# Implicit Interest Rates in Consumer Durables Purchasing Decisions – Evidence from Automobiles

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## Abstract

This paper considers the consumer's intertemporal choice problem to purchase a car with a diesel rather than a gasoline engine, a problem encountered in most European countries. This involves a trade-off between a higher initial purchase price and future savings in operating costs. We obtain implicit interest rate estimates close to capital market rates, and considerably lower than the previous estimates obtained in the literature on consumer appliances. We attribute our results partly to our approach which explicitly incorporates consumer purchasing data, and which abstracts from complicating, a-temporal decision aspects such as product differentiation. Part of our results may also follow from some specific structural features of the automobile market, such as the high financial liquidity and good available information.

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# 1 Introduction

The theory of intertemporal choice makes the sharp prediction that people should discount their future gains or losses at the market interest rate $i$. When faced with this interest rate, consumers should accept any investment opportunity paying more than $i$ and borrow the required amount on the capital market. Similarly, they should reject any investment opportunity paying less than $i$ and lend their available liquidity on the capital market. Growing empirical evidence, however, seems to suggest that this sharp prediction of economic theory is often violated in real world situations. In the context of consumer durables purchasing decisions, people need to trade-off a larger initial purchase price with future energy savings. Several studies indicate that the consumers' marginal rate of time preference – or their "implicit interest rate" – often well exceeds the market interest rate $i$. Hausman's (1979) study on air conditioner purchases finds an average implicit interest rate of about 25 percent. This puzzling evidence was confirmed and reinforced in subsequent work, with estimates of up to 300 percent, depending on the type of appliance being studied.[1]

This paper provides estimates of implicit interest rates in automobile purchasing decisions. We focus on the consumer's problem of choosing between two types of engine, the gasoline and the diesel engine. In Europe, almost all models are sold under both types. The gasoline engine is typically less fuel efficient and requires more expensive fuel (due to higher taxes) than the diesel engine. At the same time, however, the initial purchase price of a gasoline car is generally lower than the price of its diesel twin brother. The choice between gasoline or diesel cars thus contains an important investment aspect, the outcome of which will depend on the consumer's annual mileage. We construct an econometric model that explicitly takes into account these considerations. Using a sample of pairs of automobiles, we essentially infer implicit interest rates from the relative popularity of the gasoline and diesel variants, given the observed differences in initial purchase price, fuel costs per mile, and other characteristics.

We obtain implicit interest rate estimates that are considerably lower than those of previous studies on consumer durables purchasing decisions. Our estimates roughly vary between 5 and 13 percent, depending on the adopted specification. This seems slightly above, but does not differ substantially from various measures of the market interest rate. Our estimates are thus consistent with intertemporal choice theory, in contrast with most other empirical evidence on consumer durables purchasing decisions. We attribute our results partly to our improved methodology, which explicitly incorporates consumer purchasing data in the analysis. Our

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[1] See Lowenstein and Thaler (1989) for a detailed review of this literature.

results may also follow from the unique nature of our data, by which we can focus on the relatively clean gasoline/diesel investment problem, and abstract from other complicating decision aspects, such as the problem to choose one model out of a variety of differentiated products. Finally, some specific structural features of the automobile market may be responsible for our results, in particular the high liquidity due to a well-established capital market for car financing, and the good information available to consumers.

The next section provides an overview of the market for gasoline and diesel cars in Europe, including some preliminary evidence. Section 3 constructs the model and the econometric specification. In section 4 the empirical results are presented. Section 5 interprets the evidence in light of previous estimates of implicit interest rates.

## 2 Gasoline and diesel cars in Europe – a first look

The vast majority of automobile engines are fuelled with distillates of petroleum – gasoline, diesel or LPG. The first two variants are the most common in most European countries. In 1994, for example, gasoline cars constituted about 65 percent of total car sales in the European Union; diesel cars amounted to about 30 percent. In a gasoline engine, a mixture of air and fuel is ignited by a spark; in a diesel engine, the mixture explodes spontaneously due to the high pressure. These technical differences lie at the basis of the well-known differences in performance and comfort. The diesel engine has traditionally produced lower horsepower (at equal displacement), and lower speed and acceleration than the gasoline engine. Furthermore, the diesel engine has a reputation of making more noise and of a less reliable start under cold temperatures. Due to technological improvements (such as the introduction of the turbo and direct injection), these differences have diminished during the past years. A diesel engine generally has a greater fuel efficiency yielding a greater "autonomy" (the number of miles that can be driven with a full). Despite the greater fuel efficiency, the diesel engine presumably generates more air pollution than the (unleaded) gasoline alternative.[2]

We have collected data on sales, list prices and technical characteristics of 41 pairs of automobile models in three European countries, Belgium, France and Italy, during 1991-1994.[3] Models are the base models from the gasoline and the diesel

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[2] As discussed in Michaelis (1995), the diesel engine emits less carbon monoxide than the (unleaded) gasoline engine, roughly the same volatile organic compounds, and more $NO_x$. In addition, it emits airborne particulates unlike the gasoline engine.

[3] Most data are from the same sources as in Verboven (1996). List prices (including value added taxes) and technical characteristics from the following weekly retail catalogues (August issue): *De Autogids* (Belgium), *l'Automobile Magazine* (France), *Quattroruote* (Italy). Sales data

range. In cases where the base model of a gasoline variant was equipped with a different set of options than the diesel variant (e.g. air conditioner or ABS), we upgraded or downgraded the variants such that they contain the same equipment.[4] The technical characteristics include weight, displacement, horsepower, fiscal horsepower, fuel efficiency, speed and acceleration. Other characteristics such as length or width have not been collected since they are common to the gasoline and the diesel variants of each model. Information on fiscal horsepower is used to compute the annual car tax for the various cars. Table 1 provides summary statistics for the variables included in our data set. Monetary units are expressed in dollars.

