Fuel Choice and Fuel Demand Elasticities in Markets with Flex-fuel Vehicles

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The purchase of multi-fuel vehicles has been incentivized by policies across the globe. As such vehicles are able to operate on more than one source of energy, they introduce fuel (or energy) choice as one additional dimension consumers decide about. Since fuels differ in terms of carbon emissions, this choice has environmental effects. Using twelve years of monthly Swedish data, here I show that the majority of multi-fuel vehicle drivers purchase petrol when it is priced at parity with ethanol. Through policy simulations, I document that fossil fuel taxes have limited success in making drivers switch to alternative fuels, and can generate economic distortions. The findings question the cost-effectiveness of programmes incentivizing the purchase of multi-fuel vehicles that ignore the fuel choice dimension, and highlight the importance of accounting for fuel choice in the analysis of public policy and emerging technologies.

Historically, CO_2 emissions from transport command approximately 20 percent of total emissions in the European Union (EU), the biggest vehicle market worldwide. The aim to reduce this footprint led the EU to take measures such as CO_2 emission targets and a renewable fuel standard (RFS) for the transport sector. Although the policies designed to attain such targets vary across countries, their cost-benefit analyses (CBA) are similar in that they compare benefits (e.g. monetized carbon savings) and costs (e.g. monetary transfers to individuals) of the policies. Fuel choice between a (high-emission) fossil fuel and a (low-emission) alternative fuel may fundamentally affect the benefits of an environmental programme, and thus whether it is worth undertaking. This makes understanding how drivers approach fuel choice crucial to correctly pursue the CBA of such a programme.

Multi-fuel technologies introduce a trade-off typically not taken into account by policy-makers. On the one hand, multi-fuel vehicles (MFVs, where the driver has control over which fuel the car operates on) reduce concerns about range anxiety, the need of frequently refueling, and technological lock-in emerging automotive technologies often face. On the other hand, MFVs allow drivers to actively choose the fuel their vehicles operate on, thus they might operate solely using fossil fuels. In fact, little is known about the extent to which MFVs actually operate on alternative fuels, and about the substitution patterns between fossil and alternative fuels.

If two fuels provide the same service, namely transportation, they should be seen as close substitutes. If this is not the case, the assumption that consumers would adopt alternative fuels as they become more cost-competitive, even after infrastructure provision, is likely misguided, as non-price attributes may also affect consumer behavior. Moreover, programmes paying hefty incentives to consumers in order to stimulate the demand for MFVs would require additional

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policies in the fuel market due to the fact that fuel choice becomes another dimension of the consumer's decision-making process. This becomes ever more important since MFVs were at the center of recent policy initiatives in the US, China, India, Japan, and most EU countries. The study of the Swedish market is due to the fact that it is one of the few markets where one can study fuel switching between alternative and fossil fuels using a long sample.

This paper quantifies the demand for fuels in the Swedish light-duty transport sector. To do so, it estimates the demand for ethanol and petrol (gasoline), which are the fuels the leading multi-fuel technology in the Swedish market can operate on. This is important as a tool to assess the adoption of alternative fuels in the Swedish market. In the empirical analysis, I estimate the demand for petrol and ethanol using econometric methods and data on fuel and vehicle monthly sales for 2005-2016. The results point to different price-responsiveness of petrol and ethanol sales; while own-price elasticities for the former are between -0.13 and -0.12, they are between -4.57 and -3.91 for the latter. Moreover, my estimates imply that a majority of FFV drivers purchase petrol when it is priced at parity with ethanol, which suggests that non-price attributes (e.g. range anxiety, shopping costs, technological concerns) also play a role in fuel choice [1]. This finding has implications for the cost-benefit analysis of environmental programmes as carbon savings, which contribute to the benefit-side of a programme, depend crucially on the fuel a consumer purchases. While the paper examines one particular alternative fuel and technology, namely ethanol and the ethanol-gasoline FFV, the findings apply more generally. Technologies such as gasoline-CNG (compressed natural gas) vehicles and PHEVs (plug-in hybrid electric vehicles) enable drivers to actively choose the fuel the vehicle is to operate on. In particular, both allow motorists to drive only using fossil fuels despite being able to operate using an alternative fuel. On the other hand, the findings neither generalize to Electric Vehicles (e.g., Tesla models, the Nissan Leaf) nor standard hybrids such as the Toyota Prius since they do not provide motorists the option to choose fuels at all, at the cost of technological lock-in and range anxiety.

Institutional background

During most of the 2000s, European countries were subject to directives from the European Union (EU) in the same vein as US states are subject to regulations put forth by the US Environmental Protection Agency (EPA). That is, just like US states, EU countries had the freedom to choose the policy instruments in order to comply with the EU directives. Two directives are of particular importance, one tackling CO_2 emissions of newly-registered vehicles, and another tackling alternative fuels. Alternative fuels were addressed by the 2003 EU Biofuels Directive, which introduced targets for the use of biofuels. According to such renewable fuel standard, 5.75 percent of all transport fuels in the EU should be met by biofuels by 2010.

At the federal level, the key Swedish policies were the Swedish Pump Law (SPL) and the Swedish Green Car Rebate (GCR), which have acted on the supply and demand sides of the market, respectively (Supplementary Note 1 provides additional details). The SPL was introduced in 2005 and mandates that large enough stations (in terms of fuel sales) install at least one pump of an alternative (renewable) fuel. In practice, approximately 60 percent of the stations in the Swedish market supplied at least one alternative fuel by 2010, typically ethanol (E85, a 85:15 mixture of ethanol and petrol). (While ethanol has Summer and Winter blends, E85 and E75, respectively, to minimize the risk of ethanol freezing while in fuel tanks during the cold season, petrol retailed in Sweden is E5, containing 5 percent of ethanol.)

The GCR, which was in place between April 2007 and June 2009, was an environmental programme aimed at the new vehicle market [2, 3]. The cost of the GCR over 27 months was approximately USD 122mn, thus more than the amount spent in the first three years of California's Clean Vehicle Rebate Project. The programme consisted of a rebate of about USD 1,500 to all private individuals purchasing a car classified as "green". Vehicles are classified as *regular* or *alternative* according to the fuels they are able to operate on, with notably more stringent thresholds for the former than the latter.

The embracing of (or skew towards) alternative fuels and vehicles resulted in Sweden housing the largest fleet of AFVs (alternative fuel vehicles), notably petrol-ethanol hybrids (FFVs, flexible-fuel vehicles), within the EU. The market share commanded by green cars reached 26.5 percent in 2008 (6 percent in 2006), as compared to a 2.15 percent market share commanded by hybrid electric vehicles in 2007 following a related programme in the US [4].

While the technology employed in FFVs differs from the one used in , say, hybrid electric vehicles (HEVs) and petrol-CNG vehicles, the implications for fuel choice are similar, as all allow their drivers to choose the source of energy their vehicles are operating on. For instance, by not charging a HEV, its driver might drive only using petrol. The comparison with HEVs is relevant since they are a competitive alternative to electric vehicles (EVs) for being cheaper due to the smaller batteries, which face lower recharging times, and reducing range anxiety on drivers [5].

On the environmental front, [6] document that emissions from electric vehicles that are powered by the existing US power plants are generally higher than emissions from high-efficiency petrol-powered vehicles; only 12 percent of fossil fueled power plants would generate emissions to the vehicles they charge which are below those of a Toyota Prius.

