The Demand for and the Supply of Fuel Efficiency in Models of Industrial Organisation — Source link

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Published on: 01 Jan 2010

Topics: Fuel efficiency, Consumer behaviour and Willingness to pay

2010

9

DISCUSSION PAPERS

Joint Transport Research Centre

ROUND TABLE
18-19 February 2010, Paris

International Transport Forum

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OECD

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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Discussion Paper No. 2010-9

Prepared for the Round Table of 18-19 February 2010 on

Stimulating Low-Carbon Vehicle Technologies

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January 2010

The views expressed in this paper are those of the authors and do not necessarily represent positions of the K.U. Leuven, NBER and CEPR, the OECD or the International Transport Forum.

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Leuven, January 2010

ABSTRACT

This report organizes and discusses empirical estimates of the effects of fuel prices and fuel emission standards on consumer and firm behaviour. I touch only briefly on model-free estimates. The focus is on results based on explicit models, taken mostly from the industrial organization literature. First, I review studies that identify the willingness to pay for fuel efficiency using static and dynamic models of vehicle demand. Next, I take explicitly into account that firms will adjust their product portfolios and the characteristics of the vehicles they offer. These decisions will have an impact on the choice set from which consumer demand is estimated and on the trade-off that consumers face between fuel efficiency and other desirable characteristics. Finally, I discuss models where firms choose to invest in innovations to achieve fuel efficiency gains without sacrificing characteristics.

1. INTRODUCTION

A vast literature is devoted to identifying and estimating the effects of fuel prices on vehicle demand and fuel use in transportation. I have limited the discussion in this report in two respects. First, after only a brief overview of a few survey articles and recent studies that investigate the effects of fuel prices or fuel efficiency standards in a theory-free setting, in Section 2, I turn to studies that are based explicitly on models of industrial organization. Second, with only a few exceptions, only papers published in the last 15 to 20 years are included. There was a flurry of research in this area following the oil shocks of the 1970s, but the recent advances in empirical methodologies makes it hard to incorporate that work in the organizing framework I propose.

The remainder of the paper is organized as follows. I start with an overview of standard vehicle demand estimates in Section 3. Models are differentiated on many dimensions and consumers consider fuel efficiency as one desirable characteristic when making their purchase decision. Random utility models of demand are ideally suited to identify the average taste for fuel efficiency in the population. If data of individual purchases is available or if a model with random coefficients is estimated, these tastes can be allowed to vary across consumers. The standard estimates from the literature are reviewed first in Section 3.1.

Some of the dynamic features of fuel use in motor vehicle transportation are incorporated in Section 3.2. Consumers have to make a two-stage decision where first a durable good is purchased and second its intensity of use is chosen. From the demand perspective, two issues stand out. First, the error terms in both decisions are likely to be correlated and this needs to be incorporated for consistent estimation. Second, consumers have to be forward looking to some degree to value fuel efficiency.

Most of the industrial organization literature relies on observational data and uses instrumental variables to identify the demand function. Exploiting quasi-exogenous changes in taxation or regulation, for example the Corporate Average Fuel Efficiency (CAFE) standard, could provide identifying power. I discuss this in Section 3.3 and list in Section 3.4 a number of studies that evaluate the relative merits of fuel taxes and emission standards.

In the next section, I turn to the supply side. Firms will respond to changes in fuel prices or fuel efficiency standards in several ways. In Section 4.1, adjustments to vehicle characteristics are incorporated. Conditional on vehicle technology, firms face the trade-off that offering enhanced fuel efficiency, comes at the expense of other desirable characteristics such as size and horsepower. Products are positioned along this frontier and optimal positions will shift over time, for example when fuel prices change.

In Section 4.2, I consider innovation decisions that have the potential to shift the entire frontier over time. Technological breakthroughs make it possible to improve fuel efficiency, even holding other characteristics constant. When firms decide on their optimal innovation policy strategic interactions with their competitors and spillovers from technological progress take center stage.

Conclusions are summarized in Section 5.1. I mainly focus on improvements necessary to make counterfactual simulations more reliable. Two key areas for improvements are demand estimation methodology, especially robust identification, and behavioural models of the supply side.

2. THEORY-FREE ESTIMATES OF THE IMPACT OF FUEL PRICES OR FUEL EFFICIENCY STANDARDS

There is a large literature, including many contributions from fields outside of economics that investigates the direct effect of fuel prices on several variables of interest in the motor vehicle industry, such as total sales, composition of sales, etc. While some studies rely on price changes over time as source of variation to identify effects, others exploit the introduction or the tightening of fuel efficiency standards or other types of regulations. In this section, I highlight a few findings from both approaches, but I refer to other (survey) articles for a more elaborate discussion.

One issue that even studies not explicitly structured by an underlying theory need to take into account, is the fact that vehicles are durable goods. As a result, the short and long-run price elasticities of fuel use will differ as more decisions can be adjusted in the long run. Consumers can immediately adjust the intensity of vehicle use, but adjusting commuting modes will take longer. Adjusting vehicle portfolios in a firm or household will take years, and introducing different types of vehicles in the marketplace even longer. The elasticity will be (strongly) increasing in the time frame allowed for the response. This limits the comparability of estimation results from studies that do not identify primitives—technological or behavioural relations—but estimate reduced form effects directly.

2.1. Identification from observational data

The most straightforward approach is to simply follow fuel price changes over time and track how other variables co-vary with them. The conditional relationship of one endogenous variable (fuel price or average income) on another endogenous variable (vehicle sales) can be informative to understand the interactions in the adjustment process. Properly specified reduced form equations are sufficient to trace the evolution of equilibrium outcomes.

Two surveys of studies estimating price elasticities in the transportation sector, Goodwin (1992) and Oum, Waters, and Yong (1992), pay particular attention to the type of elasticities that can be identified and how. Especially in the aftermath of the oil shocks of the 1970s this was a very active area of research.

Dahl and Sterner (1991) provide an even broader survey of different estimates in the literature. They settle on an average short-run price elasticity of gasoline demand of -0.26 and an average short-run income elasticity of gasoline demand of 0.48. From a meta analysis of past estimates, Espey (1998) reaches similar conclusions: a median short-run price elasticity of -0.23 and a median short-run income elasticity of 0.39.

Following up on this earlier work, Hughes, Knittel, and Sperling (2008) provide evidence suggesting that the short-run price elasticity of fuel demand for motor vehicle use has fallen in recent years. As their data spans the entire 1975 to 2006 period, they can use the same model throughout to see how elasticities have evolved over time. The short-run price elasticity they find for the period from 1975 to 1980 ranges between -0.21 and -0.34, in line with the previous results from the literature. For the period from 2001 to 2006, the similarly estimated price elasticity has declined to a range from -0.034 to -0.077. The estimated short-run income elasticities are not significantly different between the two periods.

Different land use and commuting patterns are flagged as potential explanations, in addition to the different stock of vehicles. Consumers seem to have increasingly ignored fuel efficiency considerations in their vehicle choice following the drop in fuel prices to historically low levels in the 1990s.

A long-run elasticity of fuel use would include the adjustment of the vehicle fleet to fuel prices, but the short time span of high fuel prices in the data used by Hughes, *et al.* (2008) makes it impossible to identify this effect. Studies that accomplish this are reviewed below. It requires an explicit demand model, because vehicle prices cannot be taken as exogenous. For example, McManus (2005) provides evidence that the greater popularity and higher sales of more fuel efficient models in response to fuel price changes are concealed in the data. Fuel price increases have been accompanied by price cuts disproportionately aimed at less fuel efficient vehicles.

A final paper worth mentioning with theory-free estimates of the responses to fuel price changes is Busse, Knittel, and Zettelmeyer (2009). Using an explicitly derived reduced form model, they evaluate the equilibrium adjustment to higher fuel prices on both vehicle prices and quantities. No consumer preferences or cost primitives are uncovered, but also no assumptions on the nature of consumer choice or firm decision making have to be imposed.

