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Localized innovation, localized diffusion and the environment: an analysis of reductions of CO_2 emissions by passenger cars

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Abstract We investigate technological change with regard to CO_2 emissions by passenger cars, using a Free Disposal Hull methodology to estimate technological frontiers. We have a sample of cars available in the UK market in the period 2000–2007. Our results show that the rates of technological change (frontier movement) and diffusion (distance to frontier at the car brand level) differ substantially between segments of the car market. We conclude that successful policies should be aimed at the diffusion of best-practice technology, and take account of the different potential for further progress between different segments of the market (e.g. diesel vs. gasoline engines and small vs. large engines).

Keywords CO_2 emissions by cars · Technological change · Diffusion of innovations

JEL Q55 · O31 · O33

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1 Introduction

Technological change is seen as a key factor contributing to the reduction of emissions of greenhouse gases. Carbon dioxide (CO_2) is one of the most important of these gases, and emissions by cars contribute heavily to the amount of CO_2 in the atmosphere. Hence, it does not come as a surprise that the European Commission stimulates the development of cleaner automotive technologies. In 1995, for example, it set a target to reduce average emissions of CO_2 to 120 g/km driven by passenger cars in Europe. The population of passenger vehicles in Europe is heterogeneous, however, in terms of both size and the basic motor and fuel technologies used. From an engineering point of view, for example, diesel and gasoline engine technologies have different static and dynamic potentials for reducing CO_2 emissions.[1] Differences also exist with regard to other characteristics of cars, such as transmission systems and engine capacities. Moreover, some types of cars are natural candidates to apply radically new technologies, such as hybrid cars. Consequently, the 120 g/km target may be attained in various ways, for example, by switching between existing technologies or by exploiting technology-specific differences in development potential.

Our aim in this paper is first to provide descriptive and analytical evidence of the performance of the various technologies available in the market. It is currently believed that the actual pace of emission reductions towards the CO_2 target is too slow and that average emissions currently stand at about 160 g/km.[2] Therefore, the European Commission has announced a more stringent set of measures that should bring average emissions down to 130 g/km in 2012. We will draw conclusions regarding the most promising ways to achieve such further reduction in emissions. To this end, we ask what reductions in CO_2 emissions were actually realized in the recent past and to what extent these have differed between fuel types for various segments of the car market. Taking these results as a point of departure, we ask a second question: How important is the heterogeneity of the available technologies for achieving further progress in CO_2 emissions? Should we expect that this target will be met by a shift towards a single car type, e.g., hybrid cars? Or should we expect that technological change has been so fast and universal that the target will be attainable without losses in heterogeneity? Although we cannot provide exact numerical answers to these questions (due to the nature of our data), we can provide general insights on them.

We will use a database of all car models available in the United Kingdom over the period July 2000–May 2007. Although we have data at yearly

[1]See van den Bergh et al. (2006) for arguments in favor of environmental innovation policies focusing on maintaining or increasing diversity rather than on increasing economic efficiency. The arguments put forward are derived from insights in evolutionary economics.

[2]See, for example, Cousins et al. (2007).

intervals, we will focus here (for reasons of space and clarity), on the earliest and most recent observations. For 2000, the dataset consists of 1,738 car models, while data for 2,971 car models have been available for 2007. The data were collected by the Vehicle Certification Agency (VCA) in the UK, and are documented on its website.[3] The primary purpose of this website is to inform consumers who wish to buy a car, but it also represents the official information used for levying environmental taxes on the purchase of cars. The VCA does not carry out its own testing, but leaves this to either independent organizations or the car manufacturers and importers. The VCA does inspect the tests and the data in the database, etc. The figures on CO_2 emissions are based on a standard test-drive, which combines an urban and extra-urban stretch. Since the technical specifications of the cars do not differ from those in other European countries, the CO_2 emission levels can be considered as representative for Europe as a whole.

The main drawback of the database is that it does not include any data on car sales. Hence, we have no way of calculating average CO_2 emissions for a representative market.[4] Furthermore, we do not have much information on the actual performance characteristics of the cars (in terms of characteristics from which buyers derive utility, such as speed or comfort), which is something on which we will comment in more detail later. The database includes information on other environmental aspects of cars, such as emissions of particulates in the case of diesel cars, emission of NO_x, CO and hydrocarbons.[5] We only use the data on CO_2, however, since these are the main policy focus. Incompleteness of data concerning other pollutants is another reason not to consider other environmental aspects.

In the remainder of this paper, we first look, in Section 2, at some descriptive data on the various fuel technologies available in the market. In Section 3, we explain our methodology. The empirical results are presented in Sections 4 and 5. The first of these looks at technological change, and outlines how rates of technological change have differed between segments of the car market. The latter section focuses on technological diffusion, in particular at the brand level. Section 6 summarizes and draws conclusions.

[3] http://www.vcacarfueldata.org.uk.

[4] In fact, even information on sales of different models would not enable us to attribute changes in CO_2 emissions to effects due to technological change and effects due to a changing composition of the fleet of vehicles. As pointed out by Kwon (2005), among others, we should have data on actual distances driven by specific types of cars to arrive at such a quantification of contributions. See also Paravantis and Georgakellos (2007), who estimated models in which several economic and demographic indicators as well as variables related to alternative transport modalities are included to predict CO_2 emissions from car ownership.

[5] See Mazzi and Dowlatabadi (2007), who argue that the UK's decision to start taxing vehicles according to CO_2 emissions rates in 2001–2002 led to an increasing share of diesel cars in total sales. The increase of air pollution through particulates has been an important negative side-effect.

2 CO_2 emissions and fuel economy

Tight governmental regulations to reduce CO_2 emissions are not the only incentive for car manufacturers to produce cleaner cars. Consumer preference may also play a role: buyers might prefer to buy clean cars, especially as long as some other desirable performance criteria are met. From an economic point of view, the empirical fact that CO_2 emissions are strongly linked to fuel costs is very important. Even without environmental tax benefits, driving a cleaner car implies driving more cheaply. Hence, manufacturers have a natural tendency to increase the environmental friendliness of their cars as a consequence of their objective to increase their market shares.

CO_2 results from burning fuel in a car's engine, and hence the less fuel a car consumes (per kilometer), the less CO_2 will be emitted (see Oliver-Hoyo and Pinto 2008, for a brief explanation of the chemical principles). Figure 1 shows just how tightly fuel efficiency and CO_2 emissions are connected.