Figure 1 provides descriptive evidence on the fuel market. Following the end of the GCR programme and a period of expensive ethanol, sales of both ethanol and new FFVs decreased starkly, suggesting a feedback effect between fuel and vehicle markets. However, the overall the fuel price ratio (mean and median ratios are 1.00 and 0.98, respectively) suggests that ethanol is oftentimes cost-competitive with petrol. In particular, Panel F displays the relation between the (energy-adjusted) ethanol-petrol price ratio and the sales of ethanol as a proportion of the combined sales of ethanol and petrol, together with 95 percent confidence intervals based on a semi-parametric estimate [7] and robust standard errors. While the price ratio varies between 0.80-1.30, the share of ethanol as a proportion of combined sales of ethanol and petrol varies from zero to nearly 7 percent. The demand curve estimate suggests that the ethanol share more than halves from its lowest price (about 0.80) to price parity.

Fuel demand estimates

I start by estimating the demand for ethanol and petrol. For each of the fuels, I aim to quantify the reaction in sales to changes in prices (both in logarithms) of the fuel itself, its substitute, and a number of factors which likely influence fuel sales, such as the size of the vehicle fleet and the month of the year (the Methods section provides details). While the coefficient for the price of petrol in the petrol equation (price of ethanol in the ethanol equation) is referred to as the own-price demand elasticity of the fuel, the coefficient for the price of ethanol in the petrol equation (price of petrol in the ethanol equation) is referred to as the cross-price elasticity of petrol with respect to ethanol (cross-price elasticity of ethanol with respect to petrol). Intuitively, the price elasticity of demand of a product measures the percent change of the demand for a product given a one percent change in the price of a (potentially another) product. (Additional discussion can be found under Method and Supplementary Methods.)

The demand estimates are reported in Table 1. Each pair of columns reports estimates of a given specification of the demand system, with odd-numbered (even-numbered) columns reporting estimates for the demand of petrol (ethanol). While the demand equations for petrol all have a similar structure, with both month and year fixed-effects, and using the combined fleet of petrol and FFV vehicles as a control, the demand equations for ethanol differ across columns; in addition to controlling for the FFV fleet and fixed-effects for both month and year, I also control for the development of the ethanol distribution network. To do so, I employ polynomials of the number of stations supplying ethanol in the Swedish market; Columns (4), (6), and (8) report estimates following the use of a linear, a quadratic, and a cubic polynomial of the number of ethanol stations in the country. (Note that (2) had no such term. The results are also robust to the use of the share of stations instead of their count.)

The baseline results (1)-(2) of the demand system are robust to the inclusion of the fuel network terms and will be used below for the sake of parsimony. (Supplementary Tables reports robustness checks discussed under Supplementary Discussion.)

The main findings from Table 1 are that the demand for petrol is quite inelastic – the own-price effect estimates are about -0.120 and are (marginally) significant at the 10 percent level. Cross-price elasticities are typically higher – in the range 0.180-0.200 – and less precisely estimated, thus not always being statistically significant. When it comes to the demand for ethanol, own-price elasticities are substantially higher than those of petrol, ranging from -4.4 to -3.9. This happens because FFV motorists are able to easily substitute between ethanol and petrol, making the demand for ethanol highly responsive to (relative) prices. Following this reasoning, the cross-price elasticities are also substantially higher for ethanol given changes in petrol prices than the other way around, with estimates in the range 2.2-2.4. Importantly, I perform Wald tests of the null hypotheses of (i) equality of the own-price elasticities in the two demand equations; (ii) equality of the own- and cross-price elasticities for each of the equations; I reject all of them at the 1 percent significant level for every case in Table 1.

Despite their difference, both own-price elasticities are in line with previous estimates of the demand elasticities for petrol [8, 9, 10] and ethanol [11, 12]. For instance, [10] documents mean short- and long-run price elasticities for petrol are -0.34 and -0.84, respectively, whereas [9] obtain estimates from -0.34 to -0.21 for 1975-1980 and from -0.077 to -0.034 for 2001-2006. When it comes to ethanol, [11] reports own-price elasticities from -3.8 to -3.2, thus less elastic than the above, whereas [12] report OLS estimates in the range -4.07 to -2.52 (which implies that the IV counterparts would be more elastic).

The fact that consumers do not treat two sources of energy arguably providing the same service (transportation) as perfect substitutes suggests that they are differentiated in terms of non-price attributes. Previous findings in the literature using micro data from surveys document the significance of factors such as shopping costs, range anxiety, technological concerns, and environmental concerns among those non-price attributes [1]. While the relative importance of such factors likely varies across technologies, they seem to be present in a variety of emerging technologies. For instance, the existing battery technology yields less range than a typical tank of petrol.

Implications for fuel choice

I now compare the sales of ethanol and petrol at extreme price ratios to those at price parity. If FFV drivers view ethanol and petrol as perfect substitutes, approximately 50 percent of them should purchase each of the fuels at price parity, switching from the more expensive to the cheaper one as the price difference increases.

To perform this exercise for year 2009, when the RFS was due to be attained, in addition to assuming away the rebound effect (typically small and/or not statistically significant), I also assume the following. First, I fix fleet variables to their December 2009 values, after the SPL and GCR policies had already been implemented. Next, I fix the remaining variables – including petrol prices – at their means. Finally, I set (energy-adjusted) ethanol prices such that they are a factor of between 0.75 to 1.35 of petrol prices (from Figure 1, historical relative prices are in the range 0.84-1.27). To quantify the share of consumers purchasing each fuel at price parity, I normalize fuel demand so that 100 percent of the FFV drivers purchase ethanol when the fuel price ratio is the lowest (0.75) and compute the implied shares as ethanol becomes more expensive.

Table 2 shows the normalized demand for ethanol. If 100 percent of FFV drivers are assumed to purchase ethanol at the 0.75 price ratio, only 10 percent do so at the 1.35 price ratio. Crucially, only 34 percent of FFV drivers purchase ethanol at price parity, i.e., consumers require a price premium to purchase ethanol. As a robustness check, I also compute the share of switchers under the alternative assumptions that 100 percent of FFV drivers purchase ethanol at price ratios 0.80 and 0.85, with the share of consumers purchasing ethanol being 42 and 53 percent, respectively.

In sum, the evidence is consistent with the fact that most FFV drivers do purchase petrol at price parity. (Supplementary Note 2 provides additional details and Supplementary Tables provides robustness.) (An earlier version of the paper further documents this by calculating the effect of a *dynamic petrol tax* which makes petrol at least as expensive as ethanol in energy-adjusted terms. The little switching implies that any changes in CO_2 emissions are minimal. This happens due to a combination of the higher price-responsiveness to ethanol as compared to petrol, and the fact that ethanol still emits CO_2.) This implies that the cost-effectiveness of environmental programmes can vary substantially due to the different types of emissions generated by different fuels. For instance, the most conservative cost-benefit estimates of the GCR programme in [3] range from roughly -5,000 SEK to 5,000 SEK per-FFV, depending on whether ethanol is used 25 or 75 percent of the time by FFV drivers. This is a non-trivial amount given the 10,000 SEK rebate.

