce UK road freight energy consumption by 30.1% relative to the counterfactual. The net effect on global CO_2 emissions is likely to be somewhat less beneficial, since many of the freight movements associated with the manufacture of imported goods have simply been displaced to other countries.

Other factors contributing to the decoupling of UK road freight energy consumption from GDP are estimated to be the reduction in the empty running of vehicles (14.1%), the reduction in energy use per vehicle kilometre (8.6%), the shift towards larger vehicles (7.0%) and changes in the average length of haul (1.6%). The last result suggests that the long-established process of concentrating economic activity is beginning to weaken, although factors such as more efficient vehicle routing may also play a role. The beneficial effect of larger vehicles on road freight fuel consumption is also notable and has been driven in part by regulatory changes.

The factors acting against a decoupling of road freight energy consumption from GDP are estimated to be: reductions in the average payload weight for individual categories of vehicle (26.1%), increases in freight intensity (18.8%), shifts in the mix of domestically produced commodities (2.8%) and a modal shift (in terms of goods lifted) towards road (0.8%). The trends in payload weight suggest continued inefficiencies in the use of vehicles, perhaps as a consequence of volume constraints binding before weight constraints. The contribution of freight intensity (defined here as tonnes lifted per unit of value) suggests either that the value density of the most 'energy intensive' commodities is falling, or that their handling factor is increasing – perhaps as a consequence of more links in the supply chain. Unfortunately, the available data does not allow the relative contribution of these variables to be accurately assessed.

Generally, the results demonstrate how the trends for individual commodity groups and vehicle types can greatly influence the overall trends in road freight energy consumption. These influences may be disguised by the aggregate trends in the relevant key ratios and are only revealed by a full decomposition analysis. For example, key ratios that have in the aggregate *increased* (such as the length of haul) are found to have *reduced* overall energy consumption, and vice versa. The explanation lies in the diverging trends for these key ratios for individual commodity groups and/or vehicle types, together with the wide variation in various measures of 'energy intensity' between commodity groups and/or vehicle types.

The extent to which the identified trends will continue into the future is open to question. Further reductions in the energy intensity of road freight should be possible through improvements in the average load factor and fuel efficiency of vehicles, together with further reductions in the amount of empty running. However, the potential in each case appears to be relatively limited. A shift towards rail and waterborne transport could yield savings, but the scope for this varies greatly with both the nature of the commodity and the location of the associated manufacturing and distribution centres. Also, the associated energy savings depend very much upon the vehicles involved and their load factors (e.g. long-distance transport in >33 tonne HGVs can be relatively energy efficient). Given the inherent inflexibility of rail transport and the scale of investment required to achieve significant modal shifts, it may be more appropriate to focus on the potential for improving the efficiency of road freight, at least in the short to medium-term. A reversal of the historic trend of increasing length of haul has considerable potential for energy savings, but substantial changes appear unlikely without a major reorientation of economic activity - involving a reversal of the trends of the last 30 years. Most importantly, the future demand for road freight will depend very much upon the future demand for manufactured goods and the extent to which increases in wealth translate into increases in material consumption as opposed to the consumption of 'services' of various forms.

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