Most interestingly, they find that the adjustment differed markedly in the new vehicle and the second hand market. Most of the adjustment for new cars occurred through a shifting composition of sales, a boom in the small car segment and a bust for SUVs, with small changes in relative prices for fuel efficient and inefficient vehicles. For second hand vehicles, on the other hand, almost the entire adjustment takes place through prices. Reallocating the stock of existing vehicles to match fuel efficient vehicles to high mileage drivers seems to be a marginal process.

2.2. Identification from changes in fuel efficiency standards

Chouinard and Perloff (2007) have studied which sources of variations matter most in retail fuel price differences between regions and over time. In terms of the variation over time, the dominant factor by far is the price of crude oil.[1] The advantage is that from the perspective of motor vehicle users and car buyers this is an exogenous factor, and endogeneity is not an issue to identify short-run effects from price changes above.

However, fuel prices are notoriously hard to predict. When consumers purchase a vehicle, it is not obvious how they form expectations of future prices, which is nevertheless important. For example, if consumers treat the price process as a random walk, any price increase will be considered permanent, with strong demand adjustments. On the other hand, if price shocks are assumed to decay rapidly, a given price shock will have less of an effect on demand and measured price elasticities will be lower—irrespective of the true underlying weight of fuel efficiency in consumer demand.

Moreover, firms will also respond to fuel price changes. In the short run, they can adjust the relative price of vehicles to match sales to their production capacity. In the longer run, they can introduce vehicles with different fuel efficiencies. An exogenous change in fuel prices thus triggers endogenous changes in consumers' decision environment.

More recently, many governments have imposed or tightened fuel efficiency standards and such changes can provide an alternative source of variation to identify impacts. For one, these changes tend to be viewed as permanent and consumers are likely to take them into account completely and immediately when purchasing vehicles.

An overview of current fuel efficiency standards in different jurisdictions is provided in ICCT (2007). The flurry of changes that have been proposed and introduced recently will certainly lead to an active area of research in the coming years. In addition, governments increasingly provide incentives for higher fuel efficiency through the tax system, e.g. by making annual registration fees a function of fuel efficiency. Even discrete subsidy programs have proliferated.

Following the absence of important policy changes in this area over most of the 1990s, it will take time to obtain reliable estimates of these newly introduced incentives on fuel demand. Instead of detailing point estimates that will quickly be outdated, I only list a few studies that investigate various aspect of the North American system of Corporate Average Fuel Efficiency (CAFE) standards.

- Holland, Hughes, and Knittel (2009): A theoretical analysis of the effects of low carbon fuel standards on greenhouse gas emissions

- Jacobsen (2008): Estimates of the effects of higher CAFE standards in a model with heterogeneous consumers and producers

- NHTSA (2009): Prospective estimates of the likely effects of higher CAFE standards from the National Highway Traffic Safety Administration (U.S. Department of Transportation)

- Kleit (1990, 2002, 2004)

- Parry and Small (2005): Comparison of the existing gasoline taxes in U.K. and U.S. with the optimal fuel tax. Impacts on the average fuel efficiency in the fleet and driving patterns are included in the comparison.

3. DEMAND-SIDE EFFECTS

3.1. Static estimates of the car demand elasticity with respect to fuel efficiency or fuel cost

I now review studies that use the random utility framework to estimate demand for differentiated products. The automotive market has been an active testing ground for models that describe the available products in a consumer's choice set using a limited set of characteristics. Implicitly, these studies are thus estimating the elasticity of demand with respect to different car characteristics. The fuel efficiency per distance travelled or the monetary (fuel) cost of operating a particular vehicle is the specific characteristic we focus on.

Unfortunately, several well-known studies that estimate a random utility model of car demand do not include a measure of fuel efficiency in their list of vehicle characteristics. I will not discuss those studies here.[2]

An important issue to keep in mind is that the set of other characteristics that are included in the demand regressions will vary across studies. Because of data availability and collinearity between many characteristics, each study includes only a few variables in the demand specification. As a result, the estimated fuel efficiency elasticities will hold different other characteristics constant, e.g. different measures of size, weight, horsepower, etc. As many characteristics that influence vehicle demand will be correlated strongly with fuel efficiency—for technological reasons—the comparability of the point estimates across studies is not perfect. This dependency will be explored further in Section 4.1.

Another complication is that the way fuel efficiency is measured varies. Some studies use a technological measure of fuel use per distance travelled, liter per 100 km (l/100 km), while in North America the inverse measure, miles per gallon (mpg), is more common. Especially if the variable does not enter the demand equation in logarithms, this will also influence the estimates (Larrick and Soll, 2008) as simple linear functional forms are the standard.

Even more importantly, the technical fuel efficiency is often converted into a monetary value by dividing mpg or multiplying l/100km by the fuel price. In such a specification, the variation of fuel prices over time now contributes to the identification of the demand elasticity with respect to fuel efficiency. To give these estimates a structural interpretation, an assumption on consumers' future fuel price expectations is still needed.

Estimates using different explanatory variables cannot be compared directly. Using an average fuel price and the appropriate miles per km and liters per gallon ratios, the interested reader can express all measures into the same units.

Table 1 contains a list of fuel efficiency coefficients from discrete choice models estimated for different countries. The top panel (a) lists studies that estimate (semi-)elasticities using data on vehicle choices from individual consumers. In these studies, heterogeneity in the elasticities can be incorporated straightforwardly by interacting fuel efficiency with vehicle or consumer characteristics.

Results in the next panel (b), are for studies using market-level data that incorporate a random coefficient on the fuel efficiency effect. These models still allow for heterogeneity in the taste for fuel efficiency in the population, but they require more functional form or distributional assumptions and they are more computationally demanding to estimate. Finally, in the bottom panel (c) are market-level studies that estimate a single fuel efficiency elasticity that is common to all consumers.

Table 1. **Coefficients on fuel efficiency or fuel costs in random utility demand models**

Study	Variable	Sample	Estimate	St. Dev.
Individual purchasing data				
Goldberg (1995)	Miles/dollar (=1/MP$)	U.S. small cars big cars luxury & sports	-7.143 -1.381 0.231	(0.740) (0.744) (0.931)
Goldberg (1998)	1/MP$	U.S. (all cars)	21.23	(124.9)
McCarthy (1996)	1/MP$	U.S.	-0.450	(0.051)
McCarthy-Tay (1998)	1/MP$	U.S.	range of est.	
Berry-Levinsohn-Pakes (BLP) (2004)	MPG	U.S.	0.488 (av.) + range of est.	(0.018)
Market-level data with random coefficients				
BLP (1995)	Mean effect on MP$ Random eff. on MP$	U.S.	-0.122 1.050	(0.320) (0.272)
BLP (1999)	Mean effect on MP$ Random eff. on MP$	U.S.	0.202 0.416	(0.084) (0.132)
Petrin (2004)	Mean effect on MP$ Random eff. on MP$	U.S. (with micro moments)	-15.79 2.58	(0.87) (0.14)
Verboven (2002)	l/100km	BE-FR-IT gasoline diesel	-17.4 -27.6	(Implicitly defined)
Brenkers (2005)	Annual fuel bill ($)		-13.34	(1.44)
Market-level data, estimating mean effect only				
Brenkers-Verboven (06)	$/100km	BE–FR–GE–IT–UK	-0.037	(0.007)
Van Biesebroeck (2006)	MP$	Canada	0.089	(0.065)
Klier-Linn (2008)	$/mile	U.S. (1970-1985) (1986-2001) (2002-2007)	-10.10 -1.50 -15.28	(3.48) (2.93) (2.58)
Miravete-Moral (2009)	l/100km	Spain	-0.034	(0.006)
Van Biesebroeck-Verboven (2010)	l/100km	Canada	-0.051	(0.014)

Goldberg (1995) uses information on individual car ownership from the U.S. Consumer Expenditure Survey. She estimates a nested logit specification separately for different segments of the car market. The results indicate that the demand elasticity with respect to fuel efficiency declines rapidly for larger and more expensive vehicles. In the small car segment, the coefficient on the "cents per mile" variable, proportional to the inverse of miles per gallon, is estimated strongly negative at -7.143, but this is reduced to -1.381 for larger cars and becomes positive, but insignificant for the segment of luxury and sports cars.[3]

In Goldberg (1998) the same data is used to simulate the effects of the CAFE standards using the same demand system. Estimated on the full sample, including all segments, the fuel efficiency elasticity in the benchmark model is -0.2. When the model is generalized to incorporate the decision on vehicle utilization, using the Dubin and McFadden (1984) insights discussed below, the point estimate suggests a positive, but highly insignificant, elasticity.

