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The role of efficiency improvements vs. price effects for modeling passenger car transport demand and energy demand—Lessons from European countries

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A B S T R A C T

The objective of this paper is to analyze the impact of changes in fuel prices and fuel intensity (i.e. liters of fuel used per 100 kilometers) on overall fuel (gasoline and diesel) consumption and on the demand for vehicle km driven in car passenger transport. This is important for deriving effective policy portfolios consisting of fuel taxes and technical standards such as fuel intensity mandates or specific CO_2 emission limits.

To extract these impacts, we apply cointegration analyses to six European countries and their aggregate over the period 1970–2007. We consider the impact of fuel prices, household income and fuel intensity on fuel consumption. Furthermore, we investigate how changes in fuel prices and fuel intensity interact, analyzing the rebound effect due to lower fuel intensity and due to the switch to diesel.

Because we find a high rebound effect with 44% more km driven if fuel intensity is improved 100%, the major conclusion of our analysis for policy makers is that technical standards as the only policy instrument will have limited success. Rather we recommend increased fuel taxes along with fuel intensity standards so that the taxes compensate for the rebound due to the standards.

1. Introduction

Whether fuel taxes or technical standards for cars are more favorable policy strategies for curbing energy consumption and CO_2 emissions in car passenger transport is still under discussion. This issue is also addressed frequently in the scientific literature, see e.g. Görlich and Wirl (this issue), Sterner (2007) or Schipper (2009) for some recent work.

In the EU standards are currently favoured. In 2007 the European Commission set the goal to reduce CO_2 emissions from new cars to 120 g per km by 2012—a reduction of around 25% from 2006 levels (EC, 2007). Although currently it is not likely that this target will be achieved, new targets are also under discussion, e.g. 95 g CO_2 per km by 2020 and 70 g CO_2 per km by 2025 (EC, 2010).

The core objective of this paper is to analyze the impact of fuel intensity (FI) changes vs. price changes on overall energy consumption and demand for vehicle km driven in car passenger transport in six EU countries and their aggregate EU-6. This analysis is relevant for deriving effective policy portfolios consisting of fuel taxes and technical standards for fuel intensity. To get a reliable appraisal of the effects of these policies, it is important to know the impact of the underlying parameters – price and fuel intensity – on overall energy consumption.

To identify these impacts, we conduct cointegration analyses for six European countries and their aggregate over the period 1970–2007. We consider the impact of fuel prices, households consumption expenditures (as a proxy for income) and FI.

Note that the aggregate FI we use does not directly reflect the technical efficiency improvements. It is the amount of energy used per unit of activity; in our case as liters of fuel per hundred vehicle kilometers driven (L/100 km). More precisely, it is calculated from weighted FI of different car segments of the overall vehicle stock. Yet, the FI within the different size categories has decreased much more steeply than our weighted averages imply since customers have switched to larger cars with higher FI. This trend is reinforced by the switch from gasoline to diesel vehicles, which goes in lockstep with an increase in car size, see Schipper and Hedges (submitted). Due to this type of rebound, a share of the savings expected from technical improvements gets lost. Thus, the real increase in energy efficiency is not translated into a corresponding decrease in fuel intensity. While this is an interesting question in itself, it is not a focus of the investigation in this paper.

In the literature on considering efficiency improvements for explaining energy consumption in car passenger transport, some of the major contributions were Walker and Wirl (1993), Greene (1997) and Johansson and Schipper (1997). Walker and Wirl (1993) argued that irreversible efficiency improvements play an

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important role in estimating energy demand. A seminal contribution with respect to including technical efficiency in a pooled and decomposed model is provided by Johansson and Schipper (1997). Howarth and Schipper (1991), Schipper and Haas (1997) and Haas and Schipper (1998) depict the decomposition of energy consumption into structure, intensity and activity components. With respect to the impact of prices Dahl and Sterner (1991) provided the first comprehensive survey on estimates of price and income elasticity in transport.

A specific aspect of our investigations is to find out how changes in fuel prices and fuel intensity interact. This is especially important to get an appraisal of the rebound effect due to a lower FI. The rebound effect refers to the behavioral responses to the implementation of more efficient technologies. A lower FI reduces the cost of car travel, and may lead to further growth in vehicle kilometer driven and car size. This rebound effect has been known since the early 1980s and discussed in many papers, e.g. Khazzoom, (1980), Greene (1997), Greening et al. (2000), Sorrell (2007) and Haas et al. (2009). These rebound effects reduce the benefits of CO_2 and fuel intensity standards, so that complementary measures, such as increase in fuel taxes, will be necessary to curb this effect.

In this paper the rebound effect is estimated using the service price elasticity (elasticity of km driven with respect to the price of driving a km) derived from the cointegration analysis. To get an impression of the overall magnitude of the rebound it is compared to the technical saving effect due to efficiency improvements and the price effect. Finally, we look at the most important effects of the recent switch to diesel in some European countries. We investigate how energy consumption changed due to both the impacts of diesel: lower diesel fuel prices and lower diesel fuel intensities. Again, the service price elasticity is the most important number we need for the analysis.

So the very core objective of this paper is to estimate service price elasticity of aggregated EU-6 because it finally allows to draw conclusions for the fuel price effect and the FI effect of this area.

This paper is organized as follows:

In Section 2 the data used for our analyses and background information on the countries investigated are described. In the following sections, the method of approach and the results of the unit root tests are documented. The estimates of the cointegration analysis with and without including FI are described in Section 5. In the next section, the analysis of the impacts on service demand for vehicle km driven is shown. The rebound effect due to the change in fuel intensity and its impact on the energy conservation is discussed in Section 7. The impact of the switch from gasoline to diesel cars on the energy consumption is analyzed in Section 8. Section 9 contains the major conclusions and recommendations for policy makers.

2. Data used

In this paper we focus on identifying the long-term impact of price and fuel intensity changes. In this context it is important to include the periods of the highest price volatility and the strongest pressure on automaker to reduce car fuel intensity (1973–1986), see Fig. 3. Hence, for conducting this analysis, we looked for EU countries for which data for the whole period 1970–2007 were available in an acceptable quality. This led to the focus on the following six countries from which the requested data are available: Austria (AT), Germany (DE), Denmark (DK), France (FR), Sweden (SE) and Italy (IT).

Note that these countries have different geographical size, population density, culture and life-style preferences (consider, e.g. the difference between Sweden and Italy), as well as different policy measures implemented (e.g. different cars registration and ownership taxes). To rule out at least some of these differences, we also use time series of the aggregated numbers of these six countries, EU-6.

The data used for these analyses are mainly taken from

- ALTER-MOTIVE: country review report, see Ajanovic (2009);
- Schipper (1995);
- IEA, Energy prices & taxes;

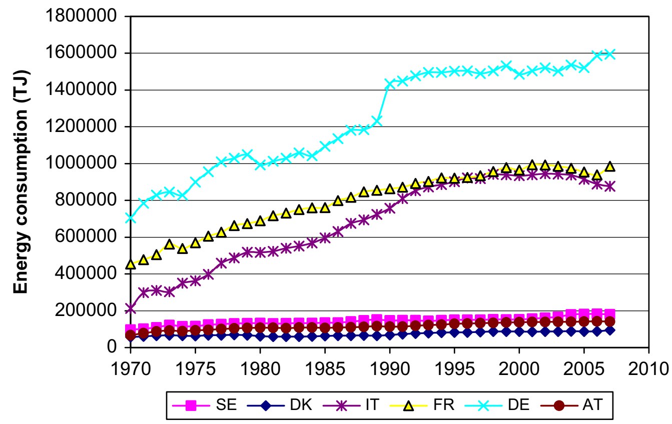

Fig. 1. Passenger car energy consumption in the investigated countries between 1970 and 2007.

