The determinants of fuel use in the trucking industry – volume, size and the rebound effect

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Abstract

We analyse the determinants of trucking firm fuel use. We develop a simple model to show that trucking firm fuel use depends, in addition to the fuel price and the traffic volume, also on the output of the trucking firm's production process (the movement of cargo) measured in ton-kilometres, characteristics of the truck stock, and congestion. We also analyse the rebound effect for road freight transportation, i.e. the percentage of increased energy efficiency that does not result in the reduction of fuel used. For the purpose of analysing the rebound effect for road freight transportation, we decompose the standard definition of the rebound effect for motor vehicles, i.e. the elasticity of traffic volume with respect to fuel cost, into the elasticity by which changes in fuel costs affects freight activity and the elasticity by which changes in freight activity affect traffic volume. We estimate these elasticities using a simultaneous-equation model based on aggregate time-series data for Denmark for 1980-2007. Our best estimates of the short run and the long run rebound effects for road freight transportation are 19% and 28%, respectively. We also find that an increase in the fuel price surprisingly has a small but significant negative effect on the fuel efficiency (measured here as vehicle kilometres travelled (VKT) per litre of consumed fuel), i.e. a 1% increase in the fuel price decreases the fuel efficiency by 0.13% in the long run. However, less distance has to be driven for the same payload. An 1% increase in the fuel price decreases the VKT by 0.19% in the short run and 0.28% in the long run. Finally, a 1% increase in the fuel price results in a 0.19% reduction in the trucking firms' overall fuel use.

Keywords: Road freight transportation, fuel use, energy efficiency, rebound effect.

JEL codes: L91, Q41, R41.

1. Introduction

This paper examines the determinants of the road freight transportation fuel use. In 2004, the transportation sector was responsible for more than a quarter of the total world energy use, and roughly a third of this energy use was dedicated to road freight transportation (IEA, 2006; WBCSD, 2004). The analysis of the determinants of the road freight transportation fuel use is relevant because the road freight transportation's energy use is expected to grow in both the EU and the US (IEA, 2010; Léonardi and Baumgartner, 2004).

In Denmark, freight transportation accounts for a rising share of the total energy use as well. The road freight transportation activity (measured in ton-kilometres) increased by 59% from 1980 to 2007. Energy use of the road freight transportation increased by 105% in the same period. The main reason for the evident energy efficiency decline is presumably the 'just-in-time' behaviour of trucking firms, which resulted in lower utilization of the vehicles' capacity (Sathaye et al., 2010).[1]

Large reductions in road freight transportation energy use can be achieved by structural changes in the trucking industry towards improved matching of truck capacity to load (Kamakaté and Schipper, 2008). However, an often observed effect of policies directed at higher utilization of the vehicles' capacity is that better-utilized trucks are regularly heavier and use more fuel per kilometre, but, in theory, less distance has to be driven for the same payload (Léonardi and Baumgartner, 2004; Sathaye et al., 2010).[2] In Denmark, improvements in fuel efficiency of individual trucks were offset by growth in production and the overall change in the structure of the truck-stock (Kveiborg and Fosgerau, 2007).

As with all changes that improve energy efficiency, there may be some rebound effect that to some extent offsets the original energy saving.[3] As the energy efficiency of road freight transportation improves, freight road transportation becomes cheaper, thereby providing an incentive to increase its use. Thus total fuel use responds less than proportionally to changes in

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[1] Just-in-time is an inventory strategy that strives to improve a business's return on investment by reducing in-process inventory and associated carrying costs (see e.g. Bonney, 1994).

[2] The reduction of freight truck trips with the general purpose to reduce congestion and environmental impacts has been a common policy goal for many governments around the world in recent years (Sathaye et al., 2010). For example, freight centres for facilitating cargo transfer have been constructed in several European countries implying significant savings for trucking firms using these centres through reduced fuel consumption (McKinnon, 2003).

[3] The rebound effect has been studied in different contexts (for survey see Greening, et al., 2000), including transportation (see e.g. Small and van Dender, 2007; Hymel, et al., 2010).

fuel efficiency. The rebound effect is typically quantified as the extent of the deviation from this proportionality.

Substitution between freight modes also has a large impact on freight transportation energy use, mostly because the energy intensity (measured in energy use per ton-kilometre) of trucks, ships and trains is considerably different (Forkenbrock, 1999). This paper focuses solely on road freight transportation because substitution between freight modes in Denmark is relatively limited and more than three quarters of all goods in Denmark are transported by trucks. According to Rich et al. (2010) a large proportion of the road freight transport services between OD pairs in Denmark cannot be substituted since there is only one option available, i.e. trucks. Moreover, Bjørner and Jensen (1997) calculated a cross-price elasticity of about 0.2 between road freight transportation versus train and ships (for a given transport demand).[4] In general, the share of road freight transportation compared to other modes is large in small countries (Kamakaté and Schipper, 2008).

Considering the debate about the road freight transportation fuel use, the absence of empirical estimates about it may be surprising. We aim to fill this gap in the literature. The aim of the current paper is to analyse the determinants of the trucking firm fuel use. We estimate a simultaneous-equation model based on aggregate time-series data for Denmark for 1980-2007. Our study deals with a range of the statistical difficulties by accounting for the endogeneity of fuel efficiency, and by distinguishing between autocorrelation and lagged effects. The paper adds to the transportation literature, contributing with two main improvements. First, we explicitly analyze the determinants of the fuel use in road freight transportation. To our knowledge, such an analysis has not been undertaken before. Matos and Silva (2011) analysed the effect of increasing energy efficiency based on the estimation of a direct rebound effect for road freight transportation in Portugal for the period between 1987 and 2006 using aggregate time series data. They estimated the demand for road freight transportation focusing on the effect of a change in energy cost of transportation on a change in demand for road freight transportation taking into account detected endogeneity of the price variable. Parry (2008) presented an analytical framework for estimating optimal taxes on the fuel use and mileage of heavy duty trucks in the United States that indirectly includes measures of the rebound effect. Bjørner (1999) carried out

[4] Surveys of the studies on price elasticities for freight transportation are given by Oum, Waters and Yong (1992) and Zlatoper and Austrian (1989).

an empirical analysis of the environmental benefits from better road freight transportation management in a Danish context, in a VAR model based on aggregate time series. Second, we show that the rebound effect for the road freight transportation can be decomposed from the standard definition of the rebound effect for motor vehicles, i.e. the elasticity of traffic volume with respect to fuel cost, into the elasticity of freight activity with respect to fuel cost per kilometre and the elasticity of traffic volume with respect to freight activity. The next section introduces the analytical model; Section 3 provides the empirical specification of the model; Section 4 presents the empirical results; and Section 5 concludes.

2. Trucking firm behaviour

We consider a small open economy where a representative competitive trucking firm ships goods at a given price denoted by $\bar{P}^Y$. Mode choice is not considered, thus there is only one means of transportation (road freight transportation). The output of the production process in trucking is the movement of cargo, or freight activity (Hubbard, 2003). A fundamental difficulty associated with studying trucking firm behaviour is finding an appropriate measure of output. Since trucking activity can be characterized by point of origin and destination, commodity type, and shipment size, the ideal measure of output would include all of these dimensions. In this study, freight activity is measured in ton-kilometres (tkm), which is the product of the mass of freight (measured in tonnes) and the distance it is carried (measured in kilometres).

Certain fundamental relationships exist between average load, aggregate ton-kilometres, vehicle kilometres travelled (VKT), and tons (Smith, 1957). The technical relation relating to freight activity (Y), traffic volume (V), and the average load (W) per shipment can be approximated as $V = Y/W$.[5] The capacity utilization depends largely on how well trucking firms can identify and agglomerate complementary demands onto individual trucks (Hubbard, 2003; Baker and Hubbard, 2003). We assume that the trucking firm can to some extent reduce traffic volume for a given freight activity through investments in logistics. These reductions will mainly be the result of better matching of the trucks capacity to shipment, i.e. change in the average load.

[5] Exact definition of the relationship between Y, V and W includes an adjustment factor to take into account the effect of the nonlinear statistical relationship between length of haul and size of load (see Smith, 1957). Due to data unavailability, we use the approximation of this relationship in an unadjusted form.

