

Frondel, Manuel; Vance, Colin

**Article — Accepted Manuscript (Postprint)**

## Re-Identifying the Rebound: What About Asymmetry?

The Energy Journal

**Provided in Cooperation with:**

RWI – Leibniz-Institut für Wirtschaftsforschung, Essen

*Suggested Citation:* Frondel, Manuel; Vance, Colin (2013) : Re-Identifying the Rebound: What About Asymmetry?, The Energy Journal, ISSN 1944-9089, International Association for Energy Economics, Cleveland, OH, Vol. 34, Iss. 4, pp. 42-54,  
<https://doi.org/10.5547/01956574.34.4.3> ,  
<https://www.iaee.org/en/publications/ejarticle.aspx?id=2524>

This Version is available at:

<https://hdl.handle.net/10419/148368>

**Standard-Nutzungsbedingungen:**

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

**Terms of use:**

*Documents in EconStor may be saved and copied for your personal and scholarly purposes.*

*You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.*

*If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.*

## Re-Identifying the Rebound: What About Asymmetry?

**Abstract.** Rebound effects measure the behaviorally induced offset in the reduction of energy consumption following efficiency improvements. Using panel estimation methods and household travel diary data collected in Germany between 1997 and 2009, this study identifies the rebound effect in private transport by allowing for the possibility that fuel price elasticities – from which rebound effects can be derived – are asymmetric. This approach rests on empirical evidence suggesting that the response in individual travel demand to price increases is stronger than to decreases. Such an asymmetric response would require referencing price elasticities derived from price decreases in order to identify the rebound effect, as it represents the response to a decrease in unit cost for car travel due to improved fuel efficiency. Failing to reject the null hypothesis of a symmetric price response, we alternatively estimate a reversible specification and obtain a rebound estimate for single-vehicle households being in the range of 46 to 70%, which is in line with an earlier German study by FRONDEL, PETERS, and VANCE (2008).

**JEL classification:** D13, Q41.

**Key words:** Automobile travel, panel estimation models, price asymmetry.

**Acknowledgements:** We are grateful for invaluable comments and suggestions by Christoph M. SCHMIDT, as well as three anonymous reviewers, and the editor, Lester HUNT. This work has been partly supported by the German Federal Ministry of Education and Research (BMBF) within the framework of the project “Social Dimensions of the Rebound Effect” and by the Collaborative Research Center “Statistical Modeling of Nonlinear Dynamic Processes” (SFB 823) of the German Research Foundation (DFG), within the framework of Project A3, “Dynamic Technology Modeling”.

# 1 Introduction

Presuming that mobility is a conventional good, a decrease in the cost of driving due to an increase in fuel efficiency would result in an increased demand for car travel. This demand increase is referred to as the rebound effect (KHAZZOOM, 1980), as it offsets – at least partially – the reduction in energy demand that would otherwise result from an increase in efficiency. Though the existence of the rebound effect is widely accepted, its magnitude remains a contentious issue (e. g. BROOKES, 2000; BINSWANGER, 2001; SORRELL and DIMITROUPOULOS, 2008).

An important issue that so far has been ignored in the debate on the rebound effect is the potential asymmetry in fuel demand, that is, that motorists may display differential responses to fuel price increases and decreases. Yet, numerous empirical studies, such as those by DARGAY (1992), GATELY (1992), HOGAN (1993), DARGAY and GATELY (1994, 1997), GATELY and HUNTINGTON (2002), HUNTINGTON (2006), ADEYEMI and HUNT (2007), and ADEYEMI et al. (2010), lend support to the view that asymmetric price responses deserve consideration.

In particular, several investigations have emerged suggesting that the response to price increases is stronger than the response to price decreases. As GATELY (1992) and others have argued, asset fixity provides one explanation for this so-called hysteresis<sup>1</sup>: improved auto design features that emerge in response to higher fuel prices are unlikely to be abandoned after prices fall, giving rise to a muted demand response. This phenomenon has implications for the analysis of the rebound effect: If the response to increases in the per-kilometer cost of driving is measurably stronger than the response to decreases, then estimates of the rebound effect based on reversible specifications may be biased.

