RATIONALITY & COMPETITION
CRC TRR 190

The Moderating Effect of Fuel Prices On the Market Value of Fuel Efficiency, Driving Intensity, and Co2 Emissions

Vlada Pleshcheva (Institute for Marketing Humboldt-University Berlin)
Daniel Klapper (Institute for Marketing Humboldt-University Berlin)

Discussion Paper No. 141

March 8, 2019

Collaborative Research Center Transregio 190 | www.rationality-and-competition.de
Ludwig-Maximilians-Universität München | Humboldt-Universität zu Berlin
Spokesperson: Prof. Dr. Klaus M. Schmidt, University of Munich, 80539 Munich, Germany
+49 (89) 2180 3405 | info@rationality-and-competition.de

The Moderating Effect of Fuel Prices on the Market Value of Fuel Efficiency, Driving Intensity, and CO_2 Emissions*

Vlada Pleshcheva
Institute for Marketing, Humboldt-University Berlin
and
Daniel Klapper
Institute for Marketing, Humboldt-University Berlin

January 15, 2019

Abstract

In the current paper, we quantify the effect that fuel prices have on vehicle prices' responsiveness to fuel economy. We apply a hedonic price model to the German automobile market by using data on detailed technical specifications of high-sales vehicles of three sequential model years. In contribution to previous research, our specification enables us to distinguish between consumers' valuation of fuel economy versus their reaction to changes in fuel prices. Two sources of changes in consumers' willingness-to-pay for better fuel economy are discussed – changes in the budget for driving a car and changes in capital investments in better car quality. We also discuss the subsequent changes in the optimal driving intensity and the resulting carbon dioxide emissions. Differences in the effects are studied for various car makes of both diesel and gasoline engines.

JEL classification: D12, L62, Q41, Q51.
Keywords: CO_2 emissions; fuel economy; fuel prices; hedonic regression.

1 Introduction

Many previous studies have investigated the role of fuel prices in shaping various market outcomes. Applied to the automobile market, there is a vast body of literature on fuel price

*Financial support by Deutsche Forschungsgemeinschaft through CRC TRR 190 is gratefully acknowledged.

effects on automobile market shares (e.g., Klier and Linn, 2010), fleet structure (e.g., Li et al., 2009), the pricing of new and used cars (e.g., Allcott and Wozny, 2014; Busse et al., 2013), and driving intensity (e.g., Frondel and Vance, 2009; Gillingham, 2014). We contribute to the literature by quantifying how exactly fuel prices influence the market value of fuel economy. We use aggregate market data on vehicle prices and attributes for diesel and gasoline cars of three sequential model years (2011 to 2013) on the German automobile market and estimate a hedonic model of automobile prices to explore co-movements of vehicle price sensitivity to fuel economy with changes in fuel prices.

Derived from the utility maximization problem for consumers, the marginal willingness-to-pay for fuel economy contains two terms – the responsiveness of car prices to fuel economy, reflecting capital investments in car quality, and responsiveness to changes in the driving budget. If the price responsiveness to fuel economy does not depend on fuel prices, the only change from an increase in the price of fuel is the increasing per distance unit cost of driving that results in a decrease in vehicle distance traveled. In contrast to previous research, where the marginal benefit of driving a car of a particular fuel economy remained fixed, we allow this benefit to vary with fuel prices. In this case, because the price responsiveness to fuel economy is also a function of fuel prices, there are two sources of changes in the willingness-to-pay for fuel economy. The first source, as in previous research, corresponds to changes in the budget for driving a car, whereas the second source reflects changes in capital investments in better fuel economy. The total effect of these two sources may lead to either a decrease or an increase in the vehicle distance traveled.

Changes in the price responsiveness to fuel economy due to changes in fuel prices may come from both supply and demand side. For example, Ohta and Griliches (1986) argue that if fuel price shocks affect consumer choices, then one should observe corresponding adjustments in automobile prices. Previous research has found that higher fuel prices increase the demand for high-fuel-economy vehicles, pushing up their prices relative to cars with low fuel economy (e.g., Klier and Linn, 2010, Li et al., 2009). At the same time, an increase in fuel prices results in increasing production costs of a better fuel economy for car manufacturers. Both these effects – from the supply and demand side – increase the implicit value of a better fuel economy.

To recover a combined effect of these two sources of change, we use a hedonic price regression, which reflects changes in the equilibrium market prices of a product and, thus, captures an interaction between the supply and demand in each state of the market (Rosen, 1974). Hedonic price regressions have often been applied to the automobile market, which is characterized by high product involvement, a high degree of product differentiation, and rapid rates of product innovation (e.g., Boyd and Mellman, 1980; Triplett, 1969; Requena-Silvente and Walker, 2006). As in the previous work involving hedonic price regressions, we recognize an econometric problem of high collinearity between fuel economy and other car characteristics due to their technological interdependence (see Knittel, 2012 for a study on the technological interdependence of car attributes). To overcome this problem, we control for advances in fuel efficiency rather than advances in fuel economy itself. We define fuel efficiency as fuel economy multiplied by the horsepower of a car. This measure thus reflects a service output measured in kilometers driven with a car of a specific performance per unit of energy input (Patterson, 1996; Sprei et al., 2008). Because horsepower is negatively correlated with fuel economy, the computed fuel efficiency provides a more suitable measure of advances in car quality. In contrast to studies that use a combined measure presented by fuel operating costs, i.e., the costs of fuel per distance driven (Klier and Linn, 2010), the current paper explicitly investigates the role of fuel prices as a moderator of the market value of fuel economy. Thus, we can differentiate between consumers' valuation of fuel economy versus their reaction to changes in fuel prices.

Our paper is closely related to Busse et al. (2013) and Busse et al. (2016). These two papers show how changes in fuel prices affect equilibrium car prices and the sales of both new and used vehicles of different fuel economies. Busse et al. (2016) focus on the car manufacturers and their associated dealerships, whereas Busse et al. (2013) focus on the consumer side. Jacobsen and Van Benthem (2015), while investigating the effect of gasoline prices on vehicle scrappage decisions, also measure the relation between gasoline prices and the valuation of used vehicles. These three studies find that cars with high fuel economy are less sensitive to an increase in fuel prices, i.e., the slope of the car price gradient with respect to fuel prices becomes less negative. Thus, there is a positive relationship between the fuel economy of a car and changes in car prices with respect to fuel prices. We reverse the logic of these studies and explore the responsiveness of vehicle prices to fuel economy, depending on the fuel price. Accordingly, we expect to have a positive relationship between the price gradient of fuel economy and fuel prices. Our study differs from the ones mentioned above in that they do not aim and are not able to recover the market value of fuel economy because the authors include fuel economy as a categorical variable in their specification. We include both fuel economy and fuel price as continuous variables, and by including a term for their interaction into a price regression, we can look at the effects that fuel prices have on the market value of fuel economy. The specification we use provides an advantage over previous work in that it allows us to use the quantified impact of fuel prices on market valuation of fuel economy in a subsequent analysis to access the implied changes in the kilometers driven with cars and resulting CO_2 emissions – two important outcomes for policy evaluation. Additionally, because we look at the variation in car prices at the time of market entry, we do not need to account for possible rebates and differences in the bargaining power between sellers and buyers.

Applied to the German automobile market, the consumers' willingness-to-pay[1] for reduced fuel consumption is examined by only a few authors. Achtnicht (2012), for example, studies the importance of CO_2 emissions per kilometer and fuel costs in € per 100 km for car choices in Germany based on the mixed logit model with data from a choice experiment. In contrast, the current paper uses data on the observed vehicle attributes and their prices. Fetscherin and Toncar (2009) use the hedonic price regression to uncover the valuation of the brand equity and other attributes in the German automobile market. However, the authors exploit the ratings for several categories of attributes instead of car characteristics themselves, which might not fully reflect their relation to vehicle prices.

In our analysis, we focus on vehicles from compact and middle classes. These two car classes are characterized by stable high market shares and high supply relative to other car types. For example, based on the data used in this study, 25.6% and 12.6% of new passenger car registrations in 2013 belonged to compact and middle classes, respectively, and accordingly amounted to 27% and 17% in the total passenger car fleet. Vehicles from

[1]Within the context of the current paper, we use the terms "willingness-to-pay" and "market value" interchangeably, as the latter also reflects the former.

larger car classes (e.g., Mercedes S from the upper class) might be used predominantly for business trips, resulting in a smaller importance of adjustments in fuel economy to high fuel prices. We argue that the selected car classes represent the market and average technological patterns best. We also focus on cars that have been issued on the market over 2011-2013, a period after major policy reforms related to the German automobile branch were introduced (e.g., the scrappage policy in 2009; the adjustment of the vehicle annual circulation tax in 2009; and information disclosure in the form of fuel economy and CO_2 emissions labeling that came into force in 2011), after the car market and fuel prices recovered from the financial crisis of 2008-2009, and before the scandal relating to the emissions from diesel engines began in 2014.

The majority of previous studies have focused primarily on gasoline vehicles because these studies are based on data from the US market, where diesel-fueled vehicles constitute only 3% of the total fleet (as of 2014[2]). This paper, in contrast, compares the effects for both diesel and gasoline cars and belongs to studies on the European automobile market (e.g., Dahl, 2012; Delsaut, 2014; Frondel and Vance, 2009). In Germany over 2011-2013, the share of diesel vehicles, on average, accounted for 48% of the total new passenger car registrations and 30% of the total passenger car fleet; the rest of both new passenger car registrations and passenger car fleet belonged to gasoline vehicles, with only tiny shares (less than 2%) of alternative engine types (e.g., hybrid, electric, etc.).[3]

Our results indicate that there are significant differences in the market values of fuel economy between diesel and gasoline vehicles and their responsiveness to changes in fuel prices. Diesel cars are characterized by a larger elasticity of the price gradient of fuel economy to fuel prices compared to gasoline cars. This finding can be explained by a relatively higher popularity of diesel cars on the German market. Car manufacturers have developed technologies to improve the fuel economy of diesel cars in response to a growing demand from the consumer side. Because the diesel fuel price is lower than that for gasoline due to a favorable fuel tax on diesel, while capital investments in diesel cars are higher, buyers who decide to purchase diesel cars might also be characterized by a higher sensitivity to fuel

[2] `http://de.statista.com/statistik/daten/studie/473962` (accessed: October 08, 2017).