The firm employs labour (L), purchases fuel, and purchases and uses trucks to produce freight service. The total number of trucks (M) and the average truck's attributes affect the firm's costs. The average truck attributes S and H could be anything that affects the trucking firm's decision making process, i.e. the trucking firm's total revenue and total costs. For concreteness, we define S as the average truck capacity (measured here as axle weight). The firm's decision making process is also affected by the truck vintage since newer trucks depreciate more than older trucks and the truck vintage is presumably correlated with truck technology (for example fuel injection), so we define H as the average truck age.[6] Moreover, the firm's choice set includes also consideration of use of fuel, and consequently traffic volume, in producing freight service. Fuel consumption (F) and traffic volume (V) are related through the identity:

$$F = \frac{V}{E(S,H,D)} , \qquad (2.1)$$

where $E = E(S,H,D)$ is the fuel efficiency measured in VKT per litre of consumed fuel. Fuel efficiency is a function of the average truck capacity (S), the average truck age (H), and the level of congestion (D), where trucks with larger capacity are assumed to have higher fuel consumption and where newer trucks through improved technology increase fuel efficiency, i.e. $E_S \leq 0$, $E_H \leq 0$ where subscripts stand for partial derivates. Increasing congestion is assumed to reduce fuel efficiency, i.e. $E_D \leq 0$.

2.1 Trucking firm profit maximization problem (PMP)

We consider a competitive market consisting of identical trucking firms producing a homogeneous service. When determining its optimal policy, the trucking firm faces the market constraint existing in any competitive market, i.e. the prices are assumed to be independent of the production plans of the firm (for discussion see Mas-Colell et al., 1995, chapter 10).[7]

The representative trucking firm attempts to maximize its profit (Π); that is the trucking firm chooses actions so as to maximize the total revenue minus total costs. It faces at least three types of the production costs: fuel costs, wages, and capital costs (Schipper and Price, 1997). Moreover, external factors (such as time of vehicle use, weather conditions, and traffic congestion) have proven to be relevant for the road freight transportation fuel efficiency, and consequently for the firm's costs (Samuelsson and Tilanus, 2002; Calthrop and Proost, 2003).

[6] For detailed discussion on vehicle vintage and fuel efficiency see Fullerton and West (2001).
[7] In a perfect competitive industry entry and exit costs are zero and firms are endowed with perfect foresight.

However, it is only the choice of the vehicle type and the implementation of the IT scheduling systems that can be influenced by the managers of trucking firms (Léonardi and Baumgartner, 2004).

The representative trucking firm is concerned only with determining the profit-maximizing levels of freight activity (Y) and inputs in production. The profit maximization problem (PMP) facing the firm can be written as simply a choice over its input levels (L, M, S, H, and V) for a given price vector and given $\overline{\mathrm{D}}$:

$$\max_{L,M,S,H,V\geq 0} \Pi = \overline{\mathrm{P}}^{\mathrm{Y}} f(L,M,S,H,V) - \left[wL + \frac{P^F}{E(S,H,\overline{D})} V + g(S,H,M;\boldsymbol{\alpha})\right], \qquad (2.2)$$

where $f(\cdot)$ is a quasi-concave differentiable production function with substitution possibilities between production inputs and $g(\cdot)$ is a differentiable cost function of S, M and H, where $\boldsymbol{\alpha}$ is the corresponding price vector. The vehicle capital costs (g) are equal to the costs of maintaining a truck fleet, i.e. costs related to S, M and H.[8] The price of labour and the price per litre of fuel are w and P^F, respectively.[9] The fuel price is divided by E to get a figure for fuel costs per kilometre (P^V). The functions that give the optimal choices of inputs and output as a function of the prices are known as the factor demand functions $Z^* = Z(\overline{D}, \overline{Y}, w, P^F, \boldsymbol{\alpha})$, $Z = L, M, S, H, V$ and output supply function, correspondingly.[10] The necessary first-order condition for Y^* to be profit maximizing is:

$$\overline{\mathrm{P}}^{\mathrm{Y}} - \frac{\partial C(Y,\overline{\mathrm{D}},\mathrm{w},\mathrm{P}^{\mathrm{F}},\boldsymbol{\alpha})}{\partial Y} \leq 0\ , \qquad (2.3)$$

with equality if $Y^* > 0$, where $C(\cdot)$ is the cost function. Thus, at an interior optimum (i.e., if $Y^* > 0$), price equals marginal costs. This result will be useful in the analysis of the trucking firm fuel use.[11]

[8] We can specify the vehicle capital costs function as $g = (P^M + P^S S + P^H H)M$, where P^M is average truck capital/maintenance costs, P^S is the price for adding one additional unit of capacity to average truck capacity (S), and P^H is the price for adding one additional unit of age (e.g. year) to average truck age (H). We consider for simplicity of notation only the more general form of the vehicle capital costs function, i.e. $g(\cdot)$.

[9] A study of Denmark showed that fuel choice is almost exclusively diesel for trucks due to the very low diesel fuel cost (Lee Schipper and Price, 1997).

[10] It is easy to show that the first-order conditions for S, H and V, and the economic rate of substitutions between inputs are adjusted for the changes in the fuel efficiency, indicating the likely existence of the rebound effect.

[11] Analysis of the effects of changes of exogenous variables on the choice set variable (for example the effect of change of P^F on L, S, H, M, and V) requires determination of the signs of the bordered Hessian matrix of the Lagrangian principal minors. Determination of the signs of these principal minors, and consequently the analysis of the effects of changes of exogenous variables on the choice set variables, is not considered in this study because of the dimensionality of the bordered Hessian.

2.2 Trucking firm fuel use

When changes in the fuel efficiency are assumed to be exogenous, it is easy to show that fuel use responds to exogenous changes in E according to the elasticity equation (see Appendix A):

$$\varepsilon_{F,E} = -1 - \varepsilon_{V,Y}\varepsilon_{Y,P^V} \ , \qquad (2.4)$$

where P^V is the per-kilometre fuel cost, $\varepsilon_{F,E}$ is elasticity of F with respect to E, $\varepsilon_{V,Y}$ is elasticity of V with respect to Y, and ε_{Y,P^V} is elasticity of Y with respect to P^V. Consequently a non-zero value of $\varepsilon_{V,Y}\varepsilon_{Y,P^V}$ implies that change in F is not proportional to change in E. Thus, $\varepsilon_{V,Y}\varepsilon_{Y,P^V}$ is taken as the measure of the rebound effect for road freight transportation. The rebound effect arises because traffic volume depends (among other things) on the freight activity, and the freight activity depends (among other things) on the variable cost per kilometre driven, a part of which is the per-kilometre fuel cost. Therefore, improved fuel efficiency reduces fuel cost per kilometre and consequently increases Y and V. The rebound effect refers to this response in Y and V which tends to reduce the beneficial effects of the improved fuel efficiency.

We analyse trucking firm fuel use by accounting for the endogeneity of fuel efficiency. We define fuel efficiency as a function of the average truck attributes and congestion. Consequently, the change in fuel efficiency will be the result of changes in the average truck capacity and the average truck age which again are determined by the level of freight activity, congestion, wages, capital costs, and fuel price. We will in this study focus on the effect of changes in fuel price on the trucking firms' total fuel use. A simple calculation using the definition of elasticity and the solution to PMP shows that (see Appendix A):

$$\varepsilon_{F,P^F} = \varepsilon_{V,P^F} + \varepsilon_{V,Y}\varepsilon_{Y,P^V}\left(1 - \varepsilon_{E,P^F}\right) - \left(\varepsilon_{E,P^F} + \varepsilon_{E,P^V}\right) , \qquad (2.5)$$

where $\varepsilon_{E,P^F} = \varepsilon_{E,S}\varepsilon_{S,P^F} + \varepsilon_{E,H}\varepsilon_{H,P^F}$ and $\varepsilon_{E,P^V} = \varepsilon_{Y,P^V}\left(\varepsilon_{E,S}\varepsilon_{S,Y} + \varepsilon_{E,H}\varepsilon_{H,Y}\right)$. ε_{E,P^F} measures the effect of fuel price on fuel efficiency and ε_{E,P^V} measures the effect of fuel cost per kilometre on fuel efficiency. The potential difference between ε_{F,P^F} and ε_{V,P^F} therefore requires that the last two terms in (2.5) be considerably different from zero. Disregarding this dependence of E on P^F may cause biased estimates of the effect of the change in the fuel price on the trucking firm fuel use and in particular biased estimates of the rebound effect.