The present article is the first that deals with the consequences of fuel price asymmetries for the identification of the rebound effect. To this end, we provide for a novel

---

<sup>1</sup>The notion of hysteresis originates from the physics of magnetism and refers to an effect that persists after its cause has been removed (DARGAY, GATELY, 1997:71).

definition of the direct<sup>2</sup> rebound effect that lends itself to an asymmetric modeling of fuel price responses. Like an earlier study by FRONDEL, PETERS, and VANCE (2008), the data used here is drawn from a panel of German households, but with the focus on those households that have not changed their cars over the three consecutive years they are surveyed, thereby reducing the possibility that mainly technical change is driving the result. The robustness of the results of our former study is checked by employing four additional waves of data for the years 2006 to 2009, so that the number of households in the database almost doubles. In contrast to FRONDEL, PETERS, and VANCE (2008), but in line with FRONDEL, RITTER, and VANCE (2012), we deliberately refrain from including any fuel efficiency measure in our model specifications, recognizing that this likely endogenous variable may be a bad control (ANGRIST, PISCHKE, 2009).

The following section outlines our strategy for quantifying the rebound effect while accounting for asymmetric fuel price responses, a hypothesis that is not supported by our empirical estimations. Section 3 describes our estimation method, followed by a concise description of the panel data set in Section 4. The presentation and interpretation of the results is given in Section 5. The last section summarizes and concludes.

## 2 Reconciling Price Asymmetry and the Rebound

To take account of demand response asymmetries is important for at least two reasons: First, if there are such asymmetries, for instance, because motorists learn to drive more efficiently due to fuel price increases, but do not stop driving efficiently when prices decrease, price volatility might be an effective conservation measure. Second, the direct rebound effect might be mis-measured when it is estimated on the basis of the conventional rebound definitions, which are catalogued by SORRELL and DIMITROUPOULOS

---

<sup>2</sup>Note that the indirect rebound effect, arising from an income effect due to lower per-unit cost of an energy service, and general equilibrium effects have also been distinguished in the literature (SORRELL, DIMITROUPOULOS, SOMMERVILLE, 2009:1356).

(2008) and concisely reiterated now: **Definition 1:**  $\eta_\mu(s) := \frac{\partial \ln s}{\partial \ln \mu}$ , the elasticity of the demand for a particular energy service in the amount of  $s$  with respect to energy efficiency  $\mu$ , **Definition 2:**  $-\eta_{p_s}(s)$ , the negative of the elasticity of service demand  $s$  with respect to service price  $p_s := p_e/\mu$ , which is proportional to the energy price  $p_e$  for given efficiency  $\mu$ , and **Definition 3:**  $-\eta_{p_e}(e)$ , the negative of the energy price elasticity of energy demand  $e$ .

Definition 1 is the most natural definition of the direct rebound effect (BERKHOUT *et al.*, 2000), as, formally, the service demand response to energy efficiency changes is described by the elasticity of service demand with respect to efficiency. However, due to the likely endogeneity of energy efficiency (SORRELL, DIMITROUPOULOS, SOMMERVILLE, 2009:1361), FRONDEL, RITTER, and VANCE (2012) argue that none of these definitions should be applied<sup>3</sup> and instead suggest a fourth rebound definition that is based on the negative of the energy price elasticity of service demand,  $\eta_{p_e}(s)$ :

$$\textbf{Definition 4:} \quad -\eta_{p_e}(s) = -\frac{\partial \ln s}{\partial \ln p_e}. \quad (1)$$

One important drawback of Definition 4, however, as well as of the conventional definitions, is that it ignores demand response asymmetries. For the purpose of exploring the consequences of travel demand response asymmetries on the estimates of direct rebound effects, we argue that the rebound effect is to be identified by an elasticity estimate that reflects changes in travel demand due to *decreases* in fuel prices, as the rebound effect represents the response to a decrease in the unit cost for car travel due to improved fuel efficiency.

With its focus on the unit cost for car travel, and, hence, the price  $p_s$  for this service, this argument would suggest taking a modification of Definition 2, i. e.  $-\eta_{p_s}(s)$ , as a basis for any generalized rebound definition that is conceived to capture asymmetric demand responses. Yet, due to the likely endogeneity of efficiency  $\mu$  that contaminates the estimation of the rebound via Definition 2, we propose the following generalization

---

<sup>3</sup>An extensive discussion on why Definitions 1-3 appear to be inappropriate for both theoretical and empirical reasons can be found in FRONDEL, RITTER, and VANCE (2012).

of Definition 4 as a viable alternative in case of asymmetry:

**Definition 5:** 
$$-\eta_{p_e^-}(s) = -\frac{\partial \ln s}{\partial \ln p_e^-} . \quad (2)$$

In this definition, distinct responses to rising and falling prices are captured by employing a price variable  $p_e^-$  that is solely linked to negative fuel price changes.

