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The rebound effect on road freight transport: Empirical evidence from Portugal

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ABSTRACT

Because a large proportion of total operating costs for transportation companies goes towards energy, a reduction in energy operating costs, brought about by an increase in fleet fuel efficiency, or an increase in operational efficiency, results in a change in the relative cost of road freight transportation. This fact could result in an increase in the demand for such services. If this is true, the result would be an increase in total fuel consumption. Consequently, that part of the energy savings obtained through the increased energy efficiency would be lost. The existence of a "Rebound Effect" is especially important in the road freight transportation sector and is crucial for the definition of a national energy policy.

In this study, data from the road freight transportation sector in Portugal for the years of 1987 through 2006 was analyzed. It was determined that an increase in energy efficiency did not cause a backfire, but did cause a total direct rebound effect of 24.1%. In addition, fleet operators were more inclined to adopt operational efficiencies than technological fuel efficiencies as a means of increasing the total operational efficiency.

1. Introduction

The relationship between energy consumption and economic growth has been indisputable since the industrial revolution. From the extraction of raw materials, to the transportation of goods to consumers, energy serves as a key resource that enables economies to benefit from all of the advantages of a globalized efficient world economy. In this sense, the rational use of energy is essential to ensure sustained economic growth.

Since the mid-eighteenth century, energy has been a highly coveted resource. The race to acquire, extract, transport and consume this resource, from the most basic forms of energy, to the forefront of new production technologies, makes the analysis of production and consumption tendencies increasingly important as a means to safeguard the future supply of a resource that is of great importance to the global economy.

The growing concern over environmental issues has led many countries to adopt policies aimed at reducing the emission of greenhouse gases. Most carbon dioxide emissions come from the consumption of fossil fuels that stimulate domestic and international economies. One way to reduce energy consumption would be to increase energy efficiency by means of efficiency standards, which would define minimum levels for energy efficiency. These types of policies have been adopted by most European Union countries and, to a lesser extent, by the United States. The gains in energy efficiency are discussed in a context where such gains are not only seen as a way to reduce CO_2 emissions, but also a way to serve as an alternative "source" of energy.

In the United States, over the last decade, many critics have voiced their concern over the effectiveness of energy policies aimed at increasing energy efficiency. Despite the incentives to industry and national programs aimed at improving the productivity of energy, the consumption of this resource continues to reach unprecedented levels. Thus, serious doubts have been raised as to the effectiveness of this tool in the fight to reduce foreign energy dependency.

The potential energy savings from improved energy efficiency can be estimated using basic physics principles and engineering models. However, the actual energy savings from such improvements generally falls short of such estimates. A possible explanation for this phenomenon could be that such improvements encourage the consumption of energy services where part or all of the gain would be offset by the increase in consumption. This is sometimes termed the rebound effect or backfire.

The nature and magnitude of the rebound or backfire effect has been the subject of strong debate among economists. To reduce the emission of greenhouse gases, many countries are now seeking ways to improve the energy efficiency of the entire economic system. It is generally accepted that such improvements will reduce

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energy consumption, compared with a scenario in which such improvements do not exist.

Backfire or the rebound effect, also known as the Khazzoom–Brookes postulate, can be defined as the difference between the projected energy savings and actual energy savings resulting from the increased energy efficiency. This effect is seen as having three primary components: a direct rebound effect, an indirect rebound effect and dynamic market effects. The first two effects are easily studied at the microeconomic level through price elasticity and the cross price elasticity of demand. The dynamic market effects are more difficult to analyze, requiring a macroeconomic approach that takes into account the change in resources prices and the impact this change would have on the demand for energy. In addition, the increase in total factor productivity must also be taken into account.

The Khazzoom–Brookes postulate was first identified in the contemporary literature by Khazzoom (1980). The postulate states that a reduction in the implicit cost of energy that results from increased energy efficiency may cause an increase in energy consumption. The direct effect can be considered as the initial energy savings that are not realized due to the change in the consumption pattern of consumers.

This paper attempts to analyze the rebound effect for road freight transportation that may question the validity of existing policies aimed at promoting energy efficiency in the Portuguese economy. We chose to examine the behavior of fleet operators whose sector is energy intensive.

Road freight transportation in Portugal accounts for 66% of the total volume of transported goods. In 2006, 291.0 million tons of goods were transported inside national borders and 30.2 million tons of goods were transported between Portugal and other EU countries. In 2006, 4093.8 million kilometers were driven and the total fleet consisted of 122 thousand vehicles that consumed a total of 871 million liters of diesel fuel.

The primary objective of this paper consists of determining whether a reduction in the amount of energy necessary to provide one unit of an energy service, which occurs at the microeconomic level and is facilitated by technological innovation, is the appropriate tool to use to reduce energy consumption at the macro level.

2. Literature review

2.1. The Khazzoom–Brookes postulate

Jevons in 1885 was the first person to identify what would come to be called the direct and indirect rebound effect, by applying the example of steel furnaces. Jevons example stated that if the amount of coal used in a furnace is reduced, maintaining the same level of production, the profitability of this activity will increase. In the context of increased profitability, new capital will be attracted, which would result in increased production and a fall in the price of the final product (steel), which would be accompanied by increased demand and greater production. The increase in the number of furnaces will offset the lower average consumption of coal for each furnace, which would result in the increased domestic consumption of coal (see as an example Clark and Foster (2001)).

Khazzoom (1980), the first contemporary author to empirically study the components of the Jevons paradox, showed that in the long-run, the elasticity of demand for various energy services (such as water heating and central heating) exceeded negative one, implying that the energy efficiency of these services may lead to an increase in household energy consumption. However, his findings focused mainly on the elasticity of demand. The Jevons paradox was fully addressed later in a work by Brookes (1990), who introduced the productivity of energy and its effect on the rest of the economy into the analysis.

