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https://doi.org/10.1038/s41560-018-0175-3
nature energy

Fuel choice and fuel demand elasticities in markets with flex-fuel vehicles

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The purchase of multifuel vehicles (MFVs) has been incentivized by policies across the globe. Such vehicles are able to operate on more than one source of energy, so they introduce fuel (or energy) choice as one additional dimension consumers decide about. As fuels differ in terms of carbon emissions, this choice has environmental effects. Using 12 years of monthly Swedish data, here I show that the majority of MFV 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 to incentivize the purchase of MFVs 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, carbon dioxide (CO_2) emissions from transport command approximately 20% of the 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. Though the policies designed to attain such targets vary across countries, their cost–benefit analyses (CBA) are similar in that they compare benefits (for example, monetized carbon savings) and costs (for example, 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 pursue correctly the CBA of such a programme.

Multifuel technologies introduce a trade-off typically not taken into account by policymakers. On the one hand, multifuel vehicles (MFVs), for which the driver has control of the fuel the car operates on, reduce concerns about range anxiety, the need for frequent refuelling and technological lock-in that emerging automotive technologies often face. On the other hand, MFVs allow drivers to choose actively the fuel their vehicles operate on, and 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 probably misguided, as non-price attributes may also affect consumer behaviour. Moreover, programmes that pay hefty incentives to consumers to stimulate the demand for MFVs require additional policies in the fuel market because fuel choice becomes another dimension of the consumer's decision-making process. This becomes ever more important because MFVs were at the centre of recent policy initiatives in the United States, China, India, Japan and most EU countries. The Swedish market is one of the few markets in which fuel switching between alternative and fossil fuels using a long sample can be studied.

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 that the leading multifuel 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 to petrol and ethanol sales; whereas 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 flexible-fuel vehicle (FFV) drivers purchase petrol when it is priced at parity with ethanol, which suggests that non-price attributes (for example, range anxiety, shopping costs and technological concerns) also play a role in fuel choice[1]. This finding has implications for the CBA of environmental programmes as carbon savings, which contribute to the benefit side of a programme, depend crucially on the fuel a consumer purchases. Though 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–compressed natural gas (CNG) vehicles and plug-in hybrid electric vehicles (HEVs) enable drivers to actively choose the fuel the vehicle is to operate on. In particular, both technologies allow motorists to drive only using fossil fuels despite being able to operate using an alternative fuel. However, the findings neither generalize to electric vehicles (EVs, for example, Tesla models and the Nissan Leaf) nor to standard hybrids, such as the Toyota Prius, as 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 EU in the same vein as US states are subject to regulations put forth by the US Environmental Protection Agency. That is, just like US states, EU countries had the freedom to choose the policy instruments to comply with the EU directives. Two directives are of particular importance, one that tackles CO_2 emissions of newly registered vehicles, and another that tackles alternative fuels.