Table 2 summarizes, by country, several essential differences between the gasoline and the diesel models. These figures provide some first intuition on the investment aspects involved in the gasoline/diesel purchase decision. The first five rows present differences in engine performance. For example, it can be seen that horsepower is on average about 7 kW lower for a diesel than for a gasoline car, whereas displacement is about 350 cc higher. This is consistent with the conventional wisdom on gasoline and diesel engines. The next two rows summarize differences in annual operating costs. Annual operating costs consist of both fuel costs (price per liter times liters per mile times annual mileage for the average driver) and annual car taxes. In all three countries there are large savings in annual fuel costs from driving a diesel car.[5] These fuel cost savings vary substantially across countries, due to differing national fuel taxation policies; the largest fuel cost savings may be realized in France, amounting to about 510 dollar per year for the average driver. Differences in the annual car tax also vary substantially across countries. In France, diesel cars obtain a favorable car tax treatment; in Belgium, a moderate car tax partly offsets the fuel cost savings from driving a diesel; in Italy, car taxes are so high that they completely outweigh the fuel cost savings, at least for the average driver.

The savings in annual operating costs can be confronted with the extra initial purchase price to be paid for diesel cars. As the eighth and ninth row of Table 2 demonstrate, in all three countries diesel cars are more expensive than gasoline cars, even after adjusting for differences in observed quality.[6] In France, for example,

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from publications on new car registrations: *Nationaal Instituut voor Statistiek* (Belgium), *l'Argus de l'Automobile et Locomotions* (France) and *A.C.I.* (Italy). Average annual gasoline and diesel fuel prices, for all three countries from: *l'Argus de l'Automobile et Locomotions.* Data on the distribution of mileage, by several principle characteristics, come from the industry associations, A.C.E.A., F.E.B.I.A.C. and from survey data by De Borger (1987) and C.B.S.

[4] Helpful and competent research assistance in this tedious data collection process was provided by Sandy Torrekens.

[5] The favorable fuel tax treatment of the diesel engine in most European countries does not have an environmental justification. Presumably, it is a means of discriminating between automobile and truck drivers, since the latter are equipped standard with a diesel engine.

[6] We used a hedonic regression to compute quality adjusted price differences. The price differ-

the average driver would need about 5 years before his diesel investment of 2730 dollar (unadjusted for quality) is paid back by the savings in annual operating cost. Observe that the extra initial purchase price for diesel cars is much higher in France than in Belgium and in Italy, which indicates that manufacturers take into account the differences in tax treatment in their pricing strategies.

To obtain some further insights in the relationship between the extra initial purchase price for diesel cars and differences in annual operating costs, one may regress the following hedonic equation using our data set of model pairs:

$$\Delta p_j = \beta_0 + \beta_1 \Delta PERF_j - \beta_2 \left( \mu_j \Delta \pi_j + \Delta \tau_j \right) + \eta_j . \tag{1}$$

This equation regresses the difference in initial purchase price between a diesel and a gasoline variant of model $j$, $\Delta p_j$, on the difference in annual operating costs, controlling for the difference in measured performance $\Delta PERF_j$. The difference in annual operating costs equals the annual car tax difference ($\Delta \tau_j$) plus the difference in fuel costs per mile ($\Delta \pi_j$) times the annual mileage of model $j$'s average driver ($\mu_j$). The term $\Delta PERF_j$ consists of the variables horsepower, displacement and weight. In a second specification, horsepower and displacement are replaced by speed and acceleration. This regression is essentially the same as in Dreyfus and Viscusi (1995), where the variables are now expressed as differences (between gasoline and diesel) rather than as levels.[7]

Our focus is on the estimate of $\beta_2$. One may interpret this coefficient as the consumers' willingness to pay for one extra dollar of savings in operating costs. If consumers capitalize their annual operating costs at an implicit interest rate $r$, using a time horizon $T$, then $\beta_2$ can be interpreted as what Dreyfus and Viscusi call the "vehicle's discounted life":

$$\beta_2 = 1 + \frac{1}{1+r} + \cdots \left( \frac{1}{1+r} \right)^{T-1} = \frac{1+r}{r} \left( 1 - (1+r)^{-T} \right). \tag{2}$$

Intuitively, if for example a car would be expected to last only one year ($T = 1$), then $\beta_2 = 1$, i.e. consumers would be willing to pay one dollar for an extra dollar saved on operating costs. Similarly, if consumers do not discount the future ($r = 0$), then $\beta_2 = T$, i.e. consumers would be willing to pay $T$ dollars for an extra dollar saved on annual operating costs (the undiscounted pay-back time). More generally, from our estimate of $\beta_2$, one can compute the consumer's implicit interest rate $r$, by

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ence between a gasoline and a diesel car was regressed on differences in the performance characteristics, horsepower, displacement and weight. The constant of such a regression can be viewed as the quality adjusted price difference, since this is what remains after all differences in characteristics are set equal to zero.

[7] The differencing takes out model-specific effects, which is feasible here since our dataset consists of *pairs* of automobiles.

assuming a certain value for the time horizon $T$. As in Dreyfus and Viscusi, we use the median automobile durability (the time at which 50 percent of the automobiles has become obsolete) as a measure of the time horizon. Median durability equals 11 years in Belgium and in France, and 15 years in Italy, compared to 13 years in Dreyfus and Viscusi's study of U.S. automobiles.[8]

The results from an ordinary least squares regression of (1), pooling the data across countries and markets, are presented in Table 3. The regression includes dummy variables for time, market, and country of production location, in addition to the variables discussed above. The $R^2$ are relatively low in both specifications compared to other hedonic studies. This is because the equation is estimated in differences, which takes away a lot of variation. Nevertheless, most technical characteristics coefficients have intuitive signs and relatively low standard errors, consistent with other hedonic regressions. In the first specification (including horsepower and displacement) the estimate of the "vehicle's discounted life" coefficient, $\beta_2$, is 4.8; the corresponding estimate of the implicit interest rate $r$ equals 23.5 percent with a standard error of 2.5. This estimate suggests that consumers use a fairly high implicit interest rate when making the gasoline/diesel investment decision. Our second specification (including speed and acceleration) reinforces this conclusion. The estimate of $\beta_2$ is here 2.8; the corresponding implicit interest rate estimate is 55.7 percent, with a standard error of 16.1. These high estimates seem consistent with the results in most other studies on consumer durable goods purchasing decisions. In particular, one may compare our results with Dreyfus and Viscusi's (1995) hedonic study for the automobile market in the U.S. They report implicit interest rate estimates ranging from 11 to 17 percent. At first sight, these estimates seem substantially lower than ours. However, one should be very cautious in making a proper comparison. In fact, Dreyfus and Viscusi's "discounted life" coefficient (our $\beta_2$) is multiplied by another parameter, which they call a "capitalization rate". This is defined as the rate at which the marketplace incorporates life-cycle operating costs (i.e. $\beta_2(\mu_j \Delta\pi_j + \Delta\tau_j)$) into vehicle prices. In our model the capitalization rate parameter is normalized to one,[9] and the implicit interest rate can be immediately uncovered from formula (2) for $\beta_2$. To obtain comparable figures for the implicit interest rates in Dreyfus and Viscusi's model, one should first multiply $\beta_2$ by the capitalization rate, before applying formula (2). Given that they

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[8] Ideally, one should use model-specific data on vehicle durability. However, as in Dreyfus and Viscusi, such detailed data are not at our disposal.

