Energy 118 (2017) 272–283

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Modelling the rebound effect with network theory: An insight into the European freight transport sector

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ARTICLE INFO

Article history:
Received 13 February 2016
Received in revised form
24 November 2016
Accepted 3 December 2016

Keywords:
Energy efficiency
European freight transport sector
Rebound effect
Network theory
Statistical mechanics of networks
Structural change

ABSTRACT

This paper presents a two pronged approach to the study of the rebound effect, with the aim of assessing the magnitude of the effect in the European freight transport sector and proposing a new modelling framework based on network theory. The (direct) rebound effect is assessed with: 1) an econometric regression; 2) a model based on network theory and statistical mechanics. According to the econometric model the European road freight transport sector undergone a negative rebound between of −74% between 1998 and 2007 and −146% between 1998 and 2011. The network analysis delivers an estimation of network rebound ranging between −29.37% and −7.25. Overall, these results indicate that energy efficiency in Europe, between 1998 and 2011, succeed in reducing the energy consumptions amid an increasing demand for transports. Results on rebound estimation depend on the decision of using GDP as an exogenous variable, an assumption that leaves questions open about the causality chain between growth and transports. Furthermore, the network analysis highlights a structural change —a migration of production factors offshore, that might partially explain this negative effect. In this view, rebound effect analysis on a local or regional scale is becoming more and more uncertain in a globally interconnected economic context.

1. Introduction

The EU has been at the forefront of international efforts towards a global climate deal. Following limited participation in the Kyoto Protocol and the lack of agreement in Copenhagen in 2009, the EU has been building a broad coalition of developed and developing countries in favour of high ambition that shaped the successful outcome of the Paris conference. One of the pillars of the EU strategy is to reduce carbon emissions is energy efficiency. The 2020 energy goals call for a binding 20% reduction in CO_2 emissions compared to 1990 levels (now raised to 40% by 2030), for a binding 20% of the energy, on the basis of consumption, coming from renewables and a 20% increase in energy efficiency, formulated as a maximum primary and final energy consumption. Now, the lingering question is, did European Union ever succeeded in reducing energy consumptions by increasing energy efficiency?

A recent study of the MIT addressing the nexus between energy efficiency and production in 10 sectors of world economy, showed that historically efficiency improvements have generally proven to be unsuccessful in reducing energy consumption [10]. The reason of this historical *fiasco*, or at least one possible reasons, if not the most important, lies in the so-called *rebound effect* [5].

In developed countries, since the late 1990s, final energy consumption in transports overtook that of industry and now is the single largest sector for energy demand [25]. In the last two decades emissions of the transport sector grew rapidly in OECD countries, in contrast to non-OECD, fast developing economies where the emissions of manufacturing and industry had still the lion's share [24]. This dichotomy suggests that production in developed countries became more and more *transport intensive* as compared to raising economies [14], pointing to the role of fragmentation of production worldwide [27]. Interestingly, but not surprisingly, this growth of transport's demand was accompanied by a constant increase in the transportation efficiency [24]. In the EU the efficiency of the freight transport sector improved by 15%

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http://dx.doi.org/10.1016/j.energy.2016.12.011
0360-5442/

Nomenclature

Tkm	Tons Kilometers
Toe/goe	Tons (grams) of oil equivalent
GDP	Gross Domestic Product
ODEX	ODEX is the index used in the ODYSSEE-MURE project to measure the energy efficiency progress by main sector
ε	Efficiency of the freight transport sector: inverse of the unit consumption of the four modes (tkm/toe)
η	Efficiency of trucks: inverse of fuel economy (km/l)
$R_\varepsilon(S)$	Direct Rebound Effect (%)
S	Energy Service Demand (TKm)
f	Spatial filling of the network (equation (4))
d_{ij}	Distance between country i and j (km)
w_{ij}	Volume of trade between country i and j ($ or Tons)
W	Total volume of trade in the network ($ or Tons)
$\varphi(NM)$	Improved measure of the spatial filing (equation (5))
NM	Null Model
ERG	Exponential Random Graphs (family of null models)
DCM	Directed Configuration Model (ERG)
DWCM	Directed Weighted Configuration Model (ERG)
RWCM	Reciprocated Configuration Model (ERG)
Radiation	Radiation Model (non-ERG)
p_{ij}^{NM}	Expected value of trade between country i and j with the given Null Model
$<f>_{NM}$	Expected filling computed with the given Null Model
$F_{max/min}$	Maximum (minimum) filling observable in the network for a given W (total volume of trade)
s_i^{in}	Total imports (strength in) of country i

between 1990 and 2010 and the service demand grew almost twice as much. Is there any nexus between the growing demand and the increase in energy efficiency? Does from this hint to a rebound effect in the European freight transport sector?