McCarthy (1996) finds a significantly negative coefficient, but does not report the necessary summary statistics to convert the estimate in an elasticity. In a follow-up paper McCarthy and Tay (1998) further let the sensitivity of demand to fuel efficiency vary by consumer characteristics, and even by fuel price, number of dealer visits, and city size. They thus obtain extremely flexible elasticities. Rather than reporting one number, a couple patterns can be highlighted: (i) higher income households have a lower demand for fuel efficient vehicles; (ii) female buyers have a stronger preference for efficient vehicles, but older buyers weaker; (iii) a higher gasoline price raises the absolute value of the elasticity.

Berry, Levinsohn, and Pakes (2004) generalized their 1995 estimation methodology to incorporate micro-level data and information on secondary choices into the estimation. Their positive point estimate on miles per gallon translates into an average semi-elasticity of only 0.10. The strength of their method, however, is the ability to include interaction effects which allows for different elasticities by consumer demographics.

In their original contribution, Berry, Levinsohn, and Pakes (1995) already illustrated that a random coefficient on all vehicle characteristics can be estimated using only market level data. No closed-form solution for the estimation equation is available anymore, but it allows very flexible substitution patterns between different models.

In the context of the fuel efficiency variable, they discuss explicitly how to interpret the estimates with a random effect:

"*The elasticities with respect to MP$ illustrate the importance of considering both the mean and standard deviation of the distribution of tastes for a characteristic. The results here are quite intuitive. The elasticity of demand with respect to MP$ declines almost monotonically with the car's MP$ rating. While a 10 percent increase in MP$ increases sales of the Mazda 323, Sentra, and Escort by about 10 percent, the demand for the cars with low MP$ are actually falling with an increase in MP$. The decreases, though, are quite close to zero. Hence, we conclude that consumers who purchase the high mileage cars care a great deal about fuel economy while those who purchase cars like the BMW 735i or Lexus LS400 are not concerned with fuel economy*. (p. 878)"

The results thus mirror the changing fuel efficiency elasticity by segment from Goldberg (1995), without a need to specify segments exogenously.

Berry, Levinsohn, and Pakes (1999) use the same demand model to study trade policy. The most notable change is that MP$ has been dropped from the marginal cost specification that enters the firm's first order condition for optimal price setting. Implicitly, this also amounts to different instruments in the demand equation. The large change in point estimates illustrates that the choice of instruments is not innocuous, although the qualitative findings are similar.

The results in Petrin (2004) further illustrate the effect of including a random coefficient on the MP$ estimates. Estimating the simple logit model with instrumental variables or with OLS yields an insignificant, but positive estimate on the effect of MP$ on demand, respectively of 0.05 (0.07) and 0.18 (0.06). If a random coefficient is introduced for this variable, the mean effect becomes negative, at -0.54 (3.4), and the random effect is estimated at 0.04 (1.22). Adding the micro-moments raises the absolute value of both coefficients and all coefficients are estimated a lot more precisely. For some consumers, increased fuel efficiency is very valuable, but for many others not. Negative tastes for fuel efficiency can be explained by the negative technological relationship between fuel efficiency and other desirable characteristics such as size, which will be discussed below.

Verboven (2002) and Brenkers (2005) use market-level data from a number of EU countries and they estimate a conditional demand model. Consumers are assumed to value fuel efficiency as an increasing function of their annual mileage. In Verboven (2002), drivers with annual mileage above a model-specific cut-off will prefer diesel cars that are more expensive, but use less and cheaper fuel. In Brenkers (2005), data on average mileage is supplemented with a random taste for fuel efficiency. The estimation strategy incorporates explicitly that a dollar is a dollar whether it enters through the vehicle purchase price or discounted present value of fuel savings. The relative weight on the annual fuel expenses can be used to derive an implicit interest rates that consumers use. In Table 1, I report the implied coefficients for one of the usual fuel efficiency measures.

In the bottom panel, a number of studies are collected that estimate a constant taste parameter for fuel efficiency that all consumers share. All point estimates have the right sign: on average consumers prefer more efficient cars.

Brenkers and Verboven (2006) use market-level data from a number of EU countries and estimate a nested logit specification. As they do allow heterogeneity in the price coefficient across consumers, the monetary value of the willingness to pay for fuel efficiency will still vary across consumers.

Finally, Klier and Linn (2008) estimate demand using OLS on first-differenced monthly data. They show in particular that the value consumers place on fuel efficiency has bounced around over time. In the 1970-1985 period the point estimate was -10.10, but over the 1986-2001 period of falling fuel prices it was only -1.50. In the most recent period of rising fuel prices the point estimate has increased in absolute value to -15.28 and has become highly significant.

3.2. Incorporating dynamic aspects into the demand model

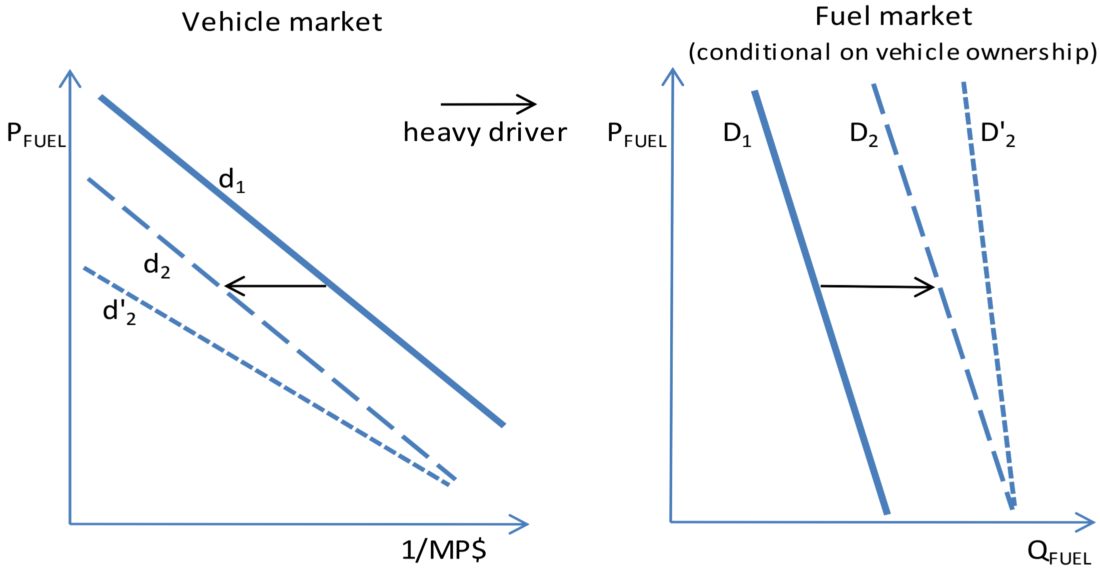
The durable goods nature of a car will matter greatly for the fuel efficiency estimates. Consumers have to solve a two-stage decision model. First, they choose a vehicle which they will keep for many years. Their driving habits will play a role, but also their expectation of the future fuel price. Second, conditional on their stock of vehicles, they choose how intensely to use them, which determines fuel consumption.

The studies in the above section only considered consumers' taste for fuel efficiency when purchasing a new vehicle. While only one aspect of the total price elasticity of fuel demand, it has received a lot of attention as the elasticity of the intensity of vehicle use, and hence the use of fuel conditional on vehicle ownership, tends to be rather low. However, the second stage environment will still influence optimal decisions in the first stage.