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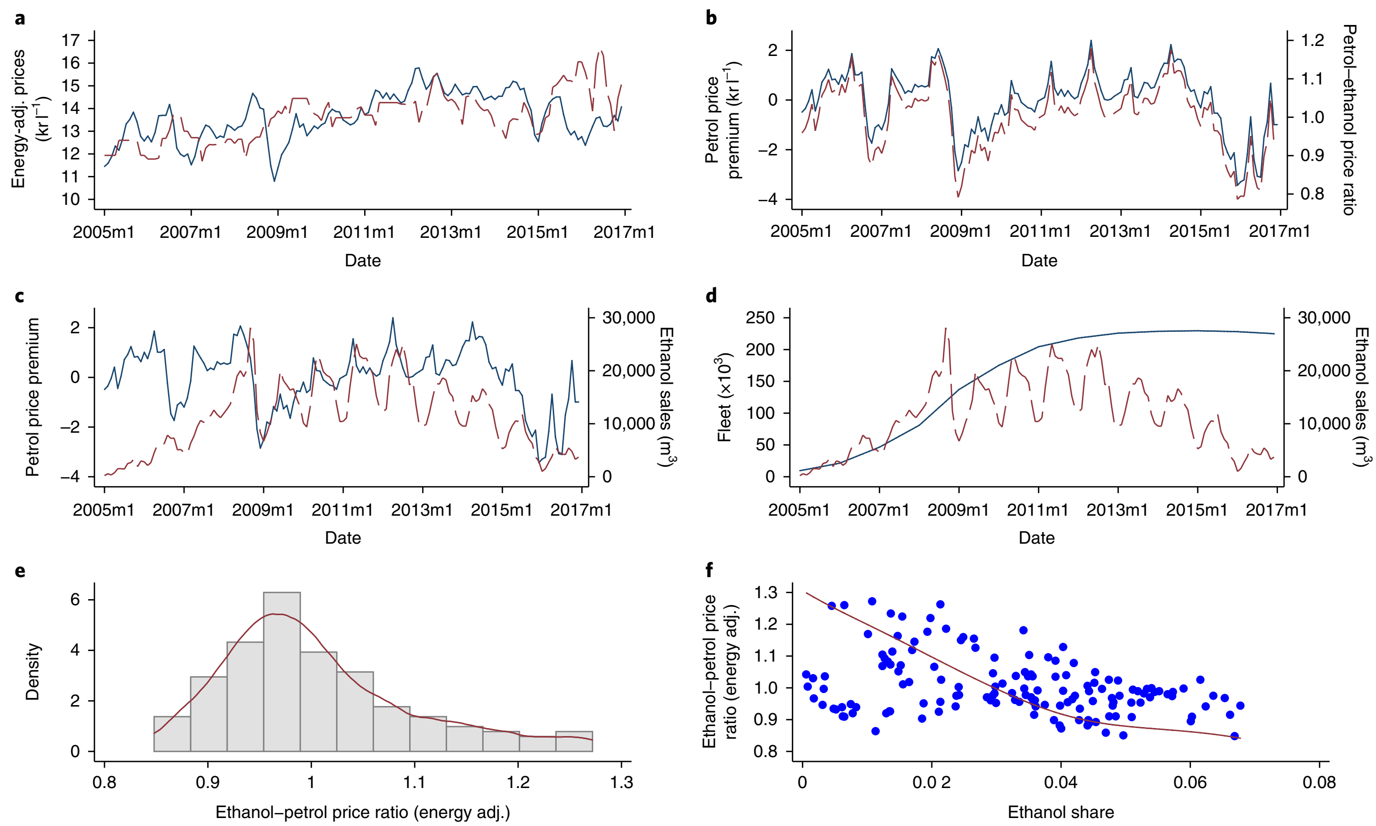

Fig. 1 | Fuel market overview. a, Monthly fuel prices (kr l−1). The fuels are petrol (full line) and energy-adjusted ethanol (dashed line), m1 denotes January for a given year. **b**, Petrol price premiums as the price difference (full line) and price ratio (dashed line). **c**, Ethanol sales and relative fuel prices. Ethanol sales (dashed line) and relative fuel prices calculated as the difference between petrol prices and energy-adjusted ethanol prices (full line). **d**, Ethanol sales (dashed line) and FFV fleet. **e**, Histogram and kernel density estimate of the fuel price ratio. The density is estimated using the kernel method and an Epanechnikov kernel. **f**, Semiparametric demand curve for ethanol. The data points and semiparametric demand curve for ethanol were obtained using the semiparametric estimator described in the text. 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 non-parametrically (sample size is 144). Panels **a**–**c**, **e** and **f** use energy-adjusted ethanol prices, which reflect the per-mile cost of fuel.

Alternative fuels were addressed by the 2003 EU Biofuels Directive, which introduced targets for the use of biofuels. According to such RFS, 5.75% of all transport fuels in the EU should have been 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% of the stations in the Swedish market supplied at least one alternative fuel by 2010, typically ethanol (E85, an 85:15 mixture of ethanol and petrol). (Though ethanol has summer and winter blends, E85 and E75, respectively, to minimize the risk of ethanol freezing when in fuel tanks during the cold season, petrol retailed in Sweden is E5, of which 5% is 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 US$122 million, 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 US$1,500 to all private individuals who purchased 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 alternative fuel vehicles (AFVs), notably petrol–ethanol hybrids (FFVs), within the EU. The market share commanded by green cars reached 26.5% in 2008 (6% in 2006), as compared to a 2.15% market share commanded by HEVs in 2007 after a related programme in the United States[4].

Though the technology employed in FFVs differs from that used in, say, 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 operate on. For instance, by not charging a HEV, its driver might drive using only petrol. The comparison with HEVs is relevant because they are a competitive alternative to EVs for being cheaper due to the smaller batteries, which have lower recharging times and reduce the range anxiety of drivers[5].