In order to apply Definition 5 empirically, in what follows we pursue the price decomposition approach introduced by TWEETEN and QUANCE (1969a, b) and provide for a concrete definition of price variable  $p_e^-$ . We will argue that only with the dummy-variable approach of TWEETEN and QUANCE is one able to estimate the fuel price elasticity that is the core of Definition 5. While we also will reference other, more common decomposition approaches, we will demonstrate that these would not allow for estimating the fuel price elasticity underlying Definition 5.

### 3 Methodology

To capture potentially different responses to rising and falling prices, many price decomposition approaches have been suggested in the literature. Among others, these approaches include the jagged ratchet model proposed by WOLFFRAM (1971), the ratchet specification of TRAILL, COLMAN, and YOUNG (1978), and the price decomposition approach employed by GATELY (1992). We deliberately refrain from employing these classical models for two reasons: First, GRIFFIN and SCHULMAN (2005:7) criticize these models for being highly dependent on the starting point of the data. In fact, while choosing the first year of the sampling period as a starting point seems natural from the perspective of an empiricist, it appears to be quite arbitrary from a theoretical point of view. A second troubling aspect of GATELY's price decomposition approach, which includes the ratchet models as special cases, may be seen in the fact that the demand curve can shift inward purely due to price volatility, although the average price level remains fixed, an issue illustrated by GRIFFIN and SCHULMAN (2005:7) by a simple example.

Following TWEETEN and QUANCE (1969a, b), we employ two price variables,  $p^+$  and  $p^-$ , with the price variable  $p^-$  taking on the role of fuel price variable  $p_e^-$  in Definition 5 and being defined as

$$p_{it}^- := p_{it}, \quad \text{if } p_{it} < p_{i(t-1)}, \quad (3)$$

and  $p_{it}^- := 0$  otherwise. Subscripts  $i$  and  $t$  are used to denote the observation and time period, respectively. With  $p^+$  being defined accordingly, by definition,  $p_{it}^+ + p_{it}^- = p_{it}$  for all  $i$  and  $t$ , so that price variable  $p$  is decomposed into the two variables  $p^+$  and  $p^-$  that are related to rising and falling prices, respectively.<sup>4</sup>

Given this price decomposition and our focus on rebound Definition 5, we regress the logged vehicle kilometers traveled,  $\ln(s)$ , on those logged fuel prices  $D^- \cdot \ln(p)$  that are observed after a price decrease from period  $t - 1$  to  $t$ , where  $D_{it}^- = 1$ , if  $p_{it} < p_{i(t-1)}$ , and zero otherwise, and on those logged fuel prices  $D^+ \cdot \ln(p)$  that are observed after a price increase or stagnation from  $t - 1$  to  $t$ , as well as a vector of control variables  $\mathbf{x}$  described in the next section:

$$\ln(s_{it}) = \alpha_0 + \alpha_0^+ \cdot D_{it}^+ + \alpha_{p^+} \cdot D_{it}^+ \cdot \ln(p_{it}) + \alpha_{p^-} \cdot D_{it}^- \cdot \ln(p_{it}) + \alpha_{\mathbf{x}}^T \cdot \mathbf{x}_{it} + \xi_i + v_{it}, \quad (4)$$

with  $D_{it}^+ = 1 - D_{it}^-$  for all  $i$  and  $t$  (for a similar specification, see also MEYER and CRAMON-TAUBADEL, 2004: 594). The superscript  $T$  designates the transposition of a vector,  $\xi_i$  denotes an unknown individual-specific term, and  $v_{it}$  is a random component that varies over individuals and time. Since travel demand shrinks with increasing fuel prices, the coefficients  $\alpha_{p^+}$  and  $\alpha_{p^-}$  should be negative, as is confirmed by our estimation results.