Simulation of renewable fuel standard

I use the demand estimates to simulate the effect of an additional petrol tax to gauge the tax level at which a renewable fuel standard – a key policy in place in the EU and other markets to guarantee a minimum volume of renewable fuels and thus reduce CO_2 emissions – is attained in year 2010. I calculate the effect of an additional petrol tax on the ethanol share, calculated as a proportion of combined ethanol, petrol, and diesel sales. To do so, I specify a tax level (in SEK/litre), compute the total fuel sales for year 2010 (when attainment of the RFS was due) and calculate the share commanded by ethanol in the fuel market. I then compute the change in CO_2 emissions, the dead-weight loss (DWL) implied by the tax, and the net effect between the monetized CO_2 emission reductions and the allocative inefficiency imposed on the economy. Finally, I add the additional tax revenues to this net effect.

Focusing on the ethanol share, the results reported in Table 3 document that the additional tax required to attain the RFS is roughly 7.50 SEK/litre. This results in a price of 21.10 SEK/litre (USD 11.88/gallon), or 55 percent above the average petrol retail price at the period. The improvement in CO_2 emissions is non-monotonic, being maximized when the additional petrol tax is 5.50 SEK/litre. This happens because at high levels of the tax, consumers switch to ethanol, which still emits CO_2.

Finally, I compute the additional tax revenues and the increase in DWL as a result of the tax increases. The higher the tax increase, the higher the increase in DWL, due to the additional distortion introduced by the tax. To compare the potential gains obtained from a reduction in CO_2 emissions (assumed to be the only externality) and the losses resulting from increases in DWL, I use the social cost of carbon estimate from [13]. I calculate the benefits minus the costs (net effects) of the tax in in two ways, labelled #1 and #2 in Table 3. These are, respectively, without and with the the tax revenue as a benefit. Net effects #1 are always negative meaning that the negative effects introduced by the DWL are not counteracted by the monetary value of carbon savings. The negative Net effects #2 document that tax revenues are not enough to counteract the negative effects of DWL either, despite the assumption of full revenue recycling.

In sum, the results in Table 3 show that extreme price increases are necessary to make consumers switch to the alternative fuel in order for the RFS to be attained. For perspective, the petrol prices required to attain the RFS would be the highest worldwide. What is more, the costly distortions introduced by such high taxes are not counteracted by the benefits coming from lower CO_2 emissions.

Discussion

The paper contributes to different strands of the litreature. First, it contributes to the litreature on fuel choice. Early studies include [11, 12], who estimate the price elasticity of ethanol based on survey data in a setting where it is far from ubiquitous and typically more expensive (in energy-adjusted terms) than petrol, and [1], who use revealed preference data to estimate the demand for fuels among FFV owners exploiting exogenous variation in relative fuel prices due to weather conditions. [1] find substantial preference for a fuel even when it is substantially more expensive than its substitute. As a result, it becomes hard to make consumers switch to the alternative fuel by taxing the fossil fuel. My contribution to this litreature is to estimate fuel demand exploiting substantial variation in absolute and relative fuel prices using a long time series of market data.

Second, the paper contributes to a litreature assessing the effects of technologies and programmes where fuel choice is an additional dimension of consumer choice [2, 3, 14]. Understanding fuel choice is crucial for the evaluation of both the environmental and economic effects of emerging technologies, in particular the cost-benefit analysis of programmes contemplating MFVs, a technology bound to be increasingly targeted by such programmes.

Third, the paper complements the empirical litreature examining network effects in the fuel-vehicle markets [15, 16, 17, 18, 19]. Typically, this litreature relates the provision of fueling infrastructure to the purchase of vehicles of a given fuel. However, little attention is devoted to *actual fuel sales* following the provision of the fueling infrastructure, i.e. the fact that infrastructure is not sufficient for the uptake of an alternative fuel.

Finally, the paper relates to a litreature examining the environmental, economic, and distributional effects of fuel taxation [20, 21, 22, 23, 24]. The findings in this litreature imply that the existing subsidies on fossil fuels in a number of countries pose an additional hurdle for alternative fuels and vehicles to overcome. My findings suggest that the extent to which MFVs will run on alternative fuels is not clear even if such subsidies are removed. Again, the reduction of price distortions in the fuel market and the resulting cost-competitiveness of alternative fuels is not a sufficient condition for the uptake of alternative fuels – even if the vehicle technology is readily available, seamlessly allows fueling, and energy-adjusted prices are competitive.

Conclusions

Drivers of FFVs strongly prefer the fossil over the alternative fuel at price parity. Making them switch *en masse* from petrol to ethanol requires prohibitively high petrol taxes. Thus, the benefits brought by lower CO_2 emissions and additional tax revenue are dominated by the costs of the allocative inefficiency (dead-weight loss) the taxes also introduce.

The results suggest that fueling infrastructure and a fleet of alternative fuel vehicles are not sufficient to ensure consumers shift to alternative fuels, despite the number of policies – and monetary transfers to consumers – governments have designed in the recent past to reduce the use of fossil fuels. Thus, the cost-benefit calculations of such programmes should account for fuel choice.

The findings suggest non-price attributes play an important role in consumer decision-making [1]. Anecdotal evidence from the Swedish market suggests additional factors could impact fuel choice. First comes the composition of ethanol, which contains some water (about 5 percent). The water content implies that ethanol is more likely to freeze than petrol, to which drivers respond by purchasing less ethanol in cold months. Moreover, some drivers seem to believe that corrosion of engine parts in direct contact with ethanol is a reason for concern, even though cars in more mature markets such as Brazil do not seem to be overly affected by it. Although producing anhydrous ethanol (ethanol with less than 1 percent of water) is feasible, it is costly in that it requires an additional distillation during the production process. Second, the "food vs. fuel debate" of the mid-2000s did not help the adoption of ethanol, despite initiatives by the Swedish Environmental Agency to certify ethanol producers. Finally, the relative novelty of the FFV technology may also be a hurdle for the embracing of ethanol.

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Acknowledgments

I am indebted to Nikita Koptyug and Claudio Lucinda for their comments on an earlier draft of the paper.

Author contributions

C. H. performed data analysis, simulations, and wrote the manuscript.

Additional information

Supplementary information is available in the online version of the paper.

Competing interests

The author declares no competing financial interests.

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Methods

This Section discusses demand estimation, identification, the calculation of the policy simulation of the renewable fuel standard, and provides additional detail on the data used. (Supplementary Methods provides additional discussion.)

I estimate a demand system using the 3SLS (three-stage least squares) method since it efficiently uses information about the demand system. That is, it accounts for any potential correlation between the ethanol and gasoline demand equations. The discussion of identification is warranted due to the potential endogeneity of some covariates in the demand equation – mainly fuel prices, but also the composition of the vehicle fleet. The fact that such variables might be simultaneously determined with the dependent variables (fuel sales) calls for the use of instrumental variables, above and beyond the estimation of the demand system. Next, I discuss the quantification of the results reported in Table 3, including the carbon content of each fuel and computation of DWL. Finally, I detail the market-level data used in the study and provide a data availability statement.

Demand estimation

I estimate a constant-elasticity demand model for fuels ethanol and gasoline (denoted by *e* and *g* below) in the Swedish market, a specification often used in the literature, see [24] and references therein. The demand equation for fuel f is given by

$$ln(q_{ft}) = \alpha_{1f} + \sum_{k=e,g} \gamma_{fk} \ln(p_{kt}) + \theta Z_{ft} + \varepsilon_{ft}, f = e, g$$

where q_{ft} denotes the sales of fuel f at month t, p_{ft} is the real price of fuel f, and Z_{ft} contains month and year fixed-effects, demand shifters such as the vehicle fleet capable of using fuel f, and a measure of the ethanol distribution network in the Swedish market. In the above specification, the coefficients γ are the own- (if $f = k$) and cross-price elasticities (if $f \neq k$), thus key to the understanding of substitution patterns across products.