In Figure 1, both demands—for vehicles and for fuel—are juxtaposed. The solid curves represent the benchmark case of an average driver. Demand for fuel as a function of the fuel price, in the right panel, is generally considered rather inelastic. Demand for fuel efficiency in vehicles, i.e. the willingness to pay for fuel efficiency improvements, is an increasing function of the fuel price.

This is illustrated, in the left panel, by a declining demand for the vehicle characteristic 1/MPS as a function of fuel price. Keeping the vehicle price constant, manufacturers are able to pack more other desirable characteristics in their vehicles if they are willing to compromise on fuel efficiency. This will be especially desirable if fuel prices are low, hence the lower demand for fuel efficiency.

Figure 1. **Demand for vehicles interacting with fuel demand**



The short-run responses in aggregate fuel use by motor vehicles, as discussed in Section 2.1, represents the elasticity of demand in the right panel. The elasticity of the demand relationship in the left panel is what was estimated in the studies reviewed in Section 3.1.

To estimate the full elasticity, heterogeneity in the population and the connection between the two demand systems has to be accounted for. A heavy driver will have a demand for fuel shifted to the right, D_2 instead of D_1, but it is also likely that the curve will be steeper, like D'_2. Recreational drivers should be able to adjust their fuel use more easily than travelling salesmen.

Similarly, heavy drivers will ceteris paribus prefer vehicles with a higher mileage at each fuel price, hence have their vehicle demand shifted left from d_1 to d_2. At the same time, heavy drivers should realize that they will be unable to adjust their fuel use after they purchase a vehicle. Their lower elasticity of fuel use should increase their elasticity of fuel efficiency demand, like d'_2.

In the estimation, there are at least three issues to be dealt with. First, the error terms in both the vehicle choice and intensity of use decisions are likely to be correlated. To estimate the overall longer term elasticity consistently this should be explicitly accounted for. Dubin and McFadden (1984) were the first to model the two-level decision making explicitly in a study of appliance choice and electricity use. Using 1975 data for individuals they find very low elasticities for space and water heaters with respect to natural gas price (+0.35) or electricity price (-0.23).[4]

A priori, the correlation between the error terms in both markets could go either way. If persistent (unobserved) individual tastes are important, people might be ranked along a "greenery" dimension. Green consumers will buy fuel efficient vehicles and use them frugally. In this case the error terms in both markets should be positively correlated. On the other hand, it might be the heavy drivers who realize greater gains from investing in fuel efficiency, leading to a negative correlation in the two market errors. Yet another model would be to allow for correlation not in the additive error, but between the random component on the taste for fuel efficiency and the fuel use error.

Second, to estimate the total elasticity of fuel demand with respect to the fuel price, the intensity of use should also be modelled. Small and Van Dender (2007) illustrate that the interaction between the two markets also runs in the opposite direction. As mentioned, heavy drivers should have a higher and more elastic demand for fuel efficient vehicles. At the same time, owners of more efficient vehicles should have a less elastic fuel demand as fuel expenditures are a smaller share of total driving costs. This gives rise to the rebound effect. As higher fuel prices leads consumers to adjust their vehicle stock, their cutback in fuel use is diminished, lowering the elasticity of total fuel demand.

A third estimating issue is that people have to be forward looking to spend more money on a vehicle with higher fuel efficiency. As long as all available vehicles used the same technology this was not a major issue. Fuel efficiency improvement necessarily had to come at the expense of other desirable characteristics. Given existing the existing technology it was virtually impossible to boost fuel efficiency without hurting other performance features.

However, when it became feasible to boost the fuel efficiency of a vehicle by introducing different technologies that come at a price, such as diesel or hybrid power trains, the extent to which consumers are forward looking becomes important.

Verboven (2002) estimates the implicit discount rate that forward looking people are using when they choose between a diesel engine and an equivalent model with gasoline engine. This involves a trade-off between higher purchase price and lower operating (fuel) costs. In contrast with earlier results, like Hausman (1979), Mannering and Winston (1985), and Dreyfus and Viscusi (1995) who found that consumers behave relatively myopically, he finds implicit discount rates roughly equal to vehicle financing rates.

Verboven (1999) explores implications for the demand model, when consumers only consider the monetary implications of fuel efficiency. It leads to a separating equilibrium where consumers driving less than a certain threshold opt for gasoline engines and heavy drivers use the more expensive diesel technology.

Sawhill (2008) also does not find any evidence that consumers underweight future operating costs. He incorporates more sophisticated fuel price expectations using an ARIMA model. Exploring information on driving patterns, he does find evidence of large heterogeneity in the population with respect to their sensitivity of operating costs, as would be expected.

3.3. Identification in demand estimation

Identification is a major issue in demand estimation. Especially in a concentrated industry with differentiated problems, it is hard to control for endogenous price setting of firms. The problem is that unobservables (to the econometrician) in the demand equation will induce a correlation between price and the error to the extent that firms know more than the researcher. In addition, other characteristics than price might be adjusted strategically.

In practice, studies estimating differentiated goods demand models have used combinations of functional form restrictions and instrumental variables to identify price coefficients. Popular instruments that are expected to be correlated with price, but do not belong in demand include (i) mark-up shifters such as characteristics of competitors (BLP, 1995), (ii) cost shifters such as price in other geographical areas (Hausman), (iii) region and city variables to capture transportation costs, opportunity costs in distribution, and strength of local demand (Nevo).[5]

An alternative would be to exploit a natural experiment setup to identification structural relationships. In the current context, there is scope to exploit policy changes such as the tightening of fuel efficiency standards to obtain some exogenous variation. Studies that exploited such changes to identify effects directly were already reviewed in Section 2.2, but policy changes might also aid in the identification of primitives, such as demand for fuel efficiency or product introduction policies.

Results in Atkinson and Halvorsen (1984) and Gramlich (2009), which are discussed below, illustrate the tight correlation between fuel efficiency and other characteristics. It makes the source of identification an important issue that has not received sufficient attention. Lingering bias in any of the parameter estimates will spillover onto the fuel efficiency estimate.

This issue is especially important as several studies have found the elasticity of vehicle demand with respect to fuel efficiency to be variable over time, see for example Klier and Linn (2008). I use an identification strategy that has similarities with Verboven (2002) -- exploiting substitution between engines conditional on the choice of car model -- to show some additional evidence. A unit of observation is a particular model (engine) in one month and all variables are expressed relative to the base model for sale.

In the demand equation, I include both the usual fuel efficiency term, measured in dollars or euro per 100km, and an interaction term between the same fuel efficiency variable and a time trend. From these estimates, I can construct the implied time-varying fuel efficiency coefficient, which is plotted in Figure 2 for the U.S. and the Belgian new car market. Because of the estimation strategy, the units are the direct fuel efficiency elasticities and incomparable to any of the estimates reported in Table 1. An estimate of -2 indicates that a 1% increase in dollars or euros per 100 km relative to the base model would lower sales by 2% relative to the base model. Over time, fuel price increases or efficiency decreases are estimated to have increasingly negative effects on the demand for low mileage vehicles.

The sudden reversal in this trend for the U.S. towards the end of the sample seems puzzling at first. However, just as we can model the fuel efficiency parameter as evolving over time, we can model it as a function of the fuel price. Those results for the same two countries are in Figure 3.