[9] Due to some specific properties in their model Dreyfus and Viscusi separately identify the vehicle's discounted life coefficient ($\beta_2$) and the capitalization rate. One such identifying property is the consideration of mortality risk and injury, which involve a different time horizon than car durability; another identifying property is the nonlinearity of the capitalized operating cost variable.

obtain the quite low estimate of 0.35 for the capitalization rate, the comparable implicit interest rates would in fact be much larger than their reported estimates of 11 and 17 percent, possibly well above 30 percent.[10] In sum, our hedonic regression analysis suggests that people behave fairly myopically in the gasoline/diesel investment decision, which seems consistent with previous studies on consumer durables, including Dreyfus and Viscusi's study once their low estimate of the capitalization rate is taken into account.

This analysis, based on the country summary statistics of Table 2 and the hedonic regression of Table 3, did not explicitly take into account consumer behavior, as measured by the relative sales of gasoline and diesel models. The last row of Table 2 reports the "dieselization rate", the percentage of diesel cars in the total car sales. Interestingly, the above discussed cross-country differences in annual operating costs seem to be reflected in the countries' dieselization rate. In Belgium and especially in France, where diesel cars may generate large savings in operating costs, the dieselization rate is high. In Italy, where diesel cars do not yield savings in operating costs, at least to the average driver, the dieselization rate only reaches 15 percent. Cross-country differences in annual operating costs thus seem responsible for differences in dieselization rate, despite our observation made above that car manufacturers may be charging a higher diesel surcharge in those countries with a more favorable tax regime towards diesel cars.

The above discussion provides some first intuition on how the relationships between prices (possibly adjusted for quality), annual operating costs and sales may say something about the attitude of consumers towards gasoline and diesel cars, and their willingness to pay for investment opportunities. Nevertheless, various issues need to be addressed to provide a more complete analysis. Does the hedonic regression model, which relates prices to operating costs, have a theoretical justification? How can/should sales data possibly be integrated in an econometric analysis? Can we justify our focus on the "average driver"? Or should we instead take into account the fact that consumers are heterogeneous and incorporate the distribution of annual mileage across consumers? How should we cope with the possibility that prices are determined endogenously by the manufacturers, in response to the same factors that influence consumer decisions?

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[10] Because Dreyfus and Viscusi allow the operating costs variable to enter nonlinearly, we cannot compute the exact comparable implicit interest rate from the information provided in their paper. The very low capitalization rate of .35 nevertheless suggests they will be quite high.

# 3 The econometric model

## 3.1 Theoretical model

To model the consumer's intertemporal choice problem of paying a higher initial purchase price (the diesel premium) in exchange for future savings in operating costs, we proceed in two steps. First, we formulate a discrete choice model of car purchasing decisions to find the consumers' indirect utility for any model $j$ coming with an engine variant $k$. Next, we derive the market share of the gasoline engine variant in the total sales of each model $j$.

Consider the following discrete choice model of car purchasing decisions. Consumers choose to purchase one particular model $j$ coming with one of the two engine variants $k$, where $k = G, D$ refers to the gasoline or the diesel engine. The utility derived from purchasing one particular model/engine variant takes the following simple form

$$u_{jk} = z + a_{jk} + \nu_j,$$

where $a_{jk}$ is the mean intrinsic utility from purchasing model $j$ with engine $k$, common to all consumers; $\nu_j$ is an individual-specific random component around that mean; and $z$ is the consumption of goods other than car services. Note that the linear specification is quite standard in the discrete choice literature. Both the mean utility term $a_{jk}$ and the individual-specific term $\nu_j$ may depend on observable characteristics such as performance, size and safety. The term $\nu_j$ is often modelled as an i.i.d. random variable (as in the popular logit model), implying no correlation of consumer preferences across cars. Advances in the discrete choice literature, most notably by Berry (1994) and Berry, Levinsohn and Pakes (1995), show how to relax this unrealistic assumption and allow consumer preferences to be correlated across cars with similar characteristics. Their specification yields a quite flexible aggregate model of product differentiation, with plausible substitution patterns between car models. As will become clear below, our approach abstracts from aspects of product differentiation between different car models, and does not require any restrictions on the distribution of $\nu_j$.

Consumers have an annual income $y$ to be spent on car services and other goods. Annual expenditures on car services include the following three terms: annualized initial purchase price, annual car taxes and annual fuel expenditures. Consider these three terms in turn. (i) The initial purchase price of a car is $p_{jk}$. With an expected durability of $T$ years and a rate of time preference, or implicit interest rate, $r$, the purchase price can be written in annualized terms as $\rho p_{jk}$, where $\rho$ is the annualization coefficient, which is simply the inverse of the discounted life coefficient given by (2),

$$\rho \equiv \frac{r}{1+r}\left(1-(1+r)^{-T}\right)^{-1}. \tag{3}$$

This is a common approach to annualizing the value of a durable good, for more details see for example Hausman (1979). (ii) In addition to the annualized purchase price $\rho p_{jk}$, the consumers need to pay an annual car tax of $\tau_{jk}$. This tax may differ across models and variants, and is usually based on the "fiscal horsepower" of a car. The fiscal horsepower is computed from characteristics such as horsepower, displacement and weight according to a formula defined by the government. (iii) Finally, consumers incur annual fuel expenditures. These depend on the fuel price $q_k$ (dollars per gallon of fuel $k$), the fuel efficiency $w_{jk}$ (gallons per mile), and the annual mileage $\theta$. Annual fuel expenditures per mile are $\pi_{jk} = q_k w_{jk}$. The annual mileage $\theta$ is a random variable which may vary from consumer to consumer. For simplicity, assume that annual mileage is not sensitive to fuel prices (inelastic demand), so that a consumer's total annual fuel expenditures equal $\pi_{jk}\theta$.[11]

