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Assessing environmental performance trends in the transport industry: Eco-innovation or catching-up?

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ABSTRACT

This paper analyses the change in environmental performance that took place in the transport industry of 38 countries between the years 1995 and 2009. Data Envelopment Analysis techniques and directional distance functions are employed to compute Luenberger productivity indicators for the change in environmental performance and its determinants, namely, environmental technical change resulting from eco-innovation and catching-up with best available environmental technologies. Eight air pollutants account for the environmental contaminants from transport activities, and these are aggregated into three main categories of environmental pressures, namely, global warming, tropospheric ozone formation and acidification potentials. Furthermore, performance evaluation is based on how these specific environmental pressures are managed. Our principal findings show that there has been a noticeable improvement in environmental performance since the 1990s, primarily as a result of eco-innovations; moreover, this improvement has been markedly greater in low- and middle-income economies, bolstered, in this case, by both environmental technical progress and catching-up. These results reveal the need for policy measures aimed at encouraging catching-up with best available technologies, particularly in more developed countries.

1. Introduction

The impact that productive activity has on the environment is currently generating great interest amongst researchers, company managers, politicians and society as a whole. The conventional view of economic growth as a rise in the quantity of goods and services available to satisfy human needs is progressively giving way to a much broader concept of growth based on *sustainability*, where satisfying present needs should also ensure that future generations can meet their needs (WCED, 1987; p.43). Moreover, acknowledging the environment as a public good has stimulated a breadth of legislation in industrialised countries directly aimed at attaining certain standards of environmental quality.

The transport sector plays an essential role in present-day economies, facilitating the transportation of passengers and freight and the functioning of goods markets by connecting them spatially. Furthermore, transport activities account for nearly 5% of value added and employment in developed economies; although this share is lower in developing and emerging economies, it is expected to increase at a much faster rate in the coming decades due to rising incomes and infrastructure development. At the same time, the transport industry is also one of the world's major contaminators, particularly as far as the emission of air pollutants is concerned. In fact, air pollution is perhaps the most pervasive of all environmental externalities from transportation, mainly because the atmosphere facilitates the rapid widespread diffusion of pollutants.

Transport activities release a number of gases into the atmosphere, including carbon dioxide, carbon monoxide, nitrous oxide, methane and non-methane volatile organic components, amongst others, mainly through the use of final energy and these have harmful effects on the

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environment and human health.[1] Some of these gases are responsible for climate change, some deplete the stratospheric ozone layer that naturally screens the earth's surface from ultraviolet radiation, while others produce acid rain that damages ecosystems and reduces agricultural crop yields. Despite the growth of the transport industry, in the past few decades we have seen a significant decrease in the emissions of some of the most harmful transportation pollutants, such as carbon monoxide and non-methane volatile organic components thanks to technological advances in both vehicles and sources of energy, as well as more stringent standards (EEA, 2012). Conversely, carbon dioxide emissions have increased almost proportionally to the growth of transport activities (Rodrigue, 2013), and, what it is more, the forecasts of future trends are very alarming.

The latest *Intergovernmental Panel on Climate Change* (IPCC) report that uses 2010 figures as the baseline reported that global carbon dioxide emissions from transportation are expected to double by 2050, and transport is set to become the biggest source of emissions unless policymakers take strong action now (IPCC, 2014).[2] Furthermore, the report states that '*Without aggressive and sustained mitigation policies being implemented, transport emissions could increase at a faster rate than emissions from the other energy end-use sector…*' (IPCC, 2014; chapter 8, p.4). Conversely, decisive policy measures could change the expected upward trend and lead to a carbon dioxide reduction; in fact, the IPCC predicts that '*For the transport sector, a reduction in total CO_2 emissions of 15–40% could be plausible compared to* (2010) *baseline activity growth in 2050…*' (IPCC, 2014; chapter 8, p.5). Additionally, several international organisations have acknowledged that effective environmental policies should be based on information from robust environmental indicators combining both environmental and economic issues (UN, 2009); such indicators should, in turn, be seen as an essential tool when assessing environmental trends, tracking progress against objectives and targets and evaluating the effectiveness of past environmental policy measures (EEA, 2014).

Against this background, this paper assesses the trends in environmental performance, understood to be the relationship between economic performance and ecological performance, in the transport industry of 38 countries between the years 1995 and 2009. In keeping with the recent publication by Picazo-Tadeo et al. (2014), we employ *Data Envelopment Analysis* (DEA) techniques and directional distance functions to compute a series of Luenberger productivity indicators of the change in environmental performance, and its decomposition into environmental technical change due to eco-innovation, and eco-efficiency change or catching-up with best available technologies. Ecological performance is accounted for through eight air pollutants grouped into three main categories of environmental pressures, namely, global warming, tropospheric ozone formation and acidification potentials. Notably, environmental performance is assessed at the level of individual environmental pressures, i.e., evaluations are based on how each of these three particular pressures is managed.

It is our contention that this approach could shed some light on relevant questions in the design of environmental policies for the transport industry, such as: *What trends exist in the relationship between economic performance and ecological performance in transport activities? Is this relationship improving?* If so, *what are the driving forces behind such improvement?* And, *which policy measures should thus be prioritised for implementation in the transport industry in order to improve its environmental performance?*

A number of papers have addressed the issue of assessing environmental performance in the transport industry from different angles, and/or have analysed environmental transport policies. These include: Acutt and Dodgson (1997), Noland and Lem (2002), Parkhurst (2004), Kuosmanen and Kortelainen (2005), Feng et al. (2007), Ruzzenenti and Basosi (2009), Yoshino et al. (2010), Heng et al. (2012), Chang et al. (2013), Loureiro et al. (2013), Bergek and Berggren (2014), Bollen and Brink (2014), and Zhou et al. (2014). Of particular note is the recent paper by Krautzberger and Wetzel (2012) that employs directional distance functions and DEA techniques, as does our paper, to compute both conventional Malmquist-Luenberger productivity indicators as well as carbon dioxide-sensitive ones, i.e., with the reduction of carbon dioxide as an additional target, for the European commercial transport industry in the period 1995–2006. One of the foremost findings of this paper is that the majority of European countries studied were unable to keep in line with the technological improvements induced by eco-innovations in transportation activities.

Our contribution to previous empirical literature in this field of research, and particularly with respect to the paper by Krautzberger and Wetzel (2012), is twofold. Firstly, instead of using only carbon dioxide emission figures, we include a much more comprehensive set of eight air pollutants to account for the environmental externalities from transport activities, and these allow a more in-depth and much more accurate assessment of environmental performance; in addition, more countries are also included. Secondly, and more interestingly, provided that performance and its determinants are assessed at the level of specific environmental pressures, our results provide information that goes beyond that of other methodological approaches and that might help policymakers to design better environmental policies for transportation activities.

The remainder of the paper is organised as follows. Section 2 describes the data and the methodology. Section 3 discusses the results, and the final section summarises and highlights certain policy conclusions.