[3] `https://de.statista.com/statistik/daten/studie/251779` and `https://de.statista.com/statistik/daten/studie/184465` (accessed: October 08, 2017).

prices at the time of a car purchase. Both factors lead to a higher elasticity of the price gradient of fuel economy to fuel prices for diesel vehicles.

Relying on the rationality assumption in the consumer choice problem, we also recover the implied optimal driving intensity based on the estimated market values of fuel economy for both engine types and the corresponding total CO_2 emissions. The resulting values of car usage and CO_2 emissions are close to the official statistics for the German automobile market. This finding highlights the reliability of the results. In contrast to the majority of previous studies measuring the elasticity of driving intensity to fuel prices as being constant, the methodology of this paper allows for a nonlinear dependency between driving intensity and fuel prices that better reflects adjustments of consumers' driving patterns to changes in fuel prices.

The remainder of the paper is organized as follows. In section 2, we present the methodology and describe data used for the analysis. Section 3 presents the results of the empirical analysis. The section 4 discusses the implications of the findings and concludes.

2 Estimation approach

This paper uses a hedonic price regression to recover consumers' willingness-to-pay for marginal improvements in fuel economy, while controlling for all other car attributes, and to examine how fuel price fluctuations affect this value, consumers' implied optimal driving intensity, and CO_2 emissions. In the following, we present the model, describe the data, and specify the hedonic price regression we use for the analysis.

2.1 Model

The hedonic price model is based on the assumption that the observed price of a durable good reflects a combination of implicit values for each of its attributes (Rosen, 1974). Implicit prices for product attributes result from an intersection between an offer curve from the supply side and a bid function from the demand side. The hedonic price function is assumed to be exogenous for both parts of the bargain.

In application to the automotive market, a representative consumer derives utility from driving a car with quality X and fuel economy (in km/liter) and consuming all other goods that are treated as a single composite C. The consumer chooses a car that provides the highest utility given her own budget, which is distributed among a purchase of a vehicle ("initial investments"), the utilization of the car ("budget for driving"), and consumption of the composite good. The budget for a vehicle purchase is represented by the hedonic price function, whereas the budget for driving can be formalized as a product of price per kilometer (p_{km}) and the expected driving intensity (Km) over the period of car ownership. For a given car, p_{km} depends on its fuel economy (FE) and fuel price (FP) in €/liter, i.e. $p_{km} = \mathrm{FP}/\mathrm{FE}$ (€/km).

Formally, the consumer's problem can be represented by the system of equations 1, where X is a vector of car attributes other than fuel economy, $\mathbf{p}(\cdot)$ is the hedonic price function, Y is the consumer's income, and the price of the composite good (C) is normalized to unity. The hedonic price function is a functional dependence of the price of a car on its attributes.

$$\begin{cases} \max\ \mathrm{U(X,\ FE,\ Km,\ C)} \\ \mathrm{s.t.}\ \ \mathrm{Y} \geq \mathbf{p}(\mathrm{X}, \mathrm{FE}) + p_{km} \times \mathrm{Km} + \mathrm{C} \end{cases} \tag{1}$$

In equilibrium, the budget constraint is binding, and for continuous product attributes, the first-order condition (FOC) for a chosen product must hold. From the FOC, the marginal rate of substitution between a product attribute X_q and the composite commodity C equals the partial derivative of the hedonic price function with regard to the attribute. Thus, Equation 2 defines the implicit price or marginal willingness-to-pay (MWTP) for each car attribute.

$$\mathrm{MWTP}(\mathrm{X}_q) = \frac{\partial u(\cdot)}{\partial X_q} / \frac{\partial u(\cdot)}{\partial C} = \frac{\partial \mathbf{p}(X, FE)}{\partial X_q} \tag{2}$$

In contrast to Ohta and Griliches (1986) and Atkinson and Halvorsen (1984), we include the fuel economy of a car into the utility function and argue that it is important since there may be a direct effect of fuel economy on the utility of driving a car (aside from its effect on the budget constraint) through its direct connection to the environmental impact (i.e., consumers with higher environmental concern may derive higher utility from better fuel economy after accounting for savings in the fuel costs via the budget constraint). Because the price per kilometer also depends on fuel economy, the willingness-to-pay for fuel economy that results from the FOC includes an additional term along with the hedonic price gradient (Equation 3).

$$\text{MWTP(FE)} = \frac{\partial u(\cdot)}{\partial FE} / \frac{\partial u(\cdot)}{\partial C} = \frac{\partial \mathbf{p}(X, FE)}{\partial FE} - FP \times \frac{Km}{FE^2} \tag{3}$$

The willingness-to-pay for marginal improvements in fuel economy is expected to be positive (i.e., MWTP(FE) > 0) and to correspond to the law of diminishing marginal utility for an "economic good" (i.e., ∂MWTP(FE)$/\partial$FE < 0). In the case of an increasing fuel price, MWTP(FE) will decrease as a result of the increased costs of driving a car ("income effect").

$$\frac{\partial \text{MWTP(FE)}}{\partial \text{FP}} = -\frac{Km}{FE^2} < 0 \tag{4}$$

However, in our application, we would like to allow the price gradient to vary with fuel prices. It will thus reflect changes in the market valuation of a car's fuel economy due to changes in the fuel price. To do this, we must add a fuel price variable into the price regression along with its interaction with fuel economy. We expect the following relationships to hold:

$$\begin{cases} \frac{\partial \mathbf{p}(\cdot)}{\partial \text{FP}} < 0 \text{ for FE} < \text{FE}^* \\ \frac{\partial \mathbf{p}(\cdot)}{\partial \text{FP}} > 0 \text{ for FE} > \text{FE}^* \\ \frac{\partial}{\partial \text{FE}} \left(\frac{\partial \mathbf{p}(\cdot)}{\partial \text{FP}} \right) > 0 \end{cases} \tag{5}$$

The first two conditions in (5) suggest a decrease in the price of a vehicle if the value of fuel economy falls below a certain threshold (FE*) and an increase in the price otherwise (similar to Jacobsen and Van Benthem, 2015 and Busse et al., 2013). The sign of the price derivative with respect to the fuel price also depends on the prevalence of the effect from either increased production costs (positive) or decreased consumer income (negative). The third condition implies that vehicle prices are less sensitive to changes in fuel prices with increasing fuel economy. Due to the symmetry of the second derivative, this condition also implies that $\partial/\partial\mathrm{FP}\big(\partial\mathbf{p}(\cdot)/\partial\mathrm{FE}\big) > 0$. The net effect of fuel prices on MWTP(FE) then depends on the magnitudes of both terms on the right-hand side of Equation 6. The first term corresponds to the changes in the capital investments in a better fuel economy with changing fuel prices, while the second term reflects the changes in the budget for driving a car.

$$\frac{\partial \mathrm{MWTP(FE)}}{\partial \mathrm{FP}} = \frac{\partial}{\partial \mathrm{FP}}\left(\frac{\partial \mathbf{p}(\cdot)}{\partial \mathrm{FE}}\right) - \frac{Km}{FE^2} \lesseqgtr 0 \tag{6}$$

Given the utility maximization principle, a consumer chooses a bundle of vehicle attributes in a way that reflects her expected usage of a car at expected realizations of fuel price. Thus, the optimal annual kilometers could be computed based on the assumption that for a marginal improvement in fuel economy, a rational consumer is willing to pay the exact same amount because this additional improvement in fuel economy would allow her to save in fuel costs over a car possession time, T. We take an undiscounted version of the formula for fuel savings from one km/l and equate it to the willingness-to-pay for this improvement, as shown in Equation 7. We use the undiscounted version of fuel savings to avoid complicating matters unnecessarily. If we assume fuel economy and annual driving to be fixed over the ownership period and fuel prices to follow a random walk, the only difference between the discounted and undiscounted versions of fuel savings lies in one parameter that is a geometrical sum of interest rates over the ownership period. Thus, we will need to make an additional assumption on the interest rate. Note that this parameter only scales the underlying relationships between willingness-to-pay and optimal kilometers by a constant but does not alter the direction of this relationship. Substituting (3) into (7) and rearranging the terms, we obtain an expression for the optimal distance driven with a car per year, as shown in Equation 8.

$$\mathrm{MWTP(FE)} \equiv (\frac{1}{\mathrm{FE}} - \frac{1}{\mathrm{FE}+1}) \times \mathrm{FP} \times \mathrm{Km/T} \times \mathrm{T} \tag{7}$$

$$\mathrm{Km/T} = \frac{\frac{\partial \mathbf{p}(\cdot)}{\partial FE} \times FE^2 \times (FE+1)}{\mathrm{FP} \times (2FE+1) \times \mathrm{T}} \tag{8}$$

From Equation 8, it follows that the demand for driving a car is decreasing in fuel prices and increasing in fuel economy but at a decreasing rate. Thus, consumers who are willing to invest in better fuel economy are those who expect to drive intensively. However, at higher fuel prices, an improvement in fuel economy results in a smaller increase in kilometers driven. All these conditions are summarized below:

$$\frac{\partial \text{Km}}{\partial \text{FP}} < 0 \quad \text{and} \quad \frac{\partial \text{Km}}{\partial \text{FE}} > 0 \quad \text{and} \quad \frac{\partial}{\partial \text{FE}}\left(\frac{\partial \text{Km}}{\partial \text{FE}}\right) < 0 \quad \text{and} \quad \frac{\partial}{\partial \text{FP}}\left(\frac{\partial \text{Km}}{\partial \text{FE}}\right) < 0$$

Without a functional dependency of the price gradient of fuel economy on fuel prices, the computed optimal driving intensity is proportional to changes in fuel prices: if fuel prices double, the driving intensity halves, ceteris paribus. In case the price gradient of fuel economy also varies with fuel prices, the change in optimal driving intensity also depends on the magnitude of the price gradient of fuel economy relative to the (second) derivative of the price gradient of fuel economy with respect to the fuel price. By computing the derivative of optimal kilometers to the fuel price, it can be shown that

$$\frac{\partial \text{Km}}{\partial \text{FP}} < 0 \text{ if and only if } \frac{\partial \mathbf{p}(\cdot)}{\partial \text{FE}} > \frac{\partial}{\partial \text{FP}}\left(\frac{\partial \mathbf{p}(\cdot)}{\partial \text{FE}}\right) \times \text{FP}$$

After rearranging the terms, the last inequality translates into a condition $E_{FP}^{\frac{\partial \text{Price}}{\partial \text{FE}}} < 1$, i.e., the elasticity of the price gradient of fuel economy to fuel prices should be less than one to lead to a decrease in the optimal driving intensity.