In the 1980s, there was a growing concern for environmental issues. During this time, Keepin and Kats (1988) published a series of articles addressing the matter of mandatory energy efficiency standards as a means of reducing energy consumption and avoiding the adverse environmental effects of energy consumption. Therefore, in 1988, energy efficiency was presented by researchers as one of the most effective ways of reducing the emission of greenhouse gases.

Keepin and Kats (1988) argued that the increased level of energy efficiency was the most important technological factor in determining the emission of greenhouse gases. The authors argued that this statement was not just a theoretical concept, as there existed a reduction in energy intensity by 12% worldwide since 1973 as proof. They stated that this development occurred in the absence of active energy efficiency promotion, which illustrates a small part of what would be possible through concerted policies at a global scale. The authors concluded that every monetary unit applied towards promoting energy efficiency will have an effect of between 2.5 and 10 times that of every monetary unit applied in the replacement of fossil energy with nuclear power in terms of reducing carbon dioxide emissions. As such, energy efficiency policies are an effective and inexpensive way of addressing the issue of global warming (Keepin and Kats, 1988).

In response to Keepin and Kats (1988), Brookes (1990) argued that energy efficiency could not be used alone to resolve the issue of growth in the consumption of energy, and hence, global warming. He argued that most advocates of energy efficiency discarded the absence of any evidence that could prove that such a policy would reduce energy consumption. Brookes provided the example of the conversion of energy into useful work that, in the last one hundred years, increased by a factor of 10. After this period of technological change, total and per capita consumption of energy was higher than at the end of the previous century. To Brookes, this could be explained as a result in the reduction of the price of energy services, which itself led to an increased demand for these services.

Brookes (1990), with the support of papers published by Schurr (1982) and Jorgenson (1984), stated that the substitution of capital and labor for energy results in an increase in total factor productivity, which increases energy productivity and reduces the energy intensity of the economy. Brookes (1990) argued that the reduction of the energy intensity evoked by some as evidence of increased energy efficiency, namely Keepin and Kats (1988), is indeed associated with an increase in energy consumption. The substitution of capital and labor for energy has a high impact on the productivity of these two factors, which increases the joint productivity of labor and capital which, in turn, exceeds the growth of energy consumption. The final result would be an increase in energy consumption and a reduction in energy intensity.

In another analysis by Brookes (1992) on domestic household energy consumption, the author claimed to observe a high correlation between income and energy consumption. Domestic consumers tended to use a fixed part of their income on energy services, such as fuel and electricity. In this case, a higher level of energy efficiency of some household energy services may cause an increase in their usage or the consumption of other energy services. The increase in purchasing power, which is a result of the reduced expenditure on consumer goods, will be redirected to the consumption of goods and services that require energy in their production and/or utilization.

The preposition advocated by Brookes found support in the work of Greenhalgh (1990). To Greenhalgh (1990), the oil shocks of 1971 and 1979 dictated the end of cheap energy and demonstrated the need for the government to assume an active role in defining energy solutions. The author exemplified this with the existence of a series of programs introduced since 1971 aimed at promoting energy efficiency to stabilize the domestic market. The performance of these programs has been evaluated based on the reduction of the energy intensity of the economy.

Like the findings of Schurr (1982) and Grubb (1990), Greenhalgh (1990) argued that there are a wide range of factors that can affect the ratio of primary energy consumption to GDP. If the structure of economic production changes from one that is based on industrial production to one based on services, the increase in GDP will most likely be accompanied by a reduction in energy consumption. Also, a change in the structure of economic production, from products with low value added to products with high value added, may also cause a change in energy intensity. In both cases, energy intensity will fall without energy efficiency playing a significant role in reducing this indicator (Greenhalgh, 1990).

Besides the issue of efficiency and its effect on household energy consumption, Greenhalgh (1990), in line with the conclusions drawn by Brookes (1990), highlighted the relationship between the productivity of energy and its effect on the welfare of society by increasing the consumption of energy services. Once more, Greenhalgh (1990) refuted Keepin and Kats (1988), stating that they did not address the benefits to consumers and only concentrated on the consumption of energy services.

In a response to Brookes (1990), Toke (1990) argued that there was no evidence that the efficient use of energy causes an increase in consumption. He argued that primary energy consumption in England in 1988 was 3% lower than in 1973, even though GDP had grown by 31%, stating that this was due to policies aimed at promoting energy efficiency. Toke (1990) challenged the assumption of Brookes (1990) and argued that the relationship between household income and expenditures on energy was constant.

Herring and Elliot (1990) expressed their doubts about the importance given by Brookes to the increased productivity of labor and capital that results from energy efficiency. They argued that although the concept of total factor productivity is relevant when studying the industrial sector, where energy represents a significant component of production costs, it should be noted that the industrial consumption of energy in the UK accounts for only 28% of total energy consumption. This concept would not be relevant when the industry in analysis does not have a significant share of its operating costs dedicated to energy (Herring and Elliot, 1990). The authors argued that since 1940, energy consumption by households did not increase, despite the considerable increase in household disposable income. Therefore, Brookes' (1990) proposition, which states that purchasing power released as a result of an increase in energy efficiency will be applied towards the consumption of energy services and lead to an increased consumption in energy, has no validity (Herring and Elliot, 1990).

The debate surrounding the issue has been enriched by many contributions, some of which are in favor of the existence of the rebound effect and some of which are against it. One such study was written by Grubb (1990), who examined the two scenarios proposed by Brookes (1990). In the first scenario, where there is restriction on the use of energy, Grubb (1990) agreed with Brookes (1990) when he stated that policies to promote energy efficiency will not lead to reduced consumption. In the second scenario, the historical data available until 1973 clearly confirmed the findings of Brookes (1990). However, Grubb (1990) argued that it would be unwise to assume that the trends of the past are reflected in the future. The 1970s and 1980s experienced great changes in the pattern of energy consumption as a result of the rising prices of fossil fuels. There are also some indications that certain energy services were reaching saturation levels. These two factors combined to change the tendencies of economic production towards goods with smaller energy components and raised doubts about the use of the past as a future reference.