3. Empirical analyses

3.1. System of simultaneous equations

The empirical specification is based on trucking firm PMP that simultaneously determines traffic volume (V), number of trucks (M), average truck capacity (S), average truck age (H), labour demand (L), and freight activity (Y). The factor demand functions are determined by the level of output and the factor input prices (see section 2.1). Thus, the trucking firm chooses traffic volume, size of the truck stock, average truck attributes, and demand labour based on freight activity, fuel price, input prices for capital (capital/maintenance costs) and labour (wages), and the level of congestion. The freight activity is determined (among other things) by the output price. Since we do not observe the output price we specify the freight activity equation based on the PMP first-order condition (see (2.3)), i.e. at the optimum output price equals marginal costs. Therefore, the freight activity is assumed to be the function of the level of congestion and the factor input prices, i.e. the fuel cost per kilometre ($P^V = P^F/E$), the input prices for capital (capital/maintenance costs), and wages.[12] The empirical specification of the freight activity also includes GDP that is used here as proxy for general economic development. We also include fuel efficiency (E) in the estimation with the purpose of explicitly analyzing the determinants of the fuel efficiency. The fuel efficiency is determined by accounting for the average truck attributes and the level of congestion. Moreover, the empirical specification of the fuel efficiency includes time trend to proxy for unmeasured changes (technology).[13] These assumptions lead to the following structural model:

[12] Notice here, $\frac{\partial C}{\partial Y} = w\frac{\partial L^*}{\partial Y} + \frac{P^F}{E}\frac{\partial V^*}{\partial Y} - V^*\frac{P^F}{E^2}\left(\frac{\partial E}{\partial S^*}\frac{\partial S^{**}}{\partial P^F} + \frac{\partial E}{\partial H^*}\frac{\partial H^*}{\partial P^F}\right) + \left(\frac{\partial g}{\partial S^*}\frac{\partial S^*}{\partial Y} + \frac{\partial g}{\partial H^*}\frac{\partial H^*}{\partial Y} + \frac{\partial g}{\partial M^*}\frac{\partial M^*}{\partial Y}\right)$ where $C = wL^* + \frac{P^F}{E(S^*,H^*,\bar{D})}V^* + g(S^*,H^*,M^*;\alpha)$ is the cost function, and $Z^* = Z(\bar{D},\bar{Y},w,P^F,\boldsymbol{\alpha})$, $Z = L,M,S,H,V$ are the conditional factor demand functions.

[13] We have also experimented with a producer provided indicator for the expected average fuel use per kilometre for a 40-tonne truck as proxy for the average truck technology. European Automobile Manufacturers' Association reports that average fuel consumption for a 40-tonne truck decreased from 50 litres per 100 km in 1967 to 32 litres per 100 km in 2004 (see ACEA, 2007). Improved fuel efficiency is the result of improvements in engine technologies (e.g. fuel injection), Selective Catalytic Reduction (SCR), telematics technologies (e.g. satellite navigation systems), tires, aerodynamics, etc., i.e. improved technology. So, the producer provided average expected fuel use per kilometre for a new 40-tonne truck has been used as proxy for the average truck technology. Moreover, this indicator has been divided by the average truck age with the purpose of accounting for speed of implementation of new truck technology in the existing truck stock. This experiment was not successful.

$$
\begin{aligned}
E &= E(S, H, \overline{D}, X_E) \\
L &= L(Y, P^F, \overline{D}, w, \boldsymbol{\alpha}, X_L) \\
S &= S(Y, P^F, \overline{D}, w, \boldsymbol{\alpha}, X_S) \\
H &= H(Y, P^F, \overline{D}, w, \boldsymbol{\alpha}, X_H) \\
M &= M(Y, P^F, \overline{D}, w, \boldsymbol{\alpha}, X_M) \\
V &= V(Y, P^F, \overline{D}, w, \boldsymbol{\alpha}, X_V) \\
Y &= Y(P^F/E\ , \overline{D}, w, \boldsymbol{\alpha}, X_Y)\ ,
\end{aligned}
\tag{3.1}
$$

where X_E, X_L, X_S, X_H, X_M, X_V, and X_Y are additional exogenous variables including constants.

We analyse the trucking firm fuel use based on the system in (3.1). Following Small and van Dender (2007) we generalize estimation in two ways to handle dynamics. First, we allow the error terms to be autoregressive of order 1. It means that unobserved factors influencing decisions in a given state will be similar from one year to the next. This could be caused by unobserved factors that persist over time, such as for instance business organizational styles. Second, we include the one-year lagged value of the dependent variable among the explanatory variables. The coefficient of this variable determines the difference between short run and long run effects on the independent variables. The inertia of such movement can arise due to lack of knowledge or slow turnover of the truck stock, or simply because trucking firms respond only slowly to changed circumstances. Consistent estimates of variables in a time series data may depend on autoregression and autocorrelation. Both autoregression and autocorrelation are important in determining the short run and long run effects, because the measurements of the lagged values of the dependent variables are sensitive to whether or not autocorrelation is controlled for. However, it is difficult to separate the presence of a lagged dependent variable from the presence of autocorrelation, especially when aggregate time-series data are used. In the current paper, we discuss the results of a specification incorporating both autoregression and autocorrelation.[14] We will explicitly address the potential bias of this specification by comparing results of this specification with results of a specification incorporating only autoregression.

We specify the equations as linear in parameters and with most variables in logarithms, leading to the following system:

[14] Survey of the empirical studies on rebound effect for motor vehicles is given by Small and van Dender (2005).

$$e_t = \alpha^e e_{t-1} + \alpha^{es} s_t + \alpha^{eh} h_t + \beta^e X_t^e + u_t^e$$
$$l_t = \alpha^l l_{t-1} + \alpha^{ly} y_t + \beta_1^l p_t^f + \beta_2^l X_t^l + u_t^l$$
$$s_t = \alpha^s s_{t-1} + \alpha^{sy} y_t + \beta_1^s p_t^f + \beta_2^s X_t^s + u_t^s$$
$$h_t = \alpha^h h_{t-1} + \alpha^{hy} y_t + \beta_1^h p_t^f + \beta_2^h X_t^h + u_t^h \qquad (3.2)$$
$$m_t = \alpha^m m_{t-1} + \alpha^{my} y_t + \beta_1^m p_t^f + \beta_2^m X_t^m + u_t^m$$
$$v_t = \alpha^v v_{t-1} + \alpha^{vy} y_t + \beta_1^v p_t^f + \beta_2^v X_t^v + u_t^v$$
$$y_t = \alpha^y y_{t-1} + \alpha^{ye} e_t + \beta_1^y p_t^f + \beta_2^y X_t^y + u_t^y$$

with autoregressive errors:

$$u_t^i = \rho^i u_{t-1}^i + \varepsilon_t^i \qquad i = e, l, s, h, m, v, y\ , \qquad (3.3)$$

where lower case notation indicates that the variable is in logarithm.[15] The individual variables in each vector X may be in either levels or logarithms. Subscript t designates a year, and u and ε are error terms assumed to have zero expected value, with ε assumed to be "white noise". The following section provides an overview of the variables used in the system (3.2).

3.2. Data and variables

The data used in the empirical analysis are aggregate time-series data for Denmark covering the years 1980-2007. Our period of observation is thus 28 years. For each year, we have information on aggregate freight activity measured in tkm, aggregate VKT of all trucks registered in Denmark, aggregate fuel consumption (of all trucks registered in Denmark), total actual hours worked in road freight transportation, average truck capacity (measured as average truck total axle weight), average truck age, number of trucks in the truck stock, fuel price, compensation of employees in road freight transportation, price index for vehicles and spare parts, and a range of explanatory variables (GDP, total annual VKT for all motor vehicles registered in Denmark, and the infrastructure measure (kilometre road in Denmark)). *Energy efficiency* (E) has been approximated as the VKT per litre of consumed fuel calculated as the ratio between the total annual VKT and the total annual fuel use. Our measure of *congestion* (D) has been compiled as the ratio of the total annual VKT for all motor vehicles registered in Denmark to the total kilometres of road in Denmark.