Figure 2. **Time-varying parameters on fuel efficiency in new vehicle demand**

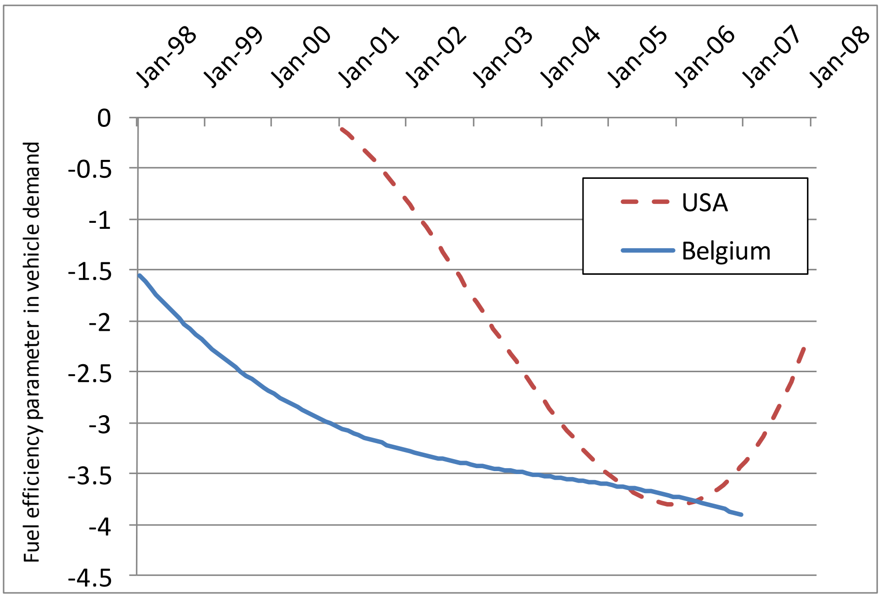
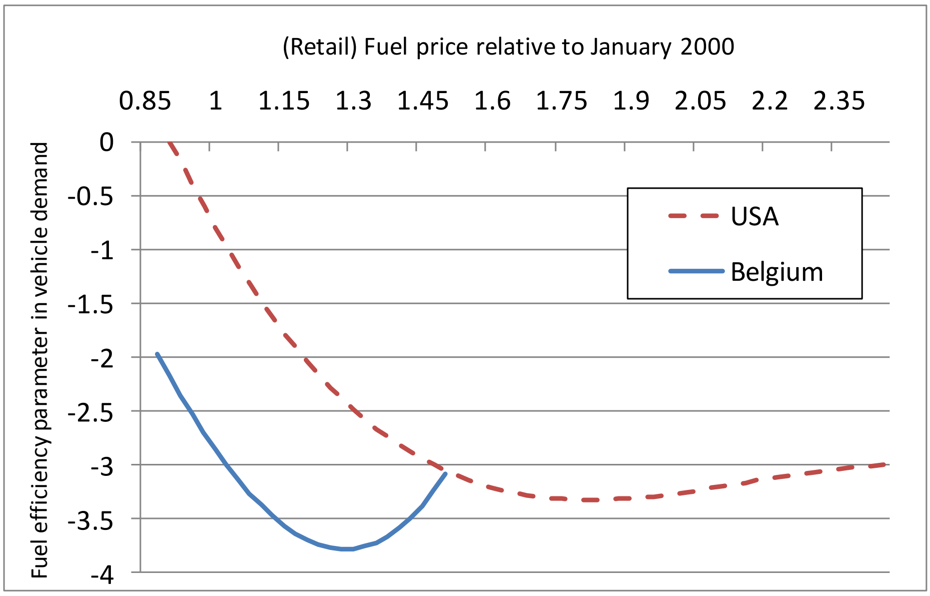


Figure 3. **Parameter on fuel efficiency in vehicle demand is varying with the fuel price**



The estimated elasticity is, especially in the U.S., increasing with the price of fuel. The strong decline in fuel prices after their peak in the summer of 2007 thus lowered consumers' sensitivity to fuel efficiency again. The effect in Belgium, where fuel prices have been a lot higher throughout and less volatile over time due to high taxes, the effects are estimated less precisely and they take a U-shape.

While these results are somewhat intuitive, they also raise doubts to what extent the demand equations can be considered representative of underlying primitives. What to make of consumer demand estimates if they turn out to be so unstable? Figure 1 does suggest one channel: when fuel prices are high, and expected to stay high, future fuel expenditures are predicted to form a larger share of the total cost of car ownership and hence should receive higher weight.

3.4. Fuel taxes or fuel standards

Many studies have used demand estimates like those above to compare policies to increase fuel efficiency for the vehicle fleet through price incentives by raising fuel taxes, or through mandated efficiency standards imposed on producers. The two policy instruments have different implications on income distribution, efficiency losses, and speed of adjustments. The consumers' price elasticity of fuel use that we have focused on is one important factor.[6]

Important studies focusing explicitly on the car market include:

- Boyd and Mellman (1980): an early study using a reduced form hedonic demand model
- Gruenspecht (1982): discusses the effects of asymmetrically applying the standards only to new vehicles. It induces consumers to hold on to older less efficient vehicles, while fuel taxes would have the reverse effect of accelerating the move to a more fuel efficient vehicle stock.
- Borenstein (1993): studies the same policy trade-off in the context of the phase-out of leaded fuel
- Koopman (1995): a partial equilibrium simulation of the predicted effects for Europe
- Goldberg (1998): calculates the cost of strengthening CAFE standards using a demand model that incorporates both the response in the car market and in fuel use, conditional on car ownership.
- Austin and Dinan (2005): redo the Goldberg (1998) analysis, but incorporate cost estimates for technologies that boost fuel efficiency and the ability to trade fuel-economy credits.
- Kleit (2004): similar analysis

The Koopman (1995) study highlights that cost-effective limiting of CO2 emissions requires an instrument that equalizes the marginal cost of emissions abatement across all sources. Economy-wide carbon fees and tradable permit schemes are therefore preferable. He shows in particular that CAFE/gas-guzzler schemes would be approximately 20% more costly to lower emissions by 10%. In addition, the emission reduction relies much more strongly on the improved fuel efficiency of new vehicles and a changed fleet-mix under the CAFE scheme. A consequence is that the cost differential is increasing in the fuel efficiency target. Raising annual taxes on car ownership or purchase taxes are even less efficient mechanisms.

Conclusions differed in Goldberg (1998) as her estimates show no evidence of utilization effects at all for U.S. consumers. In response to small increases in fuel prices, consumers did not drive less, making fuel taxes ineffective to lower fuel consumption. Austin and Dinan (2005) use similar, but more recent, U.S. data. They directly estimate the long-run elasticity of fuel demand from the relationship between vehicles-miles-travelled and the fuel price.[7] Using their estimate of -0.39 they confirm the finding in Koopman (1995) that a fuel tax would be vastly cheaper than CAFE standards to engineer a reduction in fuel consumption in the motor vehicle sector.

Kleit (2004) reaches similar conclusions, but the difference is even more stark. Estimates in Austin and Dinan (2005) put the cost to society for a reasonable reduction in fuel consumption through CAFE standards at three to four times the cost of achieving the reduction through fuel taxes. Kleit (2004) estimates the cost to be fourteen times higher. Furthermore, while the benefits of fuel consumption reduction (as estimated by the NRC) outweigh the costs of achieving them through fuel taxes, this is not the case for CAFE standards.

4. SUPPLY-SIDE EFFECTS

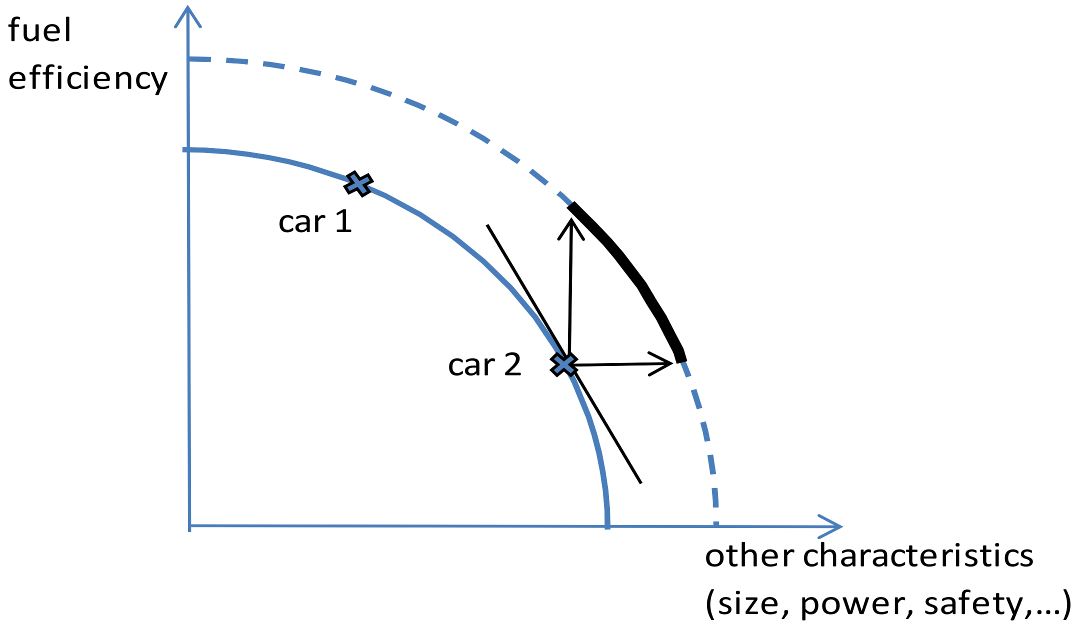
4.1. Product positioning along the technological frontier