The observations include all car models included in the VCA database, for all years between 2000 and 2007. The relation between fuel consumed (in liters per 100 km) and CO_2 emissions (in grams per kilometer) is almost perfectly linear. The tight fit implies that no significant changes have occurred in the relationship between CO_2 emissions and fuel economy. We document these relationships for the various engine technologies available in our database, which distinguishes the cars by the fuels they use. These different engine technologies provide different potentials for reducing CO_2 emissions by reducing fuel use, as is shown by the fact that the technology-specific linear relations have different intercepts and slopes. Table 1 shows the estimated linear relationships and the R^2 values of the OLS regressions. Our regression results are similar to those in Oliver-Hoyo and Pinto (2008).

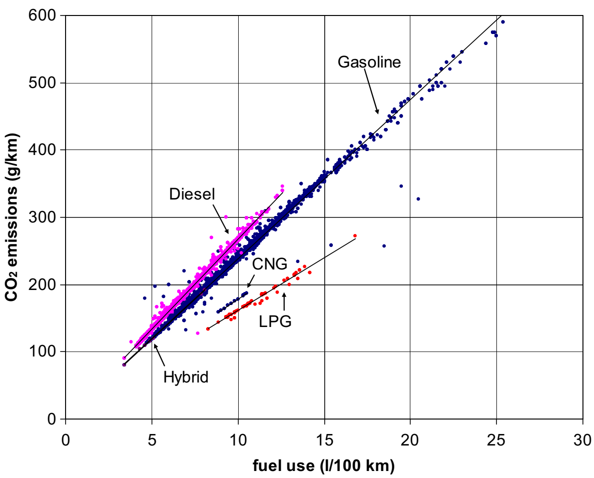

Fig. 1 Fit between CO_2 emissions and fuel use by fuel type (all observations, 2000–2007)

Table 1 Fuel-specific linear regressions between CO_2 emissions (dependent variable) and fuel consumption

	Intercept	Slope	R^2
Gasoline	2.99	23.6	0.99
Diesel	0.28	26.7	0.99
LPG	4.27	15.7	0.98
CNG	3.51	17.5	1.00
Hybrid	2.08	23.4	1.00

For a given level of fuel use, diesel engines generally emit most CO_2, while engines running on gas fuels (LPG and CNG)[6] emit the least amounts. However, there are also large differences with regard to the average fuel use of the various engine types. Cars running on gasoline exclusively account for the uneconomical half of the sample (i.e., engines using more than 15 L/100 km). Thus, because the average diesel car in the market uses less fuel per km than an average gasoline car, the average diesel car produces lower amounts of CO_2 emissions than the average gasoline car (see also Sullivan et al. 2004).

Interestingly, hybrid cars (i.e., those running on gasoline and an electric battery) do not, in Fig. 1, turn out to be significantly different from cars running on gasoline. This is explained by the fact that the CO_2 emissions from these cars are solely determined by their gasoline use. Thus, the relationship between gasoline use and CO_2 emissions is identical to that for gasoline cars, but hybrid cars use less gasoline per kilometer, and hence produce lower amounts of CO_2 emissions than the average gasoline car.

The fact that the 120 g/km (130 g/km) target is rather ambitious is illustrated by the fact that the large majority of car models in our sample emit much more than this amount of CO_2, although it should be kept in mind that we are not able to weight models by sales figures. Given the tight fit of the relationship in the figure, which holds over the complete period of 2000–2007, it is clear that there are two major ways of reducing CO_2 emissions of the average car in the market. The first is to increase mileage (decrease in liters per kilometer) for given engine types, i.e. movement along the curves towards the origin. Switching curves is the other way for consumers to reduce CO_2 emissions. In this respect, especially LPG and CNG technologies seem to have the potential for further reducing CO_2 emissions by cars. Diesel and hybrid engines provide opportunities for combining the two ways of lowering emissions by focusing on increased fuel economy.

The results in this section already show that heterogeneity (between fuel types) in the market provides different opportunities for reducing CO_2. We proceed to investigate this in more detail. In these investigations, we will pay specific attention to issues related to improvements in best-practice technologies and the diffusion of these technologies to other brands.

[6]These are in fact bi-fuel engines, which may use gasoline as a back-up fuel.

3 Localized technological change and the estimation of technological frontiers

Our aim of assessing whether emission reductions have been more or less uniform across cars with different characteristics leads us to adopt empirical techniques that are suitable to study so-called localized technological change. The notion of localized technological change was introduced into the literature on production functions by Atkinson and Stiglitz (1969). In their interpretation, localized technological change is the shift of one point on an isoquant, rather than the shift of the whole isoquant, as depicted in Fig. 2. The curves in Panel A are isoquants (K and L denote two production factors, Q is output), and the arrow indicates the localized technological progress. The dotted lines indicate fixed K/L ratios. In Panel B, the same localized technological progress is depicted using frontier analysis. The production function is now formulated in terms of a single input (K/L) and a single output (Q/L), and the curves indicate the frontiers describing maximum attainable output levels. The arrow indicates the same localized technological progress as in Panel A, and the dotted lines indicate the same K/L ratios.

The figures show that Atkinson and Stiglitz's notion of localized technological change corresponds to an uneven shift of the technological frontier in different ranges of the input. This will also be our prime notion of localized innovation in the analysis below. Not only shifts of the frontier may be localized, but shifts towards the frontier (technological diffusion through spillovers) may also be more prominent in some ranges of the product space than in others. Especially in ranges characterized by high degrees of innovation, follower firms might need more time to benefit from spillovers. This is an issue that we will also take up in our analysis below.

The product space we consider has some dimensions with a continuous nature, such as engine capacity. As will become clear below, localized innovation and diffusion in such a continuous dimension can be analyzed as in Fig. 2.

