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Dazzled by diesel? The impact on carbon dioxide emissions of the shift to diesels in Europe through 2009

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HIGHLIGHTS

- ► By 2009 diesels had captured over 55% of the new car market in the EU.
- ► New diesels in 2009 emitted only 2% lower average CO_2 than new gasoline cars.
- ► Diesel cars continue to be driven farther than gasoline cars.
- ► Overall there has been little net CO_2 reduction from the switch to diesels in Europe.

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ABSTRACT

This paper identifies trends in new gasoline and diesel passenger car characteristics in the European Union between 1995 and 2009. By 2009 diesels had captured over 55% of the new vehicle market. While the diesel version of a given car model may have as much as 35% lower fuel use/km and 25% lower CO_2 emissions than its gasoline equivalent, diesel buyers have chosen increasingly large and more powerful cars than the gasoline market. As a result, new diesels bought in 2009 had only 2% lower average CO_2 emissions than new gasoline cars, a smaller advantage than in 1995. A Laspeyres decomposition investigates which factors were important contributors to the observed emission reductions and which factors offset savings in other areas. More than 95% of the reduction in CO_2 emissions per km from new vehicles arose because both diesel and gasoline new vehicle emissions/km fell, and only 5% arose because of the shift from gasoline to diesel technology. Increases in vehicle mass and power for both gasoline and diesel absorbed much of the technological efficiency improvements offered by both technologies. We also observe changes in the gasoline and diesel fleets in eight EU countries and find changes in fuel and emissions intensities consistent with the changes in new vehicles reported. While diesel cars continue to be driven far farther than gasoline cars, we attribute only some of this difference to a "rebound effect". We conclude that while diesel technology has permitted significant fuel savings, the switch from gasoline to diesel in the new vehicle market contributed little itself to the observed reductions in CO_2 emissions from new vehicles.

1. Introduction

Transportation contributes a rising share to greenhouse gas emissions from fossil fuel consumption, particularly automobiles (IEA, 2009). In Europe, the main new effort to curb rising emissions from automobiles has been through a voluntary agreement (VA) between the European Commission (EC) and the automobile industry that unifies fuel economy objectives of all member states (European Commission. (EC), 2000; Ryan et al., 2009). The goal of the VA was to reduce the carbon dioxide emissions intensity (g CO_2/km) of new passenger vehicles to 25% below 1995 levels by 2008 to 140 g CO_2/km. The EC reports that the manufacturers missed this target, achieving only 145.6 g CO_2/km by 2009 (European Commission (EC), 2010). The target was then strengthened to a goal of 120 g CO_2/km by 2015 and made mandatory, with 10 g CO_2/km that could be achieved by means other than direct improvements to fuel economy (EC 2010).

As part of a de-facto mitigation strategy, European governments have successfully encouraged a massive shift to diesel automobiles (or "cars", including SUV) since the 1990s, for example via differential fuel taxation (Schipper et al., 2002). Fontaras and Samaras (2007) attribute most of the reduction in passenger automobile fuel consumption through 2003 to this

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dieselization of the automobile market. Sullivan et al. noted the advantage of diesel technology in saving fuel in comparison with gasoline cars, especially on a 'matched pair' (closest match between a gasoline and diesel version of the same model), confirmed by Schipper et al. (2002). But diesel vehicles are rarely purchased on a matched pair basis, i.e., the consumer often appears not to buy the identical vehicle they would have purchased if buying a gasoline car. Diesel vehicles are on average slightly heavier and more powerful when comparing matched pairs, but are much more so in most countries and the EU aggregate level when sales weighted averages are compared (Schipper et al., 2002; Schipper and Fulton, 2009).

Part of the reason the diesel — gasoline CO_2 emission difference is small is the greater carbon intensity of diesel fuel (12.1% more emissions per liter according to the IEA, 15% more tailpipe emissions per liter according to the US EPA at http://www.epa.gov/oms/climate/420f05001.htm#1). This is often forgotten when volumetric fuel economy is compared.

Finally, emissions and fuel saving depends on how cars are used, not simply their tested scores. Understanding the real evolution of new vehicle markets (and at least a cursory examination of on-road performance) is necessary to understand how much shifting to diesel per se has contributed to fuel saving and emission reduction. Average driving per vehicle must also be considered in comparing total fuel use and emissions per vehicle per year.

To explore these issues, we analyzed national data for on-road emissions per kilometer and vehicle use of the diesel and gasoline fleets of 8 countries, which represent more than 80% of the light duty vehicles in EU. This study furthers previous work by incorporating new vehicle data through 2009 (European Commission (EC), 2010) and on road data through 2008 (Schipper, 2010; Millard-Ball and Schipper, 2010). It does not conduct a matched pair analysis comparing the properties of the gasoline and diesel versions of the same car model instead, it focuses on the aggregate characteristics of what vehicles were bought in EU markets in order to further investigate the hypotheses set forth by Schipper et al. (2002) and Schipper and Fulton, 2009].