On the environmental front, ref. [6] documents that emissions from EVs that are powered by the existing US power plants are generally higher than emissions from high-efficiency petrol-powered vehicles; only 12% of fossil fuelled power plants generate emissions per vehicle they charge that are below those of a Toyota Prius.

Figure 1 provides descriptive evidence on the fuel market. After the end of the GCR programme and a period of expensive ethanol, sales of both ethanol and new FFVs decreased starkly, which suggests a feedback effect between the fuel and vehicle markets. However, the overall 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, Fig. 1f displays the relation

Table 1 | Fuel demand estimates

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	−0.132*	2.393***	−0.123*	2.246***	−0.121*	2.519***	−0.120*	2.460***
	(0.072)	(0.687)	(0.072)	(0.731)	(0.071)	(0.682)	(0.070)	(0.638)
ln p_e	0.205*	−3.907***	0.163	−4.028***	0.185*	−4.465***	0.191**	−4.420***
	(0.114)	(1.125)	(0.106)	(1.129)	(0.104)	(1.030)	(0.095)	(0.911)
Controls								
Fleet	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects								
Month FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	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^2	0.985	0.914	0.985	0.915	0.985	0.923	0.985	0.934

This table displays estimates of the fuel demand for the Swedish market obtained by estimating the demand system using a 3SLS method. Standard errors are reported in parentheses. Significance level: *10%, **5%, ***1%. The 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 the per capita total hours worked. Instruments are sugar, maize, food (L3); Brent, WTI (L1); income proxy; fuel prices (L3). L*n* denotes a variable lagged by *n* periods. q_g, demand for gasoline; q_e, demand for ethanol; p_g, price of gasoline; p_e, price of ethanol.

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% confidence intervals based on a semiparametric estimate[7] and robust standard errors. Though the price ratio varies between 0.80 and 1.30, the share of ethanol as a proportion of the combined sales of ethanol and petrol varies from zero to nearly 7%. 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

Initially, I estimate 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 that probably influence fuel sales, such as the size of the vehicle fleet and the month of the year (Methods provides details). Though 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 for the demand of a product measures the per cent change of the demand for a product given a one per cent change in the price of a (potentially another) product. (Additional discussion is given in Methods 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; odd-numbered (even-numbered) columns report estimates for the demand of petrol (ethanol). Though the demand equations for petrol all have a similar structure, with both month and year fixed effects, and with the combined fleet of petrol and FFV vehicles used 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 that supply ethanol in the Swedish market; columns (4), (6) and (8) in Table 1 report estimates from the use of a linear, a quadratic and a cubic polynomial of the number of ethanol stations in the country. (Column (2) in Table 1 has no such term. The results are also robust to the use of the share of stations instead of their count.)

The baseline results (columns (1) and (2)) of the demand system are robust to the inclusion of the fuel network terms and are used below for the sake of parsimony. (Supplementary Tables report the robustness checks discussed in 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% level. Cross-price elasticities are typically higher, in the range 0.180–0.200, and less precisely estimated, so not always statistically significant. When it comes to the demand for ethanol, own-price elasticities are substantially higher than those of petrol with a range from −4.4 to −3.9. This happens because FFV motorists are able to substitute easily between ethanol and petrol, which makes 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 (1) equality of the own-price elasticities in the two demand equations and (2) equality of the own- and cross-price elasticities for each of the equations; I reject all of them at the 1% 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[8–10] and ethanol[11,12]. For instance, ref. [10] documents that mean short- and long-run price elasticities for petrol are −0.34 and −0.84, respectively, whereas ref. [9] obtains estimates from −0.34 to −0.21 for 1975–1980 and from −0.077 to −0.034 for 2001–2006. For ethanol, ref. [11] reports own-price elasticities from −3.8 to −3.2, thus less elastic than the above, whereas ref. [12] reports ordinary least squares (OLS) estimates in the range −4.07 to −2.52 (which implies that the instrumental variable (IV) counterparts would be more elastic).