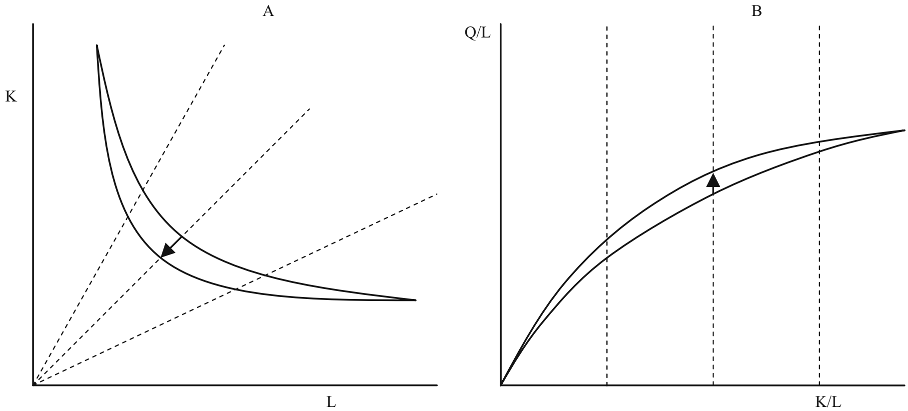

Fig. 2 Localized technological change in the setting of an isoquant (**a**) and frontier (**b**)

As was shown in Section 2 above, however, at least one of the inputs in the process of CO_2 reduction has a categorical nature: the engine type. As Table 1 and Fig. 1 show, the different engine types have different characteristics with regard to fuel use, and hence CO_2 emissions. Different engine types cannot be represented along a ratio scale type of axis, as in Fig. 2. Below, we will investigate whether there are differences in technological progress between the engine/fuel types. To the extent that we find such differences, we will also refer to them as localized technological change (localized to the engine/fuel type), although this is a process that is distinct from that depicted in Fig. 2.

In order to assess the extent to which technological progress has contributed to CO_2 reduction, we employ a series of methods aimed at estimating the type of technological frontier depicted in Panel B of Fig. 2. We will adopt the perspective that car performance is a constraint to emissions. Car manufacturers are assumed to try to minimize CO_2 emissions (and fuel use) at given levels of performance, which they would prefer to deliver in order to sell sufficient cars at a decent rate of profit. The frontiers that we estimate thus describe a technological trade-off: if a manufacturer wants to sell a high-performance car, it must accept high(er) CO_2 emissions. We thus consider CO_2 emissions as an "input" that should be minimized given an output level. Loosely speaking, a car type for which CO_2 emissions are smaller than for other types with a similar or better performance is considered to define the frontier. For several segments of performance, such best-practice types can be identified. We are interested in how the technological frontiers developed over time, how they differed between engine types, and how they differed between car manufacturers.

As a measure of performance, we use engine capacity (or "displacement"). This is an imperfect and indirect indicator, which we use instead of more direct measures of car performance, such as engine power, speed, pulling capacity, acceleration and comfort. Our dataset does not include any information on these characteristics. One advantage of using engine capacity as an approximation is that the estimation of our frontiers is greatly facilitated by the use of only a single "output". Nevertheless, we have to keep in mind that different car models in our sample may represent different trade-offs between the underlying characteristics, and, moreover, that different type of engines (such as diesel and gasoline engines) provide different trade-offs.

In the literature, three broad approaches to estimating frontiers can be identified. These are stochastic frontier analysis (SFA), data envelopment analysis (DEA) and free disposal hull (FDH) analysis.[7] SFA consists of a collection of econometric techniques, while DEA and FDH are methods based on mathematical programming. For our purposes, SFA is not a very attractive

[7] An accessible introduction to SFA and DEA is provided by Coelli et al. (2005). A more comprehensive overview is offered by Fried et al. (1993).

option, since we would have to specify a functional form for the frontier to be estimated. Although some specifications offer more flexibility than others, we feel that our focus on localized technological change (reductions of CO_2 emissions in specific ranges of engine capacity) would lose much of its appeal if we would adopt an SFA approach. The 'costs' we have to incur for choosing a mathematical programming approach are mainly related to the fact that these approaches cannot cope well with statistical noise, caused for example by measurement error. If measurement error of any kind leads to a very positive evaluation of the CO_2 emissions of a certain car type (given its engine capacity), this will immediately lead to a substantial change in the shape and location of the frontier.[8] In view of the highly standardized way in which the emissions evaluations were set up, we do not consider this a very important drawback.

Both DEA and FDH construct linear piecewise frontiers (see Lovell 1993, pp. 26–34, for detailed mathematical formulations), in contrast with Fig. 2 which depicts a smooth and continuous frontier. In our one-input, one-output context, an observation is located on the estimated frontier if there is no observation with a lower or equal value for the input (CO_2 emissions) that produced an equal or higher output value (engine capacity). This interpretation stresses the so-called output-orientation. The alternative 'input-orientation' could read as: an observation is located on the frontier if there is no observation with an equal or higher output level (engine capacity) that used an equal or smaller amount of inputs (CO_2 emissions). Irrespective of the orientation chosen, exactly the same observations determine the frontier. This result does not carry over to 'efficiency' scores, which give an indication of the distance between the frontier and dominated observations. If this distance is measured vertically, we consider the extra engine capacity that would have been possible if the car type considered would have had the best-practice technology for the corresponding CO_2 level. This distance is generally different from the horizontal distance, which is associated with the input-orientation: it represents the reduction in CO_2 emissions that would have been possible if the car (given its engine capacity) would have been designed according to best practice. In view of the political pressure on car manufacturers to meet stricter emission standards, we adopt the input-orientation perspective. This choice does not only play a role when considering distances between observations and frontiers, but also when we analyze differences in locations of frontiers between two periods: we define

[8]Very recently, bootstrapping methods have been introduced into DEA and FDH studies to alleviate the problems related to the presence of statistical noise (see, e.g. Cazals et al. 2002, and Daraio and Simar 2005). For our purposes, these techniques are not appropriate, since many observations cannot be seen as statistically independent from each other (several versions of one car type are present in our database). The assumption of identically and independently distributed observations is crucial for the use of bootstrapping techniques.

technological progress as the proportional reduction of CO_2 emission levels for a given engine capacity.[9]

Finally, our decision to prefer FDH over DEA should be discussed. The two approaches differ in one important respect: the supposed shape of the frontier between two best-practice observations. This issue can best be explained by means of an example. Let us assume that we have two frontier points, (200, 2,000) and (250, 3,000). The first coordinate represents the input level, the second the output level. If inputs and outputs would relate to the performance of machines that ran for an hour, it could safely be assumed that an input level of 225 units would suffice to produce 2,500 units by having both machines running for half an hour. DEA (pioneered by Farrell 1957, and Charnes et al. 1978) follows this reasoning in assuming that linear combinations of frontier points are feasible. In our setting, however, it does not make much sense to assume that a car with an engine capacity of 2,500 cc can be "assembled" by putting together half a car with a small best-practice engine and half a car with a big best-practice engine. FDH (see Deprins et al. 1984) incorporates this idea that linear combinations of frontier points are not necessarily feasible. It estimates a more conservative frontier, assuming that it is impossible to produce any car with a capacity of more than 2,000 cc with less than 250 g of CO_2 emissions. This leads to stepwise frontiers.