2. Methods

2.1. Major trends

Data were collected for key diesel and gasoline vehicle parameters from the EC's annexes for 2000–2009 and the EC's annual monitoring reports for 1995–2000, as reported by the major car manufacturer associations. Data for the entire EU were only available from 1995 onwards, corresponding to the reference year for the EU voluntary agreement, but Schipper et al. (2002) found that from 1980 to 1995 intensity of both diesel and gasoline new vehicles in five countries (France, Germany, Italy, Netherlands and the U.K., together about 65% of the new vehicle market) fell as did intensities of vehicles on the road. The evolution of emissions in those countries after 1995 follows closely those for the entire EU sample, hence we may infer that they give a reasonable representation of what happened before 1995.

The parameters available in the latest EU sample included new vehicle sales (S in number of vehicles), power (P in kW), engine capacity, displacement or volume (C in cubic centimeters), vehicle mass (M in kg), and CO_2 emissions intensity (E in g CO_2/km). Emissions of carbon dioxide per kilometer are related to the fuel intensity of passenger vehicles by multiplying fuel/km times the carbon content of the fuel (assuming full combustion) as noted above. This emissions intensity is the measurement tool used by EC and reported by car manufacturers in accordance with the agreement, and it allows for normalized comparison of diesel and gasoline vehicles and the aggregate emissions intensity, taking into account the difference in carbon intensity of these two fuels. From these values, efficiencies for each fuel technology were calculated with respect to power (E_P in g CO_2/km kW), with respect to capacity (E_C in g CO_2/km cm^3), and with respect to mass (E_M in g CO_2/km kg) by dividing E by the corresponding parameter. We call these power, capacity and mass-specific intensities below and focus this study on the first and third. Note that the ratio of engine power to vehicle mass closely correlates with acceleration capability, a characteristic important to many drivers.

In this paper, only the EU12 (EU15 excluding Greece, Finland, and Luxembourg, for which data were incomplete for most years)[2] are used for calculations from 1995 to 2009. In annual reports, the EC calculates averages based on the EU15 and the 10 more recent member countries. For consistency we include only countries with complete time series data, the EU12. Omission of the 3 relatively small countries causes little change to our results, as comparison with years for which complete EU15 data are available show. We also analyze the on-road performance of gasoline and diesel vehicles in 8 EU countries for which we have complete data for the entire period from official or authoritative sources in each country (Millard-Ball and Schipper, 2010; Schipper et al., 2011). In this paper we consider tailpipe emissions only.

For each type of fuel, the EU12 sales weighted average for a given year was calculated as

$$\bar{x}_s = \frac{\sum_i x_i S_i}{\sum_i S_i} \tag{1}$$

where x represents one of the parameters (P, C, M, E, E_P, E_C, or E_M) for the country i. This method was extended to a sales weighted average of both fuels, using j as a subscript for type of fuel technology:

$$\bar{x}_s = \frac{\sum_{i,j} x_{i,j} S_{i,j}}{\sum_{i,j} S_{i,j}} \tag{2}$$

while the fleet of new vehicles introduced each year is composed of a variety of car models and types, these aggregate parameters provide insight into the general changes of consumer choice by vehicle type and characteristic.

2.2. Laspeyres index decomposition

In order to identify the impact of these changes on carbon dioxide emissions from passenger transport, a simple Laspeyres index decomposition was used. This method has been widely used for many decades in the energy sector to investigate the effect of changes in product or activity mix and individual branch energy intensities and fuel mix on energy use and CO_2 emissions of individual sectors or entire economies. Laspeyres is considered the simplest of indices (Ang and Zhang, 2000) to calculate. The decomposition is conducted by varying each variable with the other(s) held constant. The basic premise is that all variables except one are held constant at reference year values. This provides an index of what would have occurred to the parameter of interest

[2] EU15 includes Austria, Belgium, Denmark, Finland, France, Greece, Germany, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and UK. The EU10 includes Cyprus, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovenia and the Slovak Republic. Our "EU-8" include Belgium, France, Germany, Italy, Netherlands, Spain, Sweden and the UK. Data sources are given in Millard-Ball and Schipper (2010) and Schipper (2010).

in a target year had everything else remained unchanged. A more complex approach, LMDI (Ang, 2005), gives similar answers.

In decomposition analysis, the term of interest usually is calculated for each year and divided by the reference year value. This provides an index from the base year value associated with the change in the parameter varied, all else held constant at base year values. One can compare actual changes in, for example, composite emissions intensity of all vehicles sold over time with a result holding market shares of diesel or gasoline cars constant, holding the emissions intensities of each technology constant, holding mass or power constant, etc. In this study, the parameters of interest are aggregate carbon dioxide emissions intensity (g CO_2/km) of new vehicles. Components of this aggregate that varied over time included the separate intensities of new gasoline and diesel vehicles, power, mass, engine displacement and two indicators of efficiency, emissions/kg of mass and emissions/kw of maximum power. For this analysis, a base year of 1995 was chosen, because it provides the most telling information about the hypothetical state of emissions in 2009 under various scenarios. Results were similar if 2009 was chosen as the base year.