The demand system consists of one equation for the demand for ethanol and another for gasoline. For the sake of efficiency, I estimate the demand system using 3SLS. I have also conducted extensive robustness checks reported in the Supplementary Information where I compare alternative specifications, instruments, and estimation methods (for instance, comparing my baseline results with equation-by-equation OLS and 2SLS).

Identification

Identification of the price coefficients relies on the variation of absolute and relative fuel prices (i.e. ethanol prices relative to gasoline prices) over time. While the former variation helps identify own-price effects, the latter helps identify cross-price effects.

Some variables may raise concerns when estimating the demand for fuels due to their potential endogeneity, which would render the parameter estimates inconsistent. First, fuel prices are likely to respond to unobserved (to the econometrician) demand shocks in a given market. Second, the (composition of the) vehicle fleet is likely to respond to fuel prices and policy changes. For instance, consumers may observe fuel prices, realize that purchasing an FFV is good value for money, and thus decide on the purchase of such a vehicle, trading-off a higher cost today with lower operating costs in the future.

To address endogeneity concerns, I employ different sets of instruments. In the case of fuel prices, I use international commodity prices (both current and lagged). These correspond to the classic cost shifters (factor prices). I use oil prices (WTI, Brent), sugar prices, and prices of commodities such as maize and the IMF food price index. The identifying assumption is that these international prices are determined in worldwide markets, thus uncorrelated with unobserved demand shocks in Sweden, a small open economy. The use of lagged factor prices stems from the fact that the pass-through from international to domestic prices might take some time to materialize.

I also employ the following two sets of instruments for the vehicle fleet. First, I use income proxies. The identifying assumption is that (predetermined) income proxies are exogenous yet correlated with the decision to purchase a vehicle. This could reflect, for instance, the increased income following a period of economic growth. Second, I use lagged fuel prices to instrument vehicle fleet given the relation between these two markets, see Section 2. For instance, consumers might learn over time that ethanol tends to be cheaper than gasoline in energy-adjusted terms and then be more inclined to purchase an FFV. The identifying assumption in this case is that predetermined fuel prices are exogenous yet correlated with the decision to purchase an FFV.

Renewable fuel standard

To quantify the effect of an additional gasoline tax, I focus on sales for year 2010, the year the RFS was due to be attained. Then, I specify a tax level, compute the resulting fuel sales and the corresponding ethanol share. As above, I calculate the changes in CO_2 emissions under the assumption that one litre of gasoline (ethanol) contains 2,392 gCO_2 (1,076 gCO_2/litre.), with value for ethanol conservatively assumed to be 55 percent lower than that of gasoline. CO_2 savings are converted into monetary amounts using the social cost of carbon of 1,060 SEK/tCO_2.

The DWL calculated is a lower bound to the measure of allocative inefficiency due to the fact that I perform a partial equilibrium rather than a general equilibrium analysis. Ethanol subsidies were disallowed by the EU their end are behind the 2015 price increase. To calculate the DWL [26], I assume a horizontal (price-inelastic) supply curve and rely on the demand specification, as in [24]. The demand for gasoline can be written as $q_g = Ap^{\epsilon}$, with ϵ being the own-price elasticity of demand for gasoline, and A being a scaling factor. To perform the DWL calculations, I fix the variables at their 2010 means and compute the corresponding DWL for each value of the tax. Letting $p_1$and p_2 denote prices before and after tax, and q_1 the equilibrium quantities in the case of the former, the DWL is obtained as the area of the approximate triangle calculated as the difference between the price increase due to the tax times the original equilibrium quantity, $(p_2 - p_1)q_1$, minus the are to the left of the demand curve in the interval $\int_{p_1}^{p_2} Ap^{\epsilon}dp$. This can be written as

$$DWL = (p_2 - p_1)q_1 - \frac{A}{1+\epsilon}\left[p_2^{1+\epsilon} - p_1^{1+\epsilon}\right]$$

Finally, I compute the net effects of each tax level by comparing monetized CO_2 savings and DWL changes.

Since the EU RFS requires attainment of a 5.75 percent target at the transport sector as a whole, i.e. as a share of total fuel consumption, and the share of other fuels is negligible, I assume that the only fuels used in the light transport sector are ethanol, diesel, and gasoline. Further, I do not model the demand for diesel, using the actual sales data for year 2010.

To gain perspective on fuel prices, in year 2010 the total tax on gasoline on the Swedish market was 5.50 SEK/litre. Moreover, Hong Kong's gasoline price was USD 7.27/gallon in 2010, see [27], and USD 7.23/gallon in 2017Q1 (Sweden's was USD 6.01/gallon). Thus, Sweden is among the top 10 countries in terms of gasoline prices, see [28].

Data

I combine a number of datasets recorded at the monthly frequency to obtain a final sample from January 2005 to December 2016 (144 months). First, I use fuel sales and prices recorded at the monthly frequency and at the national level from the Swedish Petroleum and Biofuels Institute [29]. All sales figures are reported in cubic meters and all prices are reported in SEK (Swedish *kronor*). (I have double-checked those prices with those of leading distributors in Sweden, such as *Circle K* (previously *Statoil*), which owns over 700 stations in the country, and found such fuel prices to track each other quite well over time [30].)

Nominal fuel prices were deflated using the Consumer Price Index from *SCB*, the Swedish Statistics Bureau. Given the focus on light transportation and the technology involved (ethanol-gasoline, flexible-fuel vehicles, FFVs), the fuels used in the analysis are ethanol and gasoline. Over the sample period, the Swedish market experiences a decrease in gasoline sales due to the increased participation of diesel vehicles in detriment of gasoline vehicles (consistent with the wave of dieselization across Europe in the 2000s), the overall improvement of fuel economy of vehicles (consistent with a reduction of CO_2 emissions in the new car market, which accounts for 5-10% of the total fleet), and changes in driving behaviour during the sample period.

Second, I use real commodity prices from [31]. These include Brent, WTI, and Dubai crude oil prices, a Food price index, the price of maize, and the European import price for sugar. To convert international currencies into SEK, I use exchange rate data from *Riksbanken*, the Swedish Central Bank.

Third, I use different demand shifters as follows. I construct fleet data based on registration data disaggregated at the vehicle fuel level obtained from the SCB and available at the monthly frequency. Also from the SCB, I retrieve the number of hours actually worked per week for persons aged 15-74, also at the monthly frequency, to be used as an income proxy.

Finally, the fuel distribution data I use are measures of the ethanol distribution network from [**?**]. These are the count and the share of ethanol stations as a proportion to the total number of stations, recorded at the monthly frequency.

Data Availability Statement

Data required for obtaining the baseline results of the paper are publicly available and described in the Data section. Fuel distribution data which is used only for robustness is non-public.

References

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[28] SPBI (2018). http://spbi.se/statistik/. Last accessed on 17 April 2018.

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[30] IMF (2018). http://www.imf.org/external/np/res/commod/index.aspx. Last accessed on 17 April 2018.