Based on the derived optimal driving intensity, we can also compute the total emission of CO_2 (in tons) from a car powered by a specific engine type at a given fuel price as CO_2 emissions (gram/liter) $\times$ fuel economy (km/liter)$^{-1}$ $\times$ Km/T $\times$ 10^{-6}. Thus, a functional dependency of the total CO_2 emissions on fuel prices reflects that of the total driving intensity, scaled by a factor specific to each car version.

The hedonic prices for product attributes are estimated by regressing the product price on its characteristics. From an econometric point of view, there are two main estimation issues – the decision on relevant product attributes to be included into the hedonic price regression and the choice of its functional form. Theoretically, the equilibrium price function $\mathbf{p}(\cdot)$ may take any form, and the choice of product attributes is usually determined by the data availability, research question, and engineering background of the product. Here, it is important to choose those attributes and, accordingly, a regression specification that supports either the law of diminishing marginal utility for an "economic good" or the law of increasing marginal disutility for an "economic bad". These estimation issues are discussed in detail in the following two subsections after a description of the data.

2.2 Data

The data for the investigation comes from a web database provided by the largest automobile club in Germany, ADAC.[4] It gives an overview of vehicle prices, technical and non-technical characteristics of all automobiles available in Germany since the mid-1990s, including the dates (month and year) of the start and the end of each car model's production. We also obtain monthly fuel prices from the ADAC database and merge them to the car description data. All monetary values in the dataset have been inflation-adjusted by using the consumer price index (CPI), which is normalized to one in April 2010. Fuel prices are also seasonally adjusted using X-12 ARIMA – a model that is used by both the US Census Bureau and German Federal Statistical Office.

In our estimation, we focus on the period of three years and analyze how the market value of fuel economy responds to fluctuations in fuel prices over the period from 2011 to 2013. For this period, we additionally retrieve values of new passenger car registrations per year from the German Federal Motor Transport Authority (Kraftfahrtbundesamt[5]). To avoid an influence of outlier values, we select only those car models that have more than 50 units in the new passenger car registrations per year. A car model is defined by HSN-TSN code and transmission type (e.g., manual). The HSN and TSN stand for producer (Herstellerschlüsselnummern) and type (Typschlüsselnummern) key codes, respectively, which are set by the German Federal Motor Transport Authority. The HSN-TSN code uniquely identifies a car by its model name (e.g., VW Golf), car body type (e.g., hatchback), production start date

[4] http://www.adac.de/infotestrat/autodatenbank/default.aspx.
[5] http://www.kba.de

(e.g., 01/July/2001), engine size (e.g., 1997 cm^3), horsepower (e.g., 125 HP), and fuel type (e.g., diesel). In our analysis, we consider only car models with gasoline or diesel engines. Vehicles with other engine types constitute a tiny fraction of new car registrations (less than 2%). Our focus also lies on passenger cars from compact and middle classes and with sedan, hatchback, and station wagon body types. The selected car types cover on average 71% and 68% of the sales in the compact and middle classes, respectively. The rationale behind selecting these vehicles lies in their popularity among car buyers and, thus, the well developed supply of different combinations of product attributes. Hence, the selected car classes should represent the market and average technological patterns best.

The data in ADAC are highly disaggregated – two versions of the same product defined by the HSN-TSN code and transmission type are recorded separately if they differ in optional features not included in the baseline version of a car. These optional features lead to higher prices of a car model without altering car performance and fuel economy and hence do not help explain the relation between fuel economy and vehicle prices. As the main intention of this paper is to gain a monetary value for fuel economy, we therefore perform our analysis for a baseline version of each product determined by the lowest product price.[6]

A benefit of estimating implicit prices for product attributes based on the ADAC data is that this source provides a spectrum of all available products on the market over the whole period of investigation. Thus, all technological changes in the whole vehicle supply and their corresponding prices are observed. The price information for cars is represented by the Manufacturer Suggested Retail Price (MSRP), also known as the list price. Determined by the manufacturers, this price intends to provide a standard for the pricing of a product based on its characteristics. Hence, the MSRP reflects the manufacturer's assessment of the consumer's tastes for vehicle attributes in general. In our analysis, we look at the variation in car prices of similar car specifications due to the differences in fuel prices at the time of market entry. At this stage, possible car rebates and differences in the bargaining power between sellers and buyers are irrelevant factors.

[6]Tables A1 and A2 give an overview of the selected models for gasoline and diesel cars, respectively, with the number of products and the average vehicle prices.

2.3 Selection of car attributes

For empirical applications of the hedonic price model, it is important to decide what product attributes the regression should entail to appropriately explain the relationship between the price of a good and its characteristics. The model-building strategy in terms of the variable selection technique in this paper is based on the engineering background of the automotive industry, the quality of the available data, the car characteristics that are cited as important for buyers in industry overview reports[7] and that have been used in previous studies, and various statistical criteria for a model fit (e.g., C_p, information criteria, and Adjusted R^2).

The primary focus of this paper is the parameter estimate for fuel economy used in a subsequent analysis. The ADAC data provide three measures of fuel economy – city, highway, and weighted-average among city and highway values. In this paper, the latter measure is considered. From a technological perspective, however, fuel economy is strongly related to other car characteristics. This interdependence leads to a multicollinearity problem and, thus, to highly unstable parameter estimates and imprecisely estimated implicit prices. To overcome the strong interdependence between car attributes, many authors have proposed to include a variable that represents only one aspect of either fuel economy or vehicle performance (e.g., Agarwal and Ratchford, 1980). For example, Uri (1988) advises against any inclusion of the fuel economy variable, whereas Gramlich (2008) includes two different specifications of the fuel efficiency - miles per gallon (MPG) as a proxy for all other ("negative") product qualities ("higher MPG is strongly associated with lower other quality", p. 7) and the price of fuel divided by miles per gallon ($PM) as a measure of fuel economy itself. The present paper, however, undertakes another approach. Following the engineering literature, in which one may find a value of a power-specific fuel consumption (e.g., Van den Brink and Van Wee, 2001; Sprei et al., 2008), this paper considers a measure of fuel efficiency that is defined as a product of fuel economy with some indicator of a car's performance. In general, fuel efficiency refers to the amount of fuel necessary to produce a useful service output (Patterson, 1996). A better value of fuel efficiency means that less fuel is needed for the same amount of output. Service output in the car example can be represented by various

[7]The industry overview reports can be found, for example, at http://www.dat.de.

variables for car performance (e.g., horsepower, kW, power output per liter, etc.). In this paper, we follow previous studies and define fuel efficiency as a product of fuel economy and horsepower.[8] This measure allows us to control for car performance while recovering the relationship between vehicle prices and fuel economy of a theoretically plausible direction. As can be seen in Table 1, the fuel economy of vehicles increases over model years but has a negative correlation with car prices, as shown in Table 2. We also see that fuel economy is highly correlated with various measures of car performance and engine characteristics. Advocated from a technology perspective, this pattern reflects the fact that heavier and more powerful cars cost more but also consume more fuel. Adjusted by the car performance, however, the expected positive relationship between the vehicle price and fuel economy is restored.

Table 1: Fuel prices, car prices, and fuel efficiency over years

		Diesel			Gasoline		
		2011	2012	2013	2011	2012	2013
Fuel price	Mean	1.39	1.42	1.34	1.50	1.54	1.47
	SD	0.03	0.04	0.02	0.01	0.03	0.02
Car price	Mean	29321.87	28485.04	28212.85	27352.10	27692.72	26572.58
	SD	6936.29	6646.43	6253.51	7992.11	8287.36	7956.5
Fuel economy	Mean	19.99	21.18	21.51	14.97	15.64	16.71
	SD	2.51	2.75	3.26	1.93	2.01	2.32
Fuel efficiency	Mean	2867.51	3017.62	3148.05	2369.69	2529.35	2682.21
	SD	595.79	681.83	711.78	562.56	681.34	667.31
Forced induction	Mean	1	1	1	0.71	0.75	0.86
	SD	0	0	0	0.46	0.43	0.35
N		217	233	231	177	228	227

NOTE: Fuel prices are in 2010 € per liter; car prices are in 2010 €; fuel economy is in km/l. Fuel efficiency is defined as (fuel economy × horsepower). Values for forced induction are shares of the technology within all cars started being produced in a particular model year based on the ADAC data.

On average, diesel cars consume less fuel per unit distance than otherwise comparable gasoline vehicles. For example, a car from the compact class with 140 HP and manual transmission consumes, on average, 6.26 liter of fuel per 100 kilometers (≡ 16.17 km/l) in the case of a gasoline engine and only 4.93 l/100 km (≡ 20.51 km/l) with a diesel engine.

[8] Other measures of car performance are highly correlated with horsepower and consequently yield statistically similar estimation results.