Thus far we have only considered the demand side, but in the discussion of identification it has already come up that this cannot be considered in isolation from the supply side. Firms are not passive actors. They decide on product introductions and pricing, taking fuel prices and competitor actions into account.

Most importantly, there is a technologically determined frontier that determines the trade-off between fuel efficiency and other desirable vehicle characteristics. Given the state of the art vehicle design technology, it is nearly impossible to improve size, horsepower, or even handling or safety features which tend to increase weight, without hurting fuel efficiency. At each point in time this frontier is fixed and firms have to determine where to position their models along it. At the same time, higher fuel efficiency can only be obtained by compromising on other vehicle characteristics.

In Figure 4, two hypothetical cars are shown, with car 1 a lot more fuel efficient than car 2. It could be smaller or have worse driving performance, but it has to be inferior to car 2 in some dimension or there would be no demand for car 2.

Figure 4. **Technological production possibilities frontier for fuel efficiency and other characteristics**



Note that we have fixed the vehicle price along the solid frontier in Figure 4. In the past, there was very little scope to improve a car's fuel efficiency holding the other characteristics constant, i.e. moving car 1 vertically towards the dashed frontier was virtually impossible. In principal, cars could be made lighter using aluminium instead of steel, but the high cost made it only viable for niche products. Increasingly, the availability of diesel and hybrid drivetrain technologies, has made it possible to achieve higher fuel efficiency without sacrificing features, albeit at a cost. This is discussed further in the next section.

Here we discuss the ability and the incentives for manufacturers to decide on their position along the existing frontier and set accompanying prices. Faced with a choice set, consumers will pick their preferred models based on their willingness to pay for fuel efficiency relative to other characteristics.

Implicitly, there is a relative price consumers are willing to pay for fuel efficiency, which varies across consumers. Everyone will purchase the vehicle closest to the line of tangency of their price line and the frontier. Importantly, changes in fuel prices will change everyone's price line, although not to the same extent. This depends on the demand elasticity with respect to fuel cost which is likely to vary with income, commuting habits, annual mileage, etc.

Following a fuel price increase, the adjustment process of models offered for sale will resemble the process studied in Linn (2008), in an application of manufacturing plants adjusting to fuel price changes. The direct change in energy use was very limited, just as drivers' fuel demand is highly inelastic conditional on vehicle stock. In the medium term consumers can re-optimize their vehicle portfolio which makes the demand response larger, as discussed before.

In Linn's example, most of the response in energy use only occurred once firms adopted new technologies that allowed lower fuel consumption at similar levels of performance. This goes beyond selecting different machines from the existing menu. It includes changing the menu. In the car market, the composition of vehicle sales will gradually start adjusting right away. After a couple of years the choice set for consumers will change as well as firms reposition their (limited number of) models along the frontier.

In a comparison of the fuel price in the U.K. and the U.S. Parry and Small (2005) highlight the very different average mileage attained by new vehicles. This discrepancy did not come about overnight. It was a slow process of firms deliberately installing less powerful engines in similarly sized cars as consumers implicit price line in Figure 4 became less steep.

Such adjustment will not be costless. Bresnahan and Yao (1985) estimate that the cost of complying with efficiency standards in terms of "loss of drivability" exceeded the monetary costs of changing vehicle design, at least in the short run. Desirable characteristics had to be sacrificed to lower fuel consumption, as the technological frontier was fixed in the short run.

The study of pollution control by Gruenspecht (1982), already mentioned earlier, demonstrated that consumers held on longer to older vehicles as stricter pollution standards only applied to new vehicles. The same will happen with mandatory emission standards, but fuel taxes will spur the opposite pattern of adjustment. Consumers have the greatest incentive to start replacing the least efficient vehicles, which are by and large the oldest. The increased demand for fuel efficiency will have a further effect on new vehicle introductions crowding the space at the top-left segment of the frontier in Figure 4. As a result many more consumers will find a fuel efficient vehicle fitting their own idiosyncratic tastes.

In the even longer run, technological advances will shift the frontier in Figure 4, but that will take time. Evidence in Knittel (2009) illustrates that both the average set of characteristics chosen by consumers, such as size or weight, as well as the fuel efficiency per unit of size or weight have changed a lot. The former represents mostly a shift along the frontier—which tended to be to the detriment of fuel efficiency as a long period of lowering fuel prices (in real terms) made consumers implicit price slope steeper. The latter shift represents a shift of the frontier, allowing higher fuel efficiency even holding other characteristics fixed, but this pattern was swamped by the first shift. Even though technological change improved fuel efficiency possibilities, manufacturers followed consumers' tastes in their product positioning. The introduction of a plethora of SUV models and derivatives in the 1990s was a clear manifestation of this.

In general, it seems inefficient to target fuel efficiency standards at the producers and not at the consumers. I have argued in Van Biesebroeck (2009) that the system of CAFE standards has provided the U.S. companies with perverse incentives *against* developing smaller, more fuel-efficient vehicles. Enforcing the standard by averaging the mileage over all vehicles sold by firm ignores the comparative advantage of different firms. Some firms make excellent minivans, others excel at making small cars. Charging producers fees on the average mileage of their fleet amounts to cross-subsidising large vehicle sales by smaller vehicles, but only within the same firm. It has at least two consequences with dubious merits: (1) it induces firms to lower prices on small vehicles, certainly in relative terms, making them less profitable; (2) it provides incentives to offer a full line of vehicles, in spite of comparative advantages.

The first effect distorts the directly measured profit per vehicle. Selling a fuel efficient small car has the externality of avoiding a CAFE fine that does not show up in the accounts. Measured profits on SUVs ballooned towards the end of the 1990s, partly because firms raised prices to steer consumers towards smaller vehicles and avoid CAFE fines. At the same time, profit margins on smaller cars evaporated entirely and even turned negative for some models, at least without taking account of the implicit subsidy; sales of small vehicles were a necessary condition to sell profitable SUVs without breaking the CAFE standards, which was deemed especially costly in terms of company reputation.

As different development teams within each firm vie for resources, the discrepancy between real and accounting profitability weakened the business case for small vehicle programs. No wonder Ford did not bother to bring the second-generation Focus from Europe to North America, avoiding a costly retooling of its Wayne assembly plant. No wonder Chrysler never invested a lot in a successor to its relatively popular but unprofitable Dodge Neon. And no wonder General Motors relied ever more on its Korean Daewoo subsidiary to provide it with cheaper, foreign-made compact cars. These second-best choices ended up leaving these firms vulnerable in the ensuing high gas price era. Indirectly, the CAFE norms weakened the business case for investing in small cars for these firms. Of course, these firms should take the externality of high SUV profits into account when allocating development funds to small vehicle programs, but why make it so non-transparent?