For this study, the general formula to calculate the impact of the differences or changes in emissions intensity "D" over time due to varying different parameters is thus,

$$D_E = \frac{\sum_{i,j} E_{i,j,T} S_{i,j,0} / \sum_{i,j} S_{i,j,0}}{\sum_{i,j} E_{i,j,0} S_{i,j,0} / \sum_{i,j} S_{i,j,0}} \tag{3}$$

The base year is given the subscript 0, and the target year of interest is given the subscript T. The second portion, the impact of changes in market shares of diesel or gasoline cars, is calculated as

$$D_s = \frac{\sum_{i,j} E_{i,j,0} S_{i,j,T} / \sum_{i,j} S_{i,j,T}}{\sum_{i,j} E_{i,j,0} S_{i,j,0} / \sum_{i,j} S_{i,j,0}} \tag{4}$$

In order to evaluate the impact of the different characteristics and efficiency parameters (mass-specific emissions intensity), Eqs. (3) and (4) must be modified to

$$D_x = \frac{\sum_{i,j} (E_x)_{i,j,0} x_{x,j,T} S_{i,j,0} / \sum_{i,j} S_{i,j,0}}{\sum_{i,j} (E_x)_{i,j,0} x_{x,j,0} S_{i,j,0} / \sum_{i,j} S_{i,j,0}} \tag{5}$$

where the x and E_x are sales-weighted values of M in kg and E_M in g CO_2/km kg for gasoline and diesel new vehicles. Eq. (5) quantifies the impact of the parameter x (power, capacity or mass), and, then, the impact of power-, capacity-, or mass-specific efficiency is quantified as

$$D_{Ex} = \frac{\sum_{i,j} (E_x)_{i,j,T} x_{x,j,0} S_{i,j,0} / \sum_{i,j} S_{i,j,0}}{\sum_{i,j} (E_x)_{i,j,0} x_{x,j,0} S_{i,j,0} / \sum_{i,j} S_{i,j,0}} \tag{6}$$

The results of D_E, D_S, D_x, D_{Ex} are then plotted alongside the actual percent change in emissions intensity from the base year to determine the percent change that would have occurred due to the varying parameter alone changing, ignoring residuals. A comparison of D_E to D_S (the results of Eqs. (3) and (4)) tells us the importance of changes in emissions intensity or the changes in sales shares on overall changes in aggregate EU new vehicle emissions intensity. Likewise, comparison of D_x to D_{Ex} indicates how the changes in parameter x and the changes in efficiency with respect to that parameter influenced aggregate EU emissions intensity. The key question here is whether any effects dominated or offset potential savings that other variables would have provided.

Two of the specific efficiencies noted measure how much fuel a vehicle consumes in tests to move a given mass or provide a given amount of power. By holding mass constant over time, the reduction in fuel used to move a given amount of mass in successive models gives a measure of true efficiency of the vehicle, and likewise for power. This gives to first order a way of estimating how much fuel would have been consumed had these parameters not increased over time, consistent with Sprei's (2010) results. Conversely, holding the specific efficiencies constant and letting power or mass increase provides an estimate of how much more fuel would be used for the models of 2009 had not the improvements in efficiency taken place since 1995. The Laspeyres decomposition provides both of these "counterfactuals", as well as showing how much varying only the share of gasoline or diesel vehicles contributed to the changes. One can also model whether the shifts in each country's shares of the overall market affected any of the results we sought. Testing for this possibility brought negative results, meaning that our EU-wide averages reflect what happened in most, if not all EU countries.

3. Results and discussion

3.1. General trends

From 1995 the share of diesels rose to a peak of 55% of new cars in 2007, then fell sharply to slightly over 48% in 2009 for the EU12. Fig. 1 shows total sales of all vehicles, as well as the share of diesels in both EU12 and EU15. Similarity of both pairs of curves confirms our use of EU12 to represent the EU15.

The sales weighted average for diesel and gasoline emissions-intensity dropped from 186.4 g CO_2/km in 1995 to 146.5 g CO_2/km in 2009, as shown in Fig. 2. New gasoline vehicles saw a 17.3% decrease, slightly more than the 15.7% decrease of new diesel vehicles. By 2009, diesel cars sold in that year emitted barely 2% less than those of gasoline, compared to about a 10% advantage in 2000. This reflects the fact that diesel vehicles did not show any aggregate improvement in fuel economy between 2000 and 2006, while gasoline vehicles continued to improve.

These changes were accompanied by increases in power and mass for both gasoline and diesel vehicles – but with much bigger increases for diesel – shown in Table 1 as the relative changes over the entire period. In particular, engine power and the ratio of engine power to vehicle mass, directly related to acceleration, increased significantly for diesel cars. Engine size or displacement decreased slightly, most of which occurred in the 2006–2009 period. Yet emissions per kilometer fell similarly for gasoline and diesel cars, meaning the power-specific emissions intensity — fell much more for diesel cars, as Table 1 also shows. Thus, diesels

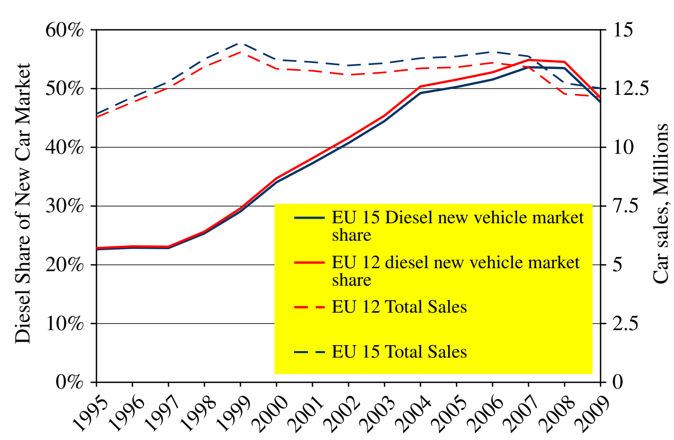

Fig. 1. Sales of new passenger vehicles and Diesel share 1995–2009.

became more efficient per unit power faster than gasoline vehicles, but this only allowed them to realize a similar reduction in CO_2 intensity per kilometer.