Figures and Tables

[see Figure1.eps]

Figure 1 | Fuel market overview. a, Monthly fuel prices. Fuels are petrol and energy-adjusted ethanol, in SEK/litre. **b,** Petrol price premia. Premia are price difference (in SEK/litre) and price ratio. **c,** Ethanol sales and relative fuel prices. Ethanol sales are in cubic meters whereas relative fuel prices are calculated as the difference between petrol prices and energy-adjusted ethanol prices. **d,** Ethanol sales and FFV fleet. Ethanol sales are in cubic meters and the FFV fleet is in thousand units. **e,** Histogram and kernel density estimate of fuel price ratio. The density is estimated using the kernel method and an Epanechnikov kernel. **f,** Semiparametric demand curve for ethanol. Data points and semiparametric demand curve for ethanol obtained using the semiparametric estimator described in the text; while the parametric part consists of controls for the size of the FFV fleet, and both month and year fixed-effects, the price-share relation is estimated nonparametrically (sample size is 144). Panels a, b, c, e, f use energy-adjusted ethanol prices, which reflect the per-mile cost of fuel.

Dependent Variable:	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$ln(p_g)$	$-.132^{*}$	2.393^{***}	$-.123^{*}$	2.246^{***}	$-.121^{*}$	2.519^{***}	$-.120^{*}$	2.460^{***}
	$(.072)$	$(.687)$	$(.072)$	$(.731)$	$(.071)$	$(.682)$	$(.070)$	$(.638)$
$ln(p_e)$	$.205^{*}$	-3.907^{***}	$.163$	-4.028^{***}	$.185^{*}$	-4.465^{***}	$.191^{**}$	-4.420^{***}
	$(.114)$	(1.125)	$(.106)$	(1.129)	$(.104)$	(1.030)	$(.095)$	$(.911)$
Controls								
Fleet	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed-effects								
Month FE's	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE's	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Distribution Network								
Linear				Yes				
Quadratic						Yes		
Cubic								Yes
N	141	141	141	141	141	141	141	141
Pseudo R-squared	0.985	0.914	0.985	0.915	0.985	0.923	0.985	0.934

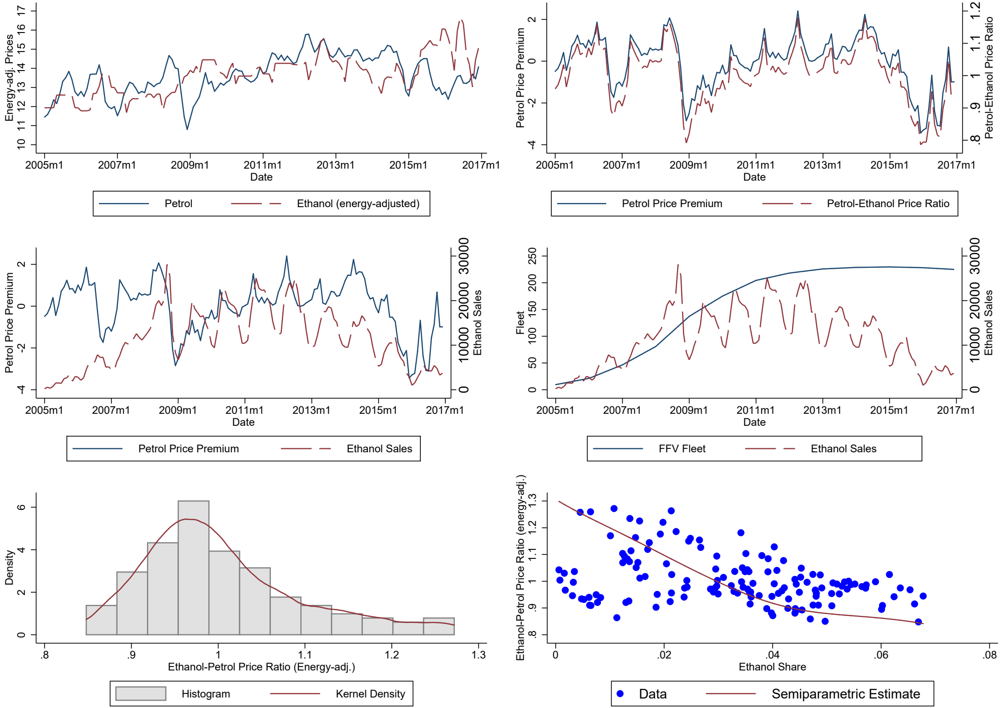
Table 1 | Fuel Demand Estimates. This table displays estimates of fuel demand for the Swedish market obtained by estimating the demand system using 3SLS (Three-stage Least-Squares). Standard errors are reported in parentheses. Significance is given at the 1% level (***), 5% level (**) and 10% level (*). Vehicle fleet in the case of petrol is the sum of petrol and FFVs, and only FFVs in the case of ethanol. The income proxy is per capita total hours worked. Instruments are Sugar, Maize, Food (L3); Brent, WTI (L1), Income proxy; Fuel prices (L3), where L[k] denotes a variable lagged by k periods.

Energy-adjusted Ethanol-Petrol Price Ratio (p_e^{adj}/p_g)	Normalized Demand for Ethanol
0.75	1.00
0.80	0.79
0.85	0.63
0.90	0.50
0.95	0.41
1.00	0.34
1.05	0.28
1.10	0.23
1.15	0.19
1.20	0.16
1.25	0.14
1.30	0.12
1.35	0.10

Table 2 | Fuel Switching by FFV Motorists. This table displays the normalized demand for ethanol (share of FFV users purchasing ethanol) implied by estimates in Columns (1)-(2) in Table 1. Fleet and network variables are fixed to their December 2009 levels and the remaining variables are fixed at their means. Ethanol energy-adjusted prices are set in a way that they correspond to factors between 0.75 and 1.35 of petrol prices (the price ratios observed in the data are in the range 0.84-1.27, with mean and median values of 1.00 and 0.98, respectively). IThe above results assume that all FFV drivers are assumed to purchase ethanol when the energy-adjusted price ratio reaches 0.75; assuming this occurs at allternative ratios 0.80 and 0.85, the share of ethanol users at price parity is 0.42 and 0.53, respectively.

Additional Tax (SEK/litre)	Ethanol Share (%)	$\triangle CO_2$ Emissions ($10^3 \times tCO_2$)	$\triangle$DWL ($10^3 \times mnSEK$)	Net Effect #1 ($10^3 \times mnSEK$)	Additional Tax Revenue ($10^3 \times mnSEK$)	Net Effect #2 ($10^3 \times mnSEK$)
0.00	2.0	-	-	-	-	-
1.00	2.4	-59.8	4.3	-4.3	4.1	-0.2
2.00	2.8	-108.6	8.7	-8.7	8.1	-0.6
3.00	3.2	-118.3	13.0	-12.8	12.0	-0.8
4.00	3.7	-147.2	17.3	-17.2	16.0	-1.2
5.00	4.3	-176.5	21.7	-21.5	19.8	-1.7
5.50	4.5	-196.8	23.8	-23.6	21.7	-1.9
6.00	4.8	-203.8	26.0	-25.8	23.6	-2.2
7.00	5.5	-208.8	30.3	-30.1	27.4	-2.7
7.50	5.8	-212.7	32.5	-32.3	29.3	-3.0
8.00	6.1	-211.8	34.7	-34.5	31.2	-3.3
9.00	6.9	-208.8	39.0	-38.9	34.9	-4.0
10.00	7.6	-197.6	43.3	-43.1	38.6	-4.5
11.00	8.4	-179.0	47.7	-47.5	42.3	-5.2

Table 3 | Effects of an Additional Petrol Tax on the Ethanol Share. This table displays the share of ethanol sales as a proportion of the combined diesel, ethanol, and petrol sales ($q_e/(q_e + q_g + q_d)$) for different levels of an additional petrol tax. All other variables are fixed at their mean levels during year 2010. At the SEK:USD exchange rate of 6.724 on 31st December 2010, the mean price of petrol (13.60 SEK/litre) is USD 7.66/gallon. For illustration, to attain an ethanol share of 5.8 percent, the price of petrol has to increase to (13.60+7.50=) 21.10 SEK/litre (USD 11.88/gallon). The social cost of carbon is 1,060 SEK/tCO_2 (USD 157.6/tCO_2) as per Mandell (2008). Net effect #1 is obtained as the difference between the product of CO_2 emissions and SCC, minus the DWL. Net effect #2 is obtained as the difference between Additional tax revenues and Net effect #1.