*A priori*,  $\alpha_{p^+}$  can be assumed to differ from  $\alpha_{p^-}$ . Whether this is the case requires testing the null hypothesis

$$H_0 : \alpha_{p^+} = \alpha_{p^-}, \quad (5)$$

---

<sup>4</sup>The logic follows other decompositions that have been employed in the literature and split up a single variable into two complementing variables in order to allow for distinct effects with respect to a certain property, such as price in- or decreases in our case. ROUWENDAL (1996), for example, employs an analogue decomposition of fuel prices into price variables for gasoline and diesel to allow for different effects of diesel and petrol prices on fuel use per kilometer.

which, if correct, implies that model (4) reduces to the reversible specifications that are typically employed to estimate the rebound effect (see e. g. FRONDEL, PETERS, and VANCE, 2008). If, however,  $H_0$  is rejected, we argue on the basis of Definition 5 that the rebound effect should be identified by the negative of the estimate of  $\alpha_{p^-}$ .

The case where  $\alpha_{p^+} \neq \alpha_{p^-}$  and, hence, demand responses to price increases differ in magnitude from those to price decreases could be visualized by demand curves kinked at the current price, so that demand is related to increasing and decreasing prices in an asymmetric way (DARGAY, 1992:168). For single-vehicle households that do not change their car within the survey period, which is our empirical focus, the intuition behind such kinked demand curves may be that these households react to price rises with a fuel-saving driving behavior that they maintain even when prices fall to original levels. DARGAY and GATELY (1997:72) have referred to this behavior as “addiction asymmetry”, reflecting the proclivity of consumers to more readily adapt new habits than abandon them.

Many other price decomposition approaches have been suggested in the empirical literature, such as those employed by DARGAY (1992) and RYAN, WANG, and PLOURDE (1996). Along the lines of the jagged ratchet model proposed by WOLFFRAM (1971), DARGAY (1992), for instance, employs two variables  $P^+$  and  $P^-$  reflecting cumulated price increases and decreases, respectively, where

$$P_{it}^+ := \sum_{s=1}^t [p_{is} - p_{i(s-1)}] \quad \text{for all } p_{is} > p_{i(s-1)}, \quad (6)$$

while  $P^-$  is generated for falling prices in a similar fashion. Yet, by including difference variables  $P^+$  and  $P^-$  in a demand function, instead of price level variables, one cannot obtain an elasticity estimate. Estimating  $\frac{\partial \ln s}{\partial \ln P^-}$  would thus be misplaced to get an estimate of the rebound effect based on Definition 5. Similar obstacles emerge when pursuing other approaches, such as the ratchet model, which incorporates cumulated price differences rather than price levels. It should be noted, however, that the history of price developments and path dependencies are ignored when using asymmetry specification (4), whereas it is accounted for in one or the other way in the classical decomposition approaches.



Furthermore, it bears noting that our approach is less restrictive than the ratchet model of TRAILL, COLMAN, and YOUNG (1978), which assumes that only price rises above the previous maximum have asymmetric effects (DARGAY, 1992:168). In contrast, specification (4) is based on the assumption that each price rise, as well as each price fall, may affect demand, albeit in a potentially different way. While this also holds true for GATELY's price decomposition approach, a final reason for choosing specification (4) is that the temporal restrictiveness of our data base does not allow for the application of the classical price decomposition approaches, nor for error-correction models (ECM). Hence, we cannot account for dynamic adjustments to long-run relationships, as is done by BETTENDORF, VAN DER GEEST, and VARKEVISSER (2003) and BORENSTEIN, CAMERON, and GILBERT (1997), for instance.

Instead, we employ a quasi-static approach in which potential inward shifts of the demand function are captured by year dummies, thereby leaving the form and curvature of the demand function unchanged. In fact, for our empirical example, we have reason to believe that these time dummies would turn out to be statistically insignificant, reflecting moderate or even vanishing shifts of the demand function, as we focus on households that did not change their cars over the maximum of three years they are surveyed. This belief is confirmed by the fact that the year dummies included in the estimation specification are statistically insignificant both individually and as a whole, and have therefore been left out in our final estimations.

## 4 Data

The data used in this research is drawn from the German Mobility Panel (MOP 2012) and covers thirteen years, spanning 1997 through 2009 (see FRONDEL, PETERS, and VANCE (2008) for more details on this survey). By focusing on single-car households that did not change their car over the maximum of three years each household is surveyed, we reduce the complexities associated with the influence of technological change. The resulting sample comprises a total of 2,969 observations covering 1,668

households.