In sum, when purchasing a particular model $j$ with engine $k$, total annual expenditures on car services are given by $\rho p_{jk} + \tau_{jk} + \pi_{jk}\theta$. The remaining income $y - \rho p_{jk} - \tau_{jk} - \pi_{jk}\theta$ is left for the consumption on other goods $z$ (at a price normalized to 1). We can then write the indirect utility derived from purchasing a model $j$ with engine $k$ as

$$u_{jk} = y - \rho p_{jk} - \tau_{jk} - \pi_{jk}\theta + a_{jk} + \nu_j.$$

Given this indirect utility function consumers can choose their most preferred model and engine variant. For our purposes it is sufficient to focus on the consumer's choice of engine variant $k$ *conditional* on purchasing a particular model $j$. This choice is crucially dependent on the consumer's annual mileage $\theta$. A consumer is indifferent between buying model $j$ with a gasoline engine $G$ and with a diesel engine $D$ if $u_{jG} = u_{jD}$, hence if her annual mileage equals

$$\theta = \theta_j^* \equiv \frac{\Delta a_j - \rho \Delta p_j - \Delta \tau_j}{\Delta \pi_j}, \tag{4}$$

where the $\Delta x_j$ denotes the difference between a diesel and a gasoline variable, i.e. $\Delta x_j \equiv x_{jD} - x_{jG}$. Notice that the random variable $\nu_j$ does not appear in this equation. Consumers driving $\theta < \theta_j^*$ prefer the gasoline engine of $j$; other consumers prefer the diesel engine of $j$. The probability that the gasoline variant is chosen, conditional upon buying $j$, is then given by

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[11] Previous studies have estimated quite low elasticities of gasoline demand, varying from 0 to around $-.2$. See for example Goldberg (1998) for a discussion. Given that we make use of aggregate demand rather than household level data, a relaxation of the inelastic demand assumption would essentially only affect the specific functional forms in our model. In the empirical results, we report some results with an elastic demand for mileage specification.

$$\Pr(\theta < \theta_j^* \mid j) = F_j(\theta_j^*), \tag{5}$$

where $F_j(\cdot)$ is the conditional cumulative distribution function of $\theta$, i.e. conditional upon choosing $j$. The empirical distribution of mileage may differ across models $j$. For example, it is observed that consumers who decide to purchase larger cars tend to drive more miles per year. This follows from a correlation between preferences for large cars and mileage.

It is now possible to obtain the main equation to be estimated. Equate the conditional probability of buying a gasoline engine of $j$ to the observed market share of the gasoline variant of $j$ in the total sales of $j$, $s_{G|j}$:

$$s_{G|j} = F_j(\theta_j^*).$$

Since the cumulative distribution function $F_j(\cdot)$ is a monotone increasing function, we can invert this equation such that $\theta_j^* = F_j^{-1}(s_{G|j})$. Rearrange using (4) to obtain:

$$F_j^{-1}(s_{G|j})\Delta\pi_j + \Delta\tau_j + \rho\Delta p_j = \Delta a_j, \tag{6}$$

where $F_j^{-1}(\cdot)$ is a monotone function defined as the inverse of $F_j(\cdot)$.

### 3.2 Econometric specification

Our interest is in estimating (6). To achieve our goal we need to specify $F_j^{-1}(\cdot)$ and $\Delta a_j$ in (6).

First consider $F_j^{-1}(\cdot)$. Econometrically, this function simply transforms the market share data $s_{G|j}$, analogous to for example a logarithmic transformation. Economically, since $F_j^{-1}(\cdot)$ is the inverse of the cumulative distribution function of mileage, one can interpret $F_j^{-1}(s_{G|j})$ as a *threshold mileage*, i.e. the mileage that is not reached during one year by a given proportion $s_{G|j}$ of consumers purchasing $j$. In principle, this information can be obtained from consumer survey tables containing, for each model, one column with annual mileage categories and a second column with the proportion of cars corresponding to each mileage category; there is no need for making parametric assumptions on the distribution function of $\theta$. In practice, we do not have such a detailed information at our disposal for the three countries. We therefore specify the cumulative distribution function of $\theta$, and its corresponding inverse, parametrically as a parsimonious function of two parameters, the mean annual mileage $\mu_j$ and the standard deviation $\sigma_j$, for which we have prior information by several principle characteristics of the models, such as horsepower and weight. Given our parametric approach, it is important to examine the robustness of our results with respect to various alternative distribution functions. We consider three different functional forms: the double exponential (which resembles the bell shape of the normal distribution), a two-parameter exponential (which is a skewed distribution function) and the uniform. All distributions contain two parameters, which are written in such a way that they obtain the interpretation of mean and standard deviation. More specifically, for these three distribution functions the market share equations $s_{G|j} = F_j(\theta_j^*)$ are given by:

$$\begin{aligned}
\text{Double exponential} &: \quad s_{G|j} = \exp\left(-\exp\left(-\left(\theta_j^* - \mu_j\right)\frac{\pi}{\sqrt{6}\sigma_j} - \gamma\right)\right) \qquad (7)\\
\text{Exponential} &: \quad s_{G|j} = 1 - \exp\left(-\frac{\theta_j^* - \mu_j + \sigma_j}{\sigma_j}\right)\\
\text{Uniform} &: \quad s_{G|j} = \frac{\theta_j^* - \mu_j + \sqrt{3}\sigma_j}{2\sqrt{3}\sigma_j}
\end{aligned}$$

where $\pi \approx 3.14$ and $\gamma \approx .577$ are constants. It is now straightforward to rearrange these market share equations to obtain a parametric solution for $\theta_j^* = F_j^{-1}(s_{G|j})$, which can then be substituted into our main equation (6).