2. Data, variables and methodological notes

2.1. Data and variables

In this paper we use information from the World Input-Output Dataset (WIOD), a project financed by the *Seventh Framework Programme for Research and Development 2007–2013* of the European Commission, which provides disaggregated sectoral data on a series of socio-economic and environmental variables for 40 countries between 1995 and 2011.[3] The WIOD includes 27 European Union (EU) countries and 13 other major countries. However, due to a lack of data on some relevant variables for our analysis, we have excluded Luxemburg and Taiwan, which reduces our sample to 38 countries. According to the World Bank,[4] these countries have been classified into two groups, namely, *high-income countries*, including Austria, Belgium, Denmark, France, Finland, Germany, Greece, Ireland, Italy, the Netherlands,

[1] Transport-related air pollution is a major cause of disease. It has been estimated that these contaminating gases contribute to six of the top ten causes of death (Global Road Safety Facility, The World Bank; Institute for Health Metrics and Evaluation, 2014), including ischemic heart disease, stroke, lung cancer or respiratory infections, amongst others. Moreover, experimental studies suggest that air pollutants from transport increase the risk of developing an allergy or cause adverse outcomes in pregnancy, such as premature birth (Krzyzanowski *et al.*, 2005). The OECD (2014) has estimated that outdoor air pollution kills more than three million people around the world every year, and causes health problems for many more; furthermore, the monetary value of illness and lives lost in developed economies plus China and India was estimated to amount to US$3.5 trillion in 2010, with this figure continuing to rise. In developed countries alone this cost reached US$1.7 trillion, with motorised and road transport being responsible for about half of this figure. Reducing health costs related to pollution created by transport activities therefore constitutes an important co-benefit from environmental improvements.

[2] According to the figures provided by the IPCC, the transport sector produced 6.7 gigatonnes of carbon dioxide (7.0 gigatonnes of carbon dioxide equivalents including non-CO_2 gases) of direct greenhouse emissions in 2010, and was responsible for approximately 23% of total energy-related carbon dioxide emissions. It is estimated that this figure will reach around 12 gigatonnes by 2050.

[3] Timmer (2012) provides an overview of the contents, sources and methods used in gathering the WIOD (also see Genty et al., 2012 for details about the compilation of the environmental accounts), which can be accessed at http://www.wiod.org. Furthermore, this dataset has recently been used in several research papers, including Johnson (2014), Koopman *et al.* (2014), Timmer *et al.* (2014), as well as in policy papers from highly reputed international organisations such as the European Central Bank (di Mauro *et al.*, 2013) or the International Monetary Fund (Saito *et al.*, 2013).

[4] See http://data.worldbank.org/about/country-and-lending-groups.

Portugal, Spain, Sweden and the United Kingdom, all of which are members of the former European Union-15, in addition to Australia, Canada, the Czech Republic, Cyprus, Estonia, Japan, Korea, Latvia, Lithuania, Malta, Poland, Russia, Slovakia, Slovenia and the United States; and *low- and middle-income countries*, including Bulgaria, Brazil, China, Hungary, India, Indonesia, Mexico, Romania and Turkey.

We use country level data for 1995–96 and 2008–09,[5] as well as a series of variables representing both the economic output of the transport industry and emissions of eight atmospheric contaminants. In keeping with the International Standard Industrial Classification (ISIC), the commercial transport sector has been defined by aggregating the activities of land transport (I60 according to ISIC nomenclature), water transport (I61), air transport (I62) and supporting and auxiliary transport activities (I63). The economic outcome of the transport industry is measured using real gross output in purchasing parity power (PPP) (constant 2005 international $). The socio-economic accounts of the WIOD provide data on gross output by industry at current basic prices in national currency, in addition to sectoral price indices, which have been employed to calculate real gross output in national currency at 2005 constant prices. These figures have been translated into PPPs using the GDP conversion factors (units of local currency per international $) provided by the World Bank in its *World Development Indicators* database.[6] Table 1 shows figures for aggregate gross output by groups of countries.

We collected WIOD environmental data on the emission of eight atmospheric contaminants generated by transport activities, including carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), oxides of nitrogen (NO_x), oxides of sulphur (SO_x), ammonia (NH_3), non-methane volatile organic components (NMVOC) and, lastly, carbon monoxide (CO).[7, 8] All these individual air pollutants have been aggregated into three categories of environmental pressures using conversion factors from the environmental assessment literature (de Leeuw, 2002; Solomon et al., 2007). These environmental pressures are global warming potential (GWP), tropospheric ozone formation potential (TOFP) and acidification potential (ACIDP).[9] It is worth noting here that some air pollutants, e.g., NO_x or CH_4, might cause more than one environmental pressure; furthermore, although conversion factors allow us to account for the relative damage impact of individual air pollutants, these environmental pressures represent *potential* rather than actual environmental impacts.

Global warming and climate change have become of increasing concern to policymakers, researchers and society as a whole in recent decades; in fact, measures against climate change constitute a cornerstone of current environmental policy in most developed countries. Furthermore, researchers generally seem to agree that changes are unequivocally caused by increasing concentrations of greenhouse gases (GHGs) resulting from human activities, principally the production and use of energy. The primary GHGs responsible for global warming are CO_2, CH_4 and N_2O.[10] In order to translate our air-pollutant data into global warming potential, we have used the conversion factors for a 100-year time horizon provided by Solomon et al. (2007; Table 2.14; p.212). In particular, the global warming potential generated by the transport industry in each period has been computed at the country level in tonnes of CO_2 equivalents as:

$$WGP = CO_2 + 25\ CH_4 + 298\ N_2O. \tag{1}$$

Our second environmental pressure is the tropospheric ozone formation potential, which has adverse effects on health, agricultural crops and ecosystems. The majority of tropospheric ozone formation occurs when NMVOC, CO, NO_x, in addition to CH_4, react in the atmosphere; in fact, these gases are called ozone precursors. Using the conversion factors proposed by de Leeuw (2002; Table 3; p.141), the tropospheric ozone formation potential generated by the transport industry has been calculated at the period and country levels in NMVOC equivalents tonnes for countries in the sample as:

$$TOFP = NMVOC + 0.11\ CO + 1.22\ NO_x + 0.014\ CH_4. \tag{2}$$

The third environmental pressure, acidification potential, is a transboundary problem that arises from the atmospheric deposition of sulphur and nitrogen compounds and causes changes to the chemical composition of soils and freshwater systems that adversely affect ecosystems, and even jeopardise some animal species. In addition, acidifying pollutants corrode materials and buildings. Here, we have calculated the acidification potential, also at the period and country levels, using the conversion factors provided by de Leeuw (2002; Table 1; p.137) in tonnes of acid equivalents:

$$ACIDP = 31.25\ SO_x + 21.74\ NO_x + 58.82\ NH_3. \tag{3}$$

Table 2 provides figures on aggregate environmental pressures for groups of countries in 1995–96 and 2008–09. While, as noted, these pressures by themselves are not measures of the environmental damage caused by transport activities, we agree with Kortelainen (2008) who concluded that the use of environmental pressures to analyse environmental performance and eco-efficiency might be a better choice than using figures on particular pollutants. The reason for this is that, unlike air pollutants alone, environmental pressures reflect specific environmental concerns for society; likewise, aggregating individual air pollutants into wider environmental pressures allows us to take into consideration a greater number of contaminants in our analysis, as aggregation increases the discriminatory power of our DEA-based models (see Cooper et al., 2007).