Another unintended consequence is that a carmaker with a comparative advantage in highly polluting vehicles, say Porsche, now has an incentive to purchase a carmaker producing smaller vehicles, such as Volkswagen, to lower the average fuel consumption of its fleet. Clearly this does not generate any environmental benefits, but it is individually rational for a firm, especially as fines are increasing convexly. Similarly, it also strengthens the incentive for Daimler-Benz to continue its perennially loss-making Smart brand and to even introduce it in North America. Building city cars does not seem to be this firm's comparative advantage. It also dilutes development resources as Daimler is now trying to replicate knowledge of how to profitably make small cars that other firms already possess.

Similar side-effects apply also to the E.U. regulation that targets a fleet average emission of 130 grams of CO2 per kilometres by 2015, a further reduction to 95 g/km by 2020, and possibly to 70 g/km by 2025 (subject to review). To mitigate some of the undesirable consequences discussed above, Regulation (EC) No. 443/2009 that was approved by the E.U. on April 23, 2009, included several mitigation mechanisms. First, the emission target follows a "limit value curve" which allows somewhat higher emissions for heavier cars, while preserving the overall fleet average. This limits the need for all manufacturers to offer a full line-up. Second, firms are allowed to pool their fleet averages. Especially in the first years when targets are not exceedingly strict and when fines are convex in the amount of emissions this mechanism would be beneficial. It can spread the incentive for further reductions to firms that already meet the standard and it can allow for more efficient abatement cost allocation by equalizing the marginal penalty. Third, to avoid excessive costs driven by the extremely fast timetable for adjustment, penalties to exceed the legislated standards are lowered until 2018 and very low emissions vehicles receive an additional weight.

The Canadian feebate program illustrates another unintended consequence. Initially, the Honda Fit exceeded the 6.5l/100km fuel consumption threshold for subsidies by the smallest of margins. Honda could have omitted the airbags from the Fit's base model, lowering its weight and qualifying new owners for a $1,000 government rebate. These savings would have been more than sufficient for customers to re-select the airbags from the options list, should they choose so, for no environmental benefit and a nice taxpayer subsidy. Crandall and Graham (1989) have illustrated that the CAFE norms more generally had an effect on vehicle safety, as should be expected from the trade-off in Figure 4.

While the trade-off in vehicle characteristics is important in its own right, it also affects demand estimates, in particular the elasticity with respect to fuel efficiency. Atkinson and Halvorsen (1984) show that the a tight (negative) correlation between fuel efficiency and other desirable vehicle characteristics, such as size and driving performance, leads to a multicollinearity problem. As a result, consumers' willingness to pay for fuel efficiency is often estimated very small or even with the wrong sign.

Their solution is to augment the hedonic model—the same could be done with a demand equation—with the technological relationship between fuel efficiency and other characteristics. Both equations can be estimated directly, obviating the need to include fuel efficiency in the demand equation. In this way, fuel efficiency is merely constraining or putting a price on other desirable characteristics.

The estimation approach in Verboven (1999, 2002) similarly incorporates that improved fuel efficiency is not a goal in itself, but a factor that influences total cost of ownership as well as performance characteristics. No structural relationship is uncovered, but the latter effect is controlled for in the conditional demand estimation.

More recently, Gramlich (2009) has argued that the current fuel efficiency frontier can be taken into account in a reduced form manner by including both MPG and MP$ together in the demand model. His results suggest that the monetary measure MP$ is a highly desirable characteristic that significantly boosts average demand—in contrast to the low estimates of the mean effect of MP$ in panel (b) of Table 1. Additionally including the physical measure MPG, produces a negative coefficient estimate in the demand equation. Once MP$ is controlled for, the MPG variable is capturing the negative impact of higher fuel efficiency on other unmeasured desirable characteristics.

4.2. Innovation to boost the fuel efficiency frontier

The frontier depicted in Figure 4 is naturally not fixed. Through innovation firms have the potential to shift the entire relationship over time. Technological breakthroughs make it possible to improve fuel efficiency, even holding other characteristics constant. To assess the cost and speed with which this is likely to happen, we need to consider both technological feasibility and firm incentives.

To gauge the potential for such improvements, it is useful to look at the past record. Results in Knittel (2009), already mentioned before, highlight that the average fuel efficiency of new vehicles in the U.S. only increased by 15% from 1980 to 2006. However, the average increase holding weight and power, and hence performance, constant amounts to fully 50%. The latter effect is the result of technological improvements, while the former is a combination of firm model positioning and pricing, and consumer choices exploiting the ability to increase performance without fuel efficiency penalty now afforded by the technology.

Kahn (1996) provides evidence that emissions by the motor vehicle sector of all pollutants but CO2 have declined tremendously even though total miles driven has increased. CO2 is still a problem, but it is an outlier.

As the energy provision in the current propulsion by fuel combustion is directly tied to hydrocarbons, it would be a major task to filter CO2 emissions from the exhausts. Carbon capture technologies are being explored in stationary power plants, but for vehicles the only viable route for many decades will be to simply use less fuel. An alternative solution, being rolled out right now, is to use electric power from batteries and worry about CO2 emissions in electricity generation separately.

The engineering approach to assessing the scope for and cost of fuel efficiency improvements amounts to projecting out existing trends of technological improvement. Among many factors that will play a role, one of the most crucial are the different trajectories for incremental versus radical innovations, which lead to different short term and long term predictions. Mature technologies tend to require increasing R&D expenditures to realize incremental fuel efficiency gains. It leads to sharply convex costs per unit of improvement increase.

Eventually, existing technologies reach a saturation level or even a bottlenecks and only radical innovations can provide further gains. As new technologies are introduced, they tend to have a much higher marginal return to R&D expenditures, at least for a while. As a result, the convexity of costs is diminished if a longer time frame is considered.

Predictions on the long-run effect of tightening CAFE standards will need, in addition to a demand model for fuel efficiency, a model of costs associated with fuel efficiency improvements. A 2002 report by the National Research Council, NRC (2002), provides estimates how expensive it would be to boost the fuel efficiency average in different vehicle segments. For example, in 2000 the average MPG of a midsize car in the U.S. was 27.1. Using the formula

$$\Delta p = a_1\left(\frac{\Delta E}{E_0}\right) + a_2\left(\frac{\Delta E}{E_0}\right)^2$$

With a_1=2799 and a_2=2152 (for midsize cars), it is estimated that the price of a midsize car would increase by $1074 if its fuel efficiency were raised to the new CAFE standard for 2016 proposed by the Obama administration of 35.5 mpg.

Greene and DeCicco (2000) review the sources of heterogeneity in different engineering estimates of the likely cost increases to boost fuel efficiency.

One difficulty using estimates like this is that there is no explicit time frame. The discussion surrounding adjustments to deal with climate change have brought to the fore that it would be a lot more costly to effectuate change more rapidly. In that context, the main mechanism is the early retirement of capital goods that have not physically depreciated. In the current context, the trade-off is to push existing technologies further up their cost curves, rather than wait for new breakthroughs.

The study of Fowlie, Knittel, and Wolfram (2009) of different treatment of NOx pollution by stationary and mobile source is another example using an engineering approach. Rather than estimating a marginal cost function associated with NOx abatement ex post, using observations on firms expenditures and observed NOx emissions, they use ex ante engineering estimates for cost abatement technologies. For their analysis they need marginal abatement cost curves for (stationary) power plants and vehicles, both for technologies that were adopted and for those that were not.

They used detailed analyses and field testing of available pollution control technologies, as carried out by industry trade groups, emissions control equipment manufacturers, and other stakeholders. For the motor vehicle sector, they use estimates by the U.S. EPA. All estimates fail to capture unanticipated changes in costs, optimization errors, or behavioural responses and idiosyncrasies that caused decision-makers to deviate from the engineering ideal. However, this is exactly what is needed to study coordination of adoption decisions, *given* the available information to policy makers.

In spite of shortcomings, some estimates are needed to do counterfactual analysis of policies right now. We can trust that better estimates will be forthcoming if there is a demonstrable demand for them. Greene, Patterson, and Singh (2005) use the above estimates to evaluate the likely effects of feebates based on fuel efficiency. They find that most of the changes would come about through technological spending to improve average fuel efficiency—with increases in vehicle prices along the lines of the calculations above. The sales reduction would be limited.