Now consider $\Delta a_j$. Recall that $\Delta a_j$ captures the difference in the mean intrinsic utility from purchasing model $j$ with a diesel engine ($a_{jD}$) or with a gasoline engine ($a_{jG}$). Note that variables measuring size and safety are common to the gasoline and diesel variants of a model $j$, so that they do not enter $\Delta a_j$. Hence only the performance variables, such as horsepower, displacement, speed and acceleration, enter $\Delta a_j$. More precisely, we specify $\Delta a_j$ as follows:

$$\Delta a_j = \alpha_0 + \alpha_1 \Delta PERF_j + \varepsilon_j, \qquad (8)$$

where $\Delta PERF_j$ captures differences in observed performance variables, for example differences in horsepower. The constant $\alpha_0$ can be interpreted as the mean extra utility from a diesel variant, possibly negative. It captures specific diesel features that are not measured by the performance variables in $\Delta PERF_j$, such as discomfort from noise, unreliability and even durability[12]. Finally, the term $\varepsilon_j$ is a mean zero i.i.d. error term. It captures diesel features specific to model $j$ that influence utility, but are unobserved by the econometrician. For example, it is possible that a Renault 19 has a diesel engine with above average reliability, whereas Volkswagen Polo has one below average.

To summarize, substituting the expression of $\Delta a_j$, (8), in equation (6), we obtain the following specification to be estimated:

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[12] In principle, differences in durability between gasoline and diesel models should be captured by allowing for differences in time horizon $T$. In practice, however, this cannot be identified from the constant term $\alpha_0$.

$$F_j^{-1}(s_{G|j})\Delta\pi_j + \Delta\tau_j + \rho\Delta p_j = \alpha_0 + \alpha_1 \Delta PERF_j + \varepsilon_j, \qquad (9)$$

where $F_j^{-1}(s_{G|j})$ can be computed from the distribution functions given by (7). The parameters to be estimated in this model are $\alpha_0$, $\alpha_1$ and $\rho$. From our estimate of $\rho$ one can compute the implicit interest rate $r$ using (3).

### 3.3 Identification and estimation

It is useful to compare our econometric model to a hedonic regression, which is the common approach to estimate implicit interest rates from aggregate data, see e.g. Dreyfus and Viscusi (1995). We presented implicit interest rate estimates using such an approach in the previous section, based on specification (1), relating price differences between gasoline and diesel cars to differences in annual operating costs, controlling for differences in characteristics. After dividing the hedonic equation (1) by $\beta_2$, and slightly rearranging, one can verify the apparent similarity to the derived structural equation (9). Our parameter $\rho$ is thus comparable to the inverse of $\beta_2$ in the hedonic specification. The essential difference between both equations is the replacement of the term $\mu_j\Delta\pi_j$, measuring differences in *average annual fuel expenditures*, with the term $F_j^{-1}(s_{G|j})\Delta\pi_j$, which can be interpreted as measuring differences in *threshold annual fuel expenditures*, since the latter is the product of our "threshold mileage term" and fuel costs per mile. Crucially, the threshold fuel expenditure term, $F_j^{-1}(s_{G|j})\Delta\pi_j$, depends on consumer behavior, as reflected by the market share variable $s_{G|j}$, in contrast to the average fuel expenditure term $\mu_j\Delta\pi_j$ from hedonic regressions. Our aggregate specification derived from an individual choice model thus replaces the somewhat arbitrary average fuel expenditure term by a threshold fuel expenditure term, which depends on the market share variable $s_{G|j}$. Put somewhat differently, by moving $\rho\Delta p_j$ to the right-hand side, we may interpret (9) as a demand function, the dependent variable being a simple monotone transformation of the market share variable $s_{G|j}$. As the price surcharge for a diesel variant of $j$, $\Delta p_j$, increases, the demand for the diesel variant of $j$ will fall in favor of the gasoline variant.[13] The larger $\rho$, the more myopic consumers are, and the more sensitive they are to changes in initial purchase price.

To estimate the parameters in our demand equation (9) consistently, in particular $\rho$, it is important to recognize that $\Delta p_j$ is an endogenous variable, determined by the pricing strategy of the car manufacturers. Consequently, $\Delta p_j$ may be correlated to the error term $\varepsilon_j$, which reflects the unobserved (to the econometrician) diesel features of model $j$. To understand this correlation intuitively, consider a car model $j$ with a particularly high $\varepsilon_j$, say due to below-average discomfort from

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[13] To verify this, bear in mind that $\Delta\pi_j < 0$.

diesel noise and above-average diesel reliability. On the one hand, given these features, the manufacturer will find it profitable to charge a relatively high extra price for this diesel variant, hence the positive correlation between $\Delta p_j$ and $\varepsilon_j$. On the other hand, one may expect a high market share for such a good diesel variant, despite the relatively high extra price. In sum, when the diesel variant of model $j$ is particularly good (a high $\varepsilon_j$), a large diesel price and a large diesel market share may coincide. Vice versa, a low diesel price and a low diesel market share may occur when $\varepsilon_j$ is small (below zero). As a result, a simple ordinary least squares (OLS) estimator will yield inconsistent demand parameter estimates; in particular our main parameter of interest, $\rho$, will be biased towards zero and may even be negative. To the extent that the manufacturer follows a profit-maximizing rather than a fully random pricing strategy, the price endogeneity problem will be of a real concern and an instrumental variable estimator should be used.

What instruments can be used? In traditional demand estimation problems, one may borrow exogenous variables from the supply side as instruments. In models of product differentiation, the choice of suitable instruments is more difficult. The variables that are commonly assumed exogenous are the non-price characteristics of the goods, such as performance, fuel efficiency or taxes.[14] These variables, however, may influence both the demand and supply (cost). Berry (1994) and Berry, Levinsohn and Pakes (1995) discuss this problem and provide a solution suitable for their application. In our framework, the restrictions that are implicit in specification (9) provide an answer to the choice of instruments. In particular, the variables $\Delta\pi_j$ and $\Delta\tau_j$ do not interact with any parameter to be estimated. We may thus use these variables as instruments for $\Delta p_j$. Using $\Delta PERF_j$, $\Delta\pi_j$ and $\Delta\tau_j$, we have one more instrument than the number of parameters to be estimated. Our specific instrumental variable method used to estimate (9), is Hansen's (1982) generalized method of moments (GMM) estimator, with heteroskedasticity-consistent standard errors.