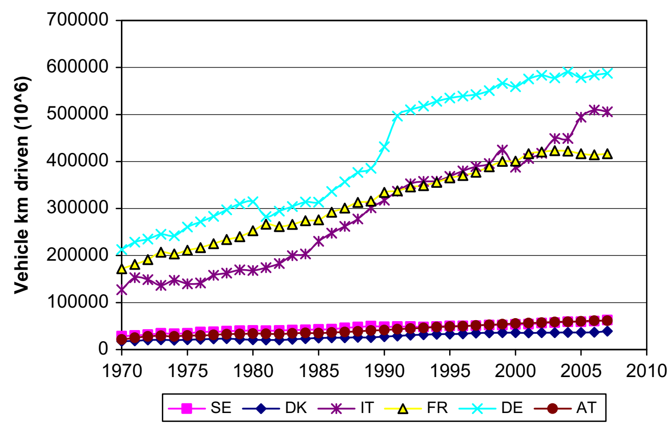

Fig. 2. Development of vehicle km driven in the investigated countries between 1970 and 2007.

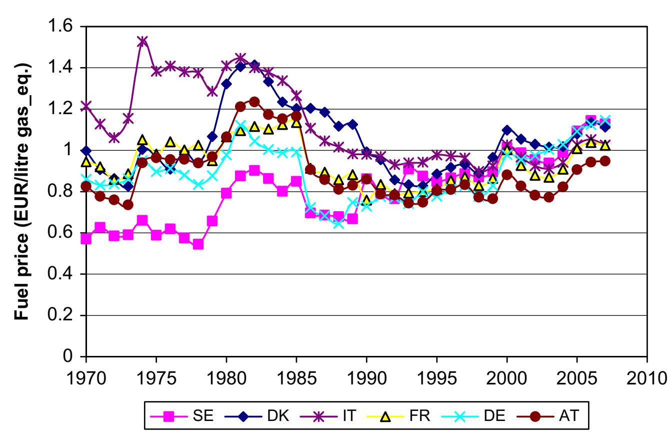

Fig. 3. Development of fuel prices (as of 2000) in the investigated countries between 1970 and 2007.
Data source: IEA Energy Prices & Taxes, 2010

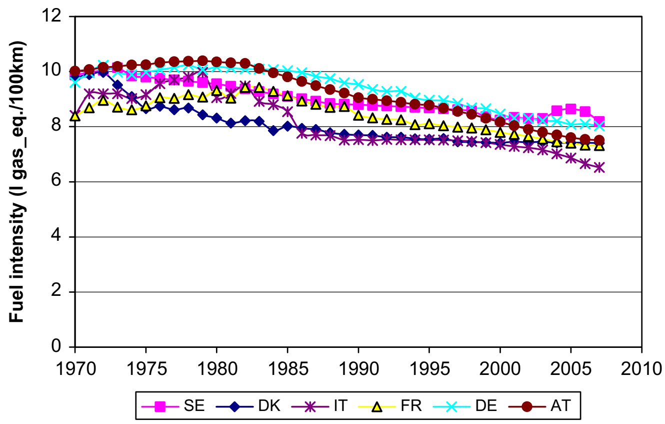

Fig. 4. Development of on-road fuel intensities of the vehicle stock in the investigated countries between 1970 and 2007.

- OECD, National accounts;
- http://www.ODYSSEE.org;
- http://www.acea.be.

Fig. 1 depicts the development of passenger car energy consumption in the investigated countries between 1970 and 2007. Figs. 2–4 show total vehicle kilometers driven, weighted average fuel prices (as of 2000) and on-road fuel intensities of the vehicle stock, respectively.

Energy consumption (E) shown in Fig. 1 is calculated as

$$E = F_g\,LHV_g + F_d\,LHV_d \tag{1}$$

where F_g is the fuel consumption (liters gasoline), F_d the fuel consumption (liters diesel) and LHV the lower heating value (energy content: 35 MJ/L gasoline; 36.4 MJ/L diesel).

The fuel price shown in Fig. 3 is the weighted average fuel price per liter gasoline equivalent. It is calculated as

$$P = \frac{P_g\,F_g + P_d\,F_d}{F_g + F_d(LHV_d/LHV_g)} \tag{2}$$

where P is the weighted fuel price (EUR/L gasoline equivalent), P_g the gasoline price (EUR/L) and P_d the diesel price (EUR/L).

In Fig. 4 we show average on-road fuel intensity of the vehicle stock in the investigated countries. The fuel intensity is calculated as

$$FI = \frac{FI_g\,S_g + FI_d\,S_d(LHV_d/LHV_g)}{S_g + S_d} \tag{3}$$

where FI_g is the average fuel intensity of gasoline cars (L/100 km), FI_d the average fuel intensity of diesel cars (L/100 km), S_g the vehicle km driven by gasoline cars and S_d the vehicle km driven by diesel cars.

3. Method of approach

The method of approach applied is based on the fundamental relationship:

$$E = S\,FI \tag{4}$$

In addition energy consumption E:

$$E = f(X_i) \tag{5a}$$

and service demand S for vehicle km driven:

$$S = g(Z_j) \tag{5b}$$

are analyzed by means of econometric approaches. To find out whether there are long-term relationships between the dependent variables (energy consumption E and service demand S for vehicle km driven) and the independent variables (X_i, Z_j), we conduct cointegration analyses using MICROFIT (see Pesaran and Pesaran (1997) and the detailed description in the next section).

4. Testing for unit roots

The first step in the cointegration analysis is to find out whether the variables are non-stationary. Of course, stationary variables also might have an impact, yet not on the dynamics. If all variables are stationary there is no need for a time series analysis. As Engle and Granger (1987) describe non-stationary variables are said to be integrated of order one, $I(1)$. This means that they have a unit root in their autoregressive representation. Whether an individual variable is stationary or non-stationary can be investigated using the Dickey–Fuller (DF) or the Augmented Dickey–Fuller (ADF) test.[1] The null hypothesis is that there is a unit root, i.e. the variable is non-stationary. If the coefficient of the ADF or DF analysis is less negative or bigger (smaller in absolute value) than the critical value, this hypothesis cannot be rejected. If it is more negative or smaller, then the variables are stationary.

The results of this analysis for the variables included in one of our cointegration analyses are reported in Table 1. Note that the variable service price P_S is calculated from the variables fuel price P and FI:

$$P_S = P\,FI \tag{6}$$

The resulting values for the ADF statistics are reported in Table 1.

The major perceptions are

For all countries and the aggregate, the null hypothesis of a unit root cannot be rejected for P_t and P_{St}. For S_t it cannot be rejected for all countries except France. For Y_t it cannot be rejected for all countries except two and for E_t it cannot be rejected for all countries except 3. For FI_t it can be rejected for four countries and the aggregate. For the EU-6 all variables except E_t and FI_t have a unit root and are non-stationary.

Thus, it is concluded that the variables for which the null hypothesis of a unit root cannot be rejected are integrated of order $I(1)$ for these countries. All other variables are stationary $I(0)$.

Next we apply the autoregressive distributed lag (ARDL) approach with a bounds test for mixed $I(0)$ and $I(1)$ variables based on Pesaran and Pesaran (1997) and Pesaran et al. (2001).

The ARDL procedure involves two stages, see Pesaran and Pesaran (1997).

At the first stage the existence of the long-run relation between the variables under investigation is tested by applying the bounds test. This bounds test allows testing for the existence of long-run relations when it is not known whether the underlying regressors are $I(1)$ or $I(0)$. It is conducted as follows: First the F-statistic for testing the significance of the lagged levels of the variables in the error-correction form of the underlying ARDL model is computed. Next F-tests are used from regressing each variable on the others. For examples, see Appendix A. All F-statistics must be outside the bounds for the equation to be cointegrated. We apply this bounds test using the critical values documented in Pesaran and Pesaran (1997). If the F-statistics falls inside this band for an equation then we can recheck for evidence

[1] The DF and ADF tests are described in detail in e.g. Pesaran and Pesaran (1997).

Table 1
Results of the augmented Dickey–Fuller (ADF) tests for unit roots.