4 Patterns of localized innovation

Figure 3 provides the most basic result of our frontier estimation, the frontiers at the beginning of our period (July 2000) and the end of the period (May 2007). Tables 2, 3 and 4 give details about the car models found on the various frontiers. As expected, the 2007 frontier lies further to the left than the 2000 frontier, which reflects a general tendency towards cleaner cars for given performance levels. Two points do not obey this rule. One of these is the second point (from the left) on the year 2000 frontier, the Seat Arosa SDI with 1.7 L diesel engine, which produced 119 g CO_2/km. This car was no longer on the market in 2007, and none of the comparable cars in the market (either Seat or other brands) performed better in terms of CO_2 emissions.

The other point at which the year 2000 frontier is further out than the 2007 frontier, is the leftmost point. In both years, this leftmost point on the frontier is a hybrid car. In 2000, it is the Honda Insight, which produced only 80 g CO_2/km. This car was taken off the market in 2006, and its position on the

[9]The frontiers for 2007 will be estimated using observations relating to car models available in 2007 only. Alternatively, we could have opted for a 'sequential' approach (see Los and Timmer 2005), in which data on car models on offer in 2000 would also be included in the analysis for 2007. The idea behind this alternative is that it is hard to believe in 'technological forgetting' over a short span of time. In the present case, we are more interested in the actual choices made by manufacturers to bring specific CO_2-technologies embodied in cars to the market, and the resulting choices that are open to consumers (abstracting from the secondhand market).

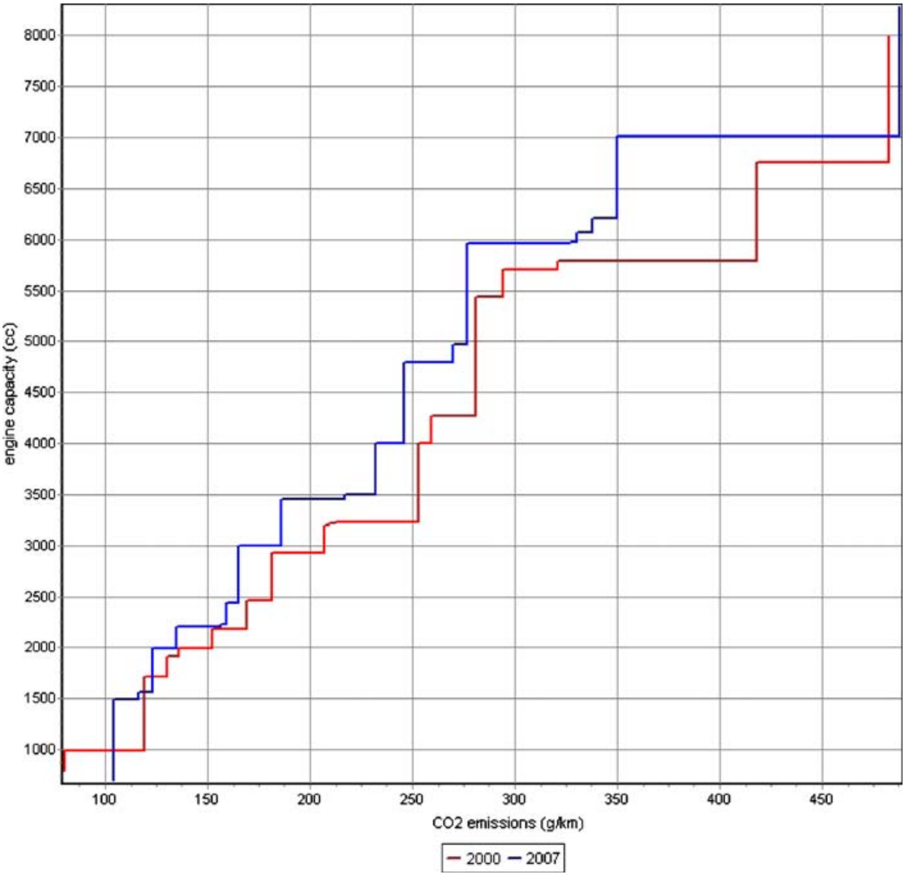

Fig. 3 Global CO_2 frontiers in 2000 and 2007

frontier was taken by the hybrid Toyota Prius, which produces 104 g CO_2/km, although with a larger engine capacity (1.5 L).

While these two hybrid cars dominate the absolute left of the frontier, diesel cars make up the subsequent part of the frontier in both years. In 2000, we already saw the Seat Arosa, which is the second point on the frontier, but in fact points 2–11 on the year 2000 frontier are diesel cars. The last one of these is a Mercedes S-class with a 4-L diesel engine. In 2007, the diesel dominance of the left half of the frontier is weaker, although still existent. Now, points 2–5 and point 7 are diesel cars. The intermediate point 6 is an interesting case: it is a Volvo S60 running on CNG.

The rightmost parts of the frontiers are dominated by gasoline engines. In the year 2000, gasoline engines become more CO_2 efficient than diesel engines at 4.3 L (this is a Mercedes E-class emitting 259 g CO_2/km). In 2007, the shift-over point between diesel and gasoline is located at 3 L (a BMW 5 series emitting 176 g CO_2/km). The 2007 frontier also has an interesting case in the

Table 2 Frontier car models, 2000 and 2007, gasoline frontier

		CO_2	Cc
2000			
MCC	Smart Cabrio	115	599
Daihatsu	Cuore	127	989
Suzuki	Swift	130	993
Toyota	Yaris	134	999
Fiat	Punto	136	1,242
Suzuki	Swift	139	1,298
Toyota	Yaris	144	1,299
Volkswagen	Lupo	151	1,390
Nissan	Almera	158	1,498
Renault	Mégane	162	1,598
Mitsubishi	Carisma	164	1,834
Renault	Mégane	181	1,998
Mitsubishi	Galant	196	2,351
Volvo	V70	205	2,435
Mitsubishi	Galant	214	2,498
BMW	3 Series	216	2,793
BMW	3 Series	218	2,979
Mercedes-Benz	CLK-Class	242	3,199
Mercedes-Benz	E-Class	259	4,266
Mercedes-Benz	CLK-Class	281	5,439
Chevrolet	Camaro	294	5,700
Mercedes-Benz	S-Class	321	5,786
Rolls-Royce & Bentley	Bentley	418	6,761
Chrysler Jeep	Viper	483	7,990
2007			
Citroen	C1	109	998
Kia	Picanto	123	999
Kia	Picanto	124	1,086
Fiat	Panda	127	1,242
Honda	Jazz	129	1,246
Citroen	C2	133	1,360
Fiat	Grande Punto	134	1,368
Mini	R56	138	1,397
Mini	R56	139	1,598
BMW	1 Series	140	1,995
Ford	New Focus	169	1,999
Mercedes-Benz	A-Class	172	2,035
BMW	5 Series	174	2,497
BMW	5 Series	176	2,996
Mercedes-Benz	CLS-Class	217	3,498
BMW	5 Series	232	4,000
BMW	5 Series	246	4,799
Mercedes-Benz	E-Class	258	4,966
Corvette	C6	277	5,967
BMW	7 Series	327	5,972
Chrysler Jeep	300C	330	6,063
Mercedes-Benz	CLK Coupé	338	6,208
Corvette	C6	350	7,011
Dodge	SRT10	488	8,285