# 4 The empirical results

The empirical results from estimating model (9), using the data set described in section 2, are presented in Table 4. The estimates are based on the bell-shaped double exponential distribution function for mileage, i.e. the first row in (7). The robustness of the results with respect to the other two distribution functions will be discussed afterwards. We present results from both an ordinary least squares estimator and our instrumental variable (GMM) estimator, which allows the price

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[14] The usual justification for this assumption is that these characteristics are variables that can only be slowly adjusted, so that they may be viewed as predetermined at the pricing stage.

variable $\Delta p_j$ to be endogenous.

For all regressions, we need to specify which technical characteristics enter in $\Delta PERF_j$. As discussed in more detail in section 2, we have collected data on the following performance variables, which may differ between the gasoline and diesel variants: horsepower, displacement, weight, speed and acceleration. We experimented with several alternative specifications. Table 4 presents results for two combinations of variables: one specification including horsepower, displacement and weight; and another in which horsepower and displacement are replaced by speed and acceleration. The estimates for our main parameter of interest, $\rho$, and the corresponding implicit interest rate, $r$, were robust with respect to various alternative specifications.[15]

We impose some further structure on the error term $\varepsilon_j$ through fixed effects. Since our sample covers three markets (Belgium, France and Italy) during the period 1991-1994, we include the appropriate market and time dummies to capture unobserved differences in consumer valuations across markets and time (the reference market is Belgium; the reference period is 1991). Similarly, we include source dummies to capture unobserved differences in valuations across country of origin. Cars may originate from France, Germany, Italy or "other countries" (Japan, Spain or the United Kingdom).

A Hausman-Wu exogeneity test statistic has been computed to compare the OLS and GMM estimates, for both specifications of the characteristics. This chi-squared distributed test-statistic looks at the difference between the least squares and instrumental variables estimates, standardizing by the difference in the covariance matrices of the two sets of estimates. Under the null hypothesis of exogeneity, the least squares estimator would be more efficient. However, as shown by the large test-statistics on the bottom of the OLS columns, we reject the hypothesis of exogeneity. This confirms our intuition of the previous section that price is an endogenous variable, correlated to the error term due to the pricing practices of the manufacturers. We therefore concentrate our discussion on the GMM results. Nevertheless, it will be instructive to return to a comparison between the OLS and GMM results afterwards.

In both specifications, the coefficients of the characteristics have the expected sign. Extra weight on diesel models, which according to consumer reports partly follows from a better insulation against diesel noise, is valued positively by con-

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[15] For example, we considered a specification with the horsepower/weight ratio and displacement as characteristics. We also considered specifications in which horsepower, displacement, weight, speed and acceleration all enter together. Due to (common) multicollinearity the parameters of some of the technical characteristics have the unexpected sign, without affecting the results on the estimate of $\rho$, our parameter of main interest.

sumers. Similarly, in the first specification, horsepower and displacement positively and significantly affect consumer valuations. In the second specification, maximum speed positively influences consumer valuations, whereas acceleration time (time to reach 100 km/hour) has a negative impact. The constant term (units expressed in dollar) is estimated significantly negative in both specifications. This implies that consumers tend to place a negative value on a diesel variant after controlling for observed differences between gasoline and diesel. This may follow from unobserved discomfort from the slower diesel start, noise or lower reliability under cold temperatures. This perceived discomfort seems especially important in France (negative fixed effect) and less important in Italy (positive fixed effect). The positive time effects (though often insignificant) suggest that the diesel discomfort became less important after 1991, consistent with conventional wisdom (more widespread use of the turbo, and direct injection which essentially eliminates most diesel disadvantages). Country of origin seems to matter only for Italian cars: consumers value the diesel version of an Italian car about 80$ higher than its gasoline twin brother.

We can now come to a discussion of our estimates of $\rho$, from which the implicit interest rate $r$ can be computed. We estimate $\rho = 0.146$ and $\rho = 0.126$ for our first and second specification, respectively, with corresponding standard errors of 0.019 and 0.018. First of all, notice that these estimates are much larger than the estimates of $\rho$ obtained using ordinary least squares (precisely estimated around 0.02 and 0.01, respectively). This is intuitive. Our Hausman tests rejected the hypothesis of exogenous prices, so that ordinary least squares will be inconsistent. In the previous section, it was argued that the bias of $\rho$ would be downwards under a positive correlation between price and the error term. The "cost" of using instruments is a reduced efficiency, as evidenced by the larger standard errors for our estimated coefficients. Nevertheless, our standard errors our still relatively low, indicating that our instruments for the price variable (the fuel and car tax variables) perform well.

The estimates of the implicit interest rate $r$ corresponding to our estimates of $\rho$ can be easily computed, using (3). Table 5 provides these estimates for both specifications of characteristics. As a further check for the robustness of our results, Table 5 also provides estimates of $r$ based on the other distribution functions of mileage referred to in (7), the exponential and uniform.[16] For example, our point estimate of $r$ under the double exponential distribution with the variables horsepower and displacement included, is equal to 11.8 percent with a 95 percentage confidence interval of $[7.88, 15.80]$. More generally speaking, the point estimates

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[16] The estimates of the parameters using the exponentional and uniform distribution do not differ by much from the estimates of the double exponential presented in Table 4. Since they yield no interesting new insights, they are not reported.

for the implicit interest rates range between 5 and 13 percent, depending on the adopted specification. The lowest estimates were obtained under the assumption that annual mileage is distributed exponentially across consumers. Yet given the magnitude of the standard errors, it seems fair to conclude that the implicit interest rate estimates are essentially robust with respect to the choice of functional form for mileage distribution.[17]

Under all specifications for the distribution of mileage, we obtain estimates of $r$ that are substantially below the reported estimates of 23.5 and 55.7 percent in the hedonic regressions. Why is it that we now obtain interest rate estimates that are so much lower than in the hedonic model? To see this, recall that our structural model incorporates the market share variable measuring the relative popularity of the gasoline and diesel variants. This relative popularity varies a lot from model to model (see Table 1). What our estimates tell us, is that this variability can be explained quite well by price and operating cost differences between the diesel and gasoline variants. Other things equal, those diesel models that offer a better financial deal are also considerably more popular. If consumers did not respond well to such financial deals, a higher estimate of the interest rate would have resulted. Clearly, such consumer responses cannot be captured appropriately in an aggregate model without market share data, as in the hedonic regressions of section 2, or in Dreyfus and Viscusi's (1995) hedonic study. Similarly, Gately's (1980) study of refrigerators does not take into account market share data. He compares three pairs of refrigerators, each pair coming in an energy-efficient and an energy-inefficient variant. Based on a high ratio of energy-savings to initial purchasing premium, he computes extremely high *returns* from purchasing the energy-efficient variants, for all three types of refrigerators (varying between 45 and 300 percent). His estimates do not, however, take into account a possible strong popularity of the energy-efficient variants. If, in an extreme example, one would observe that the energy-inefficient models have a zero market share, one cannot draw any conclusions about implicit interest rates from the computed returns.