	AT	DE	DK	FR	IT	SE	EU-6
$\ln(E_t)$	−3.10 {3} (−3.55)	−2.26 {0} (−2.95)	−2.03 {1} (−3.55)	−5.32 {0} (−2.95)	−5.05 {0} (−2.95)	−3.86 {3} (−3.55)	−4.60 {0} (−2.95)
$\ln(Y_t)$	−2.67 {0} (−3.55)	−3.19 {0} (−2.95)	−5.05 {3} (−3.55)	−2.45 {0} (−2.95)	−2.63 {4} (−2.95)	−2.44 {3} (−3.55)	−2.58 {1} (−3.55)
$\ln(P_t)$	−1.73 {1} (−2.95)	−1.57 {4} (−2.95)	−2.03 {3} (−3.55)	−1.86 {0} (−2.95)	−1.89 {4} (−2.95)	−3.35 {3} (−3.55)	−1.83 {4} (−2.95)
$\ln(FI_t)$	−4.42 {0} (−3.55)	−3.91 {1} (−3.55)	−4.89 {4} (−2.95)	−3.19 {0} (−3.57)	−3.48 {3} (−3.55)	−3.07 {1} (−3.55)	−4.10 {0} (−3.55)
$\ln(S_t)$	−1.92 {3} (−3.55)	−2.26 {4} (−3.55)	−2.4 {1} (−3.55)	−3.2 {1} (−2.95)	−1.12 {3} (−2.95)	−3.21 {3} (−3.55)	−2.50 {0} (−2.95)
$\ln(P_{St})$	−1.28 {3} (−2.95)	−1.75 {4} (−3.55)	−2.37 {3} (−3.56)	−1.61 {4} (−2.96)	1.74 {4} (−2.95)	−3.19 {3} (−3.55)	−1.79 {4} (−2.95)

Note: 5% critical values are given in parentheses. Figures in { } denote the included lags of the ADF test. A maximum of four lags was chosen for the ADF test. If the lag is 0 the ADF test corresponds to the DF test.

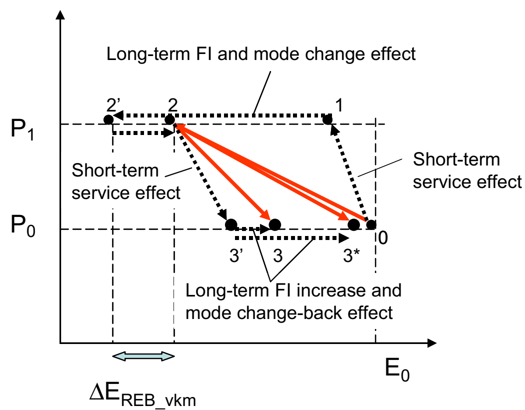

Fig. 5. Interactions between changes in prices and fuel intensities (based on Walker and Wirl(1993)).

of cointegration using the ADF-test. If all the variables are $I(1)$ we have evidence for cointegration and can proceed further.

In the second step of the analysis it is now possible to estimate the coefficients of the long run relations using the ARDL option without further needs for testing. We use the long run coefficients based on the Akaike information criteria (AIC). After that the error-correction-model (ECM) is calculated.

The result of this cointegration analysis provides the inputs for the final investigation of the service price elasticities. We use them to identify the rebound effect and to compare them to the price effect using the corresponding derivations of Eq. (4) with respect to fuel intensity and price. Finally, we apply a similar approach to extract the price and FI effects of the switch to diesel.

5. Modeling energy consumption

To analyze the impact of fuel intensity and prices on energy consumption, we proceed as follows:

(1) we sketch a basic framework on the interactions between prices, fuel intensities and energy consumption;
(2) we conduct an estimation of the symmetric approach;
(3) we test for asymmetries in price elasticities;
(4) we estimate energy and include fuel intensity and discuss its impact.

We start with the outline of a basic framework of the interactions between prices, fuel intensities and energy consumption. In this context two aspects are important: to differ between short-term and long-term effects and whether price elasticities are equal for rising and falling prices. Fig. 5 is based on the principle that energy consumption is caused by changes in service demand due to price changes, efficiency changes and other impacts (e.g. switch to public transport). The broken lines in Fig. 5 depict the actual development behind the observed effects that are described by the solid lines. As it can be seen in Fig. 5 for increase in prices the short-term component is explained by service demand reduction (less km driven) from 0 to 1. The long-term component is caused by a reduction of fuel intensity (due to switch to cars with higher efficiency or to smaller cars), or a switch to other modes (public transport, etc.) from 1 to 2′. Moreover part of the FI improvement is compensated by the rebound (ΔE_{REB_vkm}) from 2′ to 2.

If prices decrease from P_1 to P_0, energy consumption will start to increase again. The core question is to what level it will increase. The crucial aspect for symmetry is whether the state 3* (not significantly different from state 0) or a state 3 (which is significantly different from state 0) is reached.

In the following we start with a simple estimation of total energy consumption. We apply the conventional approach where energy consumption depends on price and income assuming symmetric price elasticities:

$$\ln E_t = C + \alpha \ln P_t + \beta \ln Y_t + \varepsilon_t \quad (7)$$

where C is the intercept, E_t the energy demand in year t, P_t the real energy price (calculated by means of weighted fuel prices), Y_t the real private final consumption expenditures as a proxy for income and εt the residual (error term).

The results regarding cointegration are as follows. The F-statistics of the bounds test – see Appendix A, Table A1 – rejects the null hypothesis of no-cointegration at the 5% significance level for all countries except AT and SE, where the null is rejected at the 10% level. So we continue with cointegration analyses for all countries.

The estimates for overall energy consumption assuming symmetric price elasticities are presented in Tables 2A and 2B. The major results are

- Long-term price elasticities are significant only for France, Italy and the EU-6. All significant long run price elasticities are – in absolute terms – higher than the corresponding short-term elasticities. For EU-6 we obtain (−0.55), which is in good coincidence with numbers of around (−0.5) documented in the literature.
- The long-term income elasticity is significant for all countries except France. The magnitude is reasonable but the range – between 0.49 and 1.95 – of significant values is rather broad.
- The short-term impact of prices is significant for all countries (except Sweden) and the range between (−0.06) and (−0.31) shows that demand is rather inelastic with respect to prices.
- Short-term income has a significant impact in all countries except France and Italy but the numbers vary in a quite broad range between 0.08 and 1.61.
- For the aggregate of EU-6 all variables have a significant long-term and short-term impact on energy and are of reasonable magnitude.

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Table 2A
Estimates for long-term overall energy consumption 1970–2007 (*t*-statistics in parentheses) using ARDL approach based on Akaike information criteria (AIC).

	AT	DE	DK	FR	IT	SE	EU-6
C (long-term intercept)	9.28 (32.94)	6.77 (18.59)	7.83 (2.98)	10.85 (6.62)	0.97 (0.36)	7.73 (11.82)	10.9 (10.1)
α (long-term price elasticity)	−0.16* (−1.81)	0.13* (−1.58)	−0.74 (−4.65)	−0.22* (−0.84)	−0.39 (−1.97)	−0.16* (−1.21)	−0.55 (−3.37)
β (long-term income elasticity)	0.49 (8.51)	1.01 (20.16)	0.77 (9.89)	0.42* (1.81)	1.95 (4.51)	0.84 (6.49)	0.52 (4.07)
LT (long term)	–	–	–	–	−0.02 (−2.45)	–	–

* Not significant at 10%.

Table 2B
Estimates of ECM for overall energy consumption 1970–2007 (*t*-statistics in parentheses) using ARDL approach based on Akaike information criteria (AIC).