Travel survey information, which is recorded at the level of the automobile, is used to derive the dependent and explanatory variables. With our focus on rebound Definition 5, the dependent variable is given by the total monthly distance driven in kilometers (Table 1). The key explanatory variable for identifying the direct rebound effect from this definition is the price paid for fuel per liter.<sup>5</sup>

**Table 1:** Variable Definitions and Descriptive Statistics

Variable Name	Variable Definition	Mean	Std. Dev.
$s$	Monthly kilometers driven	1,110	689
$p_e$	Real fuel price in € per liter	1.03	0.15
$p^+$	Equals $p_e$ if $(p_e)_{it} > (p_e)_{i(t-1)}$ and 0 otherwise	1.07	0.14
$p^-$	Equals $p_e$ if $(p_e)_{it} \leq (p_e)_{i(t-1)}$ and 0 otherwise	0.98	0.14
$\# children$	Number of children younger than 18 in the household	0.35	0.76
$\# employed$	Number of employed household members	0.73	0.76
$income$	Real Household income in 1,000 €	2.11	0.66
$job\ change$	Dummy: 1 if an employed household member changed jobs within the preceding year	0.11	–
$vacation\ with\ car$	Dummy: 1 if household undertook vacation with car during the survey period	0.22	–
$multi-car\ households$	Dummy: 1 if a household has more than one car	0.35	–
$population\ density$	People in 1,000 per square km in the county in which the household is situated	0.95	1.07

**Note:** The means reported for  $p^+$  and  $p^-$  are the means of the non-vanishing values.

The suite of control variables that are hypothesized to influence the extent of motorized travel encompass, among others, the demographic composition of the household, its income, the surrounding population density, and a dummy variable indicating whether any employed member of the household changed jobs in the preceding year.

<sup>5</sup>The price series was deflated using a consumer price index for Germany obtained from DESTATIS (2012).

As we believe that undertaking a vacation trip with the car crucially depends on factors other than current fuel prices, such as preferences for the vacation destination and the cost of alternative modes, such as the flight cost for the whole family, we have included the variable *vacation with car* in the model specification, indicating whether the household undertook a vacation with the car during the survey period.<sup>6</sup> As a proxy for the availability of public transit, we employ the variable *population density*, which is measured in thousand people per square kilometer.

## 5 Empirical Results

To provide for a reference point for the results obtained from panel estimation methods, we estimate specification (4) using pooled Ordinary Least Squares (OLS), although applying OLS methods generally yields neither consistent nor efficient estimation outcomes. Performing the classical test of BREUSCH and PAGAN (1979) to examine the superiority of the random-effects model over an OLS estimation using pooled data, the test statistic of this Lagrange multiplier test of  $\chi^2(1) = 145.1$  clearly rejects the null hypothesis of no heterogeneity among households:  $Var(\xi_i) = 0$ .

While the fixed-effects estimator may be a potentially superior alternative (see e. g. FRONDEL and VANCE, 2010), it fails to efficiently estimate the coefficients of time-persistent variables, i. e. , variables that do not vary much within a household over time. Furthermore, the estimation of coefficients of time-invariant variables is entirely precluded by the fixed-effects estimator. It is not surprising therefore that the fixed-effects estimates reported in Table 2 are statistically insignificant for almost all variables included; this is clearly the result of very low variability of time-persistent variables, such as the number of children or the number of employed household members.

---

<sup>6</sup>One might argue that the car vacation dummy should be left out from the model specification, as well as other variables, such as “commute with car”, that also depend on factors other than fuel prices, such as convenience, but for which we have no information. It bears noting that the omission of the car vacation dummy has no material effect on the estimation results of the fuel price elasticities. These results are available from the authors upon request.

In our discussion of the empirical results reported in Table 2, we thus focus on the random-effects estimates. Several features bear highlighting. First, noting from the discussion in Section 3 that the rebound effect is identified by the negative of the coefficient of  $D^- \cdot \ln(p_e)$ , the coefficient estimate suggests that some 62% of the potential energy savings due to an efficiency improvement is lost to increased driving. Also of note is that this estimate perfectly fits to the rebound range of 57% to 67% estimated by FRONDEL, PETERS, and VANCE (2008) for the sub-sample of single-vehicle German households observed between 1997 and 2005.