Austin and Dinan (2005) use an approach similar to Greene, Patterson, and Singh (2005), also relying on the NRC cost estimates associated with fuel efficiency improvements, but their objective is to compare the effect of CAFE standards with taxes on fuel. They thus revisit the often-studied question surveyed in Section 3.4 in a dynamic context.

Firms receive two sets of incentives to invest in fuel efficiency. Higher fuel prices, because of higher taxes, will boost sales of more efficient vehicles in proportion with the consumers' demand elasticity. The results in Figure 3 suggest the elasticity might even be increasing in the fuel price boosting this effect. At the same time, under the CAFE standard system firms are charged a penalty if the average efficiency of their fleet does not meet a minimum standard. Certainly under the newly increased standard, in force from 2016, all firms will be constrained and have an additional incentive to make their vehicles more efficient. The estimates in Austin and Dinan (2005) indicate that the first mechanism would be far more cost effective.

A second difficulty in using the above estimates is that effects are expressed as price increases rather than cost increases. In the automotive industry, the estimated price-cost mark-ups tend to be quite large, due to the concentrated market structure and strong product differentiation. Assuming an elasticity for the residual demand of -2, does the estimated $1,074 to bring the average midsize car up to the new mpg standard mean that costs would only increase by half or that profit maximizing manufacturers that implement these technologies would raise prices by double the amount?[8]

Firms' incentives to invest in innovations will influence the cost and speed of moving to greater fuel efficiency in other ways as well. Shiau, Michalek, and Hendrickson (2009) demonstrate that with heterogeneous consumers and firms, the response to higher CAFE standards will not be uniform or monotonic. Some firms will meet the standard using existing technology, perhaps only having to adjust prices to steer sales. Other firms will invest in new technologies to boost efficiency, but there are limits to this. Exceedingly high standards will make some firms rationally choose to simply pay the fines.

When firms decide on their optimal innovation policy, strategic interactions with their competitors and spillovers from technological progress can also not be ignored. Barla and Proost (2008) derive a general equilibrium model where rational firms underinvest in fuel-saving technology as competitors are able to benefit from their efforts through technology spillovers. To achieve first best in this situation, an additional policy tool is need, e.g. both fuel taxes and emission standards.

Finally, Hashmi & Van Biesebroeck (2010) study the strategic interaction of firms' innovation decisions in a dynamic context. Results suggest that in highly concentrated markets, such as the automotive industry in the last decades, innovation is subdued as strategic motives start to matter.

One channel is that firms invest partially to increase their value in the case of a merger. When taken over, the compensation for the original shareholders will generally increase with the value of the assets of the firm. With fewer independent groups left, future mergers are becoming increasingly unlikely given competition policy constraints, which provides reduced incentives for innovation.

A second channel is that firms decide on innovation expenditures strategically. Estimates of the dynamic policy in Hashmi and Van Biesebroeck (2010) suggests that innovation incentives are concave in the knowledge stock of other firms in the industry. At least in the area of the state space where knowledge is high, innovations are found to be strategic complements. Given that the direct effect of innovation on consumer demand is also concave, there is an inevitable upper bound on the optimal steady state knowledge stock.

A final channel hampering innovation given the current state of the automotive industry is that the model predicts an inverted U-relationship between market structure and innovation. Both the leaders and the distant laggards invest less than the firms in the middle that are trying to catch up to the leaders or try to avoid the absorbing state with a zero knowledge stock. As the large groups in the industry are converging to some stable oligopoly, fewer middle firms remain.

5. CONCLUSIONS

Calculations of the cost and the best way to achieve a decrease in fuel use by the motor vehicle sector will necessarily take the form of counterfactual simulations of the evolution of a market equilibrium. To have confidence in the predictions, we need to have confidence in the primitives of such a model. In these conclusions, I wish to highlight two important areas that could greatly benefit from additional research.

First, while there are many demand estimates that characterize consumers' willingness to pay for fuel efficiency improvements in this industry, the point estimates vary widely and their exact values matter in the counterfactuals. A more rigorous understanding of the nature of identification of the parameters, and ideally also a more transparent identification strategy, is needed.

To further our understanding, the instability of the demand elasticity with respect to fuel efficiency and across consumers has to be better understood. A higher elasticity at higher fuel prices is not unreasonable—given the low elasticity of fuel use, fuel cost takes up a much greater share of total cost of car ownership when prices are high—but the exact way this enters the consumers' decision process needs to be understood and modeled for it to be useful in a counterfactual simulations where fuel prices will be modified.

In addition, the current technological frontier forces manufacturers to trade-off fuel efficiency and other desirable characteristics. This imposes a strong correlation on the different vehicle characteristics. Estimation problems with one of the variables will thus immediately spillover to the other. Functional form assumptions are also more important in this context.

More generally, it should be explicitly understood that fuel efficiency has multiple effects in the vehicle choice decision. It is a fraction of the cost. It is a constraint on the other characteristics a vehicle can possess. And it might have an intrinsic value for the environmentally conscious consumer. If alternative policies differ in their impact on fuel prices, it is important to separately identify these effects.

The second area that deserves a lot more attention is the behaviour of firms. They are not passive actors that simply move along a deterministic cost curve as fuel prices shift exogenously with the crude oil price or fuel taxes.

Firms have to choose other characteristics and prices to position their vehicles along a fuel efficiency frontier. If consumer demand for fuel efficiency is one important ingredient in this decision, it is definitely not the only one. Firms will take into account where on this frontier profit margins are highest. As a result, their responses to fuel taxes and mandated emission norms could be very different if product heterogeneity is explicitly accounted for.

In recent years, an additional choice has opened up for firms. Exploiting the possibilities with diesel or hybrid technology it is now possible to offer models with similar characteristics, e.g. size and driving performance, but with enhanced fuel efficiency. To predict how firms will exploit this possibility, it is important to separately identify the willingness to pay of consumers for fuel efficiency, not only in terms of other characteristics, but also in terms of out-of-pocket spending.

Finally, existing simulations by and large treat the problem of firm innovations to shift the above frontier as a single agent problem. While natural from an engineering point of view, it leaves out strategic considerations. In a concentrated industry like automotive manufacturing, firms will take innovation decisions by competitors into account in their own decisions and technology spillovers will cause underinvestment.

NOTES

1. During the 1990s, Chouinard and Perloff (2007) document that other factors, such as taxes, mergers, and regulations, were of minor importance in explaining fuel price changes over time, but they did predict geographic differences rather well.

2. Studies that I omit from the discussion for this reason are, in chronological order, Bresnahan (JIE, 1987), Feenstra and Levinsohn (RES, 1995), Verboven (RAND, 1996), Fehrstman and Gandal (RAND, 1998), Verboven (JIE, 1999), Goldberg and Verboven (RES, 2001), Brambilla (NBER WP, 2005), and Esteban and Shum (RAND, 2007).

3. These are semi-elasticities and need to be multiplied with the mean of the explanatory variable to obtain the elasticities.

4. A lot lower than those in Houthakker (Energy Journal, 1980) who ignored the first stage and found an elasticity of 1.4 for electricity price and 0.7 for the gas price for residential electricity demand.

5. The latter two strategies only work if markets are defined geographically. Specifically for the automotive industry, prices in other markets would not work as the importance of national advertising would make demand shocks spill over to all geographic areas.

6. Borenstein (1993) is one study tackling this issue head on in the context of the phase-out of leaded fuel. Goldberg (1998) calculates the cost of strengthening CAFE standards using a demand model that incorporates willingness to pay for fuel efficiency.

7. A benefit of their approach is that the same data is used to estimate the elasticity in vehicle demand with respect to fuel efficiency and the price elasticity of fuel demand.

8. Optimal pricing of a monopolist predicts a price cost margin (p-MC)/p equal to $1/|\varepsilon|$ using the elasticity of the residual demand.

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