Figs. 3 and 4 show that diesel vehicles in the EU15 are significantly more powerful and more massive than gasoline vehicles on average. Diesel vehicle power increased at a faster rate than gasoline engine power, which only started to increase significantly after 2002. There was a noteworthy decrease in diesel power and marked increase in gasoline power in 2008, which seems to have resulted in a leveling out of composite power. Since these trends in mass and power have a direct impact on the fuel economy and the emissions intensity of a vehicle, the upward trend in the aggregate power and mass of the EU12 vehicle markets is counterproductive to its fuel economy goals, as will be examined in the Laspeyres decomposition. This trend also occurred in the US and Japanese markets (Schipper 2010).

As discussed, the diesel technology share of vehicle sales rose steadily over the last 14 years, until it fell starting in 2006 (Fig. 1). The dramatic drop in composite sales, which continued in 2009 according to preliminary data is likely due the economic crisis (European Commission.(EC), 2010). The EC noted that "the sustained

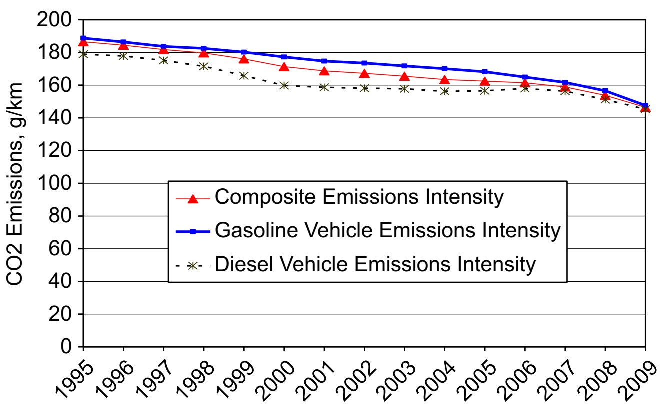

Fig. 2. Reduction in EU12 sales weighted average *emissions intensity* (*E*) of new passenger vehicles by fuel technology and by composite, 1995–2009.

Table 1
Summary of changes in gasoline and diesel vehicles in EU-12 countries.
Source: Calculations using EC (2010) data.

Characteristic	Vehicle technology	Percent changes 1995–2009	
		Characteristic (%)	Change in emissions intensity relative to characteristic (%)
Power/mass	Composite	12	
	Gasoline	1	
	Diesel	19	
Power	Composite	41	−42
	Gasoline	14	−28
	Diesel	48	−43
Engine displacement	Composite	3	−21
	Gasoline	−2	−15
	Diesel	−5	−12
Curb mass	Composite	26	−35
	Gasoline	15	−28
	Diesel	24	−32
CO_2 emissions per kilometer (based on rated fuel economy)	Composite	−18	
	Gasoline	−17	
	Diesel	−16	

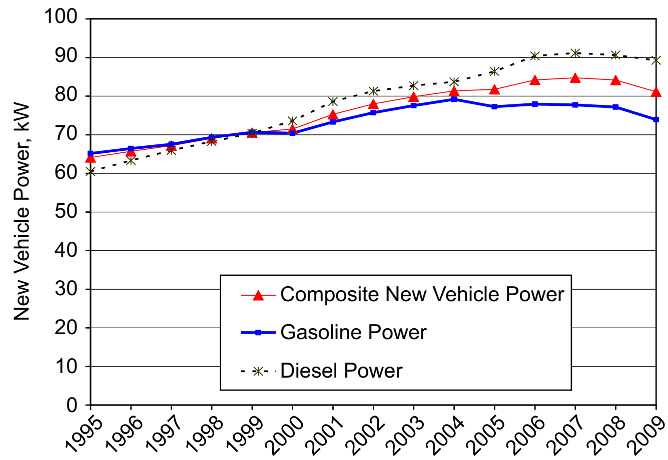

Fig. 3. Increase in EU12 sales weighted average *power* (*P*) of new passenger vehicles by fuel technology and by composite, 1995–2009.

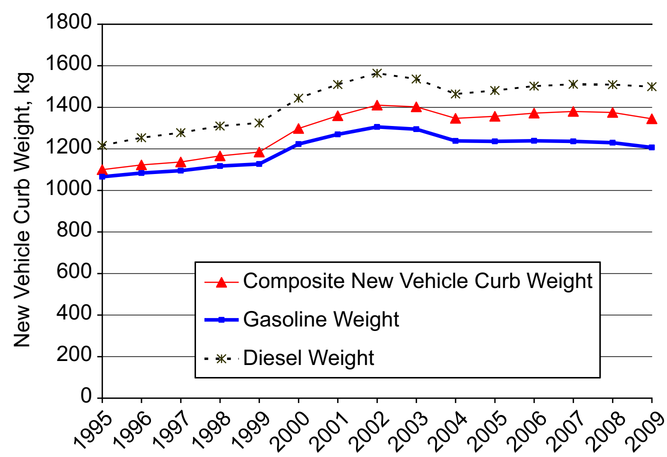

Fig. 4. Increase in EU12 sales weighted average weight or *mass* (*M*) of new passenger vehicles by fuel technology and by composite, 1995–2009.

increase of the share of diesel vehicles in the EU new passenger cars markets has been an important contribution to the overall progress achieved so far" (European Commission.(EC), 2005). Yet in the same report, a mid-term review states that "observed market changes did not influence the CO_2 emissions significantly" (European Commission.(EC), 2005). The decomposition in the next section confirms this outcome.