Table 2: Pearson correlation coefficients for a subset of vehicle attributes

	Price	FC	FE	FEff	HP	Displ	Weight
Car price, 2010 €	1	0.29	-0.26	0.67	0.79	0.76	0.70
Fuel consumption, l/100km	0.29	1	-0.97	-0.20	0.52	0.23	0.21
Fuel economy, km/l	-0.26	-0.97	1	0.23	-0.48	-0.19	-0.20
Fuel efficiency	0.67	-0.20	0.23	1	0.72	0.67	0.34
CO_2 emissions, g/km	0.39	0.96	-0.93	-0.12	0.56	0.37	0.38
			Performance Characteristics				
Horsepower (metric)	0.79	0.52	-0.48	0.72	1	0.74	0.44
Power, kW	0.79	0.52	-0.48	0.72	1	0.74	0.44
Acceleration, seconds	-0.69	-0.32	0.31	-0.74	-0.87	-0.61	-0.24
Speed maximum, km/h	0.76	0.36	-0.34	0.76	0.91	0.65	0.35
			Engine Characteristics				
Displacement, cm^3	0.76	0.23	-0.19	0.67	0.74	1	0.55
Fuel Type (Gasoline = 1)	-0.10	0.69	-0.70	-0.34	0.19	-0.26	-0.30
Forced induction ("yes"= 1)	0.30	-0.29	0.29	0.39	0.18	0.08	0.26
Transmission (Automatic = 1)	0.36	0.21	-0.22	0.12	0.25	0.24	0.20
			Size Characteristics				
Weight, kg	0.70	0.21	-0.20	0.34	0.44	0.55	1
Length, cm	0.49	0.19	-0.20	0.15	0.26	0.31	0.71
Width, cm	0.36	0.15	-0.14	0.13	0.21	0.19	0.63
Height, cm	-0.28	0.07	-0.09	-0.41	-0.30	-0.21	0.13

NOTE: All values are statistically significant, with the $p < 0.01$ unless otherwise stated; fuel efficiency is defined as (fuel economy × horsepower).

However, the fuel efficiency of gasoline cars might be significantly improved by the use of forced induction in form of a turbocharger or a supercharger – a gasoline car with similar characteristics but with forced induction achieves 18.31 km/l, an improvement of 13%. The new technology also increases the price of a car. Without accounting for forced induction, gasoline cars are cheaper than diesel cars, but both types are priced similarly when they feature forced induction (Table 3). This phenomenon can be explained by the relative novelty of this technology applied to gasoline engines compared to diesel engines and by a relative gain in a car power under forced induction. Despite a relatively higher vehicle price, the share of gasoline cars with forced induction in the supply as a whole has been increasing over time. This finding leads to the conclusion that consumers might progressively value this technology.

Table 3: Descriptive statistics for the chosen vehicle attributes

		Diesel	Gasoline		
		FI	FI	no FI	WA
Car Price, 2010 €	Mean	28659.37	28802.55	21597.06	27195.00
	SD	6618.12	7792.90	6460.56	8089.06
Fuel Consumption, l/100 km	Mean	4.88	6.40	6.59	6.44
	SD	0.69	0.99	0.78	0.95
Fuel Economy, km/l	Mean	20.91	15.97	15.39	15.84
	SD	2.93	2.32	1.75	2.22
Horsepower	Mean	146.44	174.51	130.75	164.75
	SD	37.12	54.04	40.29	54.41
Fuel Efficiency	Mean	3014.03	2698.83	1984.83	2539.54
	SD	675.04	600.97	525.44	655.91
Displacement, cm^3	Mean	1906.12	1710.19	1729.04	1714.40
	SD	306.18	387.64	399.34	390.04
Weight, kg	Mean	2045.93	1969.98	1880.94	1950.12
	SD	148.92	157.19	126.81	155.35
Automatic (0/1)	Mean	0.41	0.41	0.31	0.39
	SD	0.49	0.49	0.46	0.49
Compact class (0/1)	Mean	0.49	0.50	0.70	0.55
	SD	0.50	0.50	0.46	0.50
Middle class (0/1)	Mean	0.51	0.50	0.30	0.45
	SD	0.50	0.50	0.46	0.50
Number of observations		681	491	141	632

NOTE: "FI", "No FI", and "WA" stand for "forced induction", "no forced induction", and "weighted averages", respectively.

2.4 Hedonic price specifications

In a specification of the hedonic price regression presented in Equation 9, we allow the coefficient for fuel efficiency to vary with fuel price (FP). Because car makes can react and adjust their car offerings differently depending on the fuel price, we also interact the coefficient for fuel efficiency with an indicator variable for car make, $I(\text{Make}_j = m)$. The assumed double-log functional dependency between car prices and attributes is in line with previous studies that argue that the price differences associated with product- and brand-level variables are best represented as percentage differences rather than absolute differences (Triplett, 1969; Murray and Sarantis, 1999).

$$
\begin{aligned}
\ln \text{Price}_{jt} = {} & \alpha_1 + \alpha_2 \ln \text{FP}_t \\
& + \Big(\beta_{1m} + \beta_{2m} \ln \text{FP}_t\Big) \times \Big[\ln \text{Fuel Efficiency}_{jt} \cdot I(\text{Make}_j = m)\Big] \\
& + \gamma' X_{jt} + \tau_t + \mu_j + \varepsilon_{jt}
\end{aligned}
\tag{9}
$$

Observed vehicle attributes in X_{jt} include a logarithm of total admissible car weight ($\ln$ Weight) and indicator variables for the displacement group, transmission type (automatic or manual), forced induction, and car class (compact or middle). Displacement enters the hedonic price function as a dichotomous variable with five categories ("$\leq$ 1399"; "1400-1999"; "2000-2499"; "2500-2999"; and "$\geq$ 3000" cm^3). Displacement is taken as a categorical variable to overcome a potential problem due to its high correlation with fuel efficiency and because its distribution in the data is highly discrete. We also include year fixed effects, τ_t, to account for temporal changes in product qualities and make fixed effects, μ_j, to control for unobservable car brand qualities, such as reliability, premium status, and other make-specific features that are constant over time.

We estimate the hedonic price regression by ordinary least squares and cluster standard errors at the make level to account for a potential correlation of observations for cars belonging to the same make. The whole analysis is accomplished for two engine types (diesel and gasoline) separately while pooling the data over both time and car classes. The effects are identified by using variations in product attributes, vehicle prices, and fuel prices at various points at the time of market entry.

For the analysis, we make several assumptions. First, we must assume the equal availability of all cars on the German market. Second, fuel prices can be assumed either to follow a random walk or to be a specific function of historical value realizations. We follow previous studies and assume the former case[9] (Anderson et al., 2013, Langer and Miller, 2013). Thus, the best prediction of future fuel prices in each car entry time is the current fuel price. To check the null hypothesis that fuel prices follow a random walk, we employ a statistical test based on Dickey and Fuller (1979). The data produce test statistics of -1.99 for diesel and

[9]We additionally estimated the hedonic price regression with the fuel price being various functions of historical realizations. We did not find any statistically significant differences from the results presented in this paper.

-2.74 for gasoline, which do not exceed the 5% critical value of -2.86 in absolute value. Thus, we fail to reject the null hypothesis that fuel prices follow a random walk.

3 Empirical results

In this section, first, the overall model fit and parameter estimates are presented and discussed; second, the estimated effects of fuel prices on the market value of fuel economy, driving intensity, and total CO_2 emissions are discussed.

3.1 Model fit and parameter estimates

At this stage, the vehicle prices are regressed on the selected product attributes, controlling for the make and year fixed effects for each engine type separately. Table 4 provides the parameter estimates and model fit for the hedonic price specification. The results indicate that the variation in prices among various car models could be well explained by the controlled physical car characteristics (adjusted-R^2 is between 83-85% without [not shown] and 93-95% with year and make fixed effects).

In the double-log hedonic price specification, the regression coefficients for continuous car attributes correspond to price elasticity – they show a percentage change in the price associated with a percentage change in the attribute value. The main effect of fuel price on car prices is negative but statistically significant only for diesel vehicles. If a car make offers better fuel economy, the drop in the car prices decreases as the derivative of the car price with respect to the fuel price is less negative due to the positive interaction term.

The parameter estimates for dichotomous product attributes show a difference in prices between an attribute level and its reference level, ceteris paribus. The coefficient (say, α) for a dummy variable in the model with a log-transformed dependent variable shows the $(\exp(\alpha) - 1) \times 100$ – percent change in the prices compared to the reference category. Overall, the estimation results are in line with expectations – the vehicle attributes that are generally linked to better quality have significantly positive market values, and vice versa. For example, the estimates for transmission are consistent with observations that cars with an automatic transmission are more expensive than those with a manual one –