Grubb (1990) wrote that Brookes (1990) made the mistake of confusing the process of improving energy efficiency, which is the result of a natural economic incentive, with attempts to minimize energy consumption. Until 1973, increased energy efficiency was the result of the pursuit of objectives that were not limited to the reduction of energy consumption, such as increasing the operational efficiency through the introduction of automated processes, where energy costs were lower than the cost of labor (Grubb, 1990).

Brookes (1992) responds to the criticism raised, always defending it with the aid of economic models. His conviction is that policies aimed towards energy efficiency were a threat to the very purpose advocated by conservationists: that energy efficiency leads to a reduction of the real cost of the energy service that will increase the demand for these services.

During the last two decades, the rebound effect has been a subject that has generated discord between the proponents and opponents of energy efficiency. While the existence of this phenomenon is widely agreed upon, the magnitude of its various effects and components has generated a heated debate on the effectiveness of this policy instrument as a means to reduce energy consumption.

While economists with greater proximity to the energy sector have recognized that the direct and indirect rebound effects exist and that this could reduce the potential savings of policies aimed at promoting energy efficiency, there is no consensus on the magnitude of the combined effect. Lovins et al. (1988) and Schipper and e Grubb (2000) argue that the rebound effect is of minor importance due to the inelastic demand of energy services and the small part that energy costs represent. Others suggest that its effect is important enough to completely eliminate the initial gains from energy efficiency (Brookes, 2000; Herring, 2006).

A more recent report produced by the Sussex Energy Group for the Technology and Policy Assessment function of the UK Energy Research Center (Sorrell, 2007, concludes that evidence for the direct rebound effect for automotive transport and household heating within developed countries is relatively robust. Evidence for direct rebound effects for other consumer services is much weaker, as that for energy efficiency improvements by producers. Evidence is particularly weak for energy efficiency improvements in developing countries although theoretical considerations suggest that direct rebound effects in this context will be larger than those in developed countries.

2.2. The direct rebound effect—empirical studies

The direct rebound effect relates to individual energy services, such as personal automotive transportation, space heating, and lighting, where a change in the cost of the service causes a change in consumer behavior. In these cases, a higher level of energy efficiency reduces the marginal cost of providing the energy service. For example, after buying a more efficient car, consumers may choose to drive more due to the reduction in the cost per kilometer. Therefore, the increase in consumption of the service will offset part of the reduction in energy consumption achieved through improved efficiency.

The direct rebound effect can be decomposed into: (1) a substitution effect, where the consumption of the cheaper energy service substitutes for the consumption of other goods and services; and (2) an income effect, where the increase in real income, which results from the increased efficiency, causes an increase in the consumption of the service.

The magnitude of the direct rebound effect should be proportional to the share of energy costs of the total cost of the energy service. Furthermore, if these costs are easily communicated to consumers, the direct rebound effect should be greater. In personal automotive transportation, fuel costs are a major component of the total cost per kilometer and are easily observed every time the consumer refuels the vehicle.

As previously stated, the direct rebound effect can be decomposed into an income effect and a substitution effect. Overall, the empirical studies whose objective is to quantify the rebound effect focus on the direct rebound effect. This phenomenon is easily quantified through the analysis of secondary data regarding the demand for a particular energy service.

The direct rebound effect is related to the consumption of energy required to provide a service. Increased energy efficiency will reduce the marginal cost of usage, which should cause an increase in its consumption.

Estimates of the direct rebound effect vary considerably. They have been found to depend on the energy service studied, the time frame analyzed and the functional model applied. Regarding personal automotive transportation, the most studied energy service, estimates vary between 3% and 87%. A general consensus puts the most probable range between 10% and 30% (Sorrell, 2007).

By far the most analyzed energy service to be studied with regards to the direct rebound effect is personal automotive transportation. Most of these studies focus on the United States, given the relative abundance of data. These studies vary considerably as to the data used and their functional form. Most use aggregate data to observe the effects of this phenomenon in the long-run, but some use household surveys to analyze the behavior of individual consumers at a more microeconomic level.

Although the primary objective of this paper is to quantify the direct rebound effect for road freight transportation, personal automotive transportation has exhibited many common aspects.

3. Theoretical model

Given the technological changes that cause an increase in energy productivity, consumers and producers adjust their behavior to reflect the lower cost of the energy service. Thus, the rebound effect consists of the three components listed below:

- Direct effect—The consumer chooses to consume more of the energy service, instead of realizing cost savings. This effect can be described as an income effect.
- Indirect effects—The consumer chooses to apply the cost savings towards the purchase of other goods and services that consume energy. This effect can be described as a substitution effect.
- Economy wide effects—The reduction of demand for a resource will result in downward pressure in its price, which makes the resource more likely to be used in other forms. For example, electricity was originally only used for lighting. With the reduction of its price, it started to be used in other electronic devices.

Consider the following notations:

S = total demand of the energy service,
ε = average efficiency of the domestic transport fleet,
P_S = cost of the energy service, and
P_E = cost of energy.

The quantification of the direct effect can be obtained through one of three definitions:

Definition 1. Elasticity of demand for useful work with respect to energy efficiency

$$\eta_\varepsilon(E) = \eta_\varepsilon(S) - 1 \tag{1}$$

where

$$\eta_\varepsilon(E) = \frac{\partial E}{\partial \varepsilon}\frac{\varepsilon}{E} \text{ and } \eta_\varepsilon(S) = \frac{\partial S}{\partial \varepsilon}\frac{\varepsilon}{S}$$

Eq. (1) illustrates that the relationship between energy efficiency and energy consumption can be obtained through the elasticity of demand for useful work with respect to energy efficiency. To implement this methodology, it is necessary to determine which variables explain the relationship between the demand for useful work (energy service) and energy efficiency. The problem with the application of this methodology is in measuring the level of energy efficiency. In the case of demand for useful work, a proxy could be used. For example, in personal automotive transportation, we could use the number of kilometers driven; for road freight transportation, ton-kilometers could be considered.