**Table 2:** Estimation Results for Travel Demand of Single-Vehicle Households.<sup>7</sup>

	Pooled OLS		Fixed Effects		Random Effects	
	Coeff.s	Std. Errors	Coeff.s	Std. Errors	Coeff.s	Std. Errors
$D^+ \cdot \ln(p_e)$	** -0.671	(0.172)	-0.529	(0.282)	** -0.646	(0.154)
$D^- \cdot \ln(p_e)$	** -0.648	(0.161)	-0.442	(0.313)	** -0.621	(0.146)
<i># children</i>	-0.012	(0.023)	-0.032	(0.095)	0.018	(0.024)
<i>income</i>	* 0.078	(0.034)	-0.027	(0.049)	* 0.063	(0.029)
<i># employed</i>	** 0.175	(0.029)	-0.111	(0.064)	** 0.112	(0.029)
<i>job change</i>	** 0.163	(0.052)	** 0.186	(0.055)	** 0.178	(0.043)
<i>vacation with car</i>	** 0.423	(0.041)	** 0.289	(0.055)	** 0.352	(0.038)
<i>population density</i>	* -0.045	(0.022)	** 0.303	(0.058)	* -0.042	(0.021)
$\alpha_0^+$	-0.032	(0.035)	0.035	(0.039)	-0.017	(0.028)
$\alpha_0$	** 6.505	(0.074)	** 6.597	(0.131)	** 6.556	(0.066)
$H_0 : \alpha_{p^+} = \alpha_{p^-}$	F(1; 995) = 0.01		F(1; 995) = 0.13		$\chi^2(1) = 0.02$	

**Note:** \* denotes significance at the 5 %-level and \*\* at the 1 %-level, respectively.

Observations used: 1,105. Number of households: 732.

Second, even without performing any tests, a superficial inspection of the very close coefficient estimates of -0.646 and -0.621 tells us that the null hypothesis  $H_0 : \alpha_{p^+} = \alpha_{p^-}$  cannot be rejected at any conventional level. This impression is confirmed

<sup>7</sup>To correct for the non-independence of repeated observations from the same households over the years of the survey, observations are clustered at the level of the household, and the presented standard errors are robust to this survey design feature.

by a low  $\chi^2$ -statistic of  $\chi^2(1) = 0.02$ . In our example, therefore, the issue of whether to identify the rebound via distinguishing between demand responses due to fuel price increases or decreases appears to be moot. This finding, however, may be due to the fact that we deliberately focus here on single-vehicle households that do not change their car during the survey period, thereby minimizing the scope for technical change.

Given that  $H_0 : \alpha_{p+} = \alpha_{p-}$  is rejected, we present the outcome of the reversible specification in Table 3. The results are somewhat larger in magnitude than those reported in Table 2, but the differences are not statistically significant. A striking result is the large magnitude of the fuel price elasticity estimates, ranging from -0.46 in case of the fixed-effects estimation to -0.70 for the random-effects estimation.<sup>8</sup>

**Table 3:** Estimation Results from the Reversible Specification for Travel Demand of Single-Vehicle Households.<sup>9</sup>

	Pooled OLS		Fixed Effects		Random Effects	
	Coeff.s	Std. Errors	Coeff.s	Std. Errors	Coeff.s	Std. Errors
$\ln(p_e)$	** -0.804	(0.084)	** -0.458	(0.111)	** -0.702	(0.074)
<i># children</i>	** 0.067	(0.021)	0.014	(0.056)	* 0.040	(0.016)
<i>income</i>	0.005	(0.016)	0.001	(0.025)	* 0.041	(0.017)
<i># employed</i>	** 0.164	(0.020)	-0.066	(0.035)	** 0.114	(0.019)
<i>job change</i>	** 0.096	(0.033)	0.050	(0.037)	* 0.068	(0.029)
<i>vacation with car</i>	** 0.389	(0.027)	** 0.306	(0.031)	** 0.342	(0.024)
<i>population density</i>	* -0.058	(0.015)	0.168	(0.084)	** -0.062	(0.014)
<i>constant</i>	** 6.527	(0.046)	** 6.674	(0.099)	** 6.624	(0.040)

**Note:** \* denotes significance at the 5 %-level and \*\* at the 1 %-level, respectively.

Observations used: 2,969. Number of households: 1,668.

A key reason for the high elasticities obtained here and by FRONDEL, PETERS,

<sup>8</sup>We have also estimated the reversible model with the same observations as those used in the asymmetric specification and find a coefficient estimate for the fuel price variable of -0.61.