[15] Notice here: $\log(P^V) = \log\left(\frac{P^f}{E}\right) = \log(P^f) - \log(E)$.

We identify each variable using both the generic notation in (3.1) and the variable name used in our empirical specification (3.2). We express all the dependent variables and (most of the) independent variables in natural logarithms because this seems a more plausible relationship and because it is easy to interpret estimation results as elasticities. All monetary variables are real. Table 1 shows summary statistics for the data used in our specification. Data sources are given in Appendix B.

Table 1. *Summary statistics for selected variables*

Variable	Mean	Std. Dev.	Minimum	Maximum
Freight activity Y, ($millions\ tkm$)	9,528	1,370	6,941	11,738
Vehicle kilometre travelled V, ($millions\ VKT$)	2,041	154	1,798	2,364
Actual hours worked in road freight transportation L, (1,000 $hours$)	64,458	4,508	56,150	71,972
Number of trucks M, ($trucks$)	47,220	1,715	44,014	50,764
Average truck capacity S, ($tonnes$)	10.59	1.47	7.60	14.10
Average truck age H, ($years$)	7.01	1.11	5.02	8.40
VKT per litre of consumed fuel E, (km/l)	2.74	0.48	2.18	4.00
Fuel price P^F, (DKK/l)	5.92	0.88	3.71	7.53
Price index for vehicles and spare parts PIT, ($index$)	0.82	0.17	0.43	1.03
Compensation of employees in freight transportation w, ($DKK/hour$)	95.974	32.441	37.065	150.530

Notes: Number of observations: 28. One DKK is approximately 0.13€ in 2005.

The dependent variables are:

Y: Freight activity (logarithm: y).

V: Vehicle kilometre travelled (VKT) (logarithm: v).

L: Actual hours worked in road freight transportation (logarithm: l).

M: Truck stock (logarithm: m).

S: Average truck capacity (logarithm: s).

H: Average truck age (logarithm: h).

E: Number of driven kilometres per litre of consumed fuel (logarithm: e).

The independent variables are:

P^F : Fuel price (logarithm: p^f).

X_E includes index of congestion D (logarithm: d) and time trend to proxy for unmeasured changes (for example technological improvements).

X_L, X_S, X_H, X_M and X_V include the price index for vehicles and spare parts (PIT) (logarithm: pit), and the average compensation of employees in road freight transportation per hour (logarithm: w).

X_Y includes the price index for vehicles and spare parts (PIT) (logarithm: pit), the average compensation of employees in road freight transportation per hour (logarithm: w), and the gross national income (GDP) in constant 2000 prices (logarithm: gdp).

4. Empirical results

Two procedures are available for estimating systems of simultaneous equations containing several endogenous variables, i.e. two-stage least squares (2SLS) and three-stage least squares (3SLS). 2SLS first estimates a reduced form of the system in which each equation contains as variables only the exogenous contemporary variables and (for technical reasons) one lagged value of all the exogenous variables and two lagged values of all endogenous variables (Wooldridge, 2002, ch. 8). Then it estimates each equation by replacing the endogenous variables on its right-hand side by their predicted values from the first stage. 3SLS in addition estimates also correlations in the error terms among equations, and then re-estimates the system taking these correlations into account.[16] This is likely in our system because, for example, unobserved factors like economic expectations might influence both the truck usage and the truck stock. Moreover, there is only little difference between 3SLS and 2SLS estimates. The 3SLS provides slightly better precision of estimates. Thus, there is no indication for problems that might arise from misspecification. We therefore consider the 3SLS results as our best estimates. The ordinary least squares (OLS) results are shown for comparison.[17] Consequently, we present results from two estimation methods: OLS and 3SLS.

We reduce each equation to the simplest form including only the significant variables, due to the small number of observations and high correlation between the factor input prices. So the final model specification was obtained by a systematic process of eliminating the insignificant variables. The results of estimating the final specification of the structural system (3.2) are presented in tables 2-8.

[16] The advantage of 3SLS is that it makes more efficient use of the data, by taking advantage of the information in the correlations among the endogenous variables, and therefore permits a more precise measurement of parameters. The disadvantage is that if there are errors in the specification of one equation, then this error affects the other equations more directly than with 2SLS.

[17] Recall here that the OLS procedure ignores the reverse causation.

4.1. Structural equations

The VKT per litre of consumed fuel equation (Table 2) explains the approximated fuel efficiency for constant average truck capacity and constant average truck age. Most coefficients are measured with good precision and demonstrate strong and plausible effects. Unsurprisingly, increase in average truck capacity and average truck age decreases average VKT per litre of consumed fuel. The effect from an increase in the average truck capacity is -1.12 in the short run and $-1.12/(1-0.31) = -1.62$ in the long run. A one percent increase in the average truck capacity therefore implies a 1.12% decrease in the average VKT per litre of consumed fuel in the short run and 1.62% in the long run. The corresponding effects from an increase in the average truck age are -0.91 in the short run and -1.31 in the long run. Moreover, our measure of congestion has statistically significant negative effect on the average VKT per litre of consumed fuel (negative coefficient on d). The negative effect of congestion can be seen as a confirmation that increasing congestion implies environmental externality in the form of higher fuel use and consequently higher traffic related emissions, a result found by many other researchers. The long run effect of an increase in our measure of congestion is -2.15.

Table 2. *VKT per litre of consumed fuel equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of VKT per litre of consumed fuel (e_{t-1})	0.5410**	0.3096
	(0.1916)	(0.2027)
Natural logarithm of average truck capacity (s)	-0.7658*	-1.1200**
	(0.4092)	(0.4441)
Natural logarithm of average truck age (h)	-0.5829**	-0.9054***
	(0.2619)	(0.2789)
Natural logarithm of index of congestion (d)	-0.8538	-1.4845**
	(0.6149)	(0.5994)
Trend	0.0342**	0.0546***
	(0.0162)	(0.0165)
Constant	6.6992*	10.9149***
	(3.4695)	(3.4668)
Rho	0.0017	0.0366
	(0.2620)	(0.2578)
Adjusted R-squared	0.8620	0.8057
SSE	0.0623	0.0654
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of VKT per litre of consumed fuel (e); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

The positive significant coefficient associated with the time trend shows a tendency toward a more energy efficient truck stock for a constant average truck capacity and constant average truck age, i.e. presumably due to the improvements in the available technology. The coefficient on the lagged dependent variable implies that VKT per litre of consumed fuel demonstrates considerable inertia in trucking firm behaviour, with the adjustment in VKT per litre of consumed fuel in a given year by approximately 69% percent of the ultimate adjustment. The equation does not exhibit autocorrelation.

Table 3. *Labour demand equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of labour demand (l_{t-1})	0.2759	0.3729
	(0.3437)	(0.2343)
Natural logarithm of fuel price (p^f)	0.1046	0.0801
	(0.0875)	(0.0855)
Natural logarithm of freight activity (y)	0.1721	0.4939**
	(0.1706)	(0.1827)
Natural logarithm of wages (w)	0.0272	-0.1526**
	(0.0730)	(0.0630)
Constant	6.3156	1.9220
	(3.8081)	(1.9680)
Rho	0.6544**	0.2176
	(0.3057)	(0.2409)
Adjusted R-squared	0.8084	0.8085
SSE	0.0194	0.0161
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of labour demand (l); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

The labour demand (Table 3) is explained, unsurprisingly, by the freight activity and the wages. Increase in the freight activity has positive effect on labour demand (0.49 and 0.79 in the short run and the long run, respectively), while an increase in wages has negative effect on labour demand (-0.15 and -0.24 in the short run and the long run, respectively). The relatively small wage effect on labour demand is possibly due to the fact that a truck has to be operated by a driver regardless of the wage level. The labour demand equation does not exhibit autocorrelation (insignificant coefficient associated with rho).