Energy-adj. Prices
10 11 12 13 14 15 16 17
2005m1 2007m1 2009m1 2011m1 2013m1 2015m1 2017m1
Date
Petrol
Ethanol (energy-adjusted)
Petrol Price Premium
-4 -2 0 2
Petrol-Ethanol Price Ratio
.8 .9 1 1.1 1.2
2005m1 2007m1 2009m1 2011m1 2013m1 2015m1 2017m1
Date
Petrol Price Premium
Petrol-Ethanol Price Ratio
Petrol Price Premium
-4 -2 0 2
Ethanol Sales
0 10000 20000 30000
2005m1 2007m1 2009m1 2011m1 2013m1 2015m1 2017m1
Date
Petrol Price Premium
Ethanol Sales
Fleet
0 50 100 150 200 250
Ethanol Sales
0 10000 20000 30000
2005m1 2007m1 2009m1 2011m1 2013m1 2015m1 2017m1
Date
FFV Fleet
Ethanol Sales
Density
0 2 4 6
.8 .9 1 1.1 1.2 1.3
Ethanol-Petrol Price Ratio (Energy-adj.)
Histogram
Kernel Density
Ethanol-Petrol Price Ratio (energy-adj.)
.8 .9 1 1.1 1.2 1.3
0 .02 .04 .06 .08
Ethanol Share
Data
Semiparametric Estimate

Supplementary Information

Fuel Choice and Fuel Demand Elasticities in Markets with Flex-fuel Vehicles

Cristian Huse[1]

Supplementary Tables

Supplementary Table 1 | Summary Statistics of Selected Variables

Variable	Mean	SD	Min	Max
Ethanol prices (SEK/litre, real)	9.88	.76	8.64	11.95
Petrol prices (SEK/litre, real)	13.64	1.03	10.80	15.79
Ethanol sales (cubic meters)	11,538.38	6,694.76	218	28,120
Petrol sales (cubic meters)	346,066.40	63,388.46	219,734	478,639
FFV Fleet	158,696.80	79,816.21	9,544	229,621
Combined gasoline and FFV Fleet	3,621,023	272,240.40	3,118,978	3,926,388
Ethanol stations (count)	1,034.06	432.77	33	1,297
Ethanol stations (share)	.36	.15	.01	.45
Income proxy (Hours worked)	120.72	17.25	66.30	146.90

This table presents summary statistics of selected variables. Fuel prices are deflated using the CPI, ethanol prices are not energy-adjusted.

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Supplementary Table 2 | First-stage Regression Results

Dependent Variable:	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$ln(p_g)$	32.27		30.98		29.98		21.15	
$ln(p_e)$	19.94		19.72		19.09		8.47	
$FFV\ fleet$	–	1077.79	–	1564.17	–	1729.64	–	1758.15
$FFV\ and\ Gas\ fleet$	2970.53	–	4720.44	–	6271.54	–	6656.93	–

This table displays estimates of first-stage F-statistics associated to the regressions in Table 1. The endogenous variables are labeled in the first column. While the first-stage regressions for ethanol and petrol prices coincide for each case in a given system, the ones for the fleet variables do not, thus the formatting of the table.

Supplementary Table 3 | Robustness of Fuel Demand Estimates I

Dependent Variable:	$ln(q_g)$	$ln(q_e)$			
Variables	(1)	(2)	(3)	(4)	(5)
$ln(p_g)$	$-.132^{**}$	2.496^{***}	2.352^{***}	2.416^{***}	2.293^{***}
	$(.059)$	$(.486)$	$(.491)$	$(.440)$	$(.442)$
$ln(p_e)$	$.136^{**}$	-1.060^{**}	-1.113^{**}	-1.581^{***}	-1.732^{***}
	$(.060)$	$(.528)$	$(.525)$	$(.478)$	$(.481)$
Controls					
Fleet	Yes	Yes	Yes	Yes	Yes
Fixed-effects					
Month FE's	Yes	Yes	Yes	Yes	Yes
Year FE's	Yes	Yes	Yes	Yes	Yes
Distribution Network					
Linear			Yes		
Quadratic				Yes	
Cubic					Yes
N	144	144	144	144	144
R-squared	0.985	0.931	0.932	0.942	0.944

This table displays estimates of fuel demand for the Swedish market obtained by estimating equation-by-equation OLS (Ordinary Least-Squares). Robust standard errors are reported in parentheses. Significance is given at the 1% level (***), 5% level (**) and 10% level (*). Vehicle fleet in the case of petrol is the sum of petrol and FFVs, and only FFVs in the case of ethanol.

Supplementary Table 4 | Robustness of Fuel Demand Estimates II

Dependent Variable:	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$ln(p_g)$	$-.135^{*}$	2.383^{***}	$-.126$	2.211^{***}	$-.126$	2.482^{***}	$-.124$	2.417^{***}
	(.079)	(.817)	(.080)	(.817)	(.079)	(.764)	(.078)	(.718)
$ln(p_e)$	$.211^{*}$	-3.941^{***}	$.163$	-4.092^{***}	$.182$	-4.539^{***}	$.188^{*}$	-4.495^{***}
	(.126)	(1.246)	(.118)	(1.263)	(.115)	(1.154)	(.105)	(1.024)
Controls								
Fleet	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed-effects								
Month FE's	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE's	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Distribution Network								
Linear				Yes				
Quadratic						Yes		
Cubic								Yes
N	141	141	141	141	141	141	141	141
Pseudo R-squared	0.985	0.914	0.985	0.914	0.985	0.928	0.985	0.933

This table displays estimates of fuel demand for the Swedish market obtained by estimating the demand system using equation-by-equation 2SLS (Two-stage Least-Squares). Standard errors are reported in parentheses. Significance is given at the 1% level (***), 5% level (**) and 10% level (*). Vehicle fleet in the case of petrol is the sum of petrol and FFVs, and only FFVs in the case of ethanol. The income proxy is per capita total hours worked. Instruments are Sugar, Maize, Food (L3); Brent, WTI (L1), Income proxy; Fuel prices (L3), where L[k] denotes a variable lagged by k periods.