form of the Lexus GS450h, which is a hybrid car, but with a much larger (3.5 L) gasoline engine than the Toyota Prius, and emits 186 g CO_2/km. This car is positioned at the immediate left part of the gasoline part of the 2007 frontier, right behind the BMW 5 series car that was mentioned earlier.

Table 3 Frontier car models, 2000 and 2007, diesel frontier

		CO_2	cc
2000			
MCC	Smart City	90	799
Seat	Arosa SDI	119	1,716
Fiat	Punto	130	1,910
Peugeot	206	136	1,997
Mazda	323	149	1,998
Nissan	Almera	152	2,184
Volvo	S80	169	2,461
BMW	3 Series	181	2,926
Mercedes-Benz	E-Class	207	3,199
Mercedes-Benz	E-Class	209	3,222
Mercedes-Benz	S-Class	212	3,226
Mercedes-Benz	S-Class	253	3,996
Toyota	Landcruiser	292	4,164
2007			
Citroen	C1	109	1,398
Renault	Clio	115	1,461
Ford	Fiesta	116	1,560
BMW	1 Series	123	1,995
Honda	Civic 06	135	2,204
Toyota	Avensis	156	2,231
BMW	5 Series	165	2,993
Mitsubishi	Shogun	244	3,200
Audi	A8	249	4,134
Toyota	Land Cruiser	282	4,164
Volkswagen	Touareg	346	4,921

Comparing the two frontiers, we immediately observe that progress is uneven for ranges of values along the vertical axis. Figure 4 reveals this in a more direct way. Here, we calculated the rate of technical progress (which we define, in line with the input approach to interpreting the frontiers, as the proportional reduction between 2000 and 2007 of CO_2 emissions at a given engine capacity) at various parts of the frontier. We evaluated this at all engine capacities for which we have a defining point on either the 2000 or 2007 frontier. The figure also gives proportional reductions of CO_2 emissions at fuel-specific frontiers, i.e., diesel and gasoline (hybrids and LPG/CNG have too few points to make the calculations meaningful). As the discussion above has shown, the global frontier can be seen as a piecewise combination of these fuel-specific frontiers. The lines in the figure are estimated polynomial trends for the individual series.

We observe a number of interesting features. First, there are clear differences between the two fuel types. Diesel engines are available in a more limited range of engine capacities, and within this range, CO_2-reducing innovation for gasoline-driven cars has generally been more prominent than for diesel-fueled cars. In other words, the gasoline frontier shifted much more rapidly to the left than the one for diesel. The leftward shift of the diesel frontier almost nowhere exceeded 10%, while in the “diesel range” of approximately 1,300–4,000 cc, the corresponding shift of the gasoline frontier has usually been in the double digits.

Table 4 Frontier car models, 2000 and 2007, global frontier

		Fuel	CO_2	cc
2000				
Honda	Insight	Hybrid	80	995
Seat	Arosa	Diesel	119	1,716
Fiat	Punto	Diesel	130	1,910
Peugeot	206	Diesel	136	1,997
Mazda	323	Diesel	149	1,998
Nissan	Almera	Diesel	152	2,184
Volvo	S80	Diesel	169	2,461
BMW	3 Series	Diesel	181	2,926
Mercedes-Benz	E-Class	Diesel	207	3,199
Mercedes-Benz	E-Class	Diesel	209	3,222
Mercedes-Benz	S-Class	Diesel	212	3,226
Mercedes-Benz	S-Class	Diesel	253	3,996
Mercedes-Benz	E-Class	Gasoline	259	4,266
Mercedes-Benz	CLK-Class	Gasoline	281	5,439
Chevrolet	Camaro	Gasoline	294	5,700
Mercedes-Benz	S-Class	Gasoline	321	5,786
Rolls-Royce & Bentley	Bentley	Gasoline	418	6,761
Chrysler Jeep	Viper	Gasoline	483	7,990
2007				
Toyota	Prius	Hybrid	104	1,497
Ford	Fiesta	Diesel	116	1,560
BMW	1 Series	Diesel	123	1,995
Honda	Civic	Diesel	135	2,204
Toyota	Avensis	Diesel	156	2,231
Volvo	S60	CNG	159	2,435
BMW	5 Series	Diesel	165	2,993
BMW	5 Series	Gasoline	176	2,996
Lexus	GS	Hybrid	186	3,456
Mercedes-Benz	CLS-Class	Gasoline	217	3,498
BMW	5 Series	Gasoline	232	4,000
BMW	5 Series	Gasoline	246	4,799
Mercedes-Benz	E-Class	Gasoline	258	4,966
Corvette	C6	Gasoline	277	5,967
BMW	7 Series	Gasoline	327	5,972
Chrysler Jeep	300C	Gasoline	330	6,063
Mercedes-Benz	CLK Coupé	Gasoline	338	6,208
Corvette	C6	Gasoline	350	7,011
Dodge	SRT10	Gasoline	488	8,285

Second, the degree to which the frontier shifted varies substantially between different ranges of engine capacity. This holds both for individual fuel types, and for the combined global frontier. This feature is clearly shown by the fact that the estimated trend functions clearly have local maxima. Diesel engines show low rates of CO_2-reducing innovation in the range just to the right of the 3 L point. At this point of the frontier, the cleanest diesel-driven cars in 2007 emitted more CO_2 than the ones in 2000. This negative performance is mostly related to the fact that Mercedes, which was the leading manufacturer in this segment of the diesel range in 2000, has moved to smaller diesel engines in 2007. In this way, Mercedes has vanished from the diesel frontier completely in 2007, while the model that took over in this range (the Mitsubishi Shogun)