Table 4: Parameter estimates for hedonic price regression

	Diesel		Gasoline	
Parameter	Estimate	SE	Estimate	SE
Intercept	5.435*	2.733	-0.612	3.407
lnFP	-16.248**	6.444	-6.595	6.738
(lnFuelEfficiency)	-0.438	0.251	0.038	0.369
(lnFuelEfficiency)× Make Audi	0.019	0.046	-0.038	0.056
(lnFuelEfficiency) × Make BMW	0.066*	0.037	-0.027	0.072
(lnFuelEfficiency) × Make Chevrolet	0.134***	0.028	*NA*	
(lnFuelEfficiency)× Make Citroen	0.345***	0.067	*NA*	
(lnFuelEfficiency)× Make Fiat	0.126**	0.055	*NA*	
(lnFuelEfficiency)× Make Ford	0.059**	0.023	-0.131	0.102
(lnFuelEfficiency)× Make Hyundai	-0.092	0.059	*NA*	
(lnFuelEfficiency)× Make Mazda	0.148***	0.034	-0.250***	0.069
(lnFuelEfficiency)× Make Mercedes	0.123**	0.053	0.113**	0.046
(lnFuelEfficiency)× Make Opel	0.007	0.037	*0.035*	0.116
(lnFuelEfficiency)× Make Peugeot	0.172**	0.073	*NA*	
(lnFuelEfficiency)× Make Renault	0.258***	0.058	*NA*	
(lnFuelEfficiency)× Make SEAT	0.276***	0.025	-0.186***	0.04
(lnFuelEfficiency)× Make Skoda	0.201***	0.031	0.097	0.077
(lnFuelEfficiency)× Make VW	0.048	0.039	-0.043	0.063
(lnFuelEfficiency)× Make Volvo	*Reference*		*Reference*	
(lnFuelEfficiency)×ForcedInduction	*NA*		0.097	0.064
lnFP×(lnFuelEfficiency)	2.084**	0.801	0.784	0.871
lnFP×(lnFuelEfficiency)× Make Audi	-0.049*	0.024	-0.007	0.022
lnFP×(lnFuelEfficiency)×Make BMW	-0.134***	0.03	0.001	0.022
lnFP×(lnFuelEfficiency)×Make Chevrolet	-0.042**	0.017	*NA*	
lnFP×(lnFuelEfficiency)×Make Citroen	-0.137***	0.035	*NA*	
lnFP×(lnFuelEfficiency)×Make Fiat	0.012	0.028	*NA*	
lnFP×(lnFuelEfficiency)×Make Ford	0.004	0.013	0.173***	0.017
lnFP×(lnFuelEfficiency)×Make Hyundai	0.193***	0.04	*NA*	
lnFP×(lnFuelEfficiency)×Make Mazda	0.086*	0.047	0.318***	0.041
lnFP×(lnFuelEfficiency)×Make Mercedes	-0.253***	0.059	-0.103**	0.042
lnFP×(lnFuelEfficiency)×Make Opel	0.005	0.014	0.086**	0.033
lnFP×(lnFuelEfficiency)×Make Peugeot	-0.018	0.024	*NA*	
lnFP×(lnFuelEfficiency)×Make Renault	0.156***	0.033	*NA*	
lnFP×(lnFuelEfficiency)×Make SEAT	-0.014	0.017	-0.002	0.055
lnFP×(lnFuelEfficiency)×Make Skoda	-0.187***	0.023	-0.198***	0.031
lnFP×(lnFuelEfficiency)×Make VW	0.083***	0.024	0.164***	0.036
lnFP×(lnFuelEfficiency)×Make Volvo	*Reference*		*Reference*	
Displacement (1400 - 1999 cm^3)	0.064	0.039	0.036*	0.018
Displacement (2000 - 2499 cm^3)	0.120**	0.043	0.133**	0.045
Displacement (2500 - 2999 cm^3)	0.128***	0.042	0.153***	0.041
Displacement ($\geq$3000 cm^3)	*NA*		0.007	0.065
lnWeight	1.071***	0.112	1.412***	0.167
Compact Class	-0.121***	0.022	-0.098***	0.029
Middle Class	*Reference*		*Reference*	
Automatic Transmission	0.080***	0.008	0.063***	0.011
Forced Induction	*NA*		-0.754	0.469
Year dummies?	Yes		Yes	
Make dummies?	Yes		Yes	
Model Pr>F	< 0.0001		< 0.0001	
Number of Observations	646		510	
Number of Clusters	16		10	
Adjusted R^2	0.9266		0.9493	

NOTE: This table shows the estimation results for the hedonic price regression, where the dependent variable is ln (Car Price). All monetary values are in 2010 €. Standard errors (SE) are heteroskedasticity-consistent and clustered at the make level. The reference category is Volvo, middle class, model year 2013, manual transmission, and displacement "0-1399 cm^3". "NA" stands for "Not Applicable". *p<0.1; **p<0.05; ***p<0.01.

the coefficient indicates a difference of 6%. A similar logic is applied to the estimates for displacement groups, with larger displacement resulting in higher car prices (on average, 12-16% depending on the fuel type). After controlling for all differences in car attributes for a car with gasoline engine, forced induction does not contribute significantly to the car price variation. This finding means that the higher observed vehicle price shown in the descriptive statistics in Table 3 can be fully explained by an increase in horsepower and a consequent improvement in fuel efficiency compared to gasoline cars without forced induction. For diesel vehicles, the parameter for forced induction is not estimated because all diesel cars in the dataset are turbo-charged. Parameter estimates for fuel efficiency and its interaction with fuel prices for each car make are discussed in the next section.

3.2 Market value of fuel economy

To compute the market value of fuel economy (FE), note that for fuel efficiency, ln(Fuel Efficiency) = ln(Fuel Economy × Horsepower) ≡ ln(Fuel Economy) + ln(Horsepower) holds. Hence, the derivative of the price with respect to fuel economy does not depend on the performance value, and for each make, it is computed as in Equation 10, with standard errors computed as in Equation 11.

$$\frac{\partial \text{Price}}{\partial \text{FE}} = \left[\Big(\beta_{1m} + \beta_{2m} \ln \text{FP}\Big) \cdot I(\text{Make}_j = m)\right] \times \frac{1}{\text{FE}} \times \text{Price} \tag{10}$$

$$SE\left(\frac{\partial \text{Price}}{\partial \text{FE}}\right) = \left[SE\Big(\beta_{1m} + \beta_{2m} \ln \text{FP}\Big) \cdot I(\text{Make}_j = m)\right] \times \frac{1}{\text{FE}} \times \text{Price}, \tag{11}$$

where

$$SE\Big(\beta_{1m} + \beta_{2m} \ln \text{FP}\Big) = \Big[Var(\beta_{1m}) + Var(\beta_{2m}) \times (\ln \text{FP})^2 + 2Cov(\beta_{1m}, \beta_{2m}) \times (\ln \text{FP})\Big]^{1/2}$$

The market value of fuel economy thus depends on levels of the attribute, car price, and fuel price at which it is computed. Because car makes might differently adjust their car offerings to the fuel price fluctuations, the coefficient for fuel efficiency in the price regression is interacted with an indicator variable for car make. Thus, the market value of fuel economy also varies by car make. Table 5 gives an overview of these values for the investigated car makes of two engine types along with the standard errors computed at the median values of car prices and fuel economy for each type of vehicle and at the fuel price of 1.50 €/l (the average fuel price for both engines over the investigated period). Because values of the price gradient with respect to fuel economy are directly proportional to the vehicle price and inversely proportional to the attribute value, as the value of the price gradient increases, the potential for improvement in the attribute value increases because the market still values such improvements relatively highly. The percentage change in the vehicle price due to a 1% change in the fuel economy allows a direct comparison of the market values across different vehicles. On average, an improvement in diesel fuel economy is valued more than that for gasoline vehicles in both absolute and relative terms. Differences in values among car makes can be explained by adjustments in the supply to changes in the fuel price. Because car manufactures allocate their resources to the development of fuel economy and other car attributes differently, consumers face constraints to find a car of each possible realization of attribute bundles by a specific car make.

The resulting values for the price gradient of fuel economy as a function of fuel price are depicted in Figure 1 for each engine type. Here, only a subset of car makes is presented in order to reduce clutter in the figure. The rationale behind the figures is as follows. First, a positive slope of the dependency means that under increasing fuel prices, the market value of a given fuel economy increases. Second, the steepness of the curves indicates how sensitive the market values are to changes in fuel prices. With increasing fuel prices, the market values improvements in the fuel economy of diesel vehicles more than those of gasoline ones. This phenomenon can be explained by relatively high shares of diesel vehicles on the German car market. Both car manufacturers and consumers have shifted their preferences to diesel vehicles over the last ten years: production shares and market shares of diesel vehicles have been rapidly increasing in this period. Thus, manufacturers had to build necessary capacities to react more quickly to changing fuel prices by improving the fuel economy of each subsequent car generation. In the gasoline car market, consumers are potentially not as concerned with fuel economy as those in the diesel car market, but instead focus on other performance characteristics. Additionally, car manufacturers may not have developed necessary technologies to improve the fuel economy of gasoline vehicles in response

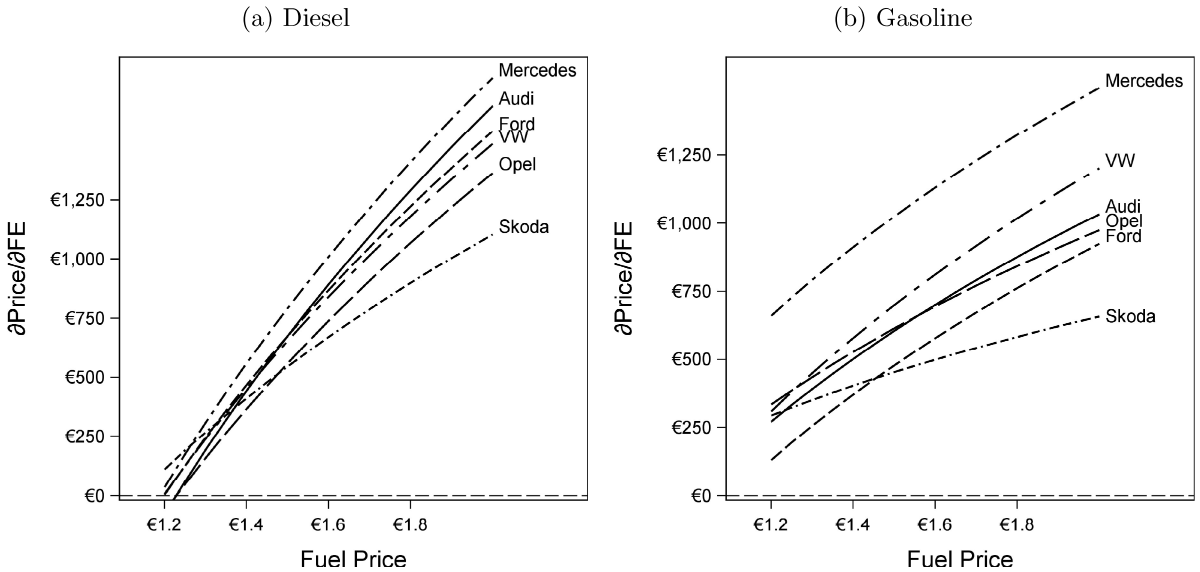
Table 5: Market value of fuel economy (km/l)