Lastly, we have calculated a measure of the intensity of environmental pressures, i.e., physical units of each environmental pressure per unit

Table 1
Aggregate gross output (*averages for 1995–96 and 2008–09; million 2005 US$ in PPP*).

	1995–96	2008–09
All countries	2,930,938	4,966,239
Low- and middle-income countries	774,637	2,079,722
High-income countries	2,156,301	2,886,517
European Union-15	842,072	1,215,780

[5] In order to minimise the effect of possible measurement errors in our variables of interest, we employ averages of the years 1995 and 1996 for the start of the period being analysed, and averages for the years 2008 and 2009 for the end of that period. It is worth noting that although the 2014 edition of the WIOD updated the socio-economic variables up to and including 2011, environmental variables are still only available for the period 1995-2009, which limits the range of our analysis.

[6] Accessed on 26th April 2014 at http://data.worldbank.org.

[7] The data were accessed on 26th April 2014 at http://www.wiod.org.

[8] These pollutants come mainly from highway vehicles, marine engines, locomotives and aircrafts, which are the major users of energy worldwide and burn most of the world's petroleum (see Lee *et al.*, 2010; Eyring *et al.*, 2010, and Uherek *et al.*, 2010, for technical details about the emissions into the atmosphere of aviation, shipping and land transport, respectively). In addition to exhaust emissions, other ways that transport activities might also cause pollution include disposal of worn-out batteries (batteries contain a number of heavy metals and toxic chemicals that cause soil and water pollution when they are not properly treated), or tyre recycling (in advanced economies it is estimated that more than half of all tyres are burnt for fuel). However, accounting for all these contaminants from transport activities would have required the use of a *Life-Cycle Assessment* (LCA) approach, which goes far beyond the aim of our research.

[9] In addition to these environmental pressures, transport activities also contribute to the formation of particles, either directly or through primary emission of NO_x, SO_x and NH_3, which, amongst other things, are detrimental to health. However, lack of industry-level data for these pollutants in the WIOD has prevented us from including them in our analysis.

[10] Other components that also affect global warming are sulphur hexafluoride (SF_6), perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs). However, due to the difficulties in assigning their emissions to specific economic activities, the environmental accounts of the WIOD do not provide information about these air pollutants (Timmer, 2012; p.45). They are, however, much less important in terms of aggregate GHGs emission (Picazo-Tadeo *et al.*, 2014; p.178).

Table 2
Aggregate environmental pressures (*averages for 1995–96 and 2008–09*).

	Global warming potential (*1000 tonnes of CO_2 equivalents*)		Tropospheric ozone formation potential (*1000 tonnes of NMVOC equivalents*)		Acidification potential (*1000 tonnes of acid equivalents*)	
	1995–96	2008–09	1995–96	2008–09	1995–96	2008–09
All countries	1,543,474	2,102,725	39,786	27,285	456,400	467,087
Low- and middle-income countries	243,372	508,720	15,577	7638	102,227	103,335
High-income countries	1,300,102	1,594,005	24,209	19,647	354,173	363,752
European Union-15	315,583	451,708	4743	5278	110,179	122,431

of output; the results are shown in Table 3. Generally speaking, the intensity of emissions decreased in all three environmental pressures during the period, with the most marked reduction corresponding to TOFP (59.6% aggregate fall) and ACIDP (39.6%), followed by GWP (only 19.6%, primarily due to rising CO_2 emissions). Moreover, reductions have been noticeably higher in low- and middle-income economies compared to high-income countries, including the European Union-15 members.[11] These results already seem to indicate environmental performance improvement in the transport industry. However, a more in-depth analysis of the extent of these trends and their determinants, which is the main purpose of our research, might help policymakers to better design their environmental policies.

2.2. Methodological notes

We follow the approach recently proposed by Picazo-Tadeo et al. (2014) for assessing environmental performance change and its determinants, namely, environmental technical change and eco-efficiency change, at the country and environmental pressure levels. This approach builds on previous work by Kuosmanen and Kortelainen (2005), Kortelainen (2008) and Picazo-Tadeo et al. (2012).

Kuosmanen and Kortelainen (2005) developed a general static framework for assessing *relative eco-efficiency* using *Data Envelopment Analysis* (DEA) techniques (Charnes et al., 1978), which Kortelainen (2008) extended to a dynamic setting; for this purpose, Mika Kortelainen developed a measure of dynamic environmental performance and its determinants based on the computation of distance functions (Shephard, 1970) and Malmquist's indexes (Malmquist, 1953). In line with the seminal paper by Färe et al. (1994), this approach allows an evaluation of the change in environmental performance resulting from environmental technical change and relative eco-efficiency change, which identify the progress made in environmental technology due to eco-innovations, and catching-up with best available environmental practices, respectively.

Later, Picazo-Tadeo et al. (2014) further developed the approach by Kortelainen (2008) proposing a series of indicators of environmental performance change and its determinants computed at the level of specific contaminants. To do so, the authors employed directional distance functions (Färe and Grosskopf, 2000) and the DEA-based approach to eco-efficiency measurement proposed by Picazo-Tadeo et al. (2012) to compute Luenberger productivity indicators (Chambers et al., 1996).

As explained in Section 2.1, here we use transport industry data from 38 countries and years 1995–96 and 2008–09, which we refer to as periods 0 and 1, respectively. Furthermore, transport activities produce an economic outcome measured by gross output, variable o, while emitting a series of damaging atmospheric gases that generate three environmental pressures, namely, GWP, TOFP and ACIDP, which are represented by the vector p = (GWP, TOFP, ACIDP).

The environmental technology in period t, either 0 or 1, can be represented by the *Pressure Requirement Set* (PRS) that represents all combinations of environmental pressures that generate, at least, an economic output o (Beltrán-Esteve et al., 2014). Formally:

$$\mathrm{PRS}^t(o^t) = \left[p^t \middle| (o^t, p^t) \in \mathrm{PGTS}^t\right] \tag{4}$$

where PGTS is the *Pressure Generating Technology Set* that includes all technologically feasible combinations of output and environmental pressures given the state of knowledge in period t (Kuosmanen and Kortelainen, 2005).

Furthermore, we assume that the environmental technology has the properties proposed by Picazo-Tadeo et al. (2012). These properties are as follows: a) transport activities inevitably generate pressures on the environment; b) lower output can always be obtained with the same amount of pressures; c) pressures can always be increased for a given output; and d) any convex combination of feasible or observed pairs of output and pressures is also feasible. Accordingly, pressures are formally treated as conventional inputs (Korhonen and Luptacik, 2004; Kuosmanen and Kortelainen, 2005; and Zhang et al., 2008).

Let us now borrow the formal definition of *environmental performance* proposed by Kortelainen (2008), as the quotient between economic performance, measured in our case study by gross output, and ecological performance, measured by a composite indicator of the environmental pressures. Formally, in period t:

$$\text{Environmental performance}^t = \frac{\text{Gross output}^t}{\text{Aggregate pressure}^t} = \frac{o^t}{w_{GWP}GWP^t + w_{TOFP}TOFP^t + w_{ACIDP}ACIDP^t} \tag{5}$$

where w_{GWP}, w_{TOFP} and w_{ACIDP} are the weightings assigned to environmental pressures GWP, TOFP and ACIDP, respectively, when calculating the aggregate pressure.