As discussed in the introduction, economic theory predicts that consumers should discount their future gains or losses at the market interest rate $i$. To which extent do our estimates of the consumers' implicit interest rate $r$, summarized in Table 5, coincide with the market interest rate $i$? Of course, there is no single market interest

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[17] Recall that our specification is based on the assumption that consumers have inelastic fuel demand. The exposition and functional forms become very tedious when elastic demand is allowed for. We nevertheless experimented with an elastic demand specification, assuming consumers have a uniform distribution across types. In this example, pinning down the elasticity to $-0.2$, we obtained an implicit interest rate estimate of 13 percent, compared to the 12 percent estimate for the corresponding inelastic demand case. Details on the derivation of the functional forms and the estimates are available on request.

rate, so one should consider some alternative measures. The three-month interbank interest rate roughly varied between 6 and 9 percent in the three countries during our sample period. The long term government bond interest rate (over 5 years) varied between 7.5 and 10 percent. We also obtained information about interest rates in Belgium on installment loans specifically for purchasing cars (value of loan of $400,000$ BF, i.e. about $10,000$\$; fixed monthly payments during 48 months).[18] The "best-buy" interest rates for these loans varied between 9.03 and 11.71 percent during 1992-1994. These market rates generally fall within the 95 percent confidence intervals for our implicit interest estimates implied by Table 5. Looking at our point estimates in Table 5, it seems safe to conclude that our estimated implicit interest rates only slightly and not significantly exceed the above measures of the market interest rate. This result is in stark contrast with most previous studies, which report much higher estimates than the market rates, usually well above 20 or even 30 percent.

# 5 Discussion of the results

We have analyzed the consumer's investment problem to buy a gasoline or a diesel car – a trade-off between a higher initial purchase price and future annual savings in operating costs. Our empirical results indicate that consumers roughly behave according to the predictions of intertemporal choice theory. Our estimated implicit interest rates vary between 5 and 13 percent, slightly but not substantially above the market interest rate. Our estimates may have implications for the debate in environmental economics about the relative effectiveness of fuel tax policies and fuel efficiency standards. We leave this as an interesting topic for further research. In the remaining part of this section, we concentrate our discussion on an interpretation of our estimates. The puzzle to be explained is not another rejection of traditional economic theory. The question is rather why we obtain implicit interest rate estimates so much lower than other studies on consumer durables purchasing decisions.

In the previous section we compared our results with those of other studies that use aggregate data, e.g. Gately (1979), Dreyfus and Viscusi (1995), and our results of section 2. We pointed out that our lower interest rate estimates may follow from our improved methodology, which explicitly takes into account consumer behavior through market share data in the aggregate model. While this may account for part of the results, it leaves unexplained the high interest rate estimates obtained in *household-level* consumption studies, which, of course, also explicitly incorporate

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[18] This historical information was kindly provided by the Belgian consumer organization Test-Aankoop.

consumer behavior. Hausman (1979) studied individual purchasing behavior for air-conditioners, in which consumers face the choice between various brands which differ in energy-efficiency. He obtains implicit interest rate estimates of on average 25 percent. In a micro-study on space and water heating choice, Dubin and McFadden (1984) obtain an estimate of about 20 percent.

A first explanation for our lower implicit interest rates, close to capital market rates, may be the presence of some specific structural features in the automobile market. Loewenstein and Thaler (1989) report experimental evidence that individual interest rates tend be lower when the time to be waited increases, when the size of the award rises, and when it concerns a loss rather than a gain (debt aversion). However, it seems that cars and other durables goods, such as airconditioners, do not significantly differ in these dimensions. Lower liquidity constraints and better consumer information may be a more plausible explanation for our lower estimates. First, there is a well-established capital market for financing automobile purchases. Automobiles can be financed through specifically designed installment loans or leasing contracts. Car manufacturers generally also offer special financing options. Although it is also possible to finance the purchase of other durable goods on the capital market, this needs to be done through the general-purpose personal loans; these are typically more expensive, by about 3 percent in Belgium during our sample period. Second, consumers receive quite detailed information regarding their "investment opportunities" in the car market. Specialized car magazines regularly publish tables with the cost per mile for very large samples of cars. A Belgian consumer report computed the critical mileages for about one hundred different cars, at which it would become profitable to purchase the diesel version.[19] Furthermore, consumer awareness about fuel costs may be particularly strong, compared to energy costs for household appliances. Consumer incur fuel costs at the gas station several times per month. Electricity and other energy costs for household appliances are incurred much less frequently and, perhaps more importantly, enter a general energy bill.

A final explanation for our low implicit interest rate estimates, compared to other studies, is the simple consumer choice problem we have focused on. Our approach considers the problem of selecting a gasoline or a diesel variant, conditional upon choosing a particular model. This is a relatively clean investment problem, unclouded by product differentiation aspects of choosing one car out of all possible models.[20] The other (household-level) studies on consumer durables infer implicit

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[19] Test-Aankoop Magazine nr. 373, January 1995. Incidently, to compute these critical mileages, the study adopted a zero interest rate.

[20] Formally, this is because the model-specific term $\nu_j$ in an individual's utility, which captures the individual-specific valuation for car $j$, is irrelevant when comparing a gasoline and diesel variant

interest rates from the more complicated individual choice problem of deciding upon the most preferred brand across a large set of brands. This problem contains a mixture of both intertemporal aspects of investment (future energy savings) and a-temporal aspects of product differentiation.