The methodology used by Berkhout et al. (2000) illustrates that real energy savings will only be equal to the estimated savings calculated through engineering models (i.e., there is no rebound effect) when the elasticity of demand for useful work with respect to energy efficiency is zero. The existence of a positive rebound effect implies that $\eta_\varepsilon(S) > 0$ and$|\eta_\varepsilon(E) < 1|$. For example, the direct rebound effect in personal automotive transportation means that the improvements in vehicle efficiency cause an increase in distance traveled, resulting in an actual energy savings that is less than originally estimated.

If the demand for useful work is inelastic $(0 < \eta_\varepsilon(S) < 1)$, improving energy efficiency should reduce energy consumption $(-1 < \eta_\varepsilon(E) < 0)$. However, if the demand for useful work is elastic $(\eta_\varepsilon(S) > 1)$, improved energy efficiency should increase the consumption of energy. This would result in the so-called backfire.

Definition 2. Energy cost elasticity of demand for useful work

$$\eta_\varepsilon(E) = -\eta_{Ps}(S) - 1 \tag{2}$$

where

$$\eta_{Ps}(S) = \frac{\partial S}{\partial Ps}\frac{Ps}{S}$$

In this case, the energy cost elasticity of demand for useful work $(\eta_{P_S}(S))$ minus one is used as a proxy for the elasticity of demand for useful work with respect to energy efficiency $(\eta_\varepsilon(S))$, which is itself the definition of the rebound effect. If the useful work is a normal good, than it is expected that $\eta_{P_S}(S) < 0$. For example, if the elasticity of distance traveled (S) with respect to the cost per kilometer (P_S) is estimated at 0.10, then the elasticity of demand for useful work with respect to energy efficiency would be -0.90. For a 10% increase in energy efficiency, one would expect a 9% reduction in fuel consumption, i.e., the real savings would be 10% lower than the projected savings as predicted by the engineering models.

The methodology used by Khazzoom (1980), Berkhout et al. (2000) and Binswanger (2001) is usually preferred to Definition 1. For many energy services, the independent variable in Definition 1 (energy efficiency) varies little, causing a high variance when estimating the direct rebound effect. However, the estimates of the direct effect using Definition 2 require accurate measurements of the cost of the energy service (P_S), which varies depending on the price of energy and efficiency.

Definition 3. Elasticity of demand for useful work with respect to changes in energy prices

$$\eta_\varepsilon(E) = -\eta_{P_E}(S) - 1 \tag{3}$$

where

$$\eta_{P_E}(S) = \frac{\partial S}{\partial P_E}\frac{P_E}{S}$$

In many cases, data regarding the efficiency of a power system may not be available or may be of poor quality. In this case, Definition 3 can be used to analyze the elasticity of demand for useful work with respect to changes in energy prices. As was the case in Definition 2, Definition 3 assumes that the consumer reacts in the same manner to a price increase or a price decrease. In this case, if energy efficiency is kept constant, Definition 3 implicitly assumes that efficiency is not affected by changes in energy prices ($\eta_{P_E}(\varepsilon)=0$). However, if changes in energy prices cause changes in energy efficiency, using this definition to determine the magnitude of the direct rebound effect may produce biased results, since the change in the price of the energy service is not directly proportional to changes in energy prices. This definition provides a method of estimating the direct rebound effect without having to directly observe the efficiency variable. Empirical studies which use Definition 3 need reliable data on the demand for useful work.

Most of the studies, which attempt to quantify the direct rebound effect, rely on Definitions 2 and 3. When using any of these three methods, two important factors must be taken into account: (1) the correlation between energy efficiency and the cost of other inputs including capital and (2) the endogeneity of the energy efficiency and the consequent need for simultaneous equations and instrumental variables.

Demand for road freight transportation can be influenced by economic activity, the operating costs of this service and the competitiveness of this means of transportation, compared to other transportation alternatives.

Consider the additional notation:

Tkm = demand for road freight transportation measured in ton-kilometers (S);
P_{Tkm} = the energy cost of transporting 1 t-km(P_S);
GDP = gross domestic product at constant prices; and
Bbl = the cost in Euros of one barrel of oil.

Then

$$Tkm = f(P_{Tkm}, GDP, Bbl) \tag{4}$$

The following exponential specification was derived after examination of several other specifications and possible combinations of variables:

$$Tkm = e^{\beta_0} P_{Tkm}^{\beta_1} GDP^{\beta_2} Bbl^{\beta_3} + e \tag{5}$$

Tkm will serve as a measure of the demand for useful work S and P_{Tkm} will serve as a measure of the cost of useful work P_S.

The production cost (or consumer price) of transporting one ton of goods at a distance of 1 km is primarily influenced by two operational aspects: how much does it cost to travel 1 km? and how much can be carried at once?

As a way of calculating the cost of every ton-kilometer transported, only the energy cost was considered, the variable that needs be examined to determine the direct rebound effect. According to ANTRAM's (2008) (Portuguese National Association of Public Freight Transport Companies) annual yearbook, fuel costs account for roughly 45% of the total operating costs for the carrier. While other costs represent more than 50% of the total operating costs, the variability of these are lower and the impact of a change in fuel prices is more quickly reflected in the price charged for the service than any other cost.

Consider

P_C inflation adjusted price of diesel fuel in year t (base 1987) measured in Euros/l;
km distance traveled by the road freight fleet measured in kilometers during year t;
Ton total freight transported in year t measured in tons; and
l/km average fleet fuel efficiency measured in liters per kilometer during year t.