Furthermore, the *directional distance function* (DDF) (Färe and Grosskopf, 2000) jointly represents economic and ecological performance, providing a measure of how economic performance could be increased in a direction g_o, while environmental pressures are reduced in a direction $-g_p$, while remaining within the PGTS.[12] Formally, the DDF in period t with respect to the contemporaneous environmental technology is:

$$\vec{D}^t\left[o^t, p^t; g = \left(g_o, -g_p\right)\right] = \mathrm{Sup}\left[\varphi \middle| \left(p^t - \varphi g_p\right) \in \mathrm{PRS}^t(o^t + \varphi g_o)\right] \tag{6}$$

with g standing for the so-called direction vector.

[11] In this paper we also present some results for the former European Union-15, excluding Luxemburg for the reasons already noted. However, given the size of its economy, this exclusion will not greatly bias the results.

[12] Zhang and Choi (2014) review recent literature in the field of energy and environmental modelling showing how directional distance functions are increasingly a focus of attention.

Table 3
Intensity of environmental pressures (*units of the environmental pressure per million 2005 US$ PPP of gross output; averages for 1995–96 and 2008–09*).

	Global warming potential (*1000 tonnes of CO_2 equivalents*)		Tropospheric ozone formation potential (*1000 tonnes of NMVOC equivalents*)		Acidification potential (*1000 tonnes of acid equivalents*)	
	1995–96	2008–09	1995–96	2008–09	1995–96	2008–09
All countries	526.6	423.4	13.6	5.5	155.7	94.1
Low and middle-income countries	314.2	244.6	20.1	3.7	132.0	49.7
High-income countries	602.9	552.2	11.2	6.8	164.3	126.0
European Union-15	374.8	371.5	5.6	4.3	130.8	100.7

The DDF provides a complete representation of the environmental technology and is a powerful tool for assessing eco-efficiency, as it measures deviations from an environmental technological frontier. In particular, the eco-efficiency (EEff) of a country, i.e., pair of gross output and environmental pressures, in period t, either 0 or 1, is:

$$\mathrm{EEff}^t = \vec{D}^t\left[o^t, p^t; g = \left(g_o, -g_p\right)\right]. \tag{7}$$

Eco-efficiency measured with the DDF of expression (6) is lower bounded to zero, score that indicates full eco-efficiency; moreover, the greater the distance from zero, the lower the level of eco-efficiency. Other properties of the DDF are described in Chambers et al. (1998).

Using the concepts of environmental performance, DDF and eco-efficiency, Picazo-Tadeo et al. (2014) suggested assessing the change in environmental performance using Luenberger productivity indicators (Chambers et al., 1996). Formally, the *Luenberger environmental performance change* indicator (LEPCh) between periods 0 and 1 is computed as the average of the change in environmental performance assessed with respect to the environmental technologies observed in periods 0 (EPCh^0) and 1 (EPCh^1), respectively[13]:

$$\begin{aligned}\mathrm{LEPCh}^{0,1}\left[o^0, p^0, o^1, p^1; g = \left(g_o, -g_p\right)\right] &= \frac{1}{2}\left(\mathrm{EPCh}^0 + \mathrm{EPCh}^1\right)\\ &= \frac{1}{2}\left\langle\left[\vec{D}^0\left(o^0, p^0; g\right) - \vec{D}^0\left(o^1, p^1; g\right)\right] + \left[\vec{D}^1\left(o^0, p^0; g\right) - \vec{D}^1\left(o^1, p^1; g\right)\right]\right\rangle.\end{aligned} \tag{8}$$

In line with the seminal paper by Färe et al. (1994), the Luenberger indicator of the change in environmental performance can be decomposed into two elements that represent the results of, respectively, *environmental technical change* (ETCh) due to shifts in the environmental technological frontier brought about by eco-innovations, and *eco-efficiency change* (EEffCh), which measures catching-up with the best existing environmental practices:

$$\mathrm{LEPCh}^{0,1}\left[o^0, p^0, o^1, p^1; g = \left(g_o, -g_p\right)\right] = \mathrm{ETCh}^{0,1} + \mathrm{EEffCh}^{0,1}. \tag{9}$$

The environmental technical change that occurred between periods 0 and 1 is computed as the average of the technical change assessed by comparing observation in 0 with respect to the technological frontiers in 0 and 1 (ETCh^0), and the technical change computed projecting observation in 1 onto the frontiers in 0 and 1 (ETCh^1), respectively.[14] Formally:

$$\begin{aligned}\mathrm{ETCh}^{0,1}\left[o^0, p^0, o^1, p^1; g = \left(g_o, -g_p\right)\right] &= \frac{1}{2}\left(\mathrm{ETCh}^0 + \mathrm{ETCh}^1\right)\\ &= \frac{1}{2}\left\langle\left[\vec{D}^1\left(o^0, p^0; g\right) - \vec{D}^0\left(o^0, p^0; g\right)\right] + \left[\vec{D}^1\left(o^1, p^1; g\right) - \vec{D}^0\left(o^1, p^1; g\right)\right]\right\rangle.\end{aligned} \tag{10}$$

On the other hand, the change in the eco-efficiency of a given country that occurred between periods 0 and 1 is assessed by the difference of its DDFs computed with respect to both contemporaneous technological frontiers, using expression (7):

$$\mathrm{EEffCh}^{0,1}\left[o^0, p^0, o^1, p^1; g = \left(g_o, -g_p\right)\right] = \left(\mathrm{EEff}^0 - \mathrm{EEff}^1\right). \tag{11}$$

A notable advantage of DDFs is their flexibility, in the sense that they allow the assessment of environmental performance in different *directions*, and these might represent the preferences of researchers, policymakers or society as a whole regarding economic and ecological performance. Thanks to this flexibility, this paper first considers a scenario where we are interested in evaluating the proportion by which all three environmental pressures could be simultaneously reduced without decreasing output. The direction vector that represents this schedule of preferences is $g = (0, -p)$, and the indicator of the change in environmental performance between periods 0 and 1, which we will refer to as the *proportional Luenberger environmental performance change indicator*, measures the proportional increase or decrease in all environmental pressures as a result of both environmental technical change and eco-efficiency change occurring between these two periods. Technical details about the formulation of this indicator and its determinants are in Picazo-Tadeo et al. (2014; pp.175–176).

In addition, we have considered a set of alternative scenarios where we are interested in assessing the amount by which the transport industry could reduce each individual environmental pressure, i.e., GWP, TOFP and ACIDP, without increasing the remaining two pressures and while still maintaining output levels. Denoting the pressure being reduced as i, the direction vector that represents this schedule of preferences is $g = [0, (-\ p_i, 0)]$.