The average truck capacity equation (Table 4) shows a significant effect of fuel price; but the effect is small (0.12). This effect is however more than four times higher in the long run (0.50). Thus, the trucking firm responses to increase in the fuel costs through expansion of the average truck capacity. The expansion of the average truck capacity increases the fuel use per kilometre (see table 2) but less distance has to be driven for the same payload. We will see that the latter effect offsets the effect of the fuel price on the average truck capacity and that an increase in the fuel price results in the reduction in the overall annual fuel use. The price index for vehicles and spare parts has as expected negative impact on the average truck capacity. Moreover, wages have positive significant effect, possibly because increase in wages decreases the labour demand (see table 3), so for a given freight activity, the trucking firm must extend the average truck capacity in order to be able to ship the same amount of cargo using less labour. The truck capacity demonstrates considerable inertia in trucking firm behaviour. The equation does not exhibit autocorrelation.

Table 4. *Average truck capacity equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of average truck capacity (s_{t-1})	0.8039***	0.7548***
	(0.1670)	(0.1660)
Natural logarithm of fuel price (p^f)	0.1282*	0.1234*
	(0.0656)	(0.0664)
Natural logarithm of price index for vehicles and spare parts (pit)	-0.2843	-0.2175
	(0.1728)	(0.1692)
Natural logarithm of wages (w)	0.1808	0.1697
	(0.1223)	(0.1187)
Constant	1.9333	1.7357
	(1.2015)	(1.1720)
Rho	-0.4108*	-0.2494
	(0.2366)	(0.2201)
Adjusted R-squared	0.9533	0.9439
SSE	0.0159	0.0158
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of average truck capacity (s); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

The results for the average truck age equation (Table 5) show a small but significant effect of fuel price, indicating that trucking firms response to increases in the fuel cost through rejuvenation of the truck stock, i.e. improvements in the truck technology. The fuel price effect on the average truck age is -0.15 in the short run and -0.53 in the long run. Predictably, the price index for vehicles and spare parts has positive effect on average truck age.

Table 5. *Average truck age equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of average truck age (h_{t-1})	0.5144**	0.7113***
	(0.1912)	(0.2299)
Natural logarithm of fuel price (p^f)	-0.1540	-0.1517*
	(0.0914)	(0.0856)
Natural logarithm of price index for vehicles and spare parts (pit)	0.0856	0.2030
	(0.2122)	(0.2188)
Natural logarithm of wages (w)	0.0294	0.1093
	(0.1493)	(0.1880)
Constant	0.9339	0.1914
	(1.3116)	(1.4101)
Rho	0.9202***	0.6053**
	(0.1153)	(0.2293)
Adjusted R-squared	0.9549	0.9639
SSE	0.0230	0.0171
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of average truck age (h); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

Wages do not have significant effect on average truck age. The average truck age equation exhibits, as expected, considerable autocorrelation and demonstrates substantial inertia in trucking firm behaviour. The long run effect of the estimated coefficients is approximately 3.5 times higher than the short run effect.

In the truck stock equation (Table 6) most of the coefficients have strong and plausible effects. As expected, fuel price has negative significant effect, but this effect is relatively small (-0.07 in the short run and -0.14 in the long run). Moreover, freight activity does not have significant effect. Since a truck is an ordinary good, the effect of the price index for vehicles and spare parts is, as expected, negative. This effect is however relatively small and significantly different from zero only at 16%. Wages have positive significant effect on truck age (an increase in wages increases the size of the truck stock) possibly for the same reason as for the average truck capacity. Unsurprisingly, there is a considerable inertia in expanding or contracting the truck stock. This most likely reflects the transaction costs of buying and selling trucks. The equation exhibits considerable autocorrelation (significant coefficient associated with rho).

Table 6. *Truck stock equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of average number of trucks (m_{t-1})	0.6233***	0.5252*
	(0.1626)	(0.2592)
Natural logarithm of fuel price (p^f)	-0.0794**	-0.0660*
	(0.0353)	(0.0340)
Natural logarithm of freight activity (y)	-0.0205	0.0343
	(0.0699)	(0.0660)
Natural logarithm of price index for vehicles and spare parts (pit)	-0.0658	-0.1274
	(0.0866)	(0.0874)
Natural logarithm of wages (w)	0.1234**	0.1280*
	(0.0536)	(0.0663)
Constant	4.9708**	5.7835*
	(1.7556)	(2.8322)
Rho	0.8216***	0.7454**
	(0.1583)	(0.2895)
Adjusted R-squared	0.8870	0.8727
SSE	0.0031	0.0033
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of average number of trucks (m); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

The VKT equation (Table 7) explains the amount of driving performed by the average trucking firm for constant freight activity. The fuel price does not have significant effect on VKT. So, the direct effect of a change in fuel price on traffic volume is unsurprisingly limited, because the trucking firm can only to some extent reduce the traffic volume for a given freight activity through better matching of the trucks' capacity to shipment (see section 2). However, the trucking firm's decision regarding the traffic volume is highly dependent of the freight activity for given factor input prices as indicated by the estimated coefficient associated with the freight activity. The elasticity of VKT with respect to freight activity is 0.40 in the short run and 0.49 in the long run. The price index for vehicles and spare parts does not have a significant effect on VKT. Wages have positive effect on traffic volume, probably because the wage indicator does not adequately measure the truck drivers' wages in this equation but instead the general economic development, since wages rise in periods of economic prosperity. VKT demonstrates mild inertia in trucking firm behaviour, reflecting the time needed to adjust planned travel behaviour. The VKT equation exhibits substantial autocorrelation.

Table 7. *VKT equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of VKT (v_{t-1})	0.3737*	0.1791
	(0.2021)	(0.1744)
Natural logarithm of fuel price (p^f)	-0.0943	-0.0005
	(0.0865)	(0.0872)
Natural logarithm of freight activity (y)	0.1568	0.4029**
	(0.1600)	(0.1629)
Natural logarithm of price index for vehicles and spare parts (pit)	-0.0085	0.0799
	(0.1918)	(0.1865)
Natural logarithm of wages (w)	0.1051	0.3790*
	(0.1251)	(0.2143)
Constant	3.8049*	2.9213
	(1.9057)	(1.7153)
Rho	0.8352***	0.9004***
	(0.1552)	(0.0351)
Adjusted R-squared	0.8616	0.8487
SSE	0.0161	0.0164
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of VKT (v); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

Table 8 shows the estimation results for freight activity. The fuel price has a significant negative effect and the VKT per litre of consumed fuel (the approximated fuel efficiency) has a positive effect, confirming that an increase in fuel cost will raise the marginal costs of production and consequently decrease the demand for freight activity.[18] The elasticity of freight activity with respect to fuel cost per kilometre is $-0.20 - 0.26 = -0.46$ in the short run and -0.57 in the long run. An increase in GDP has, as expected, a positive and significant effect on freight activity (0.55 and 0.67 in the short run and in the long run, respectively). The dynamic effects are small and insignificant, suggesting that, in the short run, the trucking firms adapt the freight activity to changes in the economic environment.

[18] Recall here that, at the market equilibrium, the output price equals marginal costs.

Table 8. *Freight activity equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of freight activity (y_{t-1})	0.1200	0.1803
	(0.1648)	(0.1522)
Natural logarithm of fuel price (p^f)	-0.1756*	-0.2048**
	(0.0915)	(0.0905)
Natural logarithm of VKT per litre of consumed fuel (e)	0.3654***	0.2614**
	(0.0946)	(0.1000)
Natural logarithm of GDP (gdp)	0.3916*	0.5517**
	(0.2002)	(0.2079)
Natural logarithm of wages (w)	0.1218	0.1066
	(0.2191)	(0.2237)
Natural logarithm of price index for vehicles and spare parts (pit)	0.3871	0.3683
	(0.2442)	(0.2308)
Constant	7.1955***	7.5793***
	(2.0766)	(2.1548)
Rho	-0.0078	0.2373
	(0.0299)	(0.1818)
Adjusted R-squared	0.9655	0.9612
SSE	0.0136	0.0132
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of freight activity (y); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

4.2 Rebound effect and other elasticities

We consider the 3SLS results our best estimates and use them for the analysis of the determinants of trucking firm fuel use and the rebound effect. Table 9 shows selected elasticities implied by the structural model, the effect of fuel price on trucking firm fuel use, and the rebound effect.