If $LF = ton/km$ then the cost of transporting 1 t-km can be defined as follows:

$$P_{Tkm} = \frac{P_C}{LF/(l/km)} \tag{6}$$

Analyzing Eq. (6), we find that the cost of transporting 1 t-km is positively affected by the price of fuel and the average consumption of the fleet while it is negatively affected by increasing the average vehicle load.

ε is a measure of operational efficiency representing a ratio of the average vehicle load (in tons) and the average fuel consumption of the fleet in the following way:

$$\varepsilon = \frac{LF}{l/km} \tag{7}$$

Eq. (6) can be written as

$$P_{Tkm} = \frac{P_C}{\varepsilon} \tag{8}$$

Thus, it is easy to identify the relationship between the cost of the service and the efficiency of the system. Like other energy systems, there is more than one way to increase operational efficiency. In this case, it is possible to increase operational efficiency by (1) increasing the average cargo per voyage, or (2) by reducing the fuel consumption of the vehicles.

The rate of GDP growth is one way of measuring the economic output of a region. As was previously mentioned, economic growth requires the transportation of people and goods between two points. Therefore, we used GDP at constant prices (base 1987) to account for inflation. This information was obtained from the Bank of Portugal statistical series for the period between 1987 and 1995 and from the Bank of Portugal annual reports for the period between 1996 and 2006.

4. Estimation

Essentially, all of the initial studies which aimed to measure the direct rebound effect used ordinary least squares as the method for estimation. Blair et al. (1984), Greene (1992), Jones (1993) and Wheaton (1982) used this method of estimation as means to measure the direct rebound effect on personal motor vehicles in the U.S. However, with the widespread introduction of more complex estimation techniques, it is now possible to correct some of the shortcomings presented by the ordinary least squares models.

A theme that generally was not addressed by the first studies on the subject was the existence of endogeneity of the independent variables. In many cases, there was correlation between energy efficiency and the cost of other inputs (Einhorn, 1982; Lovins et al., 1988). Using a model that does not directly address the issue of endogeneity may lead to the overestimation of the direct rebound effect. To these authors, the use of more sophisticated models (two and three stage least squares, structural models and the use of instrumental variables) turns the estimates from the direct rebound effect into more empirically consistent estimates.

This paper applies ordinary least squares and two stage least squares methods to estimate the parameters of the model, seeking to compare the estimates obtained and judge the existence of endogeneity in the ordinary least squares model.

4.1. Ordinary least squares (OLS)

Based on the definitions from the previous section, the demand for road transportation, according to Eq. (5), can be expressed as follows:

$$\ln Tkm = \ln \beta_0 + \beta_1 \ln \frac{P_C}{LF/(l/km)} + \beta_2 \ln GDP + \beta_3 \ln Bbl + e \tag{9}$$

Using ordinary least squares to estimate this regression, we obtained the following simple linear regression equation explaining the demand for road freight transportation:

$$\begin{aligned} &\ln Tkm = -1.165 - 0.244 \ln P_{Tkm} + 0.961 \ln GDP + 0.160 \ln Bbl \\ &(t) \quad (-0.786) \quad (-2.225) \quad (14.124) \quad (2.587) \\ &(\text{sig}) \quad (-0.443) \quad (0.041) \quad (0.000) \quad (0.020) \\ &F = 109.653 \\ &(\text{sig} = 0.115) \\ &\text{Adjusted } R\text{-squared} = 0.945 \\ &DW = 1.978 \end{aligned} \tag{10}$$

The t statistics is used to test hypothesis about any single parameter. Once all other explanatory variables have been accounted for we are testing under the null hypothesis that a particular variable has no effect on the expected value of the dependent variable (see as an example Wooldridge (2009)). We rejected the null hypothesis for all parameters in the model and concluded that the demand for road freight transportation is explained by the energy cost of transportation, the gross domestic product and the cost of one barrel of oil.

Regarding the F statistics the null hypothesis states that none of the explanatory variables has an effect on the dependent variable. Stated in terms of parameters the null hypothesis is that all slope parameters are zero and the alternative is that at least one of the slope parameters is different from zero. We rejected the null hypothesis with a 5% significance level.

The R-square is interpreted as the fraction of the sample variation in the dependent variable that is explained by the explanatory variables. A value nearly equal to 1 indicates a good fit of the OLS line.

Serial correlation is a potential problem for regressions with time series data (Wooldridge, 2009). Because the Gauss–Markov Theorem requires serially uncorrelated errors, OLS is no longer the best linear unbiased estimator in the presence of serial correlation. Even more importantly, the usual OLS standard errors and the test statistics are not valid, even asymptotically. Durbin Watson statistics allowed us to reject the hypothesis of serial correlation in Regression Eq. (10).

Nevertheless, any conclusion regarding the direct rebound effect for the road freight transportation of goods that is based on Regression Eq. (9), may be questioned, even if the model presents a high goodness of fit and statistical significance of all estimated parameters (with the exception of the constant).

4.2. Testing the exogeneity of the price variable

Economic theory dictates that the price of any good is a function of the supply of this good in the marketplace (keeping demand constant). Furthermore, the amount supplied is determined by the market price. As a result, it is difficult to identify the direction of the causality for many goods, such as when demand affects the price or price affects demand. In econometric models, this is a relevant issue, since the exogenous variables seek to explain the endogenous variables. However, the direction of causality may not be always clear and the endogenous variable may in fact determine the exogenous variable.

Regarding the econometric model in question, the objective was to predict the demand for a specific energy service using a series of variables, where the price of the energy service was just one of those variables. The energy cost of any type of transportation is composed of a set of variables, where the most important factor is the price of fuel. From the outset, since this price is dictated by market participants in international markets, and being that Portugal is a small open economy, a significant relationship between the demand for road freight in Portugal and the price of this service is not expected. However, the hypothesis of endogeneity of the price variable should be statistically tested to ensure that there is no bias in the estimated parameters.