We hereafter refer to the three indicators of environmental performance change between periods 0 and 1 calculated with individual direction vectors as *specific Luenberger environmental performance change indicators*; technical details are also in Picazo-Tadeo et al., (2014; pp.175–176). Accordingly, the specific indicator of environmental performance change in, let's say, GWP will assess the amount by which the transport industry could reduce its global warming potential,

[13] While the superscripts of the variables output and environmental pressures represent the period in which they are observed, either 0 or 1, the superscript that accompanies the DDF represents the period the environmental technology of reference belongs to.

[14] Here, the superscript indicates the period, either 0 or 1, that contains the observation used to assess environmental technical change.

Table 4
Change in proportional environmental performance: Environmental technical change *versus* eco-efficiency change (*weighted averages in percentage*).

	Luenberger Environmental Performance Change Indicator (LEPCh)	Environmental Technical Change (ETCh)	Eco-efficiency Change (EEffCh)
All countries	1.64	1.50	0.14
Low and middle-income countries	3.31	2.35	0.96
High-income countries	0.77	1.05	−0.28
European Union-15	1.22	1.38	−0.16

without increasing tropospheric ozone formation and acidification potentials, while still maintaining output levels.[15] A benefit of assessing environmental performance improvement at the level of environmental pressures is that results for both environmental technical change and eco-efficiency change could well be different from those obtained using the proportional approach,[16] thus providing reliable information for the design of better environmental transport policies.

Finally, the DDFs needed to build our Luenberger indicators of environmental performance and its determinants have been computed using *Data Envelopment Analysis* (DEA), which is a widespread non-parametric approach to efficiency measurement (see Cook and Seiford, 2009) initially proposed by Charnes et al. (1978). The main feature of these techniques is that they allow the construction of a technological frontier from observed data on best practices within a sample of decision-making units (DMUs), which could be firms, industries, regions or, as is the case in our study, countries, as well as the calculation of the distance of each DMU to that frontier in terms of a performance indicator, i.e., the DDF in our methodological approach. An advantage of DEA over other approaches when constructing composite indicators, which is of particular importance in our case study given the absence of prices for environmental pressures, is that, based on the so-called *benefit-of-the-doubt* principle (Cherchye et al., 2007), the weightings used to build the aggregate environmental pressure are endogenously generated at the country level. These weightings are those that rate each country in the most favourable light when compared to all other countries in the sample using the same set of weightings.

The mathematical programmes required to compute the directional distance functions involved in our analysis are developed in the Appendix A; in all cases, constant returns to scale have been imposed (Banker et al., 1984). According to Picazo-Tadeo et al. (2012), the size of activity matters little when assessing eco-efficiency, as our interest is in the ratio of output to an aggregate environmental pressure, and this is interpreted as a constant returns to scale model in DEA literature (Kortelainen and Kuosmanen, 2004). Moreover, as noted by Beltrán-Esteve et al. (2014), the non-radial nature of some of our measures of eco-efficiency may cause difficulties when measuring returns to scale (see Krivonozhko et al., 2012).

3. Results and discussion

As per the methodology explained in Section 2.2, in order to assess environmental performance and its determinants, we have considered four alternative scenarios that represent different schemes of preferences regarding the reduction of environmental pressures. In the first scenario the aim is to assess environmental performance through the maximum attainable proportional reduction of all three environmental pressures, namely, GWP, TOFP and ACIDP, generated by transport activities while maintaining gross output, i.e., proportional environmental performance. In the other three scenarios the aim is to determine the maximum potential reduction of each environmental pressure, while keeping both the remaining pressures and output at their observed levels, i.e., specific environmental performance. The results are shown in Tables 4 and 5, respectively, and include weighted[17] averages for groups of countries' environmental performance change (LEPCh) and its components, i.e., environmental technology change (ETCh) and eco-efficiency change (EEffCh). Furthermore, in order to make these figures more reader-friendly, all changes have been annualised using simple growth rates.

A common problem when computing Luenberger performance indicators with DDFs and DEA techniques are infeasibilities, which can arise when an observation belonging to a given period, i.e., pair of observed environmental pressures and output, is projected onto the technological frontier of a different period; in such cases, there may be no positive solution for the DDF (Briec and Kerstens, 2009). In our research, we found no solution for 32 cross-period programmes out of the 608 programmes involved in our DEA-based models, which hampers the computation of the technical change component of the Luenberger environmental performance indicator for the countries involved.

In order to manage such infeasibilities, our first choice was to relax the assumption of non-negativity for the DDFs, as proposed by Mahlberg and Sahoo (2011). This allows the projection of these *super-efficient* observations on their non-contemporaneous frontiers. While this approach ensures feasibility in the case of our proportional indicator of environmental performance change, 24 problems with no solution still remained for our specific indicators where the direction vector does not have a full dimension (see Briec and Kerstens, 2009 for details), i.e., 3.9% of all programmes involved in our analysis. Nevertheless, these figures are noticeably lower than those of other similar studies (Chung et al., 1997; Färe et al., 2001; Yörük and Zaim, 2005). Moreover, we chose to omit the remaining infeasible solutions in the computation of technical change.[18]

Let us now address our estimates for the change in environmental performance and its determinants. Starting with the proportional indicator (Table 4), the most notable result is that performance improved between 1995–96 and 2008–09 at an average rate of 1.64% per year, mainly fuelled by environmental technical progress due to eco-innovations, i.e., annual rate of 1.50%. This result is in line with those obtained by other recent studies carried out using data at country- and whole-economy level that also highlight the central role played by technical progress in explaining environmental productivity growth (Kortelainen, 2008 for 20 European economies; Mahlberg and Sahoo, 2011 for 22 OECD countries; Mahlberg and Luptacik, 2014 for the Austrian economy; or Picazo-Tadeo et al., 2014 for the European Union).

Nevertheless, our results are far from being homogeneous when analysed with respect to groups of countries. The weighted average environmental performance improvement in low- and middle-income economies reaches 3.31% per year, and has been driven by both environmental technical progress, which explains more than two thirds of

[15] Many other scenarios representing alternative schemes of preferences could also be considered, e.g., increasing output while maintaining environmental pressures, or increasing output while pressures (either all pressures or specific pressures) are being reduced. However, assessing performance in such scenarios is beyond the scope of this paper, which primarily focuses on assessing reductions in environmental pressures potentials.

[16] Picazo-Tadeo *et al.* (2014; p.177) provide a graphical illustration of how environmental technical progress might be rather different depending on the direction, either proportional or specific, in which environmental performance is evaluated.

[17] Country weightings have been computed according to their gross output.

[18] Another approach commonly used in the literature is assigning a value of no change to infeasibilities. We also calculated our specific Luenberger performance indicators and its determinants assigning a value of zero, i.e., no change, to infeasible solutions; these results are available on request but show negligible differences from those computed omitting infeasibilities.