Diesel				Gasoline			
Make	N obs	€-Δ (1 km/l)	%-Δ (1% FE)	Make	N obs	€-Δ (1 km/l)	%-Δ (1% FE)
Audi	62	674.92	0.41	Audi	77	604.34	0.31
		(99.85)	(0.06)			(139.00)	(0.07)
BMW	61	645.70	0.42	BMW	80	732.30	0.33
		(87.51)	(0.06)			(173.07)	(0.08)
Chevrolet	26	602.02	0.52	Ford	65	477.94	0.29
		(109.92)	(0.10)			(160.00)	(0.10)
Citroen	16	762.88	0.70	Mazda	26	362.99	0.23
		(38.62)	(0.04)			(53.96)	(0.03)
Fiat	16	587.42	0.54	Mercedes	21	1025.36	0.43
		(62.60)	(0.06)			(97.57)	(0.04)
Ford	66	674.57	0.47	Opel	68	613.85	0.43
		(101.99)	(0.07)			(146.78)	(0.10)
Hyundai	17	407.34	0.39	SEAT	23	206.97	0.17
		(71.73)	(0.07)			(77.70)	(0.06)
Mazda	16	820.11	0.59	Skoda	41	452.86	0.37
		(88.47)	(0.06)			(73.15)	(0.06)
Mercedes	28	791.95	0.43	VW	74	699.24	0.38
		(78.81)	(0.04)			(118.95)	(0.06)
Opel	71	558.29	0.42	Volvo	35	746.43	0.36
		(78.27)	(0.06)			(140.40)	(0.07)
Peugeot	30	666.28	0.57			Ø =592.23	Ø =0.33
		(41.95)	(0.04)			(118.06)	(0.07)
Renault	23	716.08	0.73				
		(50.15)	(0.05)				
SEAT	24	799.02	0.68				
		(105.19)	(0.09)				
Skoda	30	545.04	0.53				
		(82.03)	(0.08)				
VW	79	653.32	0.49				
		(73.65)	(0.06)				
Volvo	81	599.38	0.41				
		(117.35)	(0.08)				
		Ø =656.52	Ø =0.52				
		(80.51)	(0.06)				

NOTE: "€-Δ (1 km/l)" refers to the euro change in the car price if fuel economy changes by 1 km/l and is computed based on Equation 10 at the median values for fuel economy and car prices for each car make and at the fuel price of 1.50 €/l for both fuels. "%-Δ (1% FE)" refers to the percentage change in the vehicle price if fuel economy changes by 1%. In parenthesis are standard errors computed as in Equation 11. Ø denotes the average value over all car makes.

to increasing fuel prices as rapidly as in the diesel vehicle market.

Figure 1: Market value of fuel economy (km/l) as a function of fuel prices



NOTE: This figure presents the values for the price gradient with respect to fuel economy as a function of fuel prices. The price gradient is computed at the median values for fuel economy and vehicle prices for each type of vehicles based on Equation 10.

An elasticity measure helps to better illustrate how rapidly the market value of fuel economy changes with fuel prices. It is computed as in Equation 12:

$$E_{FP}^{\frac{\partial \text{Price}}{\partial \text{FE}}} = \frac{\partial \left(\frac{\partial \text{Price}}{\partial \text{FE}} \right)}{\partial \text{FP}} \times \frac{FP}{\left(\frac{\partial \text{Price}}{\partial \text{FE}} \right)} \tag{12}$$

Table 6 presents average elasticity values for three values of fuel prices, corresponding to the average diesel price of 1.40 €/l, the average gasoline price of 1.50 €/l, and the highest fuel price of 1.60 €/l for the period under investigation. According to our model, the elasticity varies with the fuel price at which it is computed. On average, the elasticity is greater than unity, suggesting that the price gradient of fuel economy changes more relative to the changes in fuel prices. We observe that with increasing fuel prices, the elasticity value substantially drops for both engine types. Thus, the market values improved fuel economy at a diminishing rate.

Table 6: Elasticity of $\frac{\partial \text{Price}}{\partial \text{FE}}$ to fuel prices

Fuel Price	Diesel	Gasoline
1.4	5.93	3.54
	(5.74; 6.13)	(3.26; 3.81)
1.5	4.14	2.74
	(4.05; 4.24)	(2.58; 2.90)
1.6	3.25	2.28
	(3.19; 3.31)	(2.17; 2.40)

NOTE: Average elasticity values for the price gradient of fuel economy with respect to fuel prices are presented. The values are computed as in Equation 12.

3.3 Optimal driving intensity and total CO_2 emission

Given the estimated market values of fuel economy, we compute the underlying optimal annual kilometers based on the assumption of utility-maximizing consumers discussed in the Section 2.1. We use Equation 8 and plug in the derived formula for the price gradient of fuel economy from Equation 10:

$$\text{Km/T} = \frac{\left[\left(\beta_{1m} + \beta_{2m} \ln \text{FP}\right) \cdot I(\text{Make}_j = m) \times \frac{1}{\text{FE}} \times \text{Price}\right] \times FE^2 \times (FE + 1)}{\text{FP} \times (2FE + 1) \times \text{T}}$$

The driving intensity is increasing in fuel economy and car price, i.e., $\frac{\partial \text{Km}}{\partial \text{FE}} > 0$ and $\frac{\partial \text{Km}}{\partial \text{Price}} > 0$. Thus, consumers who are willing to invest more in fuel economy are those who should also expect to drive more. Table 7 gives an overview of the implied optimal driving intensity from the computed market value of fuel economy evaluated at the fuel price of 1.50 €/l. This table also provides values for total emissions of CO_2 (tons) from a car powered by a specific engine. The total emissions of CO_2 in tons at a given fuel price are computed as CO_2 emission (gram/liter) $\times$ fuel economy (km/liter)$^{-1}$ $\times$ Km/T $\times$ 10^{-6}.

Based on the estimated market value of fuel economy, the buyers of diesel cars should be those who expect to drive on average 16538 kilometers annually over the assumed 6 years of a car ownership if diesel fuel costs 1.50 €/l on average, while the optimal annual driving

Table 7: Optimal driving intensity (in km/year) and total CO_2 emissions (in tons/year)

Diesel			Gasoline		
Make	Km/year	Total CO_2	Make	Km/year	Total CO_2
Audi	16655.49	2.12	Audi	12456.68	1.73
BMW	18104.49	2.16	BMW	13252.29	1.97
Chevrolet	14856.57	1.89	Ford	8509.84	1.26
Citroen	18448.17	2.37	Mazda	4806.61	0.74
Fiat	12374.74	1.71	Mercedes	15999.16	2.45
Ford	14210.75	1.96	Opel	9214.67	1.41
Hyundai	10479.75	1.31	SEAT	5451.50	0.73
Mazda	20238.55	2.57	Skoda	9138.87	1.23
Mercedes	19543.49	2.49	VW	11837.08	1.78
Opel	12221.20	1.65	Volvo	12394.12	1.90
Peugeot	17886.50	2.18	Ø	10306.08	1.52
Renault	20991.14	2.45			
SEAT	22403.25	2.67			
Skoda	15282.06	1.82			
VW	16122.57	2.05			
Volvo	14791.42	1.88			
Ø	16538.13	2.08			

NOTE: The values for optimal driving intensity are computed at the median values for fuel economy and vehicle prices for each type of vehicles and at the fuel price of 1.50 €/l. Ø denotes the average value over all car makes.

intensity for gasoline car buyers is 10306 kilometers under the same conditions. These values are similar to the official statistics on the average car usage in Germany – 18042 for diesel cars and 10652 km for petrol cars in 2013.[10]

The total of CO_2 emissions produced is determined solely by driving intensity and the fuel used by a vehicle. One liter of fuel produces approximately 26.5 and 23.2 grams of CO_2 per kilometer driven by diesel and gasoline vehicles, respectively.[11] Hence, for diesel cars to be at least as environmentally friendly as gasoline vehicles at a given amount of kilometers, a gain in fuel economy from diesel cars should be at least 1.1037 times the value gained from gasoline ones. Because diesel drivers are characterized by a higher car usage, as shown in Table 7, the total CO_2 emissions of 2.08 tons are also higher per year on average than for

[10]Statista Press Release 11.06.2015 – 213/15 (https://www.destatis.de/DE/PresseService/Presse/Pressemitteilungen/2015/06/PD15_213_85.html).

[11]http://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/Fachartikel/emission_20110315.pdf, p. 6 (accessed: October 08, 2017).

gasoline vehicles. The values suggest that the efficiency gain from diesel vehicles compared to gasoline cars should be respectively larger in order to offset the environmental pollution caused by more intensive car usage by diesel buyers.

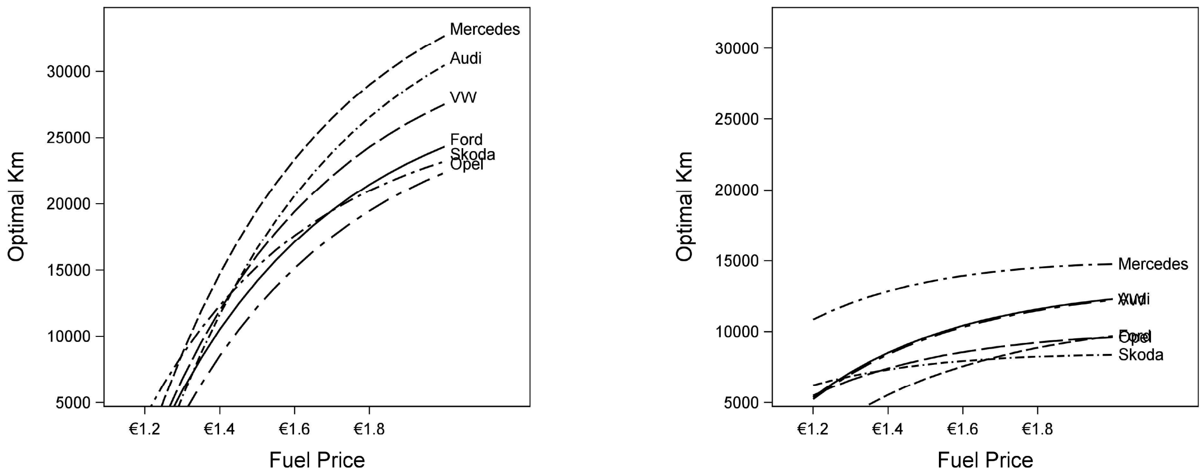
Because the hedonic price model evaluates the dependency in vehicle prices from attributes at the equilibrium, the derived optimal annual kilometrage and CO_2 emissions reflect the average market value without accounting for heterogeneity in consumer tastes while containing all possible self-selection into a car type on driving intensity. Essentially, optimal kilometers reflect the utility a consumer attaches to driving a car of a particular fuel economy, after controlling for its performance.