	AT	DE	DK	FR	IT	SE	EU-6
ARDL order	(1,0,0)	(1,1,1)	(1,1,0)	(1,1,0)	(1,0,1)	(1,0,0)	(1,1,0)
C (short-term intercept)	3.61 (5.42)	3.25 (3.61)	1.57 (2.79)	1.42 (3.24)	0.36 (0.37)	2.65 (3.29)	1.66 (5.29)
A (short-term price elasticity)	−0.06 (−2.39)	−0.21 (−3.48)	−0.31 (−8.22)	−0.15 (−3.09)	−0.14 (−2.20)	−0.05* (−1.43)	−0.23 (−6.35)
B (short-term income elasticity)	0.19 (3.21)	1.61 (3.72)	0.15 (3.02)	0.055* (1.05)	−0.19* (−0.44)	0.29 (4.24)	0.08 (1.98)
ECM (−1)	−0.39 (−4.80)	−0.48 (−3.55)	−0.20 (−2.89)	−0.13 (−2.31)	−0.37 (−3.76)	−0.34 (−3.88)	−0.15 (−3.65)
R^2	0.69	0.47	0.73	0.45	0.54	0.39	0.74
F-stat.	27.35	12.35	34.24	11.15	11.99	8.63	35.82
AIC	92.07	78.02	97.99	88.67	60.6	82.2	106
SBC[a]	88.85	73.18	93.97	84.65	55.8	78.98	102
DW[b]	1.39	1.656	1.39	2.54	1.62	2.19	1.76

* Not significant at 10%.
[a] Schwarz Bayesian criterion.
[b] Durbin–Watson statistic.

Table 3
Estimates for asymmetric price elasticities (testing the significance of an additional price elasticity for rising prices) (*t*-statistics in parentheses).

	AT	DE	DK	FR	IT	SE	EU-6
α_{rise} (additional long-term price elasticity)	−0.02* (−0.70)	−0.03* (−0.38)	0.08* (0.79)	−0.07* (−0.52)	−0.06* (−1.31)	0.01* (0.19)	−0.22* (−1.75)

* Not significant at 10%.

The next question is whether there are asymmetries in price elasticities. After the drop in oil prices in 1985, energy consumption did not increase as symmetric price elasticities projected. This led Gately (1992) and others to introduce the concept of asymmetry between rising and falling prices in energy demand estimation.

In the literature there are different asymmetric model specifications, taking into account differences for rising and falling prices and the historical maximum price, see e.g. Gately and Huntington (2001). We use a dummy variable D_{prise_t} which is 1 if the fuel price is rising and 0 vice versa. We use the following basic equation and conduct a simple OLS estimate:

$$\ln E_t = C + \alpha \ln P_t + \alpha_{rise} D_{prise_t} \ln P_t + \beta \ln Y_t \quad (8)$$

with α is the general price elasticity, $\alpha + \alpha_{rise}$ the price elasticity for rising prices and

$$D_{prise\_t} = 1 \quad \text{if} \quad P_t > P_{t-1}$$

$$D_{prise\_t} = 0 \quad \text{if} \quad P_t \leq P_{t-1}$$

In Eq. (8) we are only interested in whether the coefficient α_{rise} is significantly different from zero or not. If it is, then price elasticity asymmetry exists.

The key perception is that the additional price elasticity for rising prices (α_{rise}) is not significant for any country and hence the hypothesis of asymmetry has to be rejected for all countries and the EU-6, see Table 3.

Eq. (8) was not tested for cointegration because we did not intend to test for a long-term relationship but simply to test significance of one variable and this can be done by simple ordinary least squares (OLS).

Next we are interested in whether FI has a significant exogenous impact that goes beyond that captured by price elasticities. We include the fuel intensity directly as follows[2]:

$$\ln E_t = C + \alpha \ln P_t + \beta \ln Y_t + \gamma \ln FI_t + \varepsilon_t \quad (9)$$

The results regarding cointegration are ambiguous. The *F*-statistics of the bounds test – see Appendix A, Table A2 – on 5%-level reveals cointegration for EU-6 and DK, and on the 10%-level for AT, DE, IT and SE. For France this test does not point towards cointegration and also the ADF-test does not indicate that all variables are $I(1)$. So for France we do not continue this analysis.[3]

However, also the details of the analysis with the ARDL approach do not provide clear perceptions regarding the impact of FI and whether these estimates are clearly preferable to those in Tables 2A and 2B:

- Long-term price elasticities are slightly lower than in Tables 2A and 2B. For EU-6 the value for the estimate with FI is (−0.4) compared to (−0.55) for the estimate without FI.
- The short-term price elasticities virtually did not change.
- Also the $\bar{R}^2$ and the AIC, SBC and DW changed only slightly, sometimes better, sometimes worse.
- For the EU-6 and the DK short-term and long-term prices and FI elasticities are significant.

[2] For the relationship between α and γ see Eq. (23).

[3] One reason, why no-cointegration was detected for France could be diesel promotion policies. This may be an interesting topic for further investigations.

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Summing up, the major additional insight is that on aggregated EU-6 level we get a significant impact of price and fuel intensity.

6. Modeling demand for vehicle kilometer driven

Alternative to estimating energy consumption by means of an econometric approach we can model energy demand also using the framework described in the editorial introduction to this paper (Ajanovic et al., submitted) and in Eq. (4) of this paper. Within this approach we conduct an econometric estimate of vkm driven and finally multiply it by *FI*.

The level of service demand S[4] of, e.g. a household with respect to km driven, depends on available income Y and the price of energy service P_S:

$$S = f(P_S, Y) \tag{10}$$

That is to say, we conduct an econometric estimate of vkm driven and finally multiply it by *FI*. We estimate the impacts on vkm driven using a cointegration approach described above:

$$\ln S_t = C + \alpha \ln P_{S_t} + \beta \ln Y_t + \varepsilon_t \tag{11}$$

where C is the intercept, S_t the demand for service, vehicle km driven in year t in a country, P_{St} the weighted average price of service vkm driven (calculated by means of weighted fuel prices), Y_t the real private final consumption expenditures and ε_t the residual (error term).

The most interesting numbers of this analysis are the service price elasticities because they contain information for both price and efficiency impact, see Eq. (6) and Section 7.

The bounds test described above indicates cointegration for EU-6 and all countries except AT and IT—see Appendix A, Table A3. For these two countries we have to analyze whether all variables used in Eq. (11) are $I(1)$. From Table 1 we can see that they are. So having identified cointegration for all countries we can proceed further with the analysis of long-term relationships and the ECM.

The results of this analysis are documented in Tables 5A and 5B. The major perceptions are

- Long-term service price elasticities are significant for all countries except SE. They are between -0.19 (AT) and -0.88 (FR) for the investigated countries. The value for aggregated EU-6 is -0.44. This price elasticity is used further in Section 7 to identify the price and the fuel intensity effect, as well as the rebound effect.
- Short-term service price elasticities are significant for all countries (at 10% level) but are rather low. The range between (-0.05) and (-0.36) shows that short-term demand for vkm driven is rather inelastic with respect to service prices.
- Long-term income elasticities are significant for all countries except France. The short-term numbers are smaller for all countries except France where we also get a reasonable short-term income elasticity of 0.8 (significant at 10% level). The magnitude of significant values – either short-term or long-term – is reasonable – between 0.80 and 1.34 – and the range is smaller than for the estimates of energy with fuel intensity.
- For the EU-6 the long-term elasticities for service demand are very similar to the estimates for energy consumption including *FI*. The price elasticity of service demand is (-0.44) compared to (-0.40) for the energy price in Tables 5A and 4A. Income elasticity of service demand is virtually the same as for energy in Tables 4A and 4B (1.15 vs. 1.16).
- The $\overline{R}^2$ and the AIC, SBC and DW changed only slightly compared to the estimates in Tables 2B and 4B, sometimes better, sometimes worse.
- Summing up, cointegration was identified for all countries and the aggregated EU-6. The estimates for EU-6 imply a clear long-term relationship between vehicle kilometer driven, service price and income. Moreover, service price and income also have a significant short-term impact for EU-6.