We estimate the rebound effect based on (2.4). In system (3.2), the formula for rebound effect becomes:

$$\varepsilon_{V,Y}\varepsilon_{Y,P^V} = \alpha^{vy}\left(\beta_1^y - \alpha^{ye}\right). \tag{4.1}$$

The long run rebound effect has been calculated using the same formula, and in addition by accounting for lagged values. Our best estimate of the average rebound effect in the applied sample is 18.8% in the short run and 27.9% in the long run (see Table 9). This is in line with a range of other studies (see e.g. Matos and Silva, 2011).[19] The elasticity of VKT with respect to freight activity $(\varepsilon_{V,Y})$ and the elasticity of freight activity with respect to fuel cost per kilometre (ε_{Y,P^V}) are of more or less same magnitude. The elasticity of VKT with respect to freight activity has a slightly smaller effect. This appears to confirm the theoretical expectation that higher fuel

[19] Matos and Silva (2011) estimated the long run rebound effect for the road freight transportation in Portugal to be about 24.1%. Moreover, estimates of personal motor-vehicle rebound effect for the motor vehicles lie within a range of 10-30% (Small and van Dender, 2007; Hymel et al., 2010).

prices first and foremost imply a decrease in freight activity which again has a considerable effect on the traffic volume. Use of OLS underestimates the short run and long run rebound effects by 54.9% and 44.9%, respectively.[20] This is possibly the case because OLS ignores reverse causation.

Table 9. *Rebound effect and other elasticities*

	Short run	**Long run**
Elasticity of freight activity with respect to fuel price (ε_{Y,P^F})	-0.2048	-0.2498
Elasticity of freight activity with respect to fuel efficiency $(\varepsilon_{Y,E})$	0.2614	0.3190
Elasticity of VKT with respect to freight activity $(\varepsilon_{V,Y})$	0.4029	0.4908
Elasticity of VKT with respect to fuel price (ε_{V,P^F})	-0.0005	-0.0006
Elasticity of fuel efficiency with respect to average truck capacity $(\varepsilon_{E,S})$	-1.1200	-1.6222
Elasticity of fuel efficiency with respect to average truck age $(\varepsilon_{E,H})$	- 0.9054	-1.3114
Elasticity of average truck capacity with respect to fuel price (ε_{S,P^F})	0.1234	0.5031
Elasticity of average truck age with respect to fuel price (ε_{H,P^F})	-0.1517	-0.5255
Rebound effect $(-\varepsilon_{V,Y}\varepsilon_{Y,P^V})$	0.1878	0.2792
Elasticity of fuel use with respect to fuel price (ε_{F,P^F})	-0.1877	-0.1883

Notes: All elasticities are estimated using 3SLS; $\varepsilon_{Y,P^V} = \varepsilon_{Y,P^F} - \varepsilon_{Y,E}$.

Table 9 also shows the total effect of a change in fuel price on the average trucking firm fuel use. We estimate this effect based on (2.5). Since the effects of the freight activity on the average truck age and the average truck capacity are not significant, (2.5) reduces to:

$$\varepsilon_{F,P^F} = \varepsilon_{V,P^F} + \varepsilon_{V,Y}\varepsilon_{Y,P^V}\left(1 - \varepsilon_{E,P^F}\right) - \varepsilon_{E,P^F} , \qquad (4.2)$$

where $\varepsilon_{E,P^F} = \varepsilon_{E,S}\varepsilon_{S,P^F} + \varepsilon_{E,H}\varepsilon_{H,P^F}$. In system (3.2), the formula for the elasticity of fuel use with respect to fuel price becomes:

$$\varepsilon_{F,P^F} = \beta_1^v + \alpha^{vy}\left(\beta_1^y - \alpha^{ye}\right)\left(1 - \varepsilon_{e,p^F}\right) - \varepsilon_{e,p^F} , \qquad (4.3)$$

where $\varepsilon_{e,p^F} = \alpha^{es}\beta_1^s + \alpha^{eh}\beta_1^h$. The long run effect has been calculated using the same formula, and in addition by accounting for lagged values.

Table 9 shows that higher fuel prices decrease the average trucking firm fuel use, but only by a small amount. The estimation results suggest that the response to a fuel price increase is dominated by changes in the freight activity and the traffic volume rather than changes in the VKT per litre of consumed fuel (approximated fuel efficiency). An 1% increase in the fuel price decreases the VKT through the freight activity ($\varepsilon_{V,Y}\varepsilon_{Y,P^V}$) by 0.19% in the short run and 0.28% in the long run. As discussed in the previous section, an increase in the fuel price has more or less no effect on the VKT. Finally, changes in the VKT per litre of consumed fuel of a change in

[20] Notice the insignificant elasticity of VKT with respect to freight activity in Table 7. So, OLS fails to estimate rebound effect.

the fuel price $\left(\varepsilon_{E,S}\varepsilon_{S,P^F} + \varepsilon_{E,H}\varepsilon_{H,P^F}\right)$ also affect the trucking industry fuel use. The trucking firm responds to increase in the fuel price through expansion of the average truck capacity and an increase of the average truck capacity decreases the VKT per litre of consumed fuel, presumably because for given VKT trucks with higher capacity use more fuel. The total effect on the VKT per litre of consumed fuel of a change in the fuel price through average truck capacity is -0.14 in the short run and -0.82 in the long run. The trucking firm also responds to an increase in the fuel costs through rejuvenation of the truck stock, and the newer trucks use less fuel per kilometre. The total effect on the VKT per litre of consumed fuel of a change in the fuel price through the average truck age is 0.14 in the short run and 0.69 in the long run. Thus, an increase in the fuel price has negative effect on the average VKT per litre of consumed fuel (approximated fuel efficiency), i.e. a 1% increase in the fuel price decreases average VKT per litre of consumed fuel by 0.001% and 0.13% in the short run and in the long run, respectively. However, less distance has to be driven for the same payload, so the total effect on the average trucking firm fuel use is negative. Thus, an increase in the fuel price results in the reduction in the trucking firm's overall fuel use. The elasticity of fuel use with respect to fuel price is -0.19 in the short run and in the long run.

4.3 Robustness checks

In this section, we discuss the sensitivity of the estimation results to assumptions regarding the model dynamics (autoregression and autocorrelation) and to known problems with the aggregate freight activity data.

First, our estimates (especially long term estimates) rely on assumptions regarding the model dynamics, i.e. the one-year lagged value of the dependent variable (autoregression) and the autoregressive error terms (autocorrelation). Moreover, the role of the one-year lagged value of the dependent variable in determining the long run effect is sensitive to whether or not autocorrelation is controlled for. In order to check the dependence of the estimated effects on the autocorrelation, we estimate a model shown in Appendix C where the autoregression of the error term is omitted. The exclusion of the autoregressive error terms increases the estimates of the rebound effect from 19% to 26% in the short run and from 28% to 69% in the long run. Furthermore, in the unrestricted model (model specification incorporating both autoregression and autocorrelation), the total effect of changes in fuel price on the average trucking firm fuel use (ε_{F,P^F}) in the short run is more or less identical to this in the restricted model (model specification incorporating autoregression but not autocorrelation). The effect of changes in fuel prices on the trucking firm fuel use in the long run is almost two times higher in the restricted model than in the unrestricted model. However, the overall performance of the restricted model is unsatisfactory, especially its dynamic properties. The Godfrey Lagrange multiplier test for serially correlated residuals indicates strong autocorrelation in almost all equations (see Appendix C).[21] So, we use the model specification incorporating both autoregression and autocorrelation, since the Godfrey Lagrange multiplier test for serially correlated residuals rejects the null hypothesis that the errors are serially uncorrelated in the model specification incorporating autoregression but not autocorrelation. Therefore we have some confidence that the resulting estimates of the coefficients of the lagged endogenous variables in the preferable empirical specification are accurate and give a valid indication of the extent of long-run effects. Furthermore, including both autoregression and autocorrelation does not seem to affect the precision of the other estimates.[22]

The second robustness check concerns the aggregate freight activity data collected by the Statistics Denmark. Data are collected in quarterly sample surveys. The response rate at the closing of the survey is relatively high (98%).[23] However, about 40% of the questionnaires do not contain journey data. In these questionnaires selected vehicles were inactive in the reference period because of lacking orders, holiday closure, or vehicle technical service. Consequently, we have reason to think that this exceptionally high share of inactive vehicles in the reference period biases the estimation results. However, if the aggregate freight activity data are underestimated every year by the roughly same percent, then the impact of this high share of inactive vehicles in the reference period on the estimation results will be minimal. We have no reason to think that the sources of measurement error are persistent over time and unrelated to the independent variables, and because we do not have information of the share of inactive vehicles for every

[21] The null hypothesis of Godfrey's tests is that the equation residuals are white noise. However, if the equation includes autoregressive error model of order t ($AR(t)$) the test is for the null hypothesis that the structural errors are from an $AR(t+1)$ process versus the alternative hypothesis that the errors are from an $AR(t)$ process.
[22] The estimation of a specification including the two-year lagged value of the dependent variable could not be performed due to the limited number of observations.
[23] http://www.dst.dk/HomeUK/Guide/documentation/Varedeklarationer/emnegruppe/emne.aspx?sysrid=992 (accessed 25/12 2010).

year, we can only conclude that better data on the aggregate freight activity would add considerably to the confidence in estimation results.