3.2. Laspeyres decomposition results

We will now disentangle changes in the new vehicle market with the Laspeyres index to show how these changes affected new vehicle emissions. Fig. 5 shows emissions intensity of new vehicles using base year intensities and actual yearly market shares, and then base year market shares but actual yearly emissions intensities. Actual composite intensity is also given for comparison. Improvements in vehicle emissions intensity for each fuel technology almost completely overshadow the effects of sales shifts in terms of impact on the aggregate change in emissions. For example, if sales had remained constant at 1995 levels until 2009, we would have seen virtually the same decrease in g CO_2/km as that which actually occurred, just due to the technological improvements. Had only the shift to diesels occurred, 2009 emissions intensity would have been 184.5 g CO_2/km, only a 1% reduction from 1995!

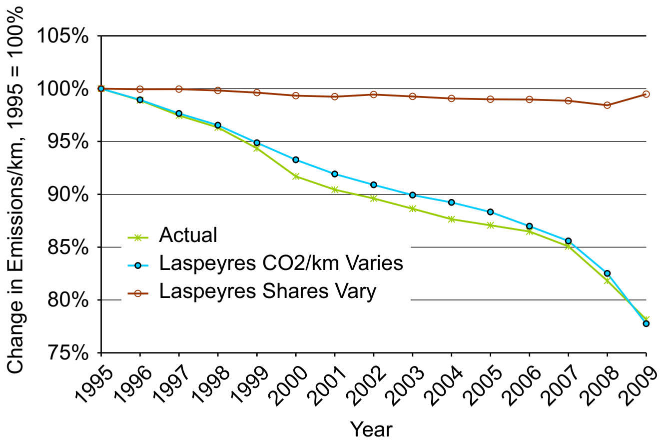

Fig. 5. Impact of emissions intensity and sales by fuel technology and composite on EU12 new passenger vehicle emissions, Laspeyres index base 1995.

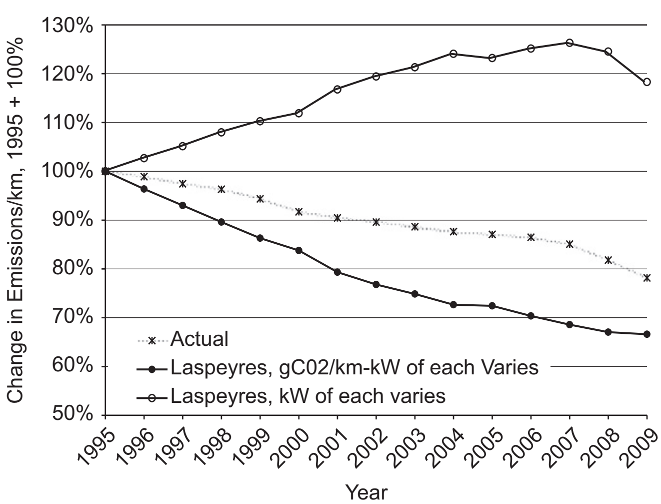

Fig. 6. Impact of power and power-specific emissions EU12 new passenger vehicle emissions, Laspeyres index with base year 1995.

It might be surmised, however, that without the large improvements in diesel performance and emissions reductions, the shifts to diesel of the magnitude observed would not have occurred. Conversely, had not the shift to diesel occurred but the observed declines in emissions intensity of both technologies taken place, almost all of the observed change in composite emissions intensity would have been obtained. These findings indicate that efforts by car manufacturers to improve both vehicle technologies were what resulted in 2009 average fuel economy levels that came close to the VA target. This analysis suggests the necessity for any fuel economy or emissions reduction strategy to hold all vehicle technologies to emissions standards in order to realize the maximum potential of the efforts, and not rely on one technology to carry the hoped-for savings.

Fig. 6 decomposes the relative importance of power and efficiency with respect to power, which we will call "power specific intensity" as Sprei (2010) has done for Sweden. All else equal, reductions in power specific intensities would have resulted in even lower emissions reductions in 2008 than those actually realized. It can be seen that increases in power of both diesel and gasoline vehicles offset these improvements in power-specific emissions. If power had remained at 1995 levels, the impact of gasoline improvements alone (i.e., lower fuel use/unit of power) would have almost met the VA goal at 142.7 g CO_2/km. Furthermore, with the decline in both diesel and gasoline power specific emissions, overall emissions intensity would have been well on its way to the 2016 goal at 125.1 g CO_2/km by 2008. Note that diesel power efficiency improvements would not have been able to realize actual level of reduction on its own. If consumers had not demanded and/or manufacturers had not produced more powerful diesel vehicles, emissions targets might have been met or exceeded.