<sup>9</sup>The number of observations used in the reversible models increases substantially relative to the asymmetric specifications, because no observations are lost from the creation of the dummy variables used to capture prices changes over consecutive years.

and VANCE (2008) might be that the elasticities from household-level data are generally larger than those from aggregate time series data (WADUD, GRAHAM, NOLAND, 2010:65). Finally, it bears noting that much of the research on this topic, particularly that using household level data, is drawn from the US, where elasticity estimates may be lower because of longer driving distances and fewer alternative modes.

## 6 Summary and Conclusion

Although several empirical studies have shown that the negative demand response to fuel price increases is higher in magnitude than the positive response to fuel price decreases, the question as to whether this reflects a behavioral reaction or a manifestation of technical change continues to stimulate discussion (GRIFFIN and SCHULMAN, 2005). Our principal interest in this asymmetry question relates to its implications for the identification of the rebound effect, the behaviorally induced offset in the reduction of energy consumption following efficiency improvements (CRANDALL, 1992).

We argue that if the demand responses to increasing and decreasing fuel prices are asymmetric, it would require us to reference the fuel price elasticity derived from price *decreases* in order to identify the rebound effect, as the rebound represents the immediate response to a decrease in unit cost for car travel due to improved fuel efficiency. Drawing on household-level mobility data from Germany, we have tested for evidence of an asymmetric response to fluctuations in fuel prices, but have failed to reject the null hypothesis that the magnitude of the response to a price increase is equal to that of a price decrease. Notwithstanding our empirical results, we argue that, generally, failure to control for asymmetry would result in a biased estimate of the rebound.

From a policy perspective, the fact that our estimates of the rebound effects are relatively high calls into question the effectiveness of the European Commission's current emphasis on efficiency standards as a pollution control instrument (FRONDEL, SCHMIDT, VANCE, 2011). The estimates resulting from the reversible specification range between 46 to 70% for single-car households, meaning that between 46 to 70% of the

potential energy saving from efficiency improvements in Germany is lost to increased driving.

## References

ADEYEMI, O. L. , BROADSTOCK, D. C. , CHITNIS, M. , HUNT, L. C. , JUDGE, G. (2010) Asymmetric Price Responses and the underlying Energy Demand Trend: Are they Substitutes or Complements? Evidence from Modelling OECD Aggregate Energy Demand, *Energy Economics* **32**, 1157-1164-134.

ADEYEMI, O. L. , HUNT, L. C. (2007) Modelling OECD Industrial Energy Demand: Asymmetric Price Responses and Energy-Saving Technical Change, *Energy Economics* **29**, 693-709.

ANGRIST, J. D. , PISCHKE, J.-S. (2009) *Mostly Harmless Econometrics – An Empiricists Companion*. Princeton University Press.

BERKHOUT, P. H. G. , MUSKENS, J. C. , VELTHUISJEN, J. W. (2000) Defining the Rebound Effect. *Energy Policy* **28**, 425-432.

BETTENDORF, L. , VAN DER GEEST, S. A. , VARKEVISSER, M. (2003) Price Asymmetry in the Dutch Retail Gasoline Market. *Energy Economics* **25**, 669-689.

BINSWANGER, M. (2001) Technological Progress and Sustainable Development: What About the Rebound Effect? *Ecological Economics* **36**, 119-132.

BORENSTEIN, S., CAMERON, A.C., GILBERT, R. (1997) Do Gasoline Prices Respond Asymmetrically to Crude Oil Price Changes? *Quarterly Journal of Economics*, **112(1)**, 305-339.

BREUSCH, T., PAGAN, A. (1979) A simple Test for Heteroscedasticity and Random Coefficient Variation. *Econometrica* **47**, 1287-1294.

BROOKES, L. (2000) Energy Efficiency Fallacies Revisited. *Energy Policy* **28**, 355-367.

CRANDALL, R. W. (1992) Corporate Average Fuel Economy Standards. *Journal of Economic Perspectives*, **6 (2)**, 171-180.



DARGAY, J. M. (1992) *The Irreversible Effects of High Oil Prices: Empirical Evidence for the Demand for Motor Fuels in France, Germany, and the UK*, in *Energy Demand: Evidence and Expectations*, ed. D. Hawdon, London: Academic Press, 165-182.

DARGAY, J. M. (1993) Demand Elasticities. A Comment. *Journal of Transport Economics and Policy* **27 (1)**, 87-90.

DARGAY, J. M. , GATELY, D. (1994) Oil Demand in the Industrialized Countries. *The Energy Journal*, Special Issue on the Changing World Petroleum Market, 39-67.