[4] It is important to note that "energy service" for cars is not just distance driven. Rather it is kg–km define or even kW–km, and efficiency is energy use/kg–km or energy use/kW–km. By these measures, efficiency increased enormously mostly by increasing weight and power and not simply by reducing fuel consumption. Thus, a large part of the increase in energy efficiency is not translated into a decrease of *FI*.

7. The impact of fuel intensity vs. fuel price

In this section we analyze the impacts of fuel intensity vs. fuel prices on energy consumption. This is important to derive conclusions with respect to the effect of the implementation of standards for fuel intensity vs. the effect of the introduction of fuel taxes increasing fuel prices.

One of the most critically discussed issues with respect to the implementation of standards for fuel intensity or corresponding CO_2 emissions is the rebound effect, see also the discussion in the introduction to this paper.

In the following, we conduct an estimation of the following effects: (i) the effect of changes in fuel intensity including a saving effect and a rebound effect because of increases in vehicle km driven and (ii) the price effect. This analysis is based on the investigation in Section 6. The definition of service demand S in Eq. (10) can be extended to

$$S = f(P\,FI, Y) = C(P\,FI)^{\alpha} Y^{\beta} \tag{12}$$

Using derivations the change in service demand (dS) can be split up into the price, the efficiency and the income effects:

$$dS = \frac{\partial f}{\partial P} dP + \frac{\partial f}{\partial FI} dFI + \frac{\partial f}{\partial Y} dY \tag{13}$$

In this paper we are further on interested in the change of service demand due to a change in the fuel price and the fuel intensity. We do not look at the income effect.

We proceed further using Eq. (4)[5] and we obtain the change in energy consumption:

$$dE2em = S\,dFI + FI\,dS \tag{14}$$

The change with respect to price is

$$\frac{dE}{dP} = \frac{S\,dFI}{dP} + \frac{FI\,dS}{dP} \tag{15}$$

The change in energy demand (if $dFI/dP = 0$)[6] due to the direct price effect is

$$\frac{dE}{dP} = \frac{FI\,dS}{dP} \tag{16}$$

The change in service demand vehicle km driven caused by the price effect and using Eq. (12) is

$$\frac{dS}{dP} = \frac{\partial f}{\partial P} = \alpha (PFI)^{\alpha - 1} FI \frac{P}{P} = \alpha \frac{S}{P} \tag{17}$$

where α is the elasticity of vehicle kilometers driven with respect to service price P_S.

Straightforward, the change in energy demand due to a change in the fuel price is

$$\frac{dE}{dP} = FI \frac{dS}{dP} = FI \alpha \frac{S}{P} \tag{18}$$

[5] See also the detailed derivation in Ajanovic et al. (submitted).

[6] In the long run, lasting price changes will have an impact, see e.g. Walker and Wirl (1993).

Table 4A
Estimates for long-term overall energy consumption 1970–2007 including fuel intensity (*t*-statistics in parentheses)[a].

	AT	DE	DK	FR	IT	SE	EU-6
C (long-term intercept)	10.62 (11.23)	7.37 (4.48)	4.01 (2.95)	–[b]	−1.73 (−0.72)	6.54 (2.84)	3.87 (2.76)
α (long-term price elasticity)	−0.18 (−2.39)	−0.14* (−1.54)	−0.57 (−6.96)	–[b]	−0.49 (−2.91)	−0.19* (−1.27)	−0.40 (−5.95)
β (long-term income elasticity)	−0.40* (−1.14)	0.97 (7.58)	1.17 (7.89)	–[b]	2.10 (6.36)	0.95 (4.09)	1.16 (10.32)
γ (long-term fuel intensity elasticity)	1.06 (2.10)	−0.13* (−0.38)	0.97 (2.76)	–[b]	0.76 (1.83)	0.30* (0.51)	0.76 (3.27)

* Not significant at 10%.
[a] For no country a significant time trend was detected.
[b] For France no signs for cointegration were detected neither from the *F*-statistics of the bounds test nor from the ADF-test for non-stationarity of the investigated variables.

Table 4B
Estimates of ECM for overall energy consumption 1970–2007 including fuel intensity (*t*-statistics in parentheses).

	AT	DE	DK	FR	IT	SE	EU-6
ARDL order	(1,0,0,0)	(1,1,1,0)	(1,1,0,0)	–[a]	(1,0,1,0)	(1,0,0,1)	(1,1,0,1)
C (short-term intercept)	4.87 (6.12)	3.37 (3.50)	1.05 (2.04)	–[a]	−0.82 (−0.67)	1.69 (1.82)	1.36 (3.48)
A (short-term price elasticity)	−0.08 (−2.80)	−0.21 (−3.44)	−0.29 (−8.73)	–[a]	−0.23 (−2.69)	−0.05* (−1.55)	−0.22 (−6.53)
B (short-term income elasticity)	−0.18* (−1.17)	1.58 (3.53)	0.31 (4.96)	–[a]	0.03* (0.06)	0.25 (3.81)	0.41 (2.99)
Γ (short-term fuel intensity elasticity)	0.49 (1.88)	−0.06* (−0.40)	0.25 (2.90)	–[a]	0.36* (1.53)	1.31 (4.21)	0.86 (3.55)
ECM (−1)	−0.46 (−5.35)	−0.46 (−3.08)	−0.26 (−4.30)	–[a]	−0.48 (−4.02)	−0.26 (−3.41)	−0.35 (−3.84)
$\bar{R}^2$	0.73	0.46	0.79	–[a]	0.56	0.59	0.79
RESS	0.0099	0.0229	0.0053	–[a]	0.0548	0.0128	0.0049
F-stat.	19.99	9.05	33.73	–[a]	10.48	14.43	36.02
AIC	93.62	77.12	98.15	–[a]	61.0	88.94	105.54
SBC	88.79	71.48	93.48	–[a]	55.4	84.1	99.91
DW	1.61	1.71	1.74	–[a]	1.60	2.25	2.16

* Not significant at 10%.
[a] For France no signs for cointegration were detected neither from the *F*-statistics of the bounds test nor from the ADF-test for non-stationarity of the investigated variables.

Table 5A
Estimates for long-term service demand (overall vehicle km driven) 1970–2007 using service prices (*t*-statistics in parentheses) using ARDL approach based on AIC[a].

	AT	DE	DK	FR	IT	SE	EU-6
C (long-term intercept)	6.64 (24.1)	4.31 (3.57)	6.21 (18.8)	18.0 (0.94)	−0.56 (−0.43)	5.88 (13.93)	7.42 (6.30)
α (long-term service price elasticity)	−0.19 (4.67)	−0.48 (−2.29)	−0.47 (−7.94)	−0.88* (−0.74)	−0.56 (−4.63)	−0.24* (−1.57)	−0.44 (−7.40)
β (long-term income elasticity)	0.88 (23.3)	1.36 (11.1)	1.13 (19.7)	−0.45* (−0.18)	1.11 (8.06)	1.10 (9.58)	1.15 (25.5)

* Not significant at 10%.
[a] For no country a significant time trend at 10% level was detected.

Table 5B
Estimates of ECM for service demand (vehicle km driven) 1970–2007 depending on service prices and income (*t*-statistics in parentheses).