Fig. 7 shows similar results to those found for the power calculation. The increases in mass as seen in Table 2 offset the positive impact of efficiency improvements. The decline in emissions per unit of vehicle mass would have led to emissions reductions below the VA target—132.1 g CO_2/km. This demonstrates that the introduction of increasingly heavier cars in the EU12 has confounded efforts to reduce emissions. However, in comparison to the effect of power increases as discussed above, limiting power would have realized more savings than limiting car mass. As Zachariadis (2008) shows, the imposition of safety measures had little impact on the overall increase in mass, and therefore did not significantly offset the impact of more fuel efficient technology.

Our results for the impact of changes in mass- and power-specific emissions are only approximate. Emissions-specific intensities for mass or power are probably not independent of the actual vehicle mass or maximum power because of scale effects. Still the last two decompositions show the importance of increased vehicle mass or power in offsetting these apparent efficiency gains. Moreover, some of the efficiency gain probably enabled consumers to buy heavier and more powerful cars by lowering the costs of using those cars, independent of which fuel technology was chosen, which could be considered a kind of rebound effect. As Schipper and Fulton (2009) noted, SUV and other large cars have become predominantly diesel in Europe. Would this have occurred had not diesel technology improved so much as to make using these vehicles affordable at European fuel prices? In other words, the rapid decline in diesel power-specific emissions probably encouraged shifting of the largest and heaviest cars to diesel engines because these engines could provide better fuel economy.

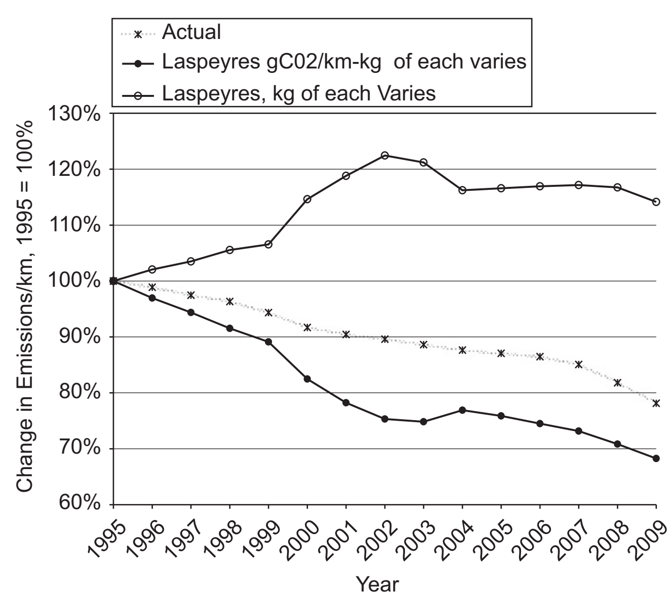

Fig. 7. Impact of mass and efficiency with respect to mass by fuel technology and composite on EU12 new passenger vehicle emissions, Laspeyres index base year 1995.

Table 2
Characteristics and usage of new and on-road diesels and gasoline cars in 8 EU countries.
Source: EC, 2010; Schipper and Fulton (2009) and national authorities noted in Millard-Ball and Schipper (2010).

	France		Germany		Spain		Italy		Netherlands		Belgium		UK		Sweden		All EU- 8	
	1995	2008	1995	2008	1995	2008	1995	2008	1995	2008	1995	2008	1995	2008	1995	2008	1995	2008
New diesels																		
New diesel, 1000s	892	1571	448	1331	275	729	178	1094	62	123	166	423	394	906	5	87	2419	6264
Share of sales, %	47%	77%	14%	44%	33%	70%	10%	54%	12%	25%	48%	79%	20%	43%	3%	35%	23%	55%
New diesel, l/100 km	6.60	5.30	6.50	6.59	6.21	5.45	6.92	5.56	6.64	5.93	6.49	5.51	6.93	5.90	7.50	6.30	6.61	5.77
L/100 km rel. to gas.	88%	88%	86%	100%	81%	83%	91%	92%	83%	90%	81%	86%	85%	88%	81%	86%	86%	91%
CO_2/km rel. to gas.	99%	98%	96%	102%	91%	*93%*	103%	104%	93%	*101%*	91%	96%	95%	99%	90%	94%	97%	99%
New gasoline, l/100 km	7.50	6.00	7.60	6.62	7.69	6.57	7.57	6.03	8.03	6.66	8.01	6.43	8.16	6.71	9.30	7.30	7.76	6.50
On road diesel stock																		
Diesels stock, '000	6622	16,335	5545	10,290	1559	8176	3100	11,900	614	1286	1393	2903	1722	6966	146	884	20,702	58,740
Share of stock, %	26%	53%	14%	25%	14%	*49%*	11%	37%	11%	*17%*	33%	57%	8%	26%	3%	17%	15%	35%
Km/car/year, 000	20.6	15.9	18.0	21.1	15.7	16.4	21.5	14.3	25.3	24.9	22.7	20.2	26.7	21.1	22	25	20.5	17.3
km/year, rel. to gas.	178%	170%	144%	177%	130%	179%	204%	162%	212%	226%	184%	220%	180%	151%	160%	190%	172%	175%
Diesel stock l/100 km	6.67	6.40	7.47	6.85	6.90	6.69	6.68	5.55	6.90	6.74	7.48	6.47	7.45	7.43	7.05	6.80	7.03	6.56
l/100 km Rel. to gas	79%	84%	82%	87%	83%	83%	84%	84%	83%	83%	84%	79%	81%	82%	81%	81%	81%	84%
CO_2/km Rel. to gas	88%	95%	92%	97%	93%	94%	95%	94%	93%	93%	94%	88%	91%	92%	91%	91%	91%	94%
Gasoline l/100 km	8.49	7.60	9.14	7.89	8.32	8.02	7.93	6.63	8.33	8.15	8.92	8.21	9.20	9.11	8.71	8.43	8.65	7.83