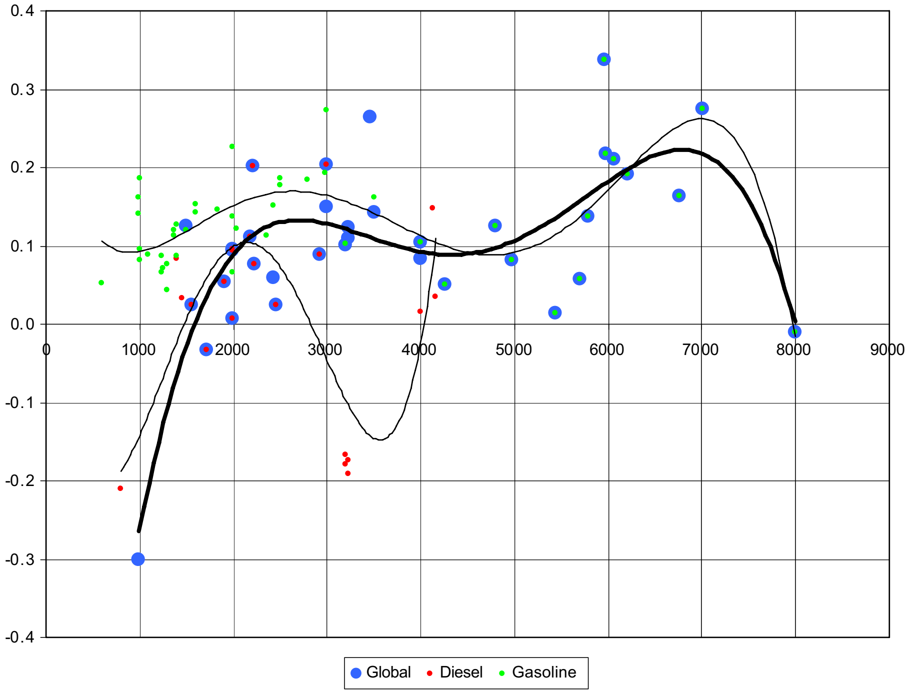

Fig. 4 Proportional reductions in CO_2 emissions on the frontier, between 2000 and 2007

still emits 15–30% more CO_2 than the Mercedes models in 2000. At the left of the diesel range, we saw an MCC Smart with 799 cc engine in 2000, which vanished from the market in 2008. Its role on the frontier in 2007 was taken over by a Citroen C1 with a much larger engine that emitted more CO_2. This led to a rightward shift of the frontier in this range of engine capacities.

For gasoline engines, we observe that progress peaked in a broad range between 2,000 and 3,000 cc, as well as in the range of large, >6 L engine cars. We also see three points just below 1,000 cc that are somewhat of an outlier.

Combining these insights in the development of the fuel type-specific frontiers, we arrive at some interesting insights about the shifts of the global frontier. We had already noticed that technological progress at the absolute left side (engines of 1,000 cc or less) is negative due to the peculiarity that only very few hybrid cars are available. Once competitors for the Toyota Prius (especially smaller cars) enter the market, we may expect that we will once again observe leftward shifts of the frontier in this segment of the market.

Beyond the low, hybrid-dominated range, diesel engines rule, and since progress of diesel technologies in terms of CO_2 reduction has generally been slower than in gasoline engines (with identical displacement), growth of the global frontier is held back by the diesel dominance. In other words, in this segment, gasoline engines have largely caught up with diesel engines in terms of CO_2 performance, although the global frontier is still defined by diesel-driven cars. The range of 3,000–4,000 cc is an illustration of what could happen in the future in the sub-3,000 cc range. Here, we have witnessed leapfrogging by gasoline-fueled cars, replacing diesel engine cars that previously dominated the frontier for this segment. Although the pace of CO_2-reducing technological progress as indicated by the gasoline frontier has been falling with engine capacity in this segment, gasoline performance shifts are still quite high, in the range just beyond 3,000 cc. However, because even the cleanest gasoline car types emitted much more CO_2 than diesel cars in 2000, the 'takeover' implied a slow growth of the global frontier. If the takeover point would shift even further to the left in the future,[10] this would imply a slowdown of reductions in CO_2 reductions in the sub-3,000 cc range, at least for the immediate future.

The range beyond 6,000 cc engines is characterized by complete dominance of gasoline, and here performance grows at a high rate. But CO_2 emission reductions in this segment will not lead to huge contributions to industry-wide reductions, due to its relatively low share of the total car market.

In general, these results underline the importance of localized innovation. The reductions in terms of CO_2 emissions that were realized over the period 2000–20007 differ substantially between fuel types, and between ranges of engine capacities. We cannot think of the global technological frontier in environment-friendly cars as something that shifts out evenly over time. Among other things, this means that in terms of pure technological change, we need to look at the composition of the market for cars as an important variable in terms of reaching an average target of CO_2 reductions.[11]

5 Patterns of technology diffusion

So far we have not looked much at what happens behind the technological frontier, except for the differences between the fuel types. However, since the majority of cars in the market are not on the actual frontier, developments behind the frontiers should not be ignored. One feature of the data makes this part of the analysis a bit difficult. Many of the car models in the database differ only in aspects that are unrelated to the main variables in our analysis (CO_2 emissions and engine capacity). For example, the May 2007 sample of the dataset has 12 Mitsubishi Shogun models. All of these are diesel cars with a 3.2-L engine, but they have only four distinct CO_2 emission levels (the other differences are either undocumented in the database, or related to the transmission system used).

[10] We have no particular reason to expect this, but it is an analytically attractive hypothesis.

[11] Fontaras and Samaras (2007) express concerns that the observed reduction in CO_2 emissions by cars is mainly due to a shift in sales towards diesel-driven cars. They feel that the market for diesel engine cars is reaching its saturation level, as a consequence of which further reductions for the industry as a whole might come to a halt.

In order to filter out the model differences that are not related to CO_2 emissions (i.e., to "reduce" the 12 Shoguns to 4), we start by estimating one frontier for every brand in the database. This frontier combines cars of all fuel types, and covers the complete range of engine capacities that the particular brand puts on the market. We use brand names and do not consider ownership of the brands (e.g., although Citroen is owned by Peugeot, we considered them as separate brands). We construct the brand-specific frontiers for 2000 and 2007, and consider them as the state-of-the-art technology of the particular brand. We are then interested in the position of the brand's state-of-the-art relative to the global frontier.