	AT	DE	DK	FR	IT	SE	EU-6
ARDL order	(1,1,0)	(1,1,1)	(1,0,1)	(1,0,1)	(1,1,0)	(1,0,0)	(1,0,0)
C (short-term intercept)	3.95 (7.56)	1.05 (2.15)	2.28 (3.94)	0.80 (1.67)	−0.25 (−0.47)	1.31 (4.17)	2.26 (7.44)
A (short-term service price elasticity)	−0.12 (−6.66)	−0.25 (−4.07)	−0.36 (−8.82)	−0.13 (−3.87)	−0.25 (−2.78)	−0.05 (−1.88)	−0.18 (−6.75)
B (short-term income elasticity)	0.27* (1.38)	1.34 (3.19)	0.41 (4.14)	0.80 (1.67)	−0.33* (−0.78)	0.25 (4.24)	0.47 (4.80)
ECM (−1)	−0.59 (−6.21)	−0.24 (−2.06)	−0.37 (−4.07)	−0.04 (−0.62)	0.44 (3.49)	−0.22 (−4.18)	−0.41 (−5.56)
R^2 Korr	0.74	0.53	0.71	0.44	0.21	0.41	0.61
RESS	0.0081	0.0233	0.0092	0.006	0.0713	0.0124	0.0069
F-stat.	35.0	15.18	29.64	9.86	4.56	9.44	19.6
AIC	98.5	77.88	89.7	90.2	58.2	91.5	102.3
SBC	94.5	73.04	85.8	86.4	63.2	95.5	99.1
DW	1.51	2.04	1.89	2.13	2.03	2.26	1.67

* Not significant at 10%.

and the total energy change from a price change is

$$dE(dP) = FI\alpha S\frac{dP}{P} \tag{19}$$

Next we analyze the effect of an exogenous fuel intensity change:

$$\frac{dE}{dFI} = FI\frac{dS}{dFI} + S\frac{dFI}{dFI} = \alpha FI(PFI)^{\alpha-1}P + S = S(\alpha+1) \tag{20}$$

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and the total energy change from a change in *FI* is

$$dE(dFI) = S(1+\alpha)dFI = S\,dFI + \alpha S\,dFI \tag{21}$$

Introducing the fuel intensity savings factor γ we can rewrite Eq. (21) as

$$dE(dFI) = \gamma S\,dFI \tag{22}$$

and we obtain for the relationship between the impact of fuel intensity and price (see also Walker and Wirl (1993) and Greene (1997)):

$$\gamma = 1+\alpha \tag{23}$$

This relationship can be illustrated by the following simple example. If the short-term price elasticity is (-0.3), the resulting elasticity for fuel intensity γ is $(1+(-0.3))=0.7$. That is to say, if fuel intensity is decreased by e.g. 10% due to a standard, the energy savings are only 7% because of a rebound in service demand due to the price elasticity of -0.3!

Fig. 6 shows the two effects due to changes in fuel intensity from Eq. (21). The first effect is the change in demand from driving more fuel efficient vehicles the same number of miles ($S\,dFI$). In Fig. 6 we see that since 1984 the total change in *FI* led to total energy savings $dE(dFI)$ of about 200 PJ in EU-6. In comparison, total energy consumption by end of 2007 was about 4000 PJ (see Fig. 8). The second effect is the energy change from driving more kilometers, ($\alpha S\,dFI$) called the rebound effect. The rebound effect led to an additional energy consumption of about 130 PJ, see Fig. 6.

Fig. 7 compares the overall effect due to a change in fuel intensity ($dE(FI)$) and the price effect ($dE(dP)$). As shown in Fig. 7,

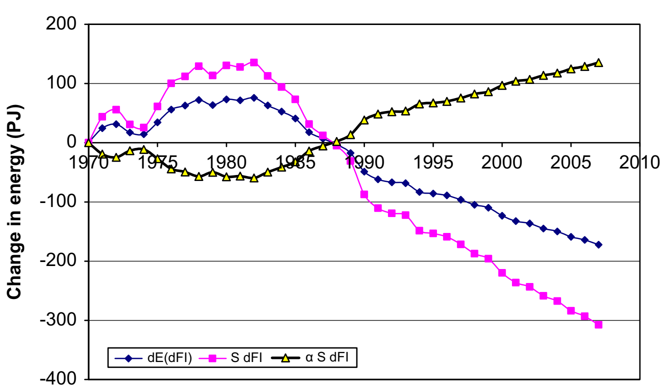

Fig. 6. The change of energy consumption due to changes in fuel intensity for EU-6, base 1970.

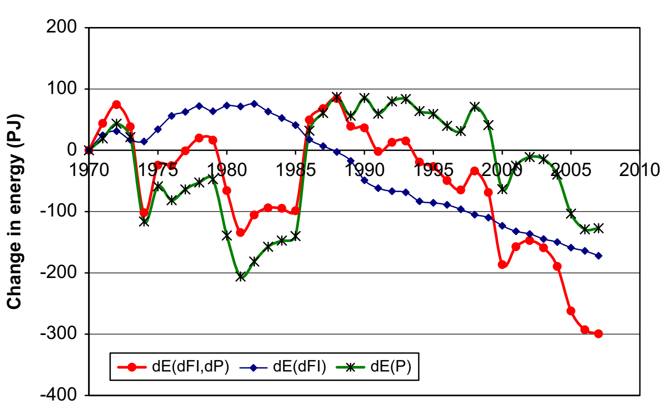

Fig. 7. The change of energy consumption due to changes in fuel intensity and fuel price for EU-6, base 1970.

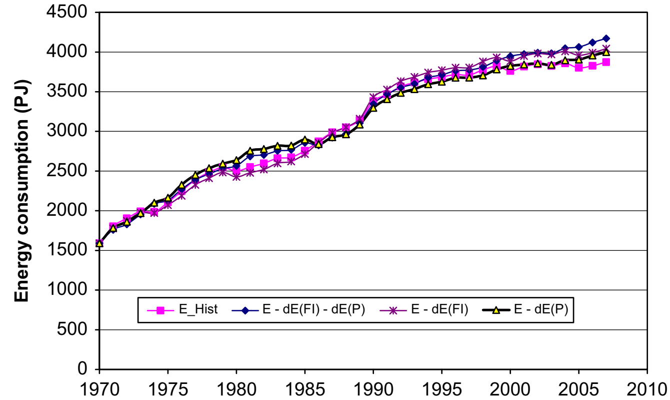

Fig. 8. Historic development of total energy consumption in comparison to the impact of fuel intensity and the fuel price for EU-6, base 1970.

due to the volatility of the fuel price, the price effect can lead to higher or lower energy consumption. With respect to the fuel intensity effect savings compared to the base year can be observed only since about 1987, see Fig. 7.

The saving effect of prices was the strongest between 1973 and 1985 and then again after 2005. After 1985 the price drop led to an increase in energy consumption. Finally at the end of the investigated period in 2007, there was a price effect of about 130 PJ ($\sim$3%) energy savings compared to 1970. In total the price and the FI effect brought about energy savings *dE* of about 300 PJ ($\sim$8%).

Fig. 8 depicts the development of total energy consumption in comparison to the impact of fuel intensity and fuel prices. Summing up, over the observed period 1970–2007 the price effect led to savings of about 3% and the FI effect reduced energy consumption by about 5%. Of specific interest is that the rebound due to driving more was of the same magnitude of about 3% as the price effect.

8. The impact of the increase in use of diesel

One of the most remarkable developments in passenger car transport in the last decades was the rapid gain of market shares of diesel vehicles. This effect was especially impressive in some European countries like France, Austria and recently in Italy, Germany, Denmark and Sweden, see Fig. 9.

While not all reasons for the switch to diesel are fully explored, two major arguments are: lower prices and lower fuel intensities. As can be seen from Fig. 11, due to the switch to diesel average *FI* of the vehicle stock declined steeper than *FI* of gasoline. These two aspects led to significantly lower service prices per km driven for diesel. Fig. 10 shows the ratio of service price of gasoline Ps_g (EUR/100 km) and the service price of diesel Ps_d (EUR/100 km) for the average of all cars on the road. Fig. 10 clearly depicts the economic benefit of diesel with service prices of gasoline being between 32% (IT) and 46% (DK) higher in 2007.

The development of the fuel intensities and fuel prices of the actual fuel mix (see also Eqs. (2) and (3)) and gasoline in the EU-6 countries is described in Fig. 11.

Of interest in this paper is how this change in service prices affected the demand for the service (vkm driven) and the resulting energy consumption.