That consumers do not treat two sources of energy that arguably provide 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

Table 2 | 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	0.79
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

This table displays the normalized demand for ethanol (share of FFV users who purchase ethanol) implied by estimates in columns (1) and (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). The above results assume that all FFV drivers are assumed to purchase ethanol when the energy-adjusted price ratio reaches 0.75; if this occurs at alternative ratios of 0.80 and 0.85, the share of ethanol users at price parity is 0.42 and 0.53, respectively.

document the significance of factors such as shopping costs, range anxiety, technological concerns and environmental concerns among those non-price attributes[1]. Though the relative importance of such factors probably 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% 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 the 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 and 1.35 of the petrol prices (from Fig. 1; historical relative prices are in the range 0.84–1.27). To quantify the share of consumers that purchase each fuel at price parity, I normalize fuel demand so that 100% 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% of FFV drivers are assumed to purchase ethanol at the 0.75 price ratio, only 10% do so at the 1.35 price ratio. Crucially, only 34% of FFV drivers purchase ethanol at price parity, that is, 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% of FFV drivers purchase ethanol at price ratios 0.80 and 0.85, with the share of consumers who purchase ethanol being 42 and 53%, 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 provide robustness). (An earlier version of the paper further documents this by calculating the effect of a dynamic petrol tax that makes petrol at least as expensive as ethanol in energy-adjusted terms. The small 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 emission generated by different fuels. For instance, the most conservative cost–benefit estimates (in Swedish krona (kr)) of the GCR programme in Huse[3] range from roughly −kr5,000 to kr5,000 per FFV, depending on whether ethanol is used 25 or 75% of the time by FFV drivers. This is a non-trivial amount given the kr10,000 rebate.

Simulation of RFS

I use the demand estimates to simulate the effect of an additional petrol tax to gauge the tax level at which a RFS—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 the year 2010. I examine 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 (kr l^{-1}), compute the total fuel sales for the 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 deadweight 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 kr7.50 l^{-1}. This results in a price of kr21.10 l^{-1} (US\$11.88 gallon^{-1}), or 55% above the average petrol retail price at the period. The improvement in CO_2 emissions is non-monotonic, as it is maximized when the additional petrol tax is kr5.50 l^{-1}. 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 that result from increases in DWL, I use the social cost of carbon (SCC) estimate from Mandell[13]. I calculate the benefits minus the costs (net effects) of the tax in two ways, net effect 1 and net effect 2 in Table 3. These are, respectively, without and with 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 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 gained by lower CO_2 emissions.

Discussion

The paper contributes to different strands of the literature. First, it contributes to the literature on fuel choice. Previous studies[11,12] estimated 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 another study[1] used revealed preference data to estimate the demand for fuels among

Table 3 | Effects of an additional petrol tax on the ethanol share

Additional tax ($kr\,l^{-1}$)	Ethanol share (%)	ΔCO_2 emissions ($10^3 \times tCO_2$)	ΔDWL ($kr \times 10^9$)	Net effect 1 ($kr \times 10^9$)	Additional tax revenue ($kr \times 10^9$)	Net effect 2 ($kr \times 10^9$)
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

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 the other variables are fixed at their mean levels during year 2010. At the kr/US\$ exchange rate of 6.724 on 31 December 2010, the mean price of petrol (kr13.60 l^{-1}) is US\$7.66 gallon^{-1}. For illustration, to attain an ethanol share of 5.8%, the price of petrol has to increase to kr13.60 + kr7.50 = kr21.10 l^{-1} (US\$11.88 gallon^{-1}). The SCC is kr1,060 per tonne of CO_2 (US\$157.6 per tCO_2) (ref. [13]). Net effect 1 is obtained as the difference between the product of CO_2 emissions and the SCC, minus the DWL. Net effect 2 is obtained as the difference between additional tax revenues and net effect 1.

FFV owners who exploited exogenous variation in relative fuel prices due to weather conditions. Salvo and Huse[1] found a 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 literature is to estimate fuel demand that exploits substantial variation in absolute and relative fuel prices using a long time series of market data.

Second, the paper contributes to literature that assesses the effects of technologies and programmes where fuel choice is an additional dimension of consumer choice[2,3,14]. Understanding fuel choice is crucial to evaluate both the environmental and the economic effects of emerging technologies, in particular the CBA of programmes that contemplate MFVs, a technology bound to be increasingly targeted by such programmes.

Third, the paper complements the empirical literature that examines network effects in the fuel–vehicle markets[15–19]. Typically, this literature relates the provision of fuelling infrastructure to the purchase of vehicles of a given fuel. However, little attention has been devoted to the actual fuel sales after the provision of the fuelling infrastructure, that is, the fact that infrastructure is not sufficient for the uptake of an alternative fuel.