5. Conclusion

This paper analyses the determinants of road freight transportation fuel use. We develop a simple model to show that the trucking firm fuel use depends on traffic volume, freight activity, characteristics of the truck stock, factor input prices, and congestion. We show that the rebound effect for road freight transportation can be decomposed into the negative of the product of the elasticity by which changes in fuel costs affect the freight activity and the elasticity by which changes in freight activity affects traffic volume. The model is applied to Danish aggregate time series data covering the years 1980-2007. The empirical results provide some insights into the determinants of the road freight transportation fuel use.

We find that higher fuel prices decrease the trucking firm fuel use, but only by a small amount. Surprisingly, an increase in the fuel price has negative effect on the fuel efficiency, i.e. a 1% increase in the fuel price decreases the fuel efficiency by 0.13% in the long run. However, less distance has to be driven for the same payload, so an increase in the fuel price results, as expected, in the reduction in the trucking firm fuel use. Moreover, we find that the short run and the long run rebound effects for road freight transportation are 19% and 28%, respectively.

Analyses of the determinants of the trucking firm fuel use and estimates of the rebound effect are highly relevant for policy. For example, measurements of the rebound effect for road freight transportation can contribute to the ongoing debate whether to adapt the rules on the optimal weights and dimensions of heavy trucks in EU. Arki (2009) shows that introducing longer and heavier vehicles (up to 20.75 meters, 44 tonnes) Europe-wide will be overall beneficial for society. Moreover, Arki (2009) argues that the introduction of longer and heavier vehicles could lower fuel consumption of road freight transportation by 3.6%. We showed that an increase in the weight of heavy trucks will reduce the fuel efficiency and consequently affect the fuel cost per kilometre implying the rebound effect that to some extent will offset the original energy saving. So, the introduction of longer and heavier vehicles will most likely not result in a 3.6% fuel saving, but only in a 2.6% reduction due to the rebound effect. This stresses the importance of including rebound effects in assessments of new policies. Moreover, strengthening fuel efficiency standards for heavy trucks in the EU can potentially result in undesirable effects on traffic congestion, because strategies that increase fuel efficiency, and therefore reduce the per-kilometre cost of driving, tend to increase total truck use. It is therefore important to account for the rebound effect to more accurately evaluate energy policy changes.

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Appendix A. Rebound effect

Assume now that E exogenously changes. We know that traffic volume V depends (among other things) on the fuel price and freight activity (see section 2.1). Moreover, we know that the freight activity depends (among other things) on marginal costs, a part of which is the per-kilometre fuel cost (P^V).[24] Fuel consumption and VKT are related through fuel efficiency (see (2.1)):

$$F = \frac{V\left(Y(P^V),\bar{D},w,P^F,\boldsymbol{\alpha}\right)}{\bar{\mathrm{E}}} \ , \tag{A.1}$$

where $\mathrm{P^V} = \frac{\mathrm{P^F}}{\mathrm{E}}$. Differentiating (A.1) with respect to E, we have:

$$\frac{\partial F}{\partial E} = \frac{-P^F}{E^3}\frac{\partial V}{\partial Y}\frac{\partial Y}{\partial P^V} - \frac{V}{E^2}. \tag{A.2}$$

Now multiplying both sides with E/F and rearranging we get:

$$\varepsilon_{F,E} = -1 - \varepsilon_{V,Y}\varepsilon_{Y,P^V}. \tag{A.3}$$

Notice now that, using the solution to PMP, fuel use can be shown to be:

$$\mathrm{F} = \frac{\mathrm{V}\left(\mathrm{Y}\left(\frac{\mathrm{P^F}}{\mathrm{E}\left(\mathrm{S}(\mathrm{P^F},\bar{\mathrm{Y}},\bar{\mathrm{D}},\mathrm{w},\boldsymbol{\alpha}),\mathrm{H}(\mathrm{P^F},\bar{\mathrm{Y}},\bar{\mathrm{D}},\mathrm{w},\boldsymbol{\alpha})\right)}\right),\bar{\mathrm{D}},\mathrm{w},\mathrm{P^F},\boldsymbol{\alpha}\right)}{\mathrm{E}\left(\mathrm{S}\left(\mathrm{Y}\left(\frac{\mathrm{P^F}}{\bar{\mathrm{E}}}\right),\bar{\mathrm{D}},\mathrm{w},\mathrm{P^F},\boldsymbol{\alpha}\right),\mathrm{H}\left(\mathrm{Y}\left(\frac{\mathrm{P^F}}{\bar{\mathrm{E}}}\right),\bar{\mathrm{D}},\mathrm{w},\mathrm{P^F},\boldsymbol{\alpha}\right)\right)}. \tag{A.4}$$

Moreover, a simple calculation using the definition of elasticity shows that:

$$\frac{\partial F}{\partial \mathrm{P^F}} = \frac{1}{E}\left[\frac{\partial V}{\partial \mathrm{P^F}} + \frac{\partial V}{\partial \mathrm{Y}}\frac{\partial Y}{\partial \mathrm{P^V}}\left(\frac{1}{E} - \frac{\mathrm{P^F}}{E^2}\left(\frac{\partial E}{\partial \mathrm{S}}\frac{\partial S}{\partial \mathrm{P^F}} + \frac{\partial E}{\partial \mathrm{H}}\frac{\partial H}{\partial \mathrm{P^F}}\right)\right)\right]$$

$$- \frac{V}{E^2}\left(\frac{\partial E}{\partial \mathrm{S}}\left(\frac{\partial S}{\partial \mathrm{P^F}} + \frac{\partial S}{\partial \mathrm{Y}}\frac{\partial Y}{\partial \mathrm{P^V}}\frac{1}{E}\right) + \frac{\partial E}{\partial \mathrm{H}}\left(\frac{\partial H}{\partial \mathrm{P^F}} + \frac{\partial H}{\partial \mathrm{Y}}\frac{\partial Y}{\partial \mathrm{P^V}}\frac{1}{E}\right)\right)$$

$\Leftrightarrow$

[24] Smith (1957) showed that the trucking firm fuel use is a function of the VKT and the vehicle gross weight, while the total aggregate fuel use by the trucking industry is a function of both VKT and freight activity.

$$\varepsilon_{F,P^F} = \varepsilon_{V,P^F} + \varepsilon_{V,Y}\varepsilon_{Y,P^V}\left(1 - \varepsilon_{E,P^F}\right) - \varepsilon_{E,P^F} - \varepsilon_{E,P^V}\ , \tag{A.5}$$

where $\varepsilon_{E,P^F} = \varepsilon_{E,S}\varepsilon_{S,P^F} + \varepsilon_{E,H}\varepsilon_{H,P^F}$ and $\varepsilon_{E,P^V} = \varepsilon_{Y,P^V}\left(\varepsilon_{E,S}\varepsilon_{S,Y} + \varepsilon_{E,H}\varepsilon_{H,Y}\right)$.