These considerations lead to an important observation: the effects we have observed so far are not to be taken as a reflection on the problems of diesel technology. On the contrary, it is the rapid maturation of diesel technology, perhaps coupled with the lower price of diesel fuel in most European countries, which fostered the developments that offset some of the fuel and emissions saving achievements of diesel. With diesel fuel prices including taxes converging on those of gasoline (IEA, 2010; Schipper, 2010), we can only speculate for now whether diesel technology will now be deployed to save fuel at greater rates in the near future.

4. When the rubber hits the road

Fuel economy on-road and actual vehicle usage determine total oil use and CO_2 emissions, not the sales weighted average of fuel economy or test properties of individual vehicles. Unfortunately, the EC monitoring report tracks only new vehicle sales weighted economy, not on-road performance or yearly vehicle use. Fortunately, complete data describing gasoline and diesel automobile usage and on-road fuel economy are available for at least eight EU countries. Table 2 gives data on the new and on-road (i.e., fleet or actual) performance of diesels for eight EU countries for which data are available, using the same national sources as Schipper and Fulton (2009). Based on new sales, these countries account for 80% of the diesel cars sold and driven in the EU12. New-vehicle values are shown as well, taken from the EU data base.

Table 2 gives the volumetric ratios of diesel to gasoline fuel intensity (in liters/100 km or l/100 km) as well as the ratios of CO_2 emissions in gm/km and ratios of distances these cars are driven. While on-road fuel intensity of diesel (l/100 km) was 20% lower than that of the gasoline cars on the road in 1995, this difference shrank to 16% in 2008. Furthermore, expressed as g CO_2/km, the difference was only 9% in 1994 versus 6% in 2008.

Comparing the new vehicle and on-road fuel economy figures is complicated. It is well known (Schipper and Tax, 1994; Smokers et al., 2006) that the emissions savings shown in tests may not reflect the real-life reductions for either gasoline or diesel due to the difference between on-road vehicle characteristics and new vehicle test data as used here and by the EU, as noted above. Smokers et al. (2006) suggest increasing the new vehicle test data by 19.5% for the European case comes close to what these will average on the road. Given the rate of change of the diesel stock and the average lifetime of a car is well over 15 years, most of the 64 million diesels on the road in 2008 in the countries in Table 2 were bought in 1995 or later. By contrast, a much smaller share of the surviving gasoline stock was as new, because of the much lower sales. With that in mind the stock wide reductions in diesel on-road intensity are not inconsistent with the changes in new vehicles alone.

Studies have shown that some and possibly significant portions of improvements in new vehicle fuel economy have been offset by changes in actual on-road driving habits and conditions, including excessive speeding, use of air conditioning, and increased street congestion (Bonilla, 2009; Schipper et al., 2002; Zachariadis, 2006). These considerations should be thoughtfully taken into consideration by policymakers when looking at the impressive reductions in emissions that have occurred since 1995 noted here. Indeed, the 19.5% adjustment from test to "real" fuel use identified by Smokers et al. (2006) should be monitored carefully.

The table also shows the average distances "on-road" diesel cars are driven. We see that diesel cars in Europe are driven 40–100% more than gasoline cars. A great part of this effect is the fact that diesel cars are on average considerably newer, as previously noted. Newer cars are always driven more than older ones, as any country's car use surveys show (see the literature cited in Millard-Ball and Schipper (2010) or Schipper et al. (2011). This could account for part of the increase over time in the diesel/gasoline distance gap, as more new vehicles come into the diesel fleet than into the gasoline fleet.

Another factor is the use of diesel cars for business other than taxis, which are driven almost twice as much as private cars according to Dutch data (CBS, 2010). Similar trends are indicated in Sweden (Kaageson, 2009; Bonilla, 2009). The small number of taxis and other professional vehicles that are diesels are driven in excess of 60,000 km/year, twice the usual amount of 30,000 km/year. These diesel cars were chosen for durability and to some extent for fuel economy. However, individual and private use remains key. The high shares of new vehicles sold as diesels, 55% in the eight EU countries considered here in Table 2 and 55% in the EU-15 in 2008, means that most new buyers are private users or individuals who receive company cars as part of their compensation, but not taxi or professional/business drivers.

It may seem odd that as the number of private users of diesel vehicles increase, the diesel/gasoline car usage gap has increased.