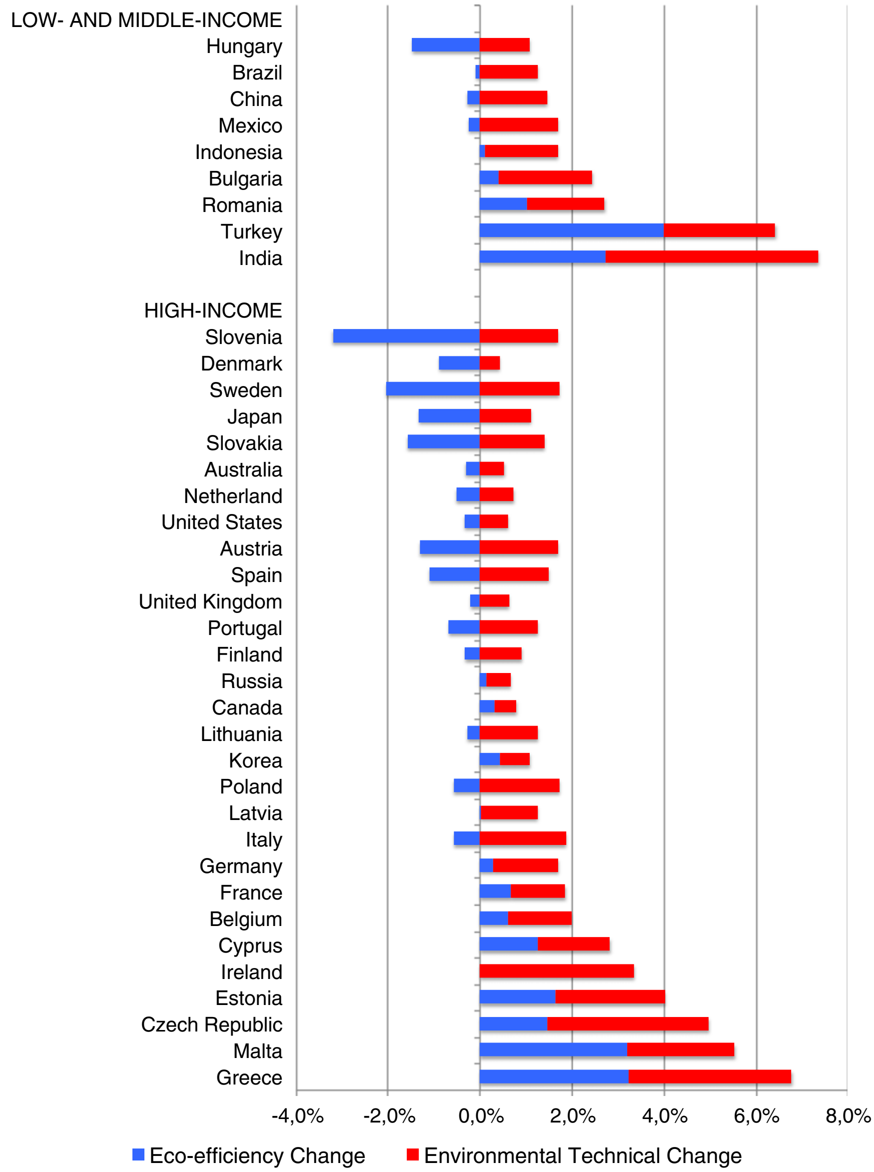

Fig. 1. Proportional environmental performance at the country level (*annual percentages of growth between 1995–96 and 2008–09*).

Table 5
Change in specific environmental performance: Environmental technical change *versus* eco-efficiency change (*weighted averages in percentage*).

	Luenberger Environmental Performance Change Indicator (LEPCh)	Environmental Technical Change (ETCh)	Eco-efficiency Change (EEffCh)
Global warming potential			
All countries	1.02	0.64	0.38
Low- and middle-income countries	2.08	0.43	1.65
High-income countries	0.48	0.76	−0.28
European Union-15	0.88	1.63	−0.75
Tropospheric ozone formation potential			
All countries	1.82	0.90	0.92
Low- and middle-income countries	3.52	0.70	2.82
High-income countries	0.93	1.00	−0.07
European Union-15	1.52	1.49	0.03
Acidification potential			
All countries	1.67	1.07	0.60
Low- and middle-income countries	3.24	1.23	2.01
High-income countries	0.85	0.99	−0.14
European Union-15	1.54	1.35	0.19

performance improvement, and catching-up. Conversely, high-income countries have recorded a weighted annual improvement in environmental performance of just 0.77%, fuelled entirely by progress in environmental technology, which even compensated for a negative change in eco-efficiency.[19] Figures for the European Union-15 members are rather similar in the sense that the improvement in performance has been entirely driven by environmental technical progress. Furthermore, this result coincides with that obtained by Krautzberger and Wetzel (2012) for the European transport industry using carbon dioxide as a measure of air pollution.

Fig. 1 depicts the rates of environmental technical change and change in eco-efficiency for countries in our sample, ranked according to their respective records in environmental productivity change within each group. In low- and middle-income countries, it highlights the improvement in environmental performance in India and Turkey with annual average rates of 7.36% and 6.44%, respectively. Environmental performance in China, the largest economy in this group, progressed in the period at a rate of just 1.19%, entirely driven by improvements in environmental technology.

In general, richer economies within the group of high-income countries, including Denmark, Sweden, Japan, Australia, the Netherlands, the United States, Austria, the United Kingdom and Finland, register the lowest rates of environmental performance improvement; furthermore, all these countries moved away from their respective environmental technological frontiers between 1995–96 and 2008–09, i.e., eco-efficiency worsened. In particular, the progress achieved in terms of environmental performance in the United States, whose economy contributes more than one quarter of the total output of the transport industry in the group of high-income countries, has certainly been minimal, i.e., only 0.28% per year, fuelled entirely by technical progress. On the other hand, high-income economies with relatively lower levels of development such as Greece, Malta, the Czech Republic, Estonia or Cyprus, record the highest rates of environmental performance improvement, in all cases fuelled by both eco-innovations and catching-up.

In summary, our proportional Luenberger indicator shows that environmental performance has improved considerably in the transport industry since the mid-1990s, mainly driven by advances in environmental technology due to eco-innovations. However, other relevant questions still remain unanswered, e.g., *Have improvements in environmental performance affected global warming, tropospheric ozone formation, and acidification potentials in the same way?* Or, *has technological progress played the same role in explaining environmental performance improvement for each of these environmental pressures? And eco-efficiency?* Our indicators of specific environmental performance in Table 5 attempt to provide an answer to these questions.

There were notable improvements in environmental performance in terms of all three environmental pressures between 1995–96 and 2008–09, the greatest progress corresponding to tropospheric ozone formation and acidification potentials (1.82% and 1.67% per year, respectively), followed by the global warming potential (1.02%). Both eco-innovations and catching-up have contributed to these advances. In all cases, the improvement in environmental performance is higher in the group of low- and middle-income countries, mostly fuelled by catching-up, especially as far as tropospheric ozone formation potential is concerned (see footnote 19). Turkey and India have seen environmental performance improve over that period at rates of around 5–6% for the management of all three environmental pressures. Likewise, Bulgaria and Romania also stand out in terms of tropospheric ozone formation and acidification potentials, with environmental performance improvement rates of around 3%.[20]

Conversely, average rates of environmental performance improvement in transport activities are considerably lower in high-income countries particularly when it comes to global warming, where performance improved by scarcely 0.48% per year. In all cases, performance improvements were exclusively fuelled by the progress made in environmental technology that even offset negative growth rates of eco-efficiency. In this group, some of the former communist economies that entered the European Union in 2004 register the poorest performance improvement rates, including Lithuania, Poland, in addition to Slovakia and Slovenia where the environmental performance in the management of the three environmental pressures decreases over this period. Likewise, more developed countries such as Japan or Denmark also registered negative performance improvement rates for all environmental pressures, while in the United States improvements have been rather limited, or even null, with growth rates of 0%, 0.38% and 0.30% in global warming, tropospheric ozone formation and acidification potentials, respectively. The improvement of environmental performance in the European Union-15 is, however, higher for all environmental pressures, boosted by greater environmental technical progress rates. Moreover, in this area eco-efficiency change contributes positively to performance improvement in terms of tropospheric ozone formation and acidification potentials, but very negatively in terms of global warming potential.