How can we proceed to identify these effects? Our first attempt was to estimate the following equation:

$$E_t = CP_t^{\alpha} Y_t^{\beta} FI^{\gamma} SHD \tag{24}$$

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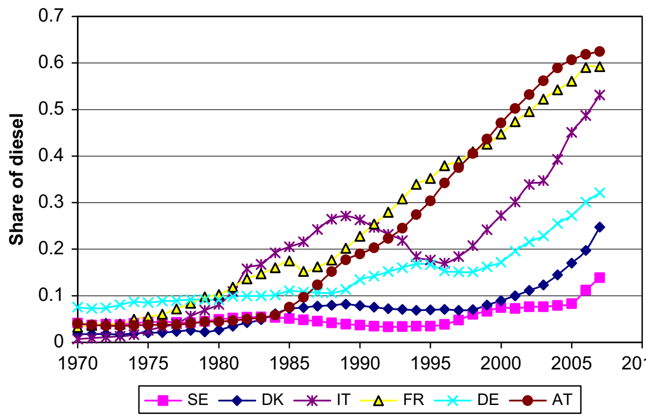

Fig. 9. Increase in the share of diesel in the countries investigated.

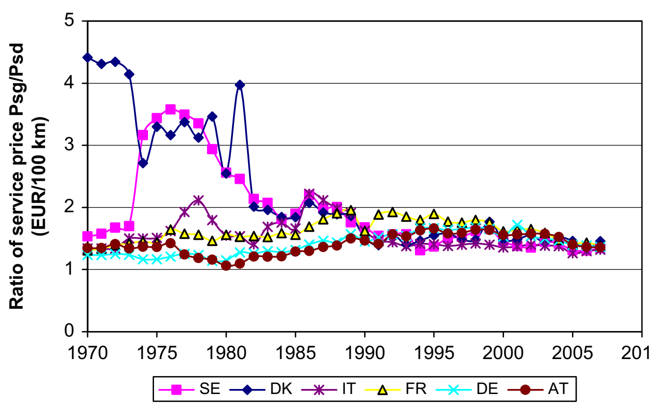

Fig. 10. Development of the ratio of service prices (P_{Sg}/P_{Sd}) in the countries investigated.

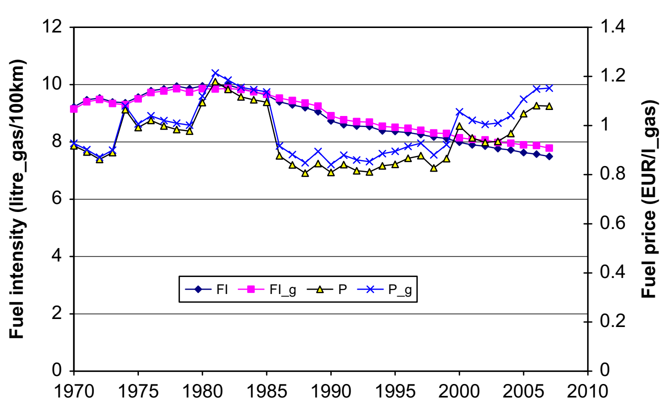

Fig. 11. Development of the fuel intensities and fuel prices of the actual fuel mix (incl. actual diesel shares) and gasoline in the aggregate of the countries.

with *SHD*=share of diesel. However, our estimates were very imprecise because of the high multicollinearity between the share of diesel and the energy price, as well as the fuel intensity.

Yet, we can extract the *FI* and the price effect in a similar way to that in Section 7. In Section 7 we were interested in the effects of changes of fuel prices and fuel intensities over time. Now we are interested in the effects of the differences in prices and FI between the fuel mix and the gasoline. The change in this mix is caused by the switch to diesel.

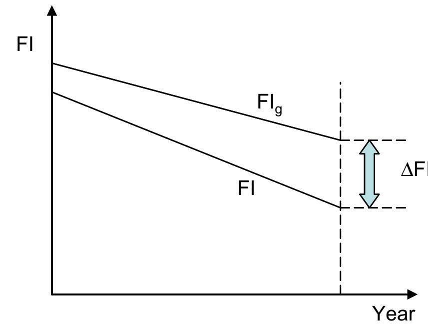

Fig. 12. Development of fuel intensity of fuel mix *FI* and gasoline FI_g.

First we look at the impact of the lower fuel intensity of diesel cars on energy consumption. We are interested in the change of the difference ΔFI_t of the fuel intensity between the fuel mix and the gasoline over time due to the switch to diesel. That is to say, of interest is how much better weighted average fuel intensity *FI* (see Eq. (3)) is than fuel intensity of gasoline cars FI_g in a specific year, see Fig. 12.

This difference ΔFI is

$$\Delta FI = FI_g - FI \tag{25}$$

To extract the fuel intensity impact of the switch to diesel we use Eq. (14).[7] We look at the impact of a change in ΔFI and we obtain

$$\frac{dE}{d(\Delta FI)} = FI\frac{dS}{d(\Delta FI)} + S\frac{dFI}{d(\Delta FI)} \tag{26}$$

Equivalently to Eq. (20) dS is

$$dS = \alpha\frac{S}{FI}d(\Delta FI) \tag{27}$$

and finally we obtain for the total change in energy consumption due to a change in ΔFI:

$$dE(d(\Delta FI)) = Sd(\Delta FI) + \alpha Sd(\Delta FI) \tag{28}$$

The two components of Eq. (28) and the total change of energy consumption depending on ΔFI are depicted in Fig. 13.

Next we look at the impact of lower or higher diesel price on energy consumption. Again we are interested in the change of the price difference of the fuel mix (ΔP) over time due to the switch to diesel. Now, of interest is how much lower the weighted average fuel price *P* (see Eq. (2)) is than gasoline price P_g in a specific year. Fig. 14 depicts the development of the price of fuel mix, the price of gasoline and ΔP with

$$\Delta P = P_g - P \tag{29}$$

Next we can extract the price impact of the switch to diesel on energy consumption using again Eq. (14). We assume that all changes of fuel intensity are based on exogenous effect so that $dFI/dP=0$. Then we obtain

$$\frac{dE}{d(\Delta P)} = FI\frac{dS}{d(\Delta P)} \tag{30}$$

Correspondingly to Eq. (20) we get

$$dS = \alpha\frac{S}{P}d(\Delta P) \tag{31}$$

[7] It is important that this difference is distorted by the fact that diesel cars are bigger than gasoline cars, see Schipper and Hedges (submitted).

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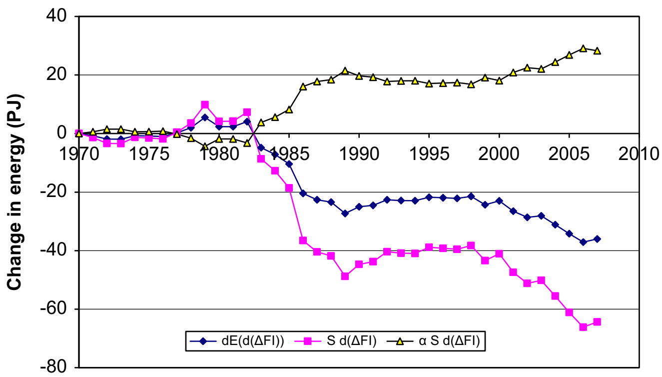

Fig. 13. Impact of changes in fuel intensity on total energy consumption due to a switch to diesel for EU-6, base 1970.

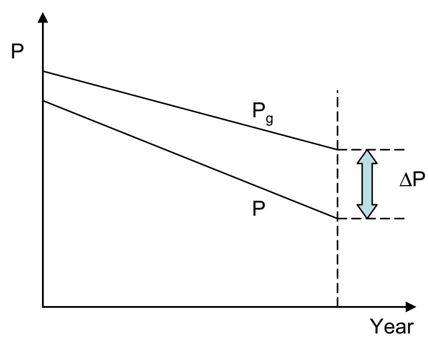

Fig. 14. Development of price of the fuel mix *P* and gasoline P_g.