If $\varepsilon_{S,Y} = 0$ and $\varepsilon_{H,Y} = 0$, then:

$$\varepsilon_{F,P^F} = \varepsilon_{V,P^F} + \varepsilon_{V,Y}\varepsilon_{Y,P^V}\left(1 - \varepsilon_{E,P^F}\right) - \varepsilon_{E,P^F}. \tag{A.6}$$

Appendix B. Data sources

Aggregate freight activity has been compiled by the National Environmental Research Institute – Aarhus University from several different reports (Statistics Denmark, 2000; The Danish Car Importers Association, 2001-2008; The Danish Road Directorate, 1998; Winther, 2007), which in turn are based on data submitted by enterprises performing transport for their own account or for hire or reward. The data are collected by Statistics Denmark in quarterly sample surveys including trucks over 6 tonnes of maximum permissible weight. The survey is described in Statistics Denmark's online documentation.[25] *Aggregate VKT* of all trucks registered in Denmark has been compiled by Statistics Denmark based on exact odometer readings from the so-called MOT tests, a more accurate basis than asking respondents to remember VKT.[26] Data on the *size of the truck stock* are published regularly by Statistics Denmark in "News from Statistics Denmark" ("Nyt fra Danmarks Statistik"), in the series "Statistical News" ("Statistiske Efterretninger"), and in Statistics Denmark's online-database www.statbank.dk (accessed 25/12 2010). *Average truck capacity* (measured as axle load in kilograms) and *average truck age* are computed from administrative register data. Data on *fuel consumption* are taken from Danish Environmental Accounts (see www.statbank.dk); the statistics on fuel consumption are reprinted in many sources, such as Winther (2007). *Fuel prices* are from The Danish Petroleum Association web page (http://oliebranchen.dk/da-DK/Service/English.aspx (accessed 25/12 2010)). Applied infrastructure measure (*kilometre road in Denmark*) is easily taken from the Danish Road Directorate's online database (http://www.vejdirektoratet.dk (accessed 25/12 2010)). Data on *total actual hours worked in road freight transportation*, *compensation of road freight transportation employees*, *price index for vehicles and spare parts*, and *GDP* are taken

[25] For detailed description of the survey see http://www.dst.dk/HomeUK/Guide/documentation/Varedeklarationer/ (accessed 25/12 2010).

[26] The MOT test is a vehicle check that is compulsory for all vehicles registered in Denmark. The name derives from the Ministry of Transport. All Danish trucks have to pass such MOT tests when first registered, and then at statutory time intervals, i.e. every year. Each time a truck passes the MOT test, the inspection authority reads the odometer on the day of the MOT test, records date of the MOT test and several different identification data regarding the vehicle.

from Statistics Denmark's online database www.statbank.dk. The data is available from the author on request.

Appendix C. Estimation results for specifications without control for autocorrelation

Table C1. *VKT per litre of consumed fuel equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of VKT per litre of consumed fuel (e_{t-1})	0.5414***	0.3843**
	(0.1668)	(0.1547)
Natural logarithm of average truck capacity (s)	-0.7664*	-0.9942**
	(0.3991)	(0.4149)
Natural logarithm of average truck age (h)	-0.5826**	-0.8434***
	(0.2460)	(0.2283)
Natural logarithm of index of congestion (d)	-0.8527	-1.1583**
	(0.5695)	(0.5164)
Trend	0.0341**	0.0465***
	(0.0155)	(0.0146)
Constant	6.6952*	9.0816***
	(3.2353)	(2.9981)
Adjusted R-squared	0.8686	0.8226
SSE	0.0623	0.0629
Godfrey LM test statistics	0.00	1.48
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of VKT per litre of consumed fuel (e); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

Table C2. *Labour demand equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of labour demand (l_{t-1})	0.5339**	0.2654
	(0.2115)	(0.1602)
Natural logarithm of fuel price (p^f)	0.0509	0.0666
	(0.0851)	(0.0730)
Natural logarithm of freight activity (y)	0.2901	0.5918***
	(0.2107)	(0.1756)
Natural logarithm of wages (w)	-0.0628	-0.1683***
	(0.0634)	(0.0568)
Constant	2.2669	2.2018 *
	(1.5754)	(1.2640)
Adjusted R-squared	0.7778	0.7900
SSE	0.0235	0.0186
Godfrey LM test statistics	4.52	3.64
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of labour demand (l); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

Table C3. *Average truck capacity equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of average truck capacity (s_{t-1})	0.7382***	0.7781***
	(0.2072)	(0.1763)
Natural logarithm of fuel price (p^f)	0.1448*	0.1336*
	(0.0783)	(0.0742)
Natural logarithm of price index for vehicles and spare parts (pit)	-0.1460	-0.1185
	(0.2079)	(0.2075)
Natural logarithm of wages (w)	0.1213	0.1042
	(0.1535)	(0.1463)
Constant	1.3083	1.0716
	(1.4981)	(1.4513)
Adjusted R-squared	0.9498	0.9426
SSE	0.0179	0.0169
Godfrey LM test statistics	3.09	2.18
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of average truck capacity (s); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

Table C4. *Average truck age equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of average truck age (h_{t-1})	0.8504***	0.8273***
	(0.1121)	(0.0698)
Natural logarithm of fuel price (p^f)	-0.0277	-0.0219
	(0.1086)	(0.0891)
Natural logarithm of price index for vehicles and spare parts (pit)	-0.0836	0.0405
	(0.3187)	(0.2449)
Natural logarithm of wages (w)	0.0875	0.0583
	(0.2099)	(0.1559)
Constant	0.9324	0.3459
	(2.0443)	(1.5417)
Adjusted R-squared	0.9220	0.9444
SSE	0.0416	0.0277
Godfrey LM test statistics	6.81	5.71
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of average truck age (h); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

Table C5. *Truck stock equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of average number of trucks (m_{t-1})	0.6390***	0.5516***
	(0.1683)	(0.0968)
Natural logarithm of fuel price (p^f)	-0.0725	-0.0659
	(0.0475)	(0.0423)
Natural logarithm of freight activity (y)	0.0390	0.0689
	(0.0934)	(0.0613)
Natural logarithm of price index for vehicles and spare parts (pit)	-0.2200	-0.2135*
	(0.1333)	(0.1047)
Natural logarithm of wages (w)	0.1669*	0.1484**
	(0.0823)	(0.0646)
Constant	5.0243**	5.6073***
	(1.8823)	(1.1877)
Adjusted R-squared	0.7728	0.7733
SSE	0.0066	0.0061
Godfrey LM test statistics	15.73	10.93
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of average number of trucks (m); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

Table C6. *VKT equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of VKT (v_{t-1})	0.4993**	0.5508***
	(0.2152)	(0.1684)
Natural logarithm of fuel price (p^f)	0.0316	-0.0284
	(0.1063)	(0.0946)
Natural logarithm of freight activity (y)	0.4036*	0.5434***
	(0.2069)	(0.1660)
Natural logarithm of price index for vehicles and spare parts (pit)	-0.1992	-0.2940
	(0.2317)	(0.2120)
Natural logarithm of wages (w)	0.0392	0.0298
	(0.1528)	(0.1362)
Constant	1.0346	-0.1330
	(1.9393)	(1.6669)
Adjusted R-squared	0.8188	0.8381
SSE	0.0221	0.0185
Godfrey LM test statistics	4.17	1.32
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of VKT (v); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

Table C7. *Freight activity equation*

	[1]	[2]
	Estimated using OLS	Estimated using 3SLS
Lagged natural logarithm of freight activity (y_{t-1})	0.1006	0.1351
	(0.1413)	(0.1410)
Natural logarithm of fuel price (p^f)	-0.1670*	-0.1714*
	(0.0837)	(0.0884)
Natural logarithm of VKT per litre of consumed fuel (e)	0.3667***	0.3196***
	(0.0920)	(0.0870)
Natural logarithm of GDP (gdp)	0.3829*	0.4731**
	(0.1928)	(0.1732)
Natural logarithm of wages (w)	0.1321	0.0464
	(0.2091)	(0.1969)
Natural logarithm of price index for vehicles and spare parts (pit)	0.3919	0.4304*
	(0.2377)	(0.2317)
Constant	7.3584***	6.8632***
	(1.9136)	(1.8520)
Adjusted R-squared	0.9671	0.9618
SSE	0.0136	0.0137
Godfrey LM test statistics	0.78	2.08
No. of observations	27	26

Notes: Dependent variable is the natural logarithm of freight activity (y); ***,**,* indicate that estimates are significantly different from zero at the 0.01, at the 0.05 and the 0.10 level, respectively; standard errors are in parentheses.

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