The estimation procedure allows the optimal driving intensity to vary with fuel prices over engine technologies. Without a dependency of the price gradient of fuel economy on fuel prices, the sensitivity of driving would be the same over engine technologies and directly proportional to fuel price changes. Because the elasticity of the price gradient of fuel economy to fuel prices is greater than unity for the estimated fuel price range ($E_{FP}^{\frac{\partial \text{Price}}{\partial \text{FE}}}$, see Table 6), the condition for decreasing kilometrage with respect to fuel prices does not hold. A visual presentation of how the derived optimal kilometers vary with the level of fuel prices is given in Figure 2. Overall, the derived optimal kilometers are higher for those cars that have better fuel economy and/or higher vehicle prices (to justify the premium paid). Figure 3 visualizes a dependency of optimal kilometers on both fuel economy and fuel price. However, with increasing fuel prices, one can increase one's own kilometrage due to a better fuel economy to a lesser degree, as $\frac{\partial}{\partial \text{FP}}\left(\frac{\partial \text{Km}}{\partial \text{FE}}\right) < 0$. Fuel prices will have a negative effect on the driving intensity starting at values denoted as inflection points. Inflection points of a curve show at which level a change in the direction of curvature occurs. On average, fuel prices should be larger than 3.18 €/l for diesel cars and larger than 2.32 €/l for gasoline cars when the utility from driving a car with a better fuel economy becomes smaller than the implied income effect of higher fuel costs on the driving budget.[12]

[12]See Table A3 for the inflection points for each car make.

Figure 2: Optimal driving per year as a function of fuel prices

(a) Diesel (b) Gasoline



NOTE: Optimal number of kilometers per year is evaluated at the median values for fuel economy and vehicle prices for each type of vehicles and for the length of car ownership of 6 years.

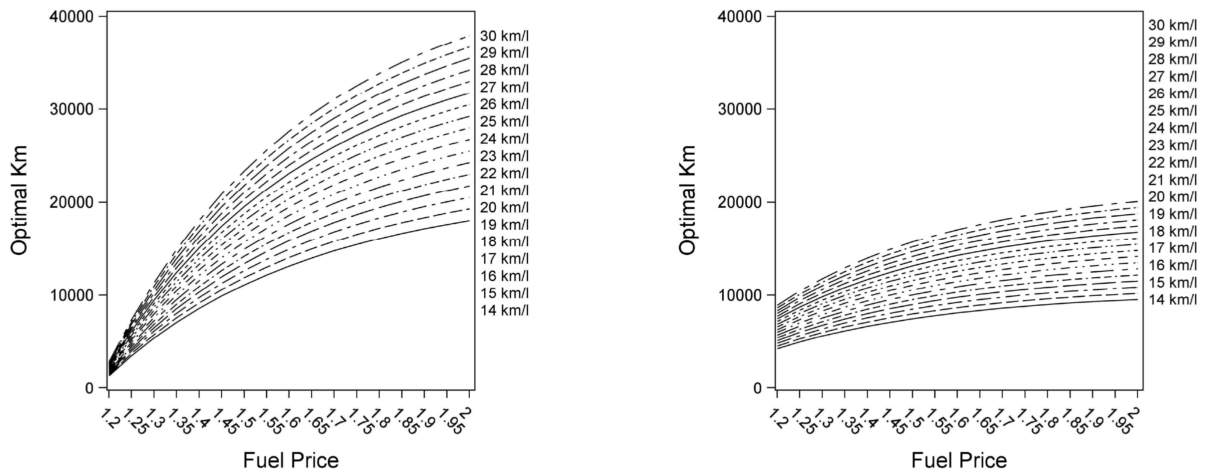
4 Discussion and conclusion

In this section, we summarize the results of our empirical study. In this paper, we aimed to quantify the effects that fluctuations in fuel prices have on the market value of fuel economy. In this line, we considered the value of fuel prices to moderate the value that consumers and manufacturers place on fuel economy, resulting in shifts of car prices' responsiveness to fuel economy. We based our empirical strategy on the hedonic price model, whereby we regressed vehicles' prices on their attributes, including fuel economy and its interaction with fuel price. For this task, we used data on detailed car specifications of frequently sold vehicles from compact and middle classes available on the German market for three subsequent model years (2011–2013). We contrasted price adjustments of a car to its fuel economy with fluctuations in fuel prices over the investigated period. A focus on the German automobile market is justified because this market is characterized by having the biggest car manufacturers in Europe, covering approximately 22% of new passenger car registrations in Europe (as of 2016[13]) and having one of the highest car penetration rates in Europe: 550

[13] https://www.statista.com/statistics/246350 (accessed: October 08, 2017).

Figure 3: Optimal driving as a function of fuel prices and fuel economy

(a) Diesel (b) Gasoline



NOTE: The figure shows a dependency of the computed optimal number of kilometers per year on fuel prices for different values of fuel economy. With increasing fuel economy, the slope of the curve becomes steeper.

vehicles per 1000 inhabitants (as of 2014[14]), which corresponds to 85% of households owning a car (as of 2014[15]).

The methodology applied in this paper enabled us to recover effects that the fuel price has on consumers' willingness-to-pay for improvements in fuel economy, implied optimal car usage, and resulting CO_2 emission values. To compute willingness-to-pay, the values of fuel economy instead of fuel consumption, which is commonly used in Germany, were taken for the analysis. This procedure was done to ensure that the product attributes entered into the regression are in line with the laws of diminishing marginal utility from economic goods. To prevent a problem of severe multicollinearity due to technological interdependence among car attributes, we related fuel economy to car performance (horsepower). This measure also assisted in a direct comparison between different types of engine technologies that differ in the underlying physics.

We found significant differences in the market values of fuel economy between diesel and gasoline vehicles and their responsiveness to changes in fuel prices. Diesel cars were characterized by a larger elasticity of the price gradient of fuel economy to fuel prices compared

[14]`https://www.statista.com/statistics/607540` (accessed: October 08, 2017).

[15]`https://www.statista.com/statistics/516280` (accessed: October 08, 2017).

to gasoline cars. We explain this finding by the relatively higher importance of diesel cars for both consumers and manufacturers on the German automobile market. During recent years, German car manufacturers have shifted their focus to the production of diesel cars, and German consumers have shifted their interest to purchasing diesel vehicles. This trend is linked to the better average fuel economy of diesel cars compared to gasoline cars and lower diesel fuel price at the pump as a result of favorable fuel taxation of diesel. Thus, diesel drivers might be more sensitive to changes in fuel prices and subsequently to improvements in fuel economy because they have to invest more at the time of car purchase in terms of vehicle prices and the annual car tax they pay for diesel cars compared to gasoline ones.

The recovered high responsiveness of the market value of fuel economy to fuel prices resulted in optimal annual driving intensity, which was an increasing function of fuel prices (but at a diminishing rate). This finding implies that the marginal benefits of driving a car of a specific fuel efficiency were still higher than the corresponding effects of changes in the fuel price on consumers' budget for driving. Additionally, we computed the total CO_2 emissions realized by the recovered optimal driving and find values similar to the official statistics. Since the total amount of carbon dioxide emissions from a vehicle is proportional to the intensity of fuel consumption determined by kilometers driven under a given fuel economy, a decrease in pollution levels can be realized through a reduction in driving intensity and/or an improvement in a car's fuel economy.

The values of CO_2 emissions could alternatively be included into the hedonic price regression instead of fuel economy as a direct target of the environmental policy. However, this specification, while yielding similar results for the market value of fuel economy, will not enable a derivation of the driving intensity. Moreover, fuel prices are directly linked to the consumer's fuel expenditures, along with the values of vehicle fuel consumption. Thus, fuel prices might affect the consumer's willingness-to-pay for marginal improvements in the fuel consumption rather than for marginal improvements in the CO_2 emissions. However, an investigation of which consumer motivations – environmental or financial – are of greater importance when choosing a car was not possible with the data used in this study, as both measures (FC and CO_2) are correlated.

Overall, the paper demonstrated how one can use the hedonic price model to estimate fuel price effects on willingness-to-pay for product attributes on a complex market as automobiles while utilizing the open-source data that are considered to represent an equilibrium outcome between the supply- and demand-side interactions.

While our analysis made full use of the available data, there are several possible extensions to the analysis presented in this paper that cannot be addressed with a help of the data used. By regressing vehicle prices on technological attributes, the current paper assumed that the implied optimal kilometers driven are the same for each consumer, who paid the same price for a car with the same fuel economy value. Accordingly, the results shed light only on the aggregate market behavior. Individual purchase data with real transaction prices and consumer-specific characteristics could be used to account for consumer heterogeneity in their tastes for cars and reactions to fuel prices. However, the current study demonstrated that even in the case of having data solely on product prices and underlying attributes, it is possible to recover plausible values for the considered market outcomes, which are in line with the official statistics.

Additionally, data on used vehicles could enrich the analysis by providing information on the actual driven kilometers and actual fuel consumption for various types of vehicles. Because the official values of fuel consumption might differ from values realized by the vehicle usage, the actual driving behavior can facilitate the investigation of effects that changes in fuel prices would imply for different consumer groups – e.g., what vehicle types would become optimal, given the driving behavior and consumer preferences for attribute bundles. Additionally, a potential asymmetric response to increasing and decreasing fuel prices could be investigated. In general, information on any factor that might influence consumers' car choices and their valuation of product attributes, such as the distributional inequality of products, out-of-stock conditions, advertising, effectiveness of the sales force, and product awareness, could enrich the analysis.

References

Achtnicht, M. (2012). German Car Buyers' Willingness to Pay to Reduce CO2 Emissions. *Climatic Change*, 113(3-4):679–697.

Agarwal, M. K. and Ratchford, B. T. (1980). Estimating Demand Functions for Product Characteristics: The Case of Automobiles. *Journal of Consumer Research*, 7(3):249–262.

Allcott, H. and Wozny, N. (2014). Gasoline Prices, Fuel Economy, and The Energy Paradox. *The Review of Economics and Statistics*, 96(5):779–795.

Anderson, S. T., Kellogg, R., and Sallee, J. M. (2013). What Do Consumers Believe About Future Gasoline Prices? *Journal of Environmental Economics and Management*, 66(3):383–403.

Atkinson, S. E. and Halvorsen, R. (1984). A New Hedonic Technique for Estimating Attribute Demand: An Application to the Demand for Automobile Fuel Efficiency. *The Review of Economics and Statistics*, 66(3):417–426.