Supplementary Table 5 | Robustness of Fuel Demand Estimates III

Dependent Variable:	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$ln(p_g)$	$-.100$	1.505	$-.101$	1.486	$-.069$	2.387^{***}	$-.067$	2.136^{**}
	(.097)	(1.099)	(.098)	(1.124)	(.094)	(.928)	(.089)	(.919)
$ln(p_e)$	$.246$	-5.779^{**}	$.215$	-5.842^{**}	$.303^{*}$	-5.157^{***}	$.311$	-5.592^{***}
	(.218)	(2.289)	(.194)	(2.297)	(.178)	(1.921)	(.153)	(1.856)
Controls								
Fleet	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed-effects								
Month FE's	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE's	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Distribution Network								
Linear				Yes				
Quadratic						Yes		
Cubic								Yes
N	141	141	141	141	141	141	141	141
Pseudo R-squared	0.985	0.883	0.985	0.883	0.984	0.916	0.984	0.912

This table displays estimates of fuel demand for the Swedish market obtained by estimating the demand system using 3SLS (Three-stage Least-Squares). Standard errors are reported in parentheses. Significance is given at the 1% level (***), 5% level (**) and 10% level (*). Vehicle fleet in the case of petrol is the sum of petrol and FFVs, and only FFVs in the case of ethanol. The income proxy is per capita total hours worked. Instruments are Maize (L3); Brent (L1); Fuel prices (L3), where L[k] denotes a variable lagged by k periods.

Supplementary Table 6 | Subsample Analysis

Dependent Variable:	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$	$ln(q_g)$	$ln(q_e)$
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$ln(p_g)$	$-.135$	3.640^{***}	$-.135$	3.640^{***}	$-.135$	3.640^{***}	$-.135$	3.640^{***}
	(.116)	(.620)	(.116)	(.620)	(.116)	(.620)	(.116)	(.620)
$ln(p_e)$	$.193^{**}$	-3.028^{***}	$.193^{**}$	-3.028^{***}	$.193^{**}$	-3.028^{***}	$.193^{**}$	-3.028^{***}
	(.114)	(.494)	(.114)	(.494)	(.114)	(.494)	(.114)	(.494)
Controls								
Fleet	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed-effects								
Month FE's	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE's	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Distribution Network								
Linear				Yes				
Quadratic						Yes		
Cubic								Yes
N	72	72	72	72	72	72	72	72
Pseudo R-squared	0.973	0.970	0.973	0.970	0.973	0.970	0.973	0.970

This table displays estimates of fuel demand for the Swedish market obtained by estimating the demand system using 3SLS (Three-stage Least-Squares) for the subsample 2011-2016 (72 months). Standard errors are reported in parentheses. Significance is given at the 1% level (***), 5% level (**) and 10% level (*). Vehicle fleet in the case of petrol is the sum of petrol and FFVs, and only FFVs in the case of ethanol. The income proxy is per capita total hours worked. Instruments are Sugar, Maize, Food (L3); Brent, WTI (L1), Income proxy; Fuel prices (L3), where L[k] denotes a variable lagged by k periods.

Supplementary Table 7 | Fuel Switching by FFV Motorists

Energy-adjusted Ethanol-petrol Price Ratio (p_e^{adj}/p_g)	Normalized Demand for Ethanol
0.75	1.00
0.80	0.77
0.85	0.59
0.90	0.45
0.95	0.36
1.00	0.29
1.05	0.23
1.10	0.19
1.15	0.16
1.20	0.13
1.25	0.11
1.30	0.09
1.35	0.07

This table displays the normalized demand for ethanol (share of FFV users purchasing ethanol) implied by estimates in Columns (7)-(8) in Table 1. Fleet and network variables are fixed to their December 2009 levels and the remaining variables are fixed at their means. Ethanol energy-adjusted prices are set in a way that they correspond to factors between 0.75 and 1.35 of petrol prices (the price ratios observed in the data are in the range 0.84-1.27, with mean and median values of 1.00 and 0.98, respectively). IThe above results assume that all FFV drivers are assumed to purchase ethanol when the energy-adjusted price ratio reaches 0.75; assuming this occurs at allternative ratios 0.80 and 0.85, the share of ethanol users at price parity is 0.38 and 0.49, respectively.

Supplementary Table 8 | Effects of an Additional Petrol Tax on the Ethanol Share

Additional Tax (SEK/litre)	**Ethanol Share** (%)	$\triangle CO_2$ **Emissions** $(10^3 \times tCO2)$	$\triangle$**DWL** $(10^3 \times mnSEK)$	**Net Effect #1** $(10^3 \times mnSEK)$	**Additional Tax Revenue** $(10^3 \times mnSEK)$	**Net Effect #2** $(10^3 \times mnSEK)$
0.00	2.0	-	-	-	-	-
1.00	2.4	-49.8	4.3	-4.3	4.1	-0.2
2.00	2.8	-88.9	8.7	-8.6	8.1	-0.5
3.00	3.3	-118.3	13.0	-12.9	12.1	-0.8
4.00	3.8	-138.3	17.3	-17.2	16.1	-1.1
5.00	4.3	-149.6	21.7	-21.5	20.0	-1.5
5.50	4.6	-152.1	23.8	-23.7	21.9	-1.8
6.00	4.9	-152.6	26.0	-25.8	23.9	-1.9
7.00	5.6	-147.4	30.3	-30.2	27.7	-2.5
7.50	5.9	-141.9	32.5	-32.3	29.6	-2.7
8.00	6.3	-134.3	34.7	-34.5	31.5	-3.0
9.00	7.1	-113.6	39.0	-38.9	35.3	-3.6
10.00	7.9	-85.36	43.3	-43.2	39.0	-4.2
11.00	8.7	-49.77	47.7	-47.6	42.7	-4.9

This table displays the share of ethanol sales as a proportion of the combined diesel, ethanol, and petrol sales ($q_e/(q_e + q_g + q_d)$) for different levels of an additional petrol tax. All other variables are fixed at their mean levels during year 2010. At the SEK:USD exchange rate of 6.724 on 31st December 2010, the mean price of petrol (13.60 SEK/litre) is USD 7.66/gallon. For illustration, to attain an ethanol share of 5.9 percent, the price of petrol has to increase to (13.60+7.50=) 21.10 SEK/litre(USD 11.88/gallon). The social cost of carbon is 1,060 SEK/tCO_2 (USD 157.6/tCO_2) as per Mandell (2008). Net effect #1 is obtained as the difference between the product of CO_2 emissions and SCC, minus the DWL. Net effect #2 is obtained as the difference between Additional Tax Revenues and Net effect #1.

Supplementary Note 1

Details on policies

At the EU level, CO_2 emissions from newly-registered vehicles were addressed by Regulation 1753/2000/EC, issued in year 2000. According to this directive, newly-registered passenger vehicles in EU countries would have to attain average emissions of 120 gCO_2/km by 2010 in order to combat climate change. This target corresponds to 47 (51.7) mpg running on petrol (diesel), thus more ambitious than the post-2011 US CAFE standards.

The 2003 EU Biofuels Directive both introduced targets for the use of biofuels and required that biofuels be certified, resulting in life-cycle CO_2 emissions of the ethanol typically used in Sweden are 55 percent lower than those of petrol [1]. These environmental gains can potentially be enhanced through the adoption of advanced biofuels.

Under the GCR, cars running on fossil fuels (or *regular fuels*) qualify as green cars if their CO_2 emissions are no greater than 120 g/km. Importantly, this emission threshold of about 193 gCO_2/mile (thus more stringent than the 250 gCO_2/mile US CAFE standard due from 2016) applies to individual vehicles rather than to the brand-level as in the US market. Vehicles (also) able to run on fuels other than petrol and diesel (or *alternative fuels*) qualify as green cars if their consumption is no greater than 220 gCO_2/km running on petrol. (Formally, energy consumption has to be no greater than the equivalent of 9.2 litres/100 km using petrol; for electric cars, the threshold is 37 kWh/100 km.)