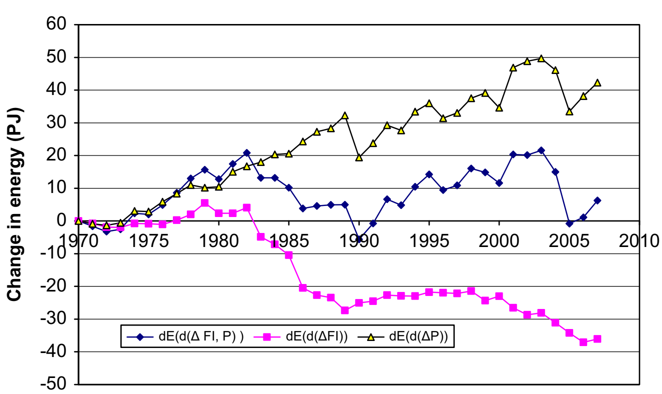

Fig. 15. The change of energy consumption due to switch to diesel: share of changes due to fuel intensity and fuel price.

and

$$dE(d(\Delta P)) = \alpha SFI \frac{d(\Delta P)}{P} \tag{32}$$

In Fig. 15 the fuel intensity effect and the price effect, as well as the total changes due to the switch to diesel, are depicted. The total change is

$$dE(d(\Delta FI, P)) = dE(d(\Delta FI)) + dE(d(\Delta P)) \tag{33}$$

The major simple perception is that the energy savings due to better *FI* are simply compensated by energy consumption due to more km driven. Over the observed period the total balance of these two effects led only in one year – 1990 – to effective savings.

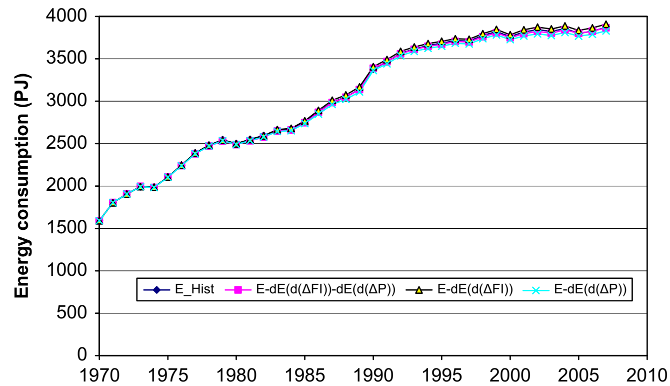

Fig. 16. Comparison of the impact of prices and fuel intensity due to the switch to diesel and total historic energy consumption for the aggregate of the investigated countries.

Finally, Fig. 16 shows the size category of the impact of prices and fuel intensity due to the switch to diesel in comparison with total energy consumption. The bottom line shows hypothetical development of energy consumption if no switch to diesel would have taken place. We can see that the differences over the whole period were virtually neglectable.

So summing up dieselization did not lead to a net energy conservation effect. On contrary a slight increase of energy consumption in most years was the sobering net balance.

9. Conclusions

The focus of this paper has been to extract the impacts of fuel intensity and fuel prices on energy consumption and demand for vehicle km driven, as well as interactions between these parameters in car passenger transport.

The major conclusions of this analysis are

The countries investigated show a broad range of patterns of energy consumption responses due to price and fuel intensity changes. To rule out at least some of country specific peculiarities we also made all estimates for the aggregate of these countries EU-6.

Regarding whether there are different responses of the market to rising vs. falling fuel prices – e.g. due to the implementation of irreversible efficiency improvements – we could not identify asymmetric patterns. For all countries and for the EU-6 the hypothesis for asymmetry had to be rejected. Hence, virtually the whole extent of efficiency improvements in times of rising prices is compensated for by a switch to larger cars in times of falling prices.

With respect to the impact of FI on energy consumption we got ambiguous results: Including FI directly in the econometric analysis gives a significant impact for three out of six countries and for the EU-6 as a whole. So finally we are in favor of considering a significant impact for the EU-6, especially because the corresponding coefficient for the EU-6 is highly significant.

Considering *FI* indirectly by means of using the service price for the estimation of service demand provides better results than all estimates for energy consumption. All variables are cointegrated for all single countries and the EU-6.

This concept of estimating vkm driven rather than energy consumption is useful also with respect to other aspects: it allows to extract the impact of the rebound due to km driven and it allows to identify the price and the FI effects of the switch to diesel.

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Regarding the rebound we got the result that with respect to vkm it is in the magnitude of about 44%. Furthermore, over the observed period of time it was almost equal to the price effect.

Concerning the impact of the switch to diesel our major perception is that the net energy saving effect is virtually zero. The slight saving effect due to better efficiency of diesel cars is virtually fully compensated by the rebound and an energy consumption increase due to lower prices.

The final recommendations for policy makers are: standards and fuel taxes are almost equally important. Moreover, a simultaneous introduction of standards and fuel taxes leads to the effect that taxes compensate for the rebound effect that emerges due to standards.

Further research areas are based on our curtailed consideration of the fuel intensity (as a proxy for efficiency). We have used time series of FI for the average of cars on the road. This leads to a *FI* that does not reflect the actual improvement of car efficiency because it is strongly influenced by the switch to larger cars. Further research work is needed to identify to what extent this impact is important and how to cope with it in policy design.

Acknowledgments

The authors are grateful to Carol Dahl and an anonymous reviewer for valuable comments.

Appendix A

See Tables A1–A3 here.

Table A1
Estimates of *F*-statistics for bounded test as described in Pesaran and Pesaran (1997) for Eq. (7) and Tables 2A and 2B.

	AT	DE	DK	FR	IT	SE	EU-6
$F(\ln(E)\|\ln(Y), \ln(P))$	4.60	2.48	0.87	8.64	2.63	6.95	1.68
$F(\ln(Y)\|\ln(E), \ln(P))$	3.81*	4.97	1.08	1.31	5.02	0.72	1.87
$F(\ln(P)\|\ln(Y), \ln(E))$	6.40	0.74	1.61	2.00	7.56	4.05*	1.15

Critical bounds due to Pesaran and Pesaran (1997): for $k=3$ with intercept and no trend: 3.22 and 4.38 for 5%.

* Significant at 10% level.

Table A2
Estimates of *F*-statistics for bounded test as described in Pesaran and Pesaran (1997) for Eq. (9) and Tables 4A and 4B.

	AT	DE	DK	FR	IT	SE	EU-6
$F(\ln(E)\|\ln(Y), \ln(P), \ln(FI))$	3.68*	1.63	1.44	3.01*	2.63	5.72	1.24
$F(\ln(Y)\|\ln(E), \ln(P), \ln(FI))$	2.06	3.86*	0.90	2.85	3.68*	0.39	1.28
$F(\ln(P)\|\ln(Y), \ln(E), \ln(FI))$	4.33	1.68	2.26	1.12	7.98	2.85	0.87
$F(\ln(FI)\|\ln(E), \ln(Y), \ln(P))$	1.12	2.65	6.46	4.55	1.40	3.55*	1.19

Critical bounds due to Pesaran et al. (1997): for $k=4$ with intercept and no trend: 2.85 and 4.05 for 5%.

* Significant at 10% level.

Table A3
Estimates of *F*-statistics for bounded test as described in Pesaran and Pesaran (1997) for Eq. (11) and Tables 5A and 5B.

	AT	DE	DK	FR	IT	SE	EU-6
$F(\ln(S)\|\ln(Y), \ln(P_S))$	3.27*	2.46	0.82	3.10	4.03*	6.14	2.52
$F(\ln(Y)\|\ln(E), \ln(P))$	4.00*	5.42	0.30	0.11	7.02	0.55	3.13
$F(\ln(P_S)\|\ln(E), \ln(Y))$	3.33*	1.13	1.10	1.14	2.80	3.20	0.88

Critical bounds due to Pesaran et al. (1997): for $k=3$ with intercept and no trend: 3.22 and 4.38 for 5%.

* Significant at 10% level.

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