4.2.1. Hausman test

The exogenous price variable will be tested using the methodology applied by Hausman (1978), which consists of comparing the ordinary least squares estimates to the two stage least squares or instrumental variable estimates.

Hausman (1978) assumes that for the estimation of a regression, the demand for a good at any given moment $t(Q_t)$ is a function of its price at moment $t(P_t)$, and a set of all other relevant variables $\bar{I}_n = I_1, I_2, \ldots, I_n$

$$Q_t = \alpha + \beta_1 P_t + \overline{\beta}_n \bar{I}_{nt} + e_t \tag{11}$$

If there are doubts about the exogeneity of the price variable, Hausman suggests the estimation of the price variable (P_t) as a function of the set of the other exogenous variables.

$$P_t = \alpha + \overline{\beta}_n \bar{I}_{nt} + v_t \tag{12}$$

Therefore, we have

$$P_t = \hat{P}_t + \hat{v}_t \tag{13}$$

If Q_t represents the demand during moment t, which is considered endogenous, the Hausman test relies on the estimation of the following regression equation, analyzing the significance of the parameter β_2

$$Q_t = \alpha + \beta_1 \hat{P}_t + \beta_2 \hat{v}_t + {}_t\overline{\beta}_n \bar{I}_{nt} + e_{2t} \tag{14}$$

By applying the Hausman test to the model in Eq. (10), we find that the parameter β_2 is statistically significant, considering a confidence level of 96%. Consequently, we do not reject the hypothesis that the price variable (P_{Tkm}) is endogenous.

4.2.2. Granger causality test

The causality test developed by Granger (1969) seeks to test the direction of causality between two variables. It can also be used to analyze the endogeneity of an independent variable. To analyze the causality relationship between two variables (X and Y), this method assumes that all of the relevant information necessary to estimate a variable (X) is limited to the information contained in the series of X and Y. Therefore, the estimates of X can be obtained from the lagged series of X and Y and vice versa.

More formally, we have the following:

$$X_t = aY_{t-1} + bX_{t-1} + e_t \tag{15}$$

$$Y_t = cX_{t-1} + dY_{t-1} + u_t \tag{16}$$

where e_t and u_t are non-correlated errors.

Given the estimates of the parameters, it is possible to distinguish among four causal relationships between variables X and Y.

1. Unilateral causality from Y to X
$$\begin{cases} a \neq 0 \\ d = 0 \end{cases}$$
2. Unilateral causality from X to Y
$$\begin{cases} a = 0 \\ d \neq 0 \end{cases}$$
3. Simultaneous dependence
$$\begin{cases} b \neq 0 \\ d \neq 0 \end{cases}$$

4. Independence

$$\begin{cases} b = 0 \\ d = 0 \end{cases}$$

Estimating the parameters for Eqs. (15) and (16), we obtained the following results:

$$Tkm_t = 0{,}054 P_{Tkmt-1} + 0{,}843 Tkm_{t-1}$$
$$(t) \quad (0.424) \quad (7.543)$$
$$(\text{sig}) \quad (0.677) \quad (0.000) \tag{17}$$

$$P_{Tkmt} = 0{,}539 Tkm_{t-1} + 0{,}478 P_{Tkmt-1}$$
$$(t) \quad (3.411) \quad (2.661)$$
$$(\text{sig}) \quad (0.004) \quad (0.017) \tag{18}$$

Analyzing the estimates obtained, it is possible to conclude that there exists a causal relationship from the variable P_{Tkm} to the variable Tkm, since $a \neq 0$ and $d = 0$.

The Granger causality test verifies the results obtained from the Hausman test and confirms the existence of the endogeneity of the price variable. The variable $P_{Tkm}$is statistically dependent on the variable Tkm.

4.3. Two stage least squares

The two stage least squares estimation technique is a method that permits the estimate of a regression when some of the assumptions of the ordinary least squares method are violated. Estimation using instrumental variables permits the estimation of consistent parameters, even if the explanatory variables are correlated with the residual. This endogeneity can occur when the dependent variable causes changes in at least one of the explanatory variables, when a relevant variable of the model is absent or when the explanatory variables are subject to a high degree of measurement error. In these cases, the ordinary least squares estimation normally returns biased parameter estimates that are not consistent. However, by using instrumental variables, it is possible to estimate consistent parameters that are not biased.

An instrumental variable is a variable that is not present in the formulation of the regression model as an explanatory variable, but is correlated with the endogenous variable (variable with problems of endogeneity). By means of the Hausman test and the Granger causality test, it was found that the explanatory variable (P_{Tkm}) is in fact endogenous, i.e., there is a causal effect from Tkm to the explanatory variable P_{Tkm}. The use of an instrumental variable can be used to overcome this violation of the ordinary least squares assumption. The instrumental variable must be correlated with the variable P_{Tkm}, $E(P_{Tkmt}, IV_t) \neq 0$, and should not be correlated with the estimation error, $E(e_t, IV_t) = 0$.

Since the variable P_{Tkm} is composed of four other variables (P_C, LF, D_C, $e\ km$), any of these variables can be used as an instrument. The choice will depend on the variable which has the highest correlation with the variable P_{Tkm} and the least correlation with the residuals.

The average fuel consumption variable (l/km) emerges as the one most suited to be used as an instrument for the regression in question, due to the following correlations:

$$E(P_{Tkm\ t}, l/km_t) = 0.755 \quad E(e_t, l/km_t) = 0.002$$

By using the two stages least squares estimation techniques and the instrumental variable (l/km) that is statistically correlated with the variable P_{Tkm} and not correlated with the error estimated from Eq. (10), we obtain the following demand function for road freight:

$$\ln Tkm = -1.607 - 0.241 \ln P_{Tkm} + 0.959 \ln GDP + 0.159 \ln Bbl$$
$$(t) \quad (-0.719)\ (-2.012)\ (13.511)\ (2.437)$$
$$(\text{sig}) \quad (0.483)\ (0.061)\ (0.000)\ (0.027)$$
$$F = 109.35$$
$$R^2 = 0.945 \tag{19}$$

The interpretations to be made on the direct effect for road freight transportation will be done by assessing the model estimated based on the instrumental variables in Eq. (19).