Former studies on rebound effect in the road freight sector (which accounts for most of the freight transports in Europe), based on price elasticity, found that rebound effect was generally negative or small.Winebrake et al. [52] presents a review of several studies base on fuel price elasticity where the elasticity is always negative (meaning that energy efficiency actually lead to a decrease in energy use). More recently, the same authors showed that the U.S. road freight sector became inelastic in the last decades [51]. Matos and Silva [31]. estimated a direct rebound effect (price elasticity) of about 24.1% for Portugal, between 1987 and 2006. Similar results, with an estimated positive rebound around 18.8% in the short run and 27.8% in the long, are obtained for Denmark for the period 1980–2007 by Ref. [11] by estimating the elasticity of traffic volume to fuel cost. Anson and Turner [3] estimate the rebound effect for the year 1999 in Scotland with a CGE model, obtaining a short run effect of 36.4% and a long run effect of 39.2% For the period from 1997 to 2001 in USA [44], estimated that the short-run elasticity of fuel cost-per-mile was only 0.03. Considering the period from 2001 to 2006 [23], found a short-run fuel price elasticity of vehicle travel of 0.04. Using national time series data for 1966 to 2007 for USA [21], found a statistically significant elasticity of vehicle travel with respect to fuel price, but no statistically significant elasticity of vehicle travel with respect to fuel economy. In a recent study [50], assess the long-term and short-term direct rebound effects in 31 provincial panel data of China from 1999 to 2011 with a double logarithmic regression, finding a direct rebound effect in the long term of 84%, 52%, 80% and 78% for, respectively, the entire China, the eastern, central and western regions.

Significantly, most of these studies considered determinants to transports' demand other than the mere efficiency of transport means. For example, growth in transport service proved to be historically proportional to the growth in GDP (of the destination/origin countries for cross-border or of the single country for national accounting). There is a copious scientific literature that addressed the issue of decoupling GDP and growth in transport service, which has ascertained that in developed countries the link between GDP and freight has loosened with time. Some prominent examples are the decomposition analysis of 10 OECD countries performed by Schipper et al. [42]; the study of McKinnon for the UK [32] and more recently that of Sorrell et al. [46]; a recent study of the Italian case [53]. Other factors that GDP seems to be important in determining the movement of goods, like the displacement of production chain and the quest for new factors' markets [1]. Furthermore, besides energy efficiency, energy service can be affected by: load factor; empty runs; speed limits; road conditions; driving behaviors and fuel prices [15]. All these factors should be carefully considered while examining the nexus between energy efficiency and service demand, compatibly with the data availability and scope.

This is paper addresses the energy efficiency evolution of the European freight transport system with the aim of assessing how this affected the flows of goods in the economic system by adopting two different approaches: 1) a canonical approach based on econometrics; 2) a new methodology based on network theory and statistical mechanics of networks. The first aim of present analysis is that of understanding if and to what extent energy efficiency, amid high energy prices, contributed to reduce energy consumptions in European freight sector in the last two decades and to assess the size of direct rebound effect in freight transports. The second purpose is that of showing the benefits and limitations of applying network theory to energy systems, with an insight into the transport sector.

2. Methods and data

The present analysis will focus on national and cross-border freight transports, inside and across the 28 EU countries plus Norway, between 1998 and 2011, in monetary and mass units. It will rely on two main data-bases, the ODYSSEE and the BACI databases (see Appendix 1).

According to our estimations, the cross-border freight transport, between 1998 and 2011, amounted for about half of global freight across Europe (Fig. 1). However, BACI data comprises energy commodities, like crude oil, gas and electricity, which are generally shipped across Europe by pipelines and power lines. In the remaining part of this work, cross-border transport statistics will not include energy commodities.

2.1. Efficiency metrics

The energy efficiency of the whole transport sector in the EU improved by 15% between 1990 and 2010 (around 0.8%/year), as measured by the ODEX indicator (see appendix 1). Greater progress was achieved in the energy efficiency of both cars and airplanes