In order to provide further insight into our results, Fig. 2 shows the relative levels of eco-efficiency in our proportional scenario for all countries in the sample for 2008–09. Moreover, within each group, countries are ranked in ascending order according to their eco-efficiency scores. To make the results more reader-friendly, and for illustrative purposes only, eco-efficiency scores have been reformulated as one minus the DDFs computed according to expression (6). Hence, a value of 1 means eco-efficiency, while lower values indicate eco-inefficiency, e.g., a score of 0.7 would mean that the transport industry could produce the same level of output generating only 70% of its observed environmental pressures. In other words, it could avoid 30% of the pressures actually generated.

Looking at these figures, several features are worth highlighting. First, countries generally perform at some distance from the environmental technological frontier, with a weighted average for eco-efficiency of 0.432 for the whole sample; in other words, the same levels of output in transport activities could be achieved with 43% of the pressures actually exerted on the environment. Second, low- and middle-income countries perform closer to the technological frontier than high-income economies, with eco-efficiency averages of 0.484 and 0.349, respectively. However, the lower results registered for the group of high-income countries is primarily due to the poor eco-efficiency of the United States and Russia (both with scores below 0.2), which jointly contribute one third of the aggregate output of the transport industry in this group; in fact, the distributions of the eco-efficiency scores of high-income and low- and middle-income countries are not statistically different (the *p-value* from a *Mann-Whitney* test is 0.757).[21] Lastly, results for eco-efficiency are quite similar when evaluated at the level of specific environmental pressures, with average scores for global warming, tropospheric ozone formation and acidification potentials of 0.319, 0.312 and 0.336, respectively.[22] Furthermore, it would appear that eco-efficiency is not influenced in a

[19] Moreover, we have assessed the statistical significance of differences in environmental performance change and its determinants, between low- and middle-income countries and high-income countries using the non-parametric *Mann–Whitney* test (see Conover, 1998). The results indicate that the differences in performance growth are all statistically significant at standard confidence levels, except for the global warming potential case, as they are the differences in eco-efficiency change (excluding the scenario in which all three environmental pressures are proportionally reduced).

[20] In order to avoid an excess of numerical information, not all the results at country and environmental pressure levels are presented here, although they are available upon request.

[21] This outcome is in line with Feng *et al.* (2007) who found that the environmental efficiency of transportation activities in cities in developed countries is no different from cities in developing economies.

[22] Furthermore, distributions of eco-efficiency between high- and low- and middle-income countries for global warming, tropospheric ozone formation and acidification potentials are not statistically different either (*p-values* from the *Mann-Whitney* test are 0.336, 0.972 and 0.353, respectively). Results for individual countries at the level of specific environmental pressures are available on request.

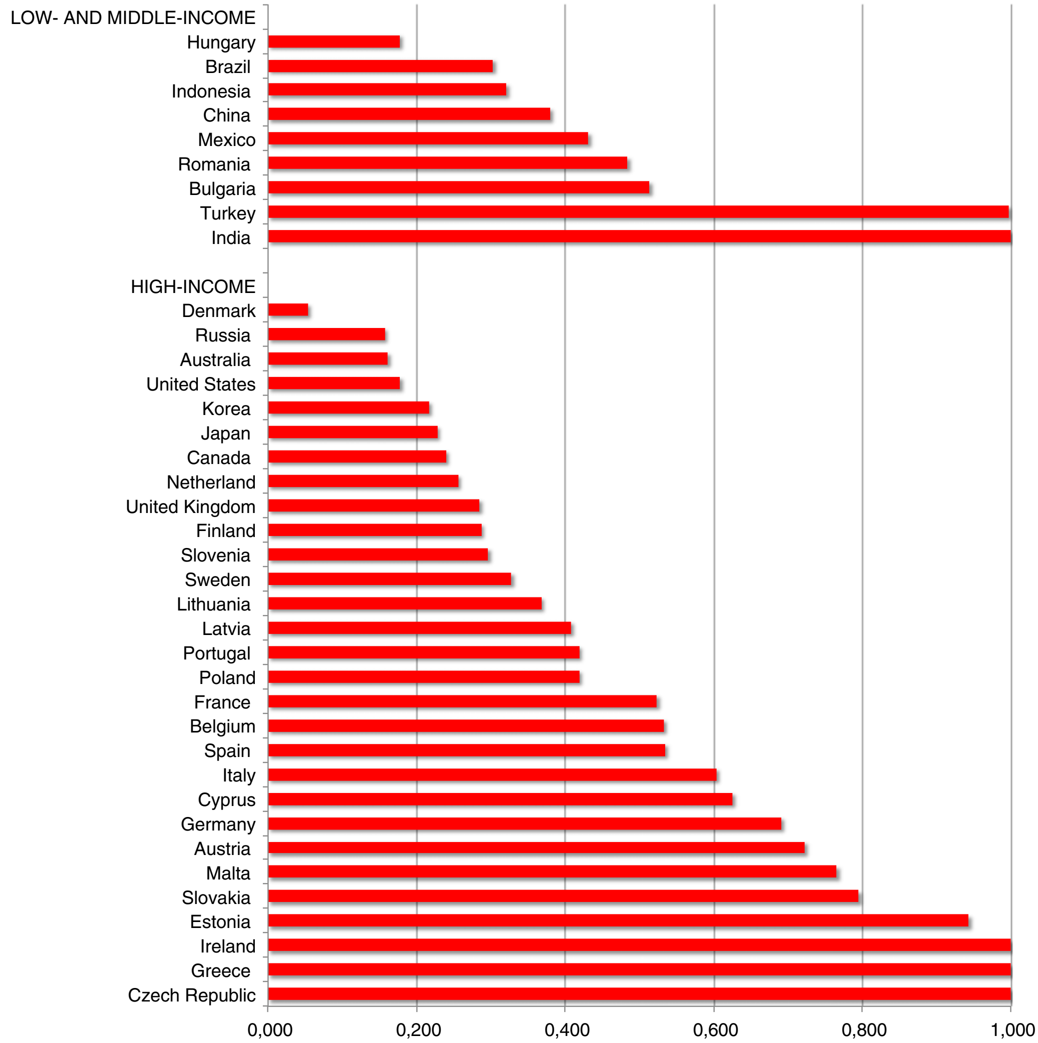

Fig. 2. Eco-efficiency at the country level, 2008–09 (*0 lower eco-efficiency, 1 higher eco-efficiency*).

statistically significant way by the sectoral composition of activities within the transport industry.[23]

Beyond the level of development or the predominance of one or another type of transportation in the industry, several other factors might also help to explain differences in environmental performance between countries, including citizens' environmental awareness or the different environmental policies aimed at reducing pollution in the transport sector. Europe is considered more environmentally conscious than other developed economies such as the United States,[24] and countries in the European Union have traditionally implemented more stringent environmental policies (Jordan and Adelle, 2013), including those regarding transportation.[25] According to results depicted in Fig. 2, weighted average eco-efficiency for countries in the former EU-15 reaches 0.521, well above the average for the rest of the high-income economies, thus pointing to better performance.[26] In addition to transport-related environmental policies implemented at the European Union level, some European countries have adopted state-level programmes targeted at improving energy efficiency in transportation; these include fiscal and financial incentives, as well as measures relating to regulation, organisation, information, education and training, and cooperation. Valeri et al. (2012) describe the evolution of the transport energy efficiency policies carried out in several European countries and their effectiveness from the 1990s to the end of the 2000s, which broadly coincides with the period analysed in our research.