After all, as the market for long-range drivers noted above saturates, first time diesel drivers will be those who drive less. Yet there may be a significant "self-selection" effect, as those who drive farther are more likely to switch to diesel, leaving those who drive less in gasoline cars. Moreover, diesels may be used more as first family cars or for touring, since they are larger than their gasoline counterparts (Cerri and Hivert, 2003). These effects cause diesel vehicles to use more fuel because they are replacing gasoline vehicles, but possibly less fuel than would have been used by gasoline vehicles in the same situation. On the other hand, diesels are generally cheaper to drive, given an efficiency and fuel price advantage (quite significant in some countries). As a result, owners of diesel vehicles may be driving more because of that lower fuel cost, which is a straight-up increase in driving and fuel use (i.e., the traditional 'rebound effect' see Hymel et al., 2010]). Both of these effects are most likely significant, but are very difficult to separate statistically.

We caution that the 'rebound effect' as measured over the entire stock of light duty vehicles is typically measured to be fairly small (Hymel et al., 2010). Indeed, overall per capita driving in these countries has been stagnant or falling in recent years, as fuel prices have risen (Millard Ball and Schipper, 2010). Here we have found a more complex effect that does include some increase in driving because of the lower driving cost, but other factors noted above must also be important. Interestingly, the real price of diesel fuel rose more than the real price of gasoline over the period studied (IEA 2010), such that the cost/km of using diesel fuel went up considerably more than the cost/km of using gasoline in the entire fleets of cars in the eight countries shown. At the same time diesel car kilometers driven fell less than that of gasoline, suggesting at least that diesel drivers may be less sensitive to fuel costs than are gasoline vehicle drivers.

In addition to the fuel cost advantage of diesel vehicles, there are other factors contributing to their higher average utilization rates. Certainly those who buy diesel vehicles have different socio-demographic and economic characteristics than those buying gasoline cars (Cerri and Hivert, 2003). The younger age of the diesel fleet is also an important factor.

Interestingly, however, the weighted average per capita car driving distance is falling slowly in most countries. This is consistent with the "*switchers*" from gasoline to diesel being the longest distance drivers among those who use gasoline. Those who remain with gasoline cars (or buy new ones) are those with low annual driving distances. This shift gradually lowers the average distance gasoline cars are driven, and if the switchers drive less on average than existing diesel drivers, the diesel distance falls as well, even if the switchers drive more after the switch (Cerri and Hivert, 2003). Whatever the combination of effects, the analysis shows that car usage, not simply new vehicle test fuel economy must be analyzed carefully to understand what has taken place as the share of diesels rises among automobiles. Similar considerations should be taken when trying to understand the impact of gasoline or diesel hybrid or electric, plug-in vehicles on fuel use and CO_2 emissions.

5. Conclusions

We analyzed the shift of the new car market in Europe to diesel technology between 1995 and 2009. We found that the shift to diesel cars itself played little role in the reductions in aggregate new vehicle CO_2 emissions intensity for the EU12. Strong reductions in the emissions intensity of both gasoline and diesel vehicles led to almost all of the observed new-vehicle improvements. Indicators of vehicle efficiency, such as the ratio of test fuel use (or emissions) to peak power, mass, or engine size fell for both new gasoline and new diesel vehicles, with the decline for diesels greater. But growth in mass and power of new diesels outpaced that of gasoline cars, resulting in a bigger overall decline in emissions/km for gasoline than for diesel vehicles.

Model by model, the diesel engine version of new cars continues to offer a significant efficiency advantage over the gasoline model, as well as lower CO_2 emissions. However, when averaged over all vehicles bought in a given year, this margin is much smaller and has shrunk year by year. Diesel buyers have selected heavier and more powerful cars — beyond the normal power difference between a diesel and gasoline version of the same model. More broadly, this reinforces the findings of Cerri and Hivert (2003) that diesel and gasoline car buyers have had different socioeconomic backgrounds. The fact that diesel cars are driven so much more than gasoline ones is explained in part by the fact that diesel cars are on average newer than gasoline cars, as evidenced by their much more rapid rate of growth in the stock. But the lower price of diesel fuel, the advantage in fuel use per kilometer, and the fact that high-mileage drivers may select diesel cars because of these lower costs all add to this difference in usage.

Comparing the on-road experience of diesel fleets and their gasoline counterparts in eight EU countries accounting for roughly 80% of vehicle use and emissions gave similar results. The difference between on-road emissions of all gasoline and all diesel cars narrowed over time, even though the diesel fleet was younger and therefore in principle more affected by recent technological improvements. This same relatively low age of diesel cars accounts in part for the widening gap in yearly use between diesel and gasoline cars. But as for new cars, factors such as lower driving costs for the fleet of diesel vehicles also has played a key role. It continues to be difficult to disentangle rebound effects, such as more driving triggered by lower cost driving, from self-selection effects, reflecting choices based on previously planned actions such as long distance driving or large car buying.

The bottom line is that there are very little energy and emissions savings associated directly with diesel cars or the switch to these in Europe. This is not the fault of the technology, as Schipper and Fulton (2009) noted, but rather the result of a complex process of car selection and use. Indeed, the EU data we analyzed show clearly the large gains in performance and fuel economy afforded by diesel technology. But buyers and manufactures together used those improvements in part to offer more performance, which in turn attracted buyers of higher classes of cars (including SUV) away from gasoline technology to diesel. Ultimately there is a need to look beyond technology improvements to consider the choices made, and the way that vehicles are used by consumers.

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