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of the same model.

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# 6 Tables

**Table1. Summary statistics** (406 observations)

| | Mean | Std Dev | Minimum | Maximum |
|---|---|---|---|---|
| gasoline market share | .5807 | .2317 | .0435 | .9961 |
| initial purchase price (in $) | 19255 | 7530 | 9203 | 42654 |
| annual car tax (in $) | 229.8 | 140.0 | 41.5 | 629.6 |
| horsepower (kW) | 62.48 | 18.75 | 33.50 | 107.50 |
| displacement (cc) | 1784 | 309 | 1151 | 2496 |
| weight (kg) | 1102 | 204 | 678 | 1475 |
| speed (km/hour) | 173.1 | 16.7 | 142.5 | 209 |
| acceleration (sec. to 100 km/hour) | 14.21 | 2.31 | 10.00 | 20.00 |
| fuel efficiency (liter per 100 km) | 6.805 | 0.848 | 4.833 | 8.700 |
| French origin | 0.160 | 0.367 | 0 | 1 |
| German origin* | 0.431 | 0.496 | 0 | 1 |
| Italian origin | 0.305 | 0.461 | 0 | 1 |

* Includes G.M. (Opel) and Ford cars produced in Germany.

**Table 2. Differences between gasoline and diesel cars**

| | Belgium | France | Italy |
|---|---|---|---|
| average difference in specification | | | |
| horsepower | -6.80 | -6.64 | -7.12 |
| displacement | 362 | 353 | 359 |
| weight | 81.3 | 83.9 | 80.1 |
| speed | -7.18 | -6.82 | -7.56 |
| acceleration | 1.95 | 1.92 | 1.98 |
| average difference in annual operating cost (in $) | | | |
| annual fuel costs* | -390 | -509 | -420 |
| annual car taxes | 66.7 | -40.3 | 493.1 |
| average difference in initial purchase price (in $) | | | |
| quality-unadjusted | 2129 | 2733 | 1901 |
| quality-adjusted | 994 | 1397 | 347 |
| dieselization rate | | | |
| | 0.442 | .537 | .152 |

[*] Annual fuel costs are computed for the average driver by model.

**Table 3. Estimates of hedonic model (1)**

| | OLS estimates | |
|---|---|---|
| constant | -227.6 | 210.0 |
| | (71.2) | (158.1) |
| time92 | -6.1 | 6.6 |
| | (39.4) | (74.1) |
| time93 | -94.9 | -136.9 |
| | (40.2) | (77.5) |
| time94 | -100.3 | -128.4 |
| | (44.5) | (85.1) |
| French market | -98.0 | -27.4 |
| | (34.8) | (70.5) |
| Italian market | 335.0 | 299.4 |
| | (41.0) | (78.3) |
| French origin | -27.2 | -102.0 |
| | (59.3) | (109.5) |
| German origin | 87.3 | 185.2 |
| | (56.0) | (108.5) |
| Italian origin | 56.6 | 39.0 |
| | (55.2) | (101.3) |
| horsepower | 5.10 | |
| | (1.90) | |
| displacement | .741 | |
| | (.081) | |
| weight | 1.417 | 4.401 |
| | (.456) | (1.000) |
| speed | | 23.66 |
| | | (6.21) |
| acceleration | | -18.31 |
| | | (25.25) |
| operating costs ($\beta_2$) | 4.795 | 2.779 |
| | (.511) | (.495) |
| $R^2$ | .366 | .247 |

Standard errors are in parentheses. Coefficients (and standard errors) other than the price coefficient are divided by $\beta_2$, see discussion later in text.

**Table 4. Estimates of demand model (9)**

| | GMM estimates | | OLS estimates | |
|---|---|---|---|---|
| constant | -306.4 | -188.6 | -359.5 | -338.9 |
| | (52.0) | (43.3) | (34.0) | (35.9) |
| time92 | 57.1 | 53.8 | 51.7 | 59.1 |
| | (31.7) | (25.2) | (18.9) | (19.7) |
| time93 | 33.2 | 36.3 | 66.6 | 75.5 |
| | (29.5) | (23.8) | (19.0) | (19.8) |
| time94 | 39.1 | 50.9 | 86.6 | 102.9 |
| | (30.7) | (24.2) | (21.0) | (22.0) |
| French market | -54.4 | -70.3 | -149.7 | -160.8 |
| | (22.8) | (18.9) | (15.6) | (16.3) |
| Italian market | 105.1 | 133.8 | -164.9 | 171.8 |
| | (36.9) | (30.2) | (19.4) | (20.2) |
| French origin | 49.8 | -4.2 | 6.6 | -16.2 |
| | (27.7) | (23.8) | (28.1) | (29.1) |
| German origin | 42.1 | -10.8 | -67.0 | -61.8 |
| | (27.6) | (26.0) | (24.8) | (25.6) |
| Italian origin | 79.1 | 33.8 | -4.5 | -8.0 |
| | (26.5) | (22.6) | (25.5) | (26.2) |
| horsepower | 3.02 | | 3.22 | |
| | (1.43) | | (.91) | |
| displacement | .409 | | .264 | |
| | (071) | | (.034) | |
| weight | .943 | 1.465 | -.189 | .296 |
| | (.336) | (.294) | (.207) | (.206) |
| speed | | 12.75 | | 11.62 |
| | | (1.84) | | (1.60) |
| acceleration | | -24.75 | | -38.75 |
| | | (8.00) | | (6.60) |
| $\rho$ | .146 | .126 | .020 | .011 |
| | (.019) | (.018) | (.005) | (.005) |
| Hausman-Wu exogeneity test | | | 52.6 | 48.3 |

Standard errors are in parentheses.

**Table 5. Estimates of implicit interest rates $r$ (in percent), alternative distributions**

| characteristics include: | double exponential<br>(bell-shaped) | exponential<br>(skewed) | uniform |
|---|---|---|---|
| horsepower and displacement | 11.84 | 10.53 | 12.24 |
| | (2.02) | (1.67) | (2.23) |
| speed and acceleration | 8.61 | 4.99 | 13.18 |
| | (1.32) | (0.67) | (2.64) |

Standard errors are in parentheses.