5. Elasticities

To determine the magnitude of the direct rebound effect for fuel consumption regarding road freight transportation, a log–log functional form was used to facilitate the interpretation of the elasticities, as was conducted in Gateley (1992), Greene (1992), Jones (1993) and Schimek (1996).

Through a comprehensive analysis of the quality of regression Eq. (19), it was established that the estimated parameters are both efficient and consistent. The model also features an R-squared in the order of 94.5%. As a result, it is safe to say that this formulation is the one most suited to analyze the phenomenon during the period in question.

Using the estimated parameter of regression Eq. (19), we obtained estimates for the magnitude of the direct rebound effect using the three definitions from Sorrell (2007).

Consider Eq. (5) described in Section 3

$$Tkm = P_{Tkm}{}^{\beta_1} PIB^{\beta_2} Bbl^{\beta_3}$$

Given that $P_{Tkm} = P_C/\varepsilon$, the equation is re-written as

$$Tkm = \left(\frac{P_C}{\varepsilon}\right)^{\beta_1} PIB^{\beta_2} Bbl^{\beta_3}$$

Notice that in our model the demand for useful work (S) is given by Tkm, the cost of useful work (P_S) is given by P_{Tkm} and energy prices (P_E) by P_C.

The elasticity of demand for useful work in respect to energy efficiency is then

$$\eta_\varepsilon(S) = \frac{\partial Tkm}{\partial \varepsilon} \frac{\varepsilon}{Tkm}$$

or

$$\eta_\varepsilon(S) = \beta_1 \left(\frac{P_C}{\varepsilon}\right)^{\beta_1 - 1} \left(-\frac{P_C}{\varepsilon^2}\right) PIB^{\beta_2} Bbl^{\beta_3} \frac{\varepsilon}{Tkm}$$

Replacing Tkm by its expression results in the following:

$$\eta_\varepsilon(S) = \beta_1 \left(\frac{P_C}{\varepsilon}\right)^{\beta_1 - 1} \left(-\frac{P_C}{\varepsilon^2}\right) PIB^{\beta_2} Bbl^{\beta_3} \frac{\varepsilon}{(P_C/\varepsilon)^{\beta_1} PIB^{\beta_2} Bbl^{\beta_3}}$$

After some calculations we obtain

$$\eta_\varepsilon(S) = -\beta_1$$

Using the value estimated in Eq. (19):

$$\eta_\varepsilon(S) = 0{,}241 \text{ and } \eta_\varepsilon(E) = \eta_\varepsilon(S) - 1 = -0{,}759$$

Proceeding in a similar way to Definition 2 we obtain

$$\eta_{P_S}(S) = \frac{\partial Tkm}{\partial P_{Tkm}} \frac{P_{Tkm}}{Tkm}$$

$$\eta_{P_S}(S) = \beta_1 P_{Tkm}{}^{\beta_1 - 1} PIB^{\beta_2} Bbl^{\beta_3} \frac{P_{Tkm}}{Tkm}$$

and

$$\eta_{P_S}(S) = \beta_1$$

Therefore in our computations,

$$\eta_{P_S}(S) = -0{,}241 \text{ and } \eta_\varepsilon(E) = -\eta_{P_S}(S) - 1 = -0{,}759$$

Finally for Definition 3 we obtain,

$$\eta_{P_E}(S) = \frac{\partial Tkm}{\partial P_C}\frac{P_C}{Tkm}$$

$$\eta_{P_E}(S) = \beta_1\left(\frac{P_C}{\varepsilon}\right)^{\beta_1-1}\left(\frac{1}{\varepsilon}\right)PIB^{\beta_2}Bbl^{\beta_3}\frac{P_C}{Tkm}$$

and

$$\eta_{P_E}(S) = \beta_1$$

Using the value estimated in Eq. (19)

$$\eta_{P_E}(S) = -0{,}241 \text{ and } \eta_{\varepsilon}(E) = -\beta_1 - 1 = -0.759$$

As was stated in the literature prepared by Sorrell (2007), the demand elasticity of energy (or energy service) regarding the price $-\eta_{PE}(S)$ e $\eta_{Ps}(S)$ can be considered the upper bound of the direct rebound effect of a given energy service (Hanly et al. (2002); Taylor et al. (1977)). However, due to issues that relate to the asymmetric reaction of consumers in relation to changes in energy prices (the consumer does not respond to a price reduction in the same magnitude as an increase) the estimate of the direct effect using definition two – $\eta_{\varepsilon}(S)$ – should be more consistent.

Thus, the direct rebound effect for road freight transportation, the percentage of increased energy efficiency that does not result in the reduction of energy consumption and is caused by a reduction in the marginal cost is 24.1%.

Although the sector in the analysis is fundamentally different from most studies on the topic of transportation (personal transportation vs. freight), the results are consistent with those obtained by Blair et al. (1984), Mayo and Mathis (1988), Greene (1992) and Schimek (1996). Moreover, Sorrell (2007) argued that the likely range of the direct effect of automobile transportation was somewhere between 3% and 87%, with a best guess of 10–30%.

Analyzing the results of the present study, and using as a reference value for the direct effect of 10%, any operational improvements that result in a lower energy cost of 1% causes a reduction in energy consumption of 0.759%. That is, any technological change (reduced consumption in l/km) or operational (less kilometers traveled without cargo) does not result in a corresponding reduction in the aggregate consumption of fuel.