Since any point below a brand-specific frontier cannot lie on the global frontier by construction, the latter can be found by considering all points on the brand-specific frontiers. For a given point in time, the collection of brand-specific frontiers could then consist of two types of points: those on the global frontier, and those below it. Those lying on the frontier were already discussed in the previous section. The points that lie below the frontier are inefficient (i.e., for a given engine capacity, lower CO_2 levels are achieved by other manufacturers). The inefficiency for each point on a brand-specific frontier can be expressed as CO_2 emissions at the global frontier divided by model emissions, evaluated at the same engine capacity level. Thus, maximum efficiency (a point on the global frontier) corresponds to a value of 1.

At first instance, we look at a summary measure for how far the brand-specific frontiers are behind the global frontier. This is depicted in Fig. 5, for each of the 2 years we considered before.[12] The leftmost (rightmost) point consists of the smallest (largest) engine in the dataset, and this is always a unique model. However, for parts of the cc-range that are just beyond (before) the minimum (maximum), we see the number of car models rising quickly, and the points in Fig. 4 generally represent six to 30 models.[13]

Starting with the year 2000, we see that average inefficiency is rather large on the immediate left, i.e., in the sub-1,000 cc range. This is due to the low-emission performance of the hybrid Honda Insight. In the 1,000–3,000 cc, average efficiency is fluctuating along a roughly constant level of approximately 70–75%. The next segment, from 3,000 cc onwards, shows higher average efficiency, 75–80%.

The existence of these significant deviations from frontier CO_2 emission levels indicates that there is a substantial potential for technological diffusion.

[12]The points on the horizontal axis of this figure constitute the set of all observed engine capacities on brand-specific frontiers in the particular year. Obviously, not all brands have a model for every point in this set. Consistent with the FDH approach, we use, for all brands in the dataset, the smallest engine capacity that is larger than the point we are evaluating. We do not use a brand if the engine capacity we are evaluating is outside the range of the smallest and largest engine capacity of that particular brand. For example, if Volvo produces cars in the 1,560–4,414 cc range, we do not use Volvo in the calculation of average efficiency at 1,300 or 5,000 cc.

[13]Since the car with the largest engine capacity will always be located on the frontier, no value should be attached to the average efficiency of 1 for the rightmost points in Fig. 4. For both years in our sample, the engine with the largest capacity was only present in one car type.

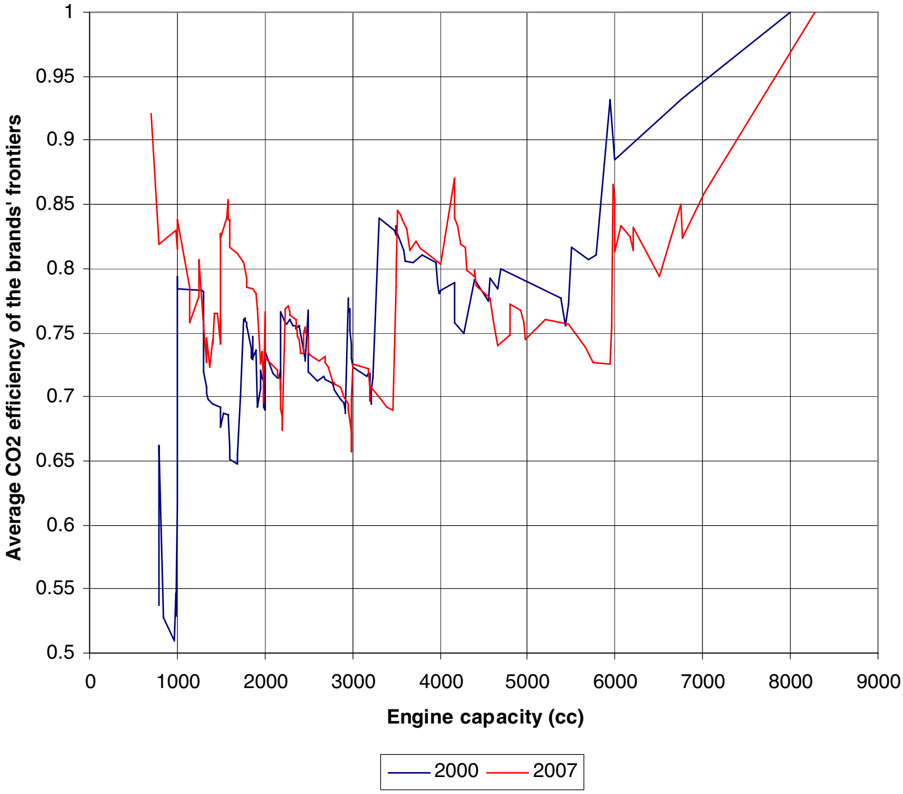

Fig. 5 Average efficiencies of brands, at various points of the global frontier

Judging from the year 2000 data, if all new cars on the market would have CO_2 emissions equal to the frontier, average emissions would be cut by some 20–30% on average. We may note that this is a conservative estimate, since we did not look at cars that were not on a brand's frontier.

To what extent has this potential for technological diffusion been realized? And which brands were particularly good in realizing it? The 2007 curve in Fig. 5 shows that there are two ranges in which diffusion has been strong. This is the sub-1,000 cc range, and the 1,300–2,000 cc range. Average efficiency levels have increased considerably in these ranges. In other ranges, they have remained constant or even decreased somewhat (the latter is the case in the >5,000 cc range). We may thus conclude that, especially in the smaller engine capacity range, which is already the one that has lowest CO_2 emission levels, technological diffusion has been strong. It is interesting to note that these ranges have been characterized by relatively slow rates of CO_2-reducing innovation, according to Fig. 4. In segments featuring a high rates of localized technological progress (such as the 2,000–3,000 cc range), diffusion seems to have been much less prominent. Apparently, not only innovation has been localized in specific engine capacity ranges, but technology diffusion as well has been localized in nature.

The data at brand level, which we do not document explicitly for reasons of space, can provide us with some hints on the mechanisms underlying the dynamics of technological change and diffusion in the various segments. One thing we notice is that the range of sub-1,300 cc engine capacity is rather different from the other ranges. All six brands that are present in this segment in both 2000 and 2007 increased their efficiency levels over the period. As noticed already, hybrid cars are a dominant force in this segment. Another notable feature is that in this segment, we find many manufacturers that do not belong to the group of traditional brands. For example, we find the MCC Smart as a trend-setting gasoline car in this segment, as are the Malaysian brands Perodua and Proton. The latter two brands are specific to the UK, and are not sold in other parts of the EU. In general, the traditional brands, such as VW, Ford, or Toyota are not found in this segment.[14] Thus, we conclude that the sub-1,300 cc range is one in which radical technological change plays a large role, and outsider firms have a relatively large impact on aggregate dynamics.