Finally, the paper relates to literature that examines the environmental, economic and distributional effects of fuel taxation[20–24]. The findings in this literature 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 and seamlessly allows fuelling, and the energy-adjusted prices are competitive.

Conclusions

Drivers of FFVs strongly prefer the fossil over the alternative fuel at price parity. To make 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 (DWL) the taxes also introduce.

The results suggest that fuelling infrastructure and a fleet of AFVs 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 that additional factors could impact fuel choice. First is the composition of ethanol, which contains some water (about 5%). 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 the 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. Though producing anhydrous ethanol (ethanol with less than 1% water) is feasible, it is costly in that it requires an additional distillation during the production process. Second, the 'food versus 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.

Methods

Here I discuss demand estimation, identification, the calculation of the policy simulation of the RFS and provide additional detail on the data used. (Supplementary Methods provides additional discussion.)

I estimate a demand system using the three-stage least squares (3SLS) method as 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. That such variables might be simultaneously determined with the dependent variables (fuel sales) calls for the use of IVs, 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 the computation of DWL. Finally, I detail the market-level data used in the study and discuss the data availability.

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

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

where q_{ft} denotes the sales of fuel f at month t, p_{ft} is the real price of fuel f at month t 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, and α is a fuel-specific intercept term. In the above specification, the coefficients γ are the own- (if $f = k$) and cross-price elasticities (if $f \neq k$), and thus are 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, in which 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 (that is, ethanol prices relative to gasoline prices) over time. Though 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 to purchase 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 and 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, and 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 that follows a period of economic growth. Second, I use lagged fuel prices to instrument the vehicle fleet given the relation between these two markets. 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 and yet correlated with the decision to purchase an FFV.

RFS. 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, and compute the fuel sales and corresponding ethanol share that result. As above, I calculate the changes in CO_2 emissions under the assumption that one litre of gasoline (ethanol) contains 2,392 g CO_2 (1,076 gCO_2 l^{-1}), with value for ethanol conservatively assumed to be 55% lower than that for gasoline. CO_2 savings are converted into monetary amounts using the SCC of kr1,060 per tCO_2.

The DWL calculated is a lower bound to the measure of allocative inefficiency because I perform a partial equilibrium rather than a general equilibrium analysis. Ethanol subsidies were disallowed by the EU—their end is behind the 2015 price increase. To calculate the DWL[25], I assume a horizontal (price-inelastic) supply curve and rely on the demand specification[24]. The demand for gasoline can be written as $q_g = Ap^{\varepsilon}$, where ε is the own-price elasticity of demand for gasoline and A is 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 area to the left of the demand curve in the interval $\int_{p_2}^{p_1} Ap^{\varepsilon}\,\mathrm{d}p$. This can be written as:

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

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

As the EU RFS requires the attainment of a 5.75% target at the transport sector as a whole, that is, as a share of the 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, but use the actual sales data for year 2010.

To gain a perspective on fuel prices, in the year 2010 the total tax on gasoline on the Swedish market was kr5.50 l^{-1}. Moreover, Hong Kong's gasoline price was US\$7.27 gallon^{-1} in 2010[26] and US\$7.23 gallon^{-1} in the first quarter of 2017 (Sweden's was US\$6.01 gallon^{-1}). Thus, Sweden is among the top ten countries in terms of gasoline prices[27].

Data. I combine a number of datasets recorded at a 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[28]. All sales figures are reported in cubic metres and all prices are reported in Swedish krona. (I have double-checked these 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[29].)

Nominal fuel prices were deflated using the Consumer Price Index from the Swedish Statistics Bureau (SCB). Given the focus on light transportation and the technology involved (ethanol–gasoline FFV), 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 to the 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 the International Monetary Fund[30]. These include Brent, West Texas Intermediate (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 Swedish krona, 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. 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. The data required to obtain the baseline results of the paper are publicly available and described above. Fuel distribution data, which are used only for robustness, are not public.

Received: 14 September 2017; Accepted: 4 May 2018;
Published online: 11 June 2018

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Acknowledgements
I am indebted to N. Koptyug and C. Lucinda for their comments on an earlier draft of the paper.

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

Competing interests
The author declares no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41560-018-0175-3.

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