Since most studies on this topic were devoted to the analysis of personal automotive transportation, it is important to identify the relevant factors that influence the existence of a direct rebound effect for road freight and personal transportation. The characteristics of road freight have some similarities to personal transportation, in particular, with regard to key indicators of efficiency, but vary significantly regarding the decision making process of the economic agent.

Indicators such as the energy consumption of vehicles and fuel cost can be analyzed in the same context since, in any case, the change of any of these indicators leads to a change in the cost of the service. In the case of personal transportation, it results in a change in the individuals' utility structure. In the case of a freight company, it changes the optimum balance between production factors, thereby affecting the kilometers driven and the demand for other inputs.

Regarding road freight, we found that the estimated direct rebound effect was very similar to the values estimated by previous studies for personal transportation. Although this result is consistent with the literature, it raises some questions. Saunders (2000) stated that the greater the possibility of substitution between energy and other production factors, the greater the direct rebound effect should be. Thus, if the carrier was to choose a more efficient vehicle, they would be effectively replacing energy consumption with capital consumption.

Given the high share of energy costs in the cost structure of this sector (almost 50%), the carrier will be encouraged to substitute capital for energy. Even more, being that this is a high-intensity activity (driving for days on end), it enables the firm to dilute any additional fixed costs through economies of scale. These two factors are not present in personal automobile transportation, where the cost of energy only represents a small part of the total costs and the equipment is only used during a few hours of every day. All these factors lead us to expect that the direct effect should be greater in freight transportation compared with personal transportation.

Given that the direct rebound effect estimated in this study was identical to early studies, it is possible to identify some factors that might have contributed to this phenomenon. While there is indeed a stronger incentive to substitute energy with capital in this sector, the absence of alternative technologies used on a large scale makes the option to purchase a more efficient vehicle less attractive. Alternatively, the carriers are opting for operational improvements by purchasing larger vehicles that allow for the transportation of more goods as a way of improving operational efficiency. This can be demonstrated by the fact that mean transportation per kilometer went from 4.1 t/km in 1987 to 7.6 t/km in 2006. During the same period, the average fuel consumption increased from 14.1 to 37.8 l per 100 km. Thus, in this particular sector, gains in operational efficiency were more favored than the technological gains.

We found a small number of studies in the literature dealing with freight transport. It is believed that the demand for freight transport is determined by a complex hierarchy of choices. This hierarchy can be structured on the basis of the time lag involved in changing decisions in response to changes in the transport system or market situation. This shows that a truly comprehensive freight demand model should, in principle, include all decision variables. There are, however, several methodological difficulties and the studies of demand for freight transport have been confined in scope to only subsets of the possible decisions involved, usually to those that are short and intermediate-run in nature (Abdelwahab and Sargious, 1992). In addition Abdelwahab and Sargious (1992) notes that in many cases the receiver (purchaser) will have to enter into a multi-order contract (ordering routine) with a supplier, making it difficult to alter the terms of the contract in the short-run.

The focus in freight demand studies has principally been on identifying different elasticities for different commodity groups. Winston (1981) developed a disaggregate model of the demand for intercity freight transportation. The author concludes that the size of the elasticities varies considerably across commodity groups. In general, larger freight charge elasticities are associated with those commodities where the ratio of transportation expenses tends to be high, as in the case of transport equipment.

Graham and Glaister (2004) found that despite the fact that demand for road freight is often assumed to be price inelastic, or at least more so than general traffic, the studies reviewed in their paper indicate that in fact this may not be the case. The price demand elasticity estimates are, almost without exception, negative and in many cases exceed unity. However, they also conclude that different elasticities emerge from different commodity groups, for different trip types and for different levels of market coverage. Thus, the specifics of any particular context have an important bearing on the magnitude of the estimates. We believe that this may also be the case in measuring the effects of energy savings.

Friedlaender and Spady (2001) argue that in analyzing the demand for freight transportation, it is important to recognize that it has the following characteristics: first, freight transportation is a productive input and should be treated analytically like any other input; second, the full costs of transportation include the rate and inventory costs associated with shipping and storage; and third, the rate and shipment characteristics affecting inventory costs (e.g., length of haul, size of shipment) are typically jointly determined by the firm. We were not able to find in the literature any reference to the relationship between fuel efficiency and fixed cost to the firm (e.g. truck purchase for renovation), nevertheless, this is surely an interesting issue to investigate.

6. Conclusions

The efficient use of energy has been touted as the ideal solution for current limitations of energy use in developed economies. Proponents of this philosophy argue that this is the ideal solution to two of the constraints of economic growth: energy scarcity and the emissions of greenhouse gases. However, the effect that technological change will have on the behavior of those who use it cannot be overlooked. A technological improvement is equivalent to the expansion of the existing production possibilities frontier. As a result, it would be unwise to consider that economic agents will limit output growth for irrational reasons.

The effect of increasing energy efficiency in fuel consumption was analyzed based on the estimation of a direct rebound effect for road freight transportation in Portugal for the period between 1987 and 2006. The functional form chosen was a log–log model and the estimation method used was the two stage least squares model.

It was determined that increasing energy efficiency by 1% results in a reduction of 0.759% in energy consumption, a direct rebound effect of about 24.1%. Given these findings, and taking into account the fuel consumption of this sector in 2006 in Portugal, estimates of reduced fuel consumption without considering the direct rebound effect may be overestimated by about 0.87 million liters of diesel per year for each percentage point increase in energy efficiency. This value becomes relevant as any energy strategy will have to take into account the direct rebound effect when developing energy policies.

It was also found that in Portugal, fleet operators overlooked the technological improvements of more efficient cars in favor of operational improvements. These improvements do not depend on imported technology, but depend on better suiting the firms' resources to the demand for the service. This may explain the absence of more efficient technologies in this sector.

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