DARGAY, J. M. , GATELY, D. (1997) The Demand for Transportation Fuels: Imperfect Price-Reversibility. *Transportation Research Part B: Methodological*, **31 (1)**, 71-82.

DESTATIS (Federal Statistical Office Germany) (2012) <http://www.destatis.de/>.

FRONDEL, M., PETERS, J., VANCE, C. (2008) Identifying the Rebound: Evidence from a German Household Panel. *The Energy Journal*, **29 (4)**, 154-163.

FRONDEL, M., RITTER, N. , VANCE, C. (2012) Heterogeneity in the Rebound: Further Evidence for Germany. *Energy Economics*, **34**, 388-394.

FRONDEL, M., SCHMIDT, C. M. , VANCE, C. (2011) A Regression on Climate Policy: The European Commission's Legislation to Reduce CO2 Emissions from Automobiles. *Transportation Research Part A: Policy and Practice* **45 (10)**, 1043-1051.

FRONDEL, M., VANCE, C. (2010) Fixed, Random, or Something in Between? A Variant of Hausman's Specification Test for Panel Data Estimators. *Economics Letters*, **107**, 327-329.

GATELY, D. (1992) Imperfect Price-Reversibility of U. S. Gasoline Demand: Asymmetric Responses to Price Increases and Decreases. *The Energy Journal* **13 (4)**, 179-207.

GATELY, D. , HUNTINGTON, H. G. (2002) The Asymmetric Effects of Changes in Price and Income on Energy and Oil Demand. *The Energy Journal* **23 (1)**, 19-55.

GRIFFIN, J. M. SCHULMAN, T. C. (2005) Price Asymmetry: A Proxy for Energy Saving

Technical Change. *The Energy Journal* **26** (2), 1-21.

HOGAN, W. W. (1993) OECD Oil Demand Dynamics: Trends and Asymmetries, *The Energy Journal* **14** (1), 125-157.

HUNTINGTON, H. G. (2006) A Note on Price Asymmetry As Induced Technical Change. *The Energy Journal* **27** (3), 1-7.

KHAZZOOM, D. J. (1980) Economic Implications of Mandated Efficiency Standards for Household Appliances. *The Energy Journal* **1**, 21-40.

MEYER, J. , CRAMON-TAUBADEL, S. von (2004) Asymmetric Price Transmission: A Survey. *Journal of Agricultural Economics*, **50**, 581-611.

MOP (German Mobility Panel) (2012) Mobilitätspanel. <http://mobilitaetspanel.ifv.uni-karlsruhe.de/de/studie/index.html>.

ROUWENDAL, J. (1996) An Economic Analysis of Fuel Use Per Kilometer by Private Cars. *Journal of Transport Economics and Policy*, **30** (1), 3-14.

RYAN, D. L. , WANG, Y., PLOURDE, A. (1996) Asymmetric Price Responses of Residential Energy Demand in Ontario. *Canadian Journal of Economics*, **29** (Special Issue Part 1), S317-S323.

SORRELL, S., DIMITROUPOULOS, J. , SOMMERVILLE, M. (2009) Empirical Estimates of the Direct Rebound Effect: A Review. *Energy Policy* **37**, 1356-1371.

SORRELL, S. , DIMITROUPOULOS, J. (2008) The Rebound Effect: Microeconomic Definitions, Limitations, and Extensions. *Ecological Economics* **65** (3), 636-649.

TRAILL, B. , COLMAN, D. , YOUNG, T. (1978) Estimating Irreversible Supply Elasticities. *American Journal of Agricultural Economics* **60**, 528-531.

TWEETEN, L. G. , QUANCE, (1969a) Positivistic Measures of Aggregate Supply Elasticities: Some New Approaches. *American Journal of Agricultural Economics* **51**, 342-352.

TWEETEN, L. G. , QUANCE, (1969b) Positivistic Measures of Aggregate Supply Elasticities: Some New Approaches. *American Economic Review Papers and Proceedings* **59**, 175-183.

WADUD, Z., GRAHAM, G. J., NOLAND, R. B. (2010) Gasoline Demand with Heterogeneity in Household Responses. *The Energy Journal*, **31 (1)**, 47-74.

WOLFFRAM, R. (1971) Positivistic Measures of Aggregate Supply Elasticities: Some New Approaches – Some Critical Notes. *American Journal of Agricultural Economics* **53**, 356-359.