Although most European countries adopt a policy mix, the most widely-implemented groups of measures are those that rely on regulation and incentive-based policies. Command-and-control measures based on permission, prohibition, standard setting and enforcement, which oblige stakeholders to change their behaviour, have been

[23] To arrive at this conclusion, we computed the *Spearman* correlation coefficient between our eco-efficiency indicators, on the one hand, and the percentage share of land, water and air transport, in addition to support and auxiliary transport activities, in aggregate output, on the other. Correlations for proportional eco-efficiency are −0.044, −0.131, 0.200 and 0.180, respectively. None of these figures, however, are statistically significant at standard confidence levels, i.e., *p-values* are always above 20%. Results are quite similar for scores of specific eco-efficiency.

[24] The United States, one of the major emitters of air pollutants worldwide, signed the Kyoto Protocol on November 12, 1998; however, the Clinton Administration never ratified the Protocol, and the Bush Administration rejected it on March 2001. Furthermore, Canada was the first signatory to withdraw from the Kyoto Protocol in 2012. In addition, Japan and Russia participated in the first round of Kyoto but they have not taken on new binding targets in the second commitment period.

[25] Button (1993) examines the economic theories underlying environmental transport policies and reviews the policy options to deal with transport-related environmental problems; Banister (1998) investigates the conflicts arising from the implementation of different policy options.

[26] Averages of eco-efficiency in the scenarios where only specific environmental pressures are reduced also show a better performance of the EU-15.

implemented in almost all European countries. In terms of financial incentives, Austria, France, Germany, Italy and Spain have implemented, for instance, temporary bonus systems for scrapping old vehicles, while the Italian government launched financial assistance programmes in order to encourage the modernisation of regional and municipal public transport services. Fiscal measures penalising vehicles generating higher emissions and favouring those with lower fuel consumption have also been used in countries such as Austria, Germany, Spain and Italy. Information, education and training measures have been put in practice in most European countries, e.g., eco-driving programmes set up in Austria, France, Germany, Sweden and Spain. Cooperative measures, most of them based on voluntary agreements with vehicle producers, have been implemented in Germany, Italy and Sweden, principally in an attempt to reduce carbon dioxide emissions and promote the use of renewable energy sources. In addition to all the abovementioned measures, many European countries have implemented other policies such as supported R + D programmes targeted at developing new technologies to minimise the environmental impact of transportation, or cross-cutting transport sector policies including measures aimed at shifting transport of people and freight to more energy-efficient and environmentally-friendly modes.

4. Summary, policy remarks and suggestions for further research

Fuelled by the increasing concern of researchers, politicians and society as a whole about the impact of economic activity on the environment, a burgeoning scientific literature has emerged in the past two decades aimed at assessing environmental performance. Our paper contributes to this literature by assessing trends in the environmental performance of the transport industry in 38 countries between 1995 and 2009. In addition, the change in environmental performance is decomposed into two components representing the results of environmental technical change and eco-efficiency change, which assess eco-innovation and catching-up with best available environmental practices, respectively. The main contribution of this study is that environmental performance is assessed based on the management of specific environmental pressures, thus providing information beyond that available using other methodological approaches; furthermore, a broad set of eight air pollutants is used to account for the impact of the transport industry on the environment.

Our main findings are summarised as follows. First, there has been a noticeable improvement in the environmental performance of the transport industry since the mid-1990s. Second, said improvement has been mainly driven by environmental technical progress due to eco-innovation rather than by catching-up. Third, improvement in environmental performance greatly differs according to the environmental pressure considered, with the worst results being registered for the global warming potential. Lastly, the improvement in environmental performance in low- and middle-income economies is greater than in high-income ones; moreover, while catching-up constitutes an outstanding source of environmental performance improvement in low- and middle-income countries, in the group of high-income economies, average eco-efficiency worsened over the same period.

The abovementioned results lead, in our opinion, to relevant policy conclusions. In particular, although technological change powered by eco-innovation has boosted the environmental frontier in the transport industry, insufficient progress and even declining eco-efficiency indicate that the majority of countries, especially those with the most developed economies, have not been able to keep to their technological frontier. This finding reveals the need to implement policy measures aimed at making eco-efficiency a source of environmental performance improvement in the transport industry. In other words, measures introducing new incentives for the use of best available environmental technologies are urgently needed, particularly in high-income economies.

The transport industry constitutes a strong case for promoting the development of new alternative fuels or sources of energy and vehicle design, in order to compensate for the impacts of oil depletion and tackle the impacts of transport activities on the environment (EC, 2009). However, as shown by the results of this research, technological progress alone might not be sufficient to meet the demands of society regarding environmental air quality; incorporating new available technologies in freight and people transportation activities is strongly required as well. Furthermore, catching-up with best environmental practices in the transport industry can offer much more immediate results than pursuing new technologies through eco-innovation.

But, *what can governments do to boost eco-efficiency in the transport industry?* Governments should encourage the uptake of alternative fuel technologies that reduce air emissions, particularly carbon dioxide. Imposing more demanding quality standards, e.g., more ambitious targets for reducing greenhouse gas emissions from transport, and requiring action to achieve these standards could do just that. Similarly, encouraging the use of greener transport services by providing consumers with better and more transparent information on green products, or creating incentives for transport firms to invest in eco-efficient technologies, e.g., providing loans and access to venture capital for small and medium enterprises (SMEs) or promoting public–private partnerships as instruments to leverage private capital, are also highly recommendable.

Finally, we would like to highlight some topics that, in our opinion, deserve further investigation in this promising field of research. On the one hand, it would certainly be interesting to assess environmental performance in the transport industry while controlling for the composition of output, or even, performing separate analyses by activities, i.e., land transport, air transport or water transport. Including other contaminants in the analysis such as the formation of particles linked to primary emissions of some air pollutants, as well as analysing more countries, would also improve the estimates of environmental performance trends and its determinants. On the other hand, proposing new measures of environmental performance with directional distance functions or considering non-linear schemes of preferences when computing the aggregate pressure in the definition of eco-efficiency are interesting methodological challenges, but ones that we will leave for future research.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2015.08.018.

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