In the 1,300–2,000 cc range, as in all larger ranges, we find a strong dominance of the more traditional European brands, with some catching-up of non-European brands in 2007. Looking at the list of 24 brands that were present in this range in the period 2000–2007, the 12 most efficient brands were European (Mercedes, Peugeot and VW were leading). In 2000, the first non-European brand, Ford, ranked 13th in terms of average efficiency. In 2007, we find Toyota second (mostly due to the Prius), Honda fifth and Ford seventh. The strong European performance supports the hypothesis that the relatively strict EU policies are indeed a stimulus for European car manufacturers to produce cleaner cars.

6 Conclusions and discussion

Our analysis shows that CO_2 emissions in cars sold in Europe have indeed been reduced over the period 2000–2007. European car manufacturers appear relatively efficient in minimizing CO_2 emissions, as compared to manufacturers from Asia or North America. But as is well known, average emissions are far from the 120 g/km target set by the EU. Judging by the rates of technological progress that we observe for various segments of the car market during 2000–2007, it is highly unlikely that the next 4–5 years will bring a reduction to an average level of 130 g/km. With an average reduction of 15% over the past 8 years, we expect that a 10% reduction until 2012 is already much to expect.

[14]Note that this does not necessarily mean these that brands do not sell any cars with engine capacity <1,300 cc. We just do not find any cars <1,300 cc on the frontiers of these brands, which means they have cars with larger engines that have better or equal CO_2 performance. The Toyota Prius is a prime example of this: it sets the standard in the sub 1,300 cc range, but it has >1,300 cc capacity itself.

This would imply that not even in the market segment of cars with <2,000 cc engines would we observe a complete convergence to 130 g/km.

But such a view, which is essentially based on extrapolation of existing trends, may be too pessimistic on several accounts. First, one may object that car manufacturers may step up their efforts in response to stronger policy incentives, and hence that the rates of technological progress over the coming years would be higher than those seen in the past. Given that there may be decreasing marginal returns to R&D efforts, e.g. because the easiest technological opportunities are applied first, this seems unlikely to us.

Second, we must note that the rates of technological progress that we estimated for the 2000–2007 period underestimate the potential for progress in the wider market, because many brands sold in the market lag behind the technological frontier. A policy aimed at diffusion of best-practice technology seems to hold much (more) potential for reducing CO_2 levels significantly. This is obviously controversial, since what we are saying is that technologies that are proprietary to a specific manufacturer should, from the point of view of an efficient CO_2 technology in the market as a whole, be diffused to a larger group of manufacturers. This is a complex policy issue that may require original and radical thinking, and is connected to a range of legal issues, such as intellectual property law (patents) and competition law.

Third, we find that switching between fuel types may provide important benefits in terms of CO_2 emissions. In other words, the heterogeneity in terms of fuel type engines that we find in the market may still be better used in terms of reducing CO_2 emissions by cars. With new diesel engines now equipped with particulate filters, many of the traditional drawbacks of diesel engines as compared to gasoline engines are no longer as relevant as they used to be. This creates a large potential for "dieselization" of the car park with engines <3,000 cc. We must note, however, that although this is expected to yield short-run benefits (diesel engines that are now on the market emit less CO_2 than comparable gasoline engines), there seems to be a counteracting long-run tendency. Over the 2000–2007 period, gasoline engines have shown a more rapid increase of technological change related to CO_2 emissions than diesel engines. Whether this will continue into the future is hard to judge.

References

Atkinson AB, Stiglitz JE (1969) A new view of technological change. Econ J 30:573–578

Cazals C, Florens P, Simar L (2002) Nonparametric frontier estimation: a robust approach. J Econom 106:1–25

Charnes A, Cooper WW, Rhodes E (1978) Measuring the efficiency of decision-making units. Eur J Oper Res 2:429–444

Coelli TJ, Prasada Rao DS, O'Donnell CJ, Battese GE (2005) An introduction to efficiency and productivity analysis. Springer, New York

Cousins SH, Garcia Bueno J, Palomares Coronado O (2007) Powering or de-powering future vehicles to reach low carbon outcomes: the long term view 1930–2020. J Clean Prod 15:1022–1031

Daraio C, Simar L (2005) Introducing environmental variables in nonparametric frontier models: a probabilistic approach. J Prod Anal 24:93–121

Deprins D, Simar L, Tulkens H (1984) Measuring labor-efficiency in post offices. In: Marchand M, Pestieau P, Tulkens H (eds) The performance of public enterprises: concepts and measurement. North-Holland, Amsterdam

Farrell MJ (1957) The measurement of productive efficiency. J R Stat Soc Ser A 120:253–281

Fontaras G, Samaras Z (2007) A quantitative analysis of the European automakers' voluntary commitment to reduce CO_2 emissions from new passenger cars based on independent experimental data. Energ Pol 35:2239–2248

Fried HO, Lovell CAK, Schmidt SS (eds) (1993) The measurement of productive efficiency; techniques and applications. Oxford University Press, New York

Kwon T-H (2005) Decomposition of factors determining the trend of CO_2 emissions from car travel in Great Britain (1970–2000). Ecol Econ 53:261–275

Los B, Timmer MP (2005) The 'appropriate technology' explanation of productivity growth differentials: an empirical approach. J Dev Econ 77:517–531

Lovell CAK (1993) Production frontiers and productive efficiency. In: Fried HO, Lovell CAK, Schmidt SS (eds) The measurement of productive efficiency; techniques and applications. Oxford University Press, New York, pp 3–67

Mazzi E, Dowlatabadi H (2007) Air quality impacts of climate mitigation: UK policy and passenger vehicle choice. Environ Sci Technol 41:387–392

Oliver-Hoyo MT, Pinto G (2008) Using the relationship between vehicle fuel consumption and CO_2 emissions to illustrate chemical principles. Chemistry for Everyone 81:218–220

Paravantis JA, Georgakellos DA (2007) Trends in energy consumption and carbon dioxide emissions of passenger cars and buses. Technol Forecast Soc Change 74:682–707

Sullivan JL, Baker RE, Boyer BA, Hammerle RH, Kenney TE, Muniz L, Wallington TJ (2004) CO_2 emission benefit of diesel (versus gasoline) powered vehicles. Environ Sci Technol 38:3217–3223

van den Bergh JCJM, Faber A, Idenburg AM, Oosterhuis FH (2006) Survival of the greenest: evolutionary economics and policies for energy innovation. Environ Sci 3:57–71