Supplementary Note 2

Fuel choice

The results in Table 2 depend on (but are robust to) the assumption on the price ratio at which all FFV drivers will purchase ethanol. Decreasing such price ratio assigns more weight to the extremes of the demand curve. Survey evidence from Swedish stations suggests that consumers are relatively attentive to price changes, partly due to the increasing use of phone apps, so that more switching should occur close to parity, making either 0.75 (or even the 0.80) the price ratio where 100 percent of FFVs are more likely to purchase ethanol. The results are also robust to changes to other specifications in Table 1, and to fixing all variables (other than ethanol prices) to their sample means.

Supplementary Discussion

In this section, I first report summary statistics and first-stage results in Supplementary Tables 1 and 2. Next, I report a number of alternative demand estimates to those presented in the paper in Supplementary Tables 3-6. Finally, I report results based on Columns (7)-(8) in Table 1 of the paper (the text reports results based on Columns (1)-(2)), documenting the robustness of the results to changes in the specification of the demand system.

Supplemetary Table 3 reports equation-by-equation OLS estimates of the demand system. Column (1) reports demand estimates for petrol whereas the remaining ones report estimates for the demand for ethanol. All specifications are the uninstrumented versions of the ones in Table 1, so they all include fleet controls. Columns (3)-(5) include a polynomial in the number of ethanol stations in the Swedish market, from linear to cubic. The results are robust to using the share of ethanol stations instead of the station count, to inclusion of the income proxy as a control, and to lagged measures of the station data. The own price elasticity of petrol is -0.132 whereas the cross-price elasticity of petrol with respect to ethanol is 0.136. The own price elasticity of ethanol is in the range -1.7 to -1.1 across specifications. Finally, the cross-price elasticity of ethanol with respect to petrol has estimates in the range 2.3-2.5. In sum, the own price effects for petrol and both sets of cross-price effects are largely robust and similar to the preferred ones reported in the main text. The main difference comes from the own-price effects of ethanol, which increase substantially when instrumented for.

The remaining tables have the same structure as Table 1 in the main text, differing with respect to either the estimation method or the instruments used. The instruments in Supplemetary Table 4 are the same as in Table 1; the difference stems from the estimation method, system estimation (3SLS) in Table 1 and equation-by-equation estimation (2SLS) here. The 2SLS point estimates are very similar to those reported in the text, the main take-away being that 3SLS seems to provide an increase in efficiency as compared to 2SLS due to the smaller standard errors across the board.

Supplemetary Table 5 is the just-identified version of Table 1. That is, the instruments used are maize and Brent prices, for ethanol and petrol, respectively, and lagged fuel prices for the fleet variables. The estimates for the own-price effects of petrol are now less elastic and not statistically significant, which suggests that over-identification through the additional instruments in Table 1 is providing efficiency gains. While the cross-price effect estimates change slightly, the most noticeable effect is the increase in the own-price effects for ethanol; whereas the estimates in Table 1 are between -4.5 and -3.9, here they are between -5.8 and -5.2 and statistically significant throughout.

Supplementary Table 6 is the version of Table 1 for the sub-sample 2011-2016. Before comparing estimates, two things are of note. First, the sample is essentially halved, with important price variation used to identify the key parameters being now left out of the estimation sample. Second, the little variation in the measures of the distribution network renders the related variables collinear, resulting in similar estimates across columns. This can be attributed to the end of the Swedish Pump Law, which was behind the increase in fueling infrastructure in the early part of the sample.

Focusing on the estimates, the own- and cross-price elasticities for petrol are now -0.135 and 0.193. The own- and cross-price elasticities for ethanol are now -3.028 and 3.640. Thus, despite halving the sample and dropping important variation, the estimates are largely robust.

Supplementary Table 7 reports results directly comparable to those in Table 2 in the text. At price parity ($p_e^{adj}/p_g = 1$), Panel A reports that only 29 percent of FFV motorists purchase ethanol, as compared to 34 percent in Table 2. Moreover, by changing the assumption of the price ratio at which all motorists purchase ethanol only marginally changes the share of motorists who purchase petrol, again as compared to Table 2. For instance, one would require a price ratio in excess of 0.85 (that is, all motorists purchase ethanol when it is priced at 85 percent the price of petrol, energy-adjusted), to get 50 percent of motorists purchasing petrol at price parity.

Turning to the simulation of the RFS and the resulting ethanol share, Supplementary Table 8 reports results largely robust to those in Table 3. For instance, additional petrol tax required to attain the RFS is approximately 7.50 SEK/litre, just as in Table 3. Also as in Table 3, the improvement in CO_2 emissions is non-monotonic, being maximized when the additional petrol tax is 6.00 SEK/litre (as compared to 5.50 SEK/litre in Table 3). The results for changes in DWL, Net effect #1 and Net effect #2 also very close to the results reported in Table 3.

Supplementary Methods

Demand estimates

In an ideal setting, the econometrician would have access to consumer-level data on fuel purchases and estimate a discrete-continuous model of fuel choice where the discrete decision consists of the decision of *which* fuel to purchase and the continuous decision consists of *how much* fuel (in litres or gallons) to purchase [2]. In practice this is seldom the case and data availability guides the demand estimation method. Moreover, even when data are available, the very fact that the ethanol market is still in its infancy imposes further challenges in estimation. For instance, the formulae of both own- and cross-price elasticities of the widely used multi-stage budgeting model of critically rely on the (value-weighted) market share of the different products, mechanically determining them [3, 4].

An alternative estimation strategy sometimes pursued in the litreature is the estimation of a car fleet equation [5]. One of the key lessons from the litreature on the demand for differentiated product, such as automobiles, is that there is substantial heterogeneity of both consumers and products that need to be accounted for so that the estimates become realistic. As a result, I rather control for than model the size of the car fleet.

To assess whether instruments are weak, I perform a set of first-stage regressions and retrieve their F-statistics. For each case, I regress the endogenous variable on the exogenous variables of the demand specification plus the set of instruments. The results are reported in Supplemetary Table 2, whose columns correspond to those in Table 1. Typically, the highest F-statistics are obtained for the slow-moving fleet variables. For instance, for the specifications reported in Columns (1)-(2), the first-stage regression on petrol prices returns an F-statistic of 32.27 whereas the corresponding one for ethanol prices, FFV, and the combined petrol-FFV fleet return F-statistics of 19.94, 1077.79, and 2970.53. As more controls are added, the F-statistics decrease slightly in the case of fuel prices, but except for one case their values do not drop below 10 – values above this threshold are identified by [6] as indication of absence of a weak instrument problem.

While the F-statistics of the first-stage regressions for ethanol prices in (7)-(8) might suggest a weak instrument problem, the increase in the own price elasticities of demand is apparent when comparing the instrumented, 3SLS estimates with their uninstrumented, OLS counterparts (see Appendix on Robustness Checks for additional details). This suggests that the instruments are able to counteract the simultaneity bias originating from the joint determination of prices and quantities in the market for ethanol. Moreover, one could also argue that the less-informativeness of the instruments in this case are due to the information arguably added by the cubic polynomial of the network measure.

To gain perspective on magnitudes, an increase in ethanol prices by one standard deviation starting from the sample average leads to an increase of 1.4 percent in petrol sales and a decrease of 27.9 percent in ethanol sales. Performing the same exercise for petrol, one obtains a 0.9 percent decrease in petrol sales and a 19.7 percent increase in ethanol sales. Changing prices from the 25th to the 75th percentile of the price distributions leads to larger responses.

Supplementary References

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