Boyd, J. and Mellman, R. E. (1980). The Effect of Fuel Economy Standards on the U.S. Automotive Market: An Hedonic Demand Analysis. *Transportation Research Part A: General*, 14(5-6):367–378.

Busse, M. R., Knittel, C. R., Silva-Risso, J., and Zettelmeyer, F. (2016). Who is Exposed to Gas Prices? How Gasoline Prices Affect Automobile Manufacturers and Dealerships. *Quantitative Marketing and Economics*, 14(1):41–95.

Busse, M. R., Knittel, C. R., and Zettelmeyer, F. (2013). Are Consumers Myopic? Evidence from New and Used Car Purchases. *American Economic Review*, 103(1):220–256.

Dahl, C. A. (2012). Measuring Global Gasoline and Diesel Price and Income Elasticities. *Energy Policy*, 41:2–13.

Delsaut, M. (2014). The Effect of Fuel Price on Demands for Road and Rail Travel: An Application to the French Case. *Transportation Research Procedia*, 1(1):177–187.

Dickey, D. A. and Fuller, W. A. (1979). Distribution of the Estimators for Autoregressive Time Series with a Unit Root. *Journal of the American Statistical Association*, 74(366):427–431.

Fetscherin, M. and Toncar, M. (2009). Valuating Brand Equity and Product Related Attributes in the Context of the German Automobile Market. *Journal of Brand Management*, 17(2):134–145.

Frondel, M. and Vance, C. (2009). Do High Oil Prices Matter? Evidence on the Mobility Behavior of German Households. *Environmental and Resource Economics*, 43(1):81–94.

Gillingham, K. (2014). Identifying the Elasticity of Driving: Evidence from a Gasoline Price Shock in California. *Regional Science and Urban Economics*, 47:13–24.

Gramlich, J. (2008). Gas Prices, Fuel Efficiency, and Endogenous Product Choice in the U.S. Automobile Industry. *Working Papers*.

Jacobsen, M. R. and Van Benthem, A. A. (2015). Vehicle Scrappage and Gasoline Policy. *American Economic Review*, 105(3):1312–1338.

Klier, T. and Linn, J. (2010). The Price of Gasoline and New Vehicle Fuel Economy: Evidence from Monthly Sales Data. *American Economic Journal: Economic Policy*, 2(3):134–153.

Knittel, C. R. (2012). Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector. *American Economic Review*, 101(December 2011):3368–3399.

Langer, A. and Miller, N. H. (2013). Automakers' Short-Run Responses to Changing Gasoline Prices. *The Review of Economics and Statistics*, 95(4):1198–1211.

Li, S., Timmins, C., and von Haefen, R. H. (2009). How Do Gasoline Prices Affect Fleet Fuel Economy? *American Economic Journal: Economic Policy*, 1(2):113–137.

Murray, J. and Sarantis, N. (1999). Price-Quality Relations and Hedonic Price Indexes for Cars in the United Kingdom. *International Journal of the Economics of Business*, 6(1):5–27.

Ohta, M. and Griliches, Z. (1986). Automobile Prices and Quality: Did the Gasoline Price Increases Change Consumer Tastes in the U.S.? *Journal of Business & Economic Statistics*, 4(2):187–198.

Patterson, M. G. (1996). What is Energy Efficiency? Concepts, Indicators and Methodological Issues. *Energy Policy*, 24(5):377–390.

Requena-Silvente, F. and Walker, J. (2006). Calculating Hedonic Price Indices with Unobserved Product Attributes: An Application to the UK Car Market. *Economica*, 73(291):509–532.

Rosen, S. (1974). Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition. *Journal of Political Economy*, 82(1):34–55.

Sprei, F., Karlsson, S., and Holmberg, J. (2008). Better Performance or Lower Fuel Consumption: Technological Development in the Swedish New Car Fleet 1975–2002. *Transportation Research Part D: Transport and Environment*, 13(2):75–85.

Triplett, J. E. (1969). Automobiles and Hedonic Quality Measurement. *Journal of Political Economy*, 77(3):408–417.

Uri, N. D. (1988). The Market Valuation of New Car Quality. *Transportation Research Part A: General*, 22A(5):361–373.

Van den Brink, R. M. and Van Wee, B. (2001). Why has Car-Fleet Specific Fuel Consumption Not Shown Any Decrease Since 1990? Quantitative Analysis of Dutch Passenger Car-Fleet Specific Fuel Consumption. *Transportation Research Part D: Transport and Environment*, 6(2):75–93.

APPENDIX

(not for print)

Table A1: Overview of car models with a diesel engine

Make	Model	N products	N observations	Car Price
Audi	Audi A3/RS3/S3	10	18	26834.27
Audi	Audi A4/S4	18	32	35882.13
Audi	Audi A5/S5	6	12	40250.98
BMW	BMW 1	14	24	28341.12
BMW	BMW 3	21	37	38341.1
Chevrolet	Chevrolet Cruze	6	24	23486.41
Chevrolet	Chevrolet Malibu	1	2	29529.3
Citroen	Citroen Berlingo	2	5	21132.24
Citroen	Citroen C4	2	2	21513.22
Citroen	Citroen C5	1	2	29919.58
Citroen	Citroen DS4	2	5	25227.82
Citroen	Citroen DS5	1	2	31200.77
Fiat	Fiat Bravo	1	5	20988.01
Fiat	Fiat Doblo	4	10	20509.83
Fiat	Fiat Sedici	1	1	20739.67
Ford	Ford Focus	12	31	23261.93
Ford	Ford Mondeo	8	35	31423.59

Continues on the next page

Make	Model	N products	N observations	Car Price
Hyundai	Hyundai i30	6	12	20269
Hyundai	Hyundai i40	3	5	28131.68
Mazda	Mazda 3	4	5	24155.47
Mazda	Mazda 6	7	11	31116.34
Mercedes	Mercedes A	2	2	25275.31
Mercedes	Mercedes C	13	25	39685.7
Mercedes	Mercedes Citan	1	1	20439
Opel	Opel Astra	15	33	23673.7
Opel	Opel Combo	3	4	20160.9
Opel	Opel Insignia	18	34	32344.47
Peugeot	Peugeot 308	7	11	22417.11
Peugeot	Peugeot 508	9	16	29178.61
Peugeot	Peugeot Partner	2	3	20188.92
Renault	Renault Kangoo	4	6	19060.08
Renault	Renault Laguna	4	7	27811.49
Renault	Renault Megane	7	10	22267.05
SEAT	SEAT Exeo	4	10	27439.53
SEAT	SEAT Leon	7	13	24108.41
SEAT	SEAT Toledo	1	1	18845.79
Skoda	Skoda Octavia	15	25	23349.23

Continues on the next page

Make	Model	N products	N observations	Car Price
Skoda	Skoda Rapid	3	5	17804.01
VW	VW Beetle/New Beetle	2	8	23838.26
VW	VW Caddy	8	17	26975.49
VW	VW Golf	11	24	24826.55
VW	VW Jetta	2	4	26481.39
VW	VW Passat	10	26	35072.11
Volvo	Volvo C30	2	3	25107.27
Volvo	Volvo S40	3	5	28745.35
Volvo	Volvo S60	6	23	32485.13
Volvo	Volvo V40	6	23	27994.56
Volvo	Volvo V60	7	27	34537.24
		$\sum = 48$	$\sum = 646$	Ø =28865.15

NOTE: Number of products is based on HSN-TSN key in the ADAC data. Car prices are average values over time in 2010 €.

Table A2: Overview of car models with a gasoline engine

Make	Model	N products	N observations	Car Price
Audi	Audi A3/RS3/S3	16	33	27348.68
Audi	Audi A4/S4	15	31	35519.69
Audi	Audi A5/S5	6	13	39119.73
BMW	BMW 1	11	31	28356.11
BMW	BMW 3	18	49	37910.25
Ford	Ford Focus	21	34	21107.67
Ford	Ford Mondeo	9	31	30679.04
Mazda	Mazda 3	8	14	20871.79
Mazda	Mazda 6	8	12	27779.27
Mercedes	Mercedes A	3	4	35928.33
Mercedes	Mercedes C	10	17	38010.4
Opel	Opel Astra	20	49	21034.87
Opel	Opel Combo	1	2	16826.53
Opel	Opel Insignia	7	17	32467.06
SEAT	SEAT Exeo	6	6	26421.81
SEAT	SEAT Leon	9	13	21150.37
SEAT	SEAT Toledo	3	4	16913.43
Skoda	Skoda Octavia	20	35	21659.54
Skoda	Skoda Rapid	6	6	16468.11
VW	VW Beetle/New Beetle	4	16	24470.04
VW	VW Caddy	3	4	22215.78
VW	VW Golf	12	22	24940.41
VW	VW Jetta	3	5	26620.96
VW	VW Passat	7	27	34690.65
Volvo	Volvo S60	2	5	32342.57
Volvo	Volvo V40	6	13	27885.18
Volvo	Volvo V60	5	17	37129.09
		$\sum$= 27	$\sum$=510	Ø =28552.05

NOTE: Number of products is based on HSN-TSN key in the ADAC data. Car prices are average values over time in 2010 €.

Table A3: Inflection point for optimal kilometers as a function of fuel price by car make

Diesel		Gasoline	
Make	FP, €/l	Make	FP, €/l
Audi	3.34	Audi	2.26
BMW	3.29	BMW	2.22
Chevrolet	3.15	Ford	2.65
Citroen	2.85	Mazda	3.23
Fiat	3.15	Mercedes	1.71
Ford	3.26	Opel	2.19
Hyundai	3.43	SEAT	2.79
Mazda	3.11	Skoda	1.66
Mercedes	3.23	VW	2.35
Opel	3.34	Volvo	2.14
Peugeot	3.09	Ø	2.32
Renault	2.95		
SEAT	2.94		
Skoda	3.08		
VW	3.25		
Volvo	3.35		
Ø	3.18		

NOTE: Inflection point of a curve shows level of fuel prices at which a change in the direction of curvature occurs. Ø denotes the average value over all car makes.