Fast and Furious (and Dirty): How Asymmetric Regulation May Hinder Environmental Policy*

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Abstract

In the first year after the inception of the Swedish Green Car Rebate (GCR), *green cars* had carved a 25 percent share of the new vehicle market, an effect of unprecedented scale as compared to recent policies incentivizing the purchase of fuel-efficient vehicles. By awarding vehicles satisfying certain emission criteria a rebate, but giving alternative (renewable) fuels a more lenient treatment than regular (fossil) ones, the GCR led carmakers to introduce a number of high-emission alternative models. This paper examines the impact of regulation on market developments focusing on CO2 emissions of alternative and regular vehicles. Despite a decrease in the short-run, once carmakers adjust their product lines to the policy, CO2 emissions of alternative vehicles increased significantly in relation to those of regular ones, thus undermining the very objectives of the GCR.

JEL Classification: H23, L51, L62, L98, Q42, Q48, Q53.

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1 Introduction

Economists have been interested in the interplay between regulation and market outcomes at least since David Ricardo's analysis of the English Corn Laws in the early 1800s. Over one century later, following the seminal contributions of Olson (1965), Stigler (1971) and Peltzman (1976), a substantial body of literature studying the effects of regulation developed. For instance, Greenstone (2002) and Holmes (1998) examine the effect of regulation on industrial activity and industry location, respectively, whereas Berman and Bui (2001) and Kahn and Mansur (2010) study how productivity and employment respond to new regulation.

This paper examines the effect of regulation on a particular market, the Swedish automobile market. Specifically, it evaluates the effect of the Swedish "Green Car Rebate" (GCR) on CO2 emission levels of newly-registered passenger cars. The GCR is one among a number of policies designed to incentivize the purchase of fuel-efficient vehicles worldwide amid the ever growing concern with greenhouse gases (GHG) and the quest for oil independence. Although the precise policy instrument used varies, the robust finding is that such policies have typically not applied widely enough to affect a large fraction of the new vehicle market (Sallee 2011a).[1] Against this background, vehicles benefiting from the GCR commanded an unprecedented market share of 25 percent in 2008, the first calendar year after its inception. Besides its breadth, the GCR also distinguishes itself for its embracing of *alternative* (renewable) fuels. As a result, alternative vehicles – vehicles able to operate using alternative fuels – make about 80 percent of the vehicles which were eligible for the rebate in 2008.[2]

Environmental Policy The Swedish Green Car Rebate, introduced in April 2007, aimed at reducing both GHG emissions of newly-registered vehicles and oil dependence. These aims were to be achieved through a rebate to individuals purchasing environmentally friendly cars, the so called *green cars*. The GCR can be seen as a combination of increased fuel economy standards of the means of transport and increased emphasis on alternative fuels and technologies for the transportation sector. It defined green cars according to which fuels a vehicle is able to operate on and on how much CO2 it emits. While cars able to run only on fossil fuels such as gasoline and diesel – the so called regular fuels – were considered green cars provided their emissions were below a 120 gCO2/km threshold, those able to run on alternative fuels (ethanol, gas and electricity) were given a more lenient treatment (roughly equivalent to a threshold of 220 gCO2/km).[3] [4] This asymmetric treatment effectively created a regulatory loophole duly explored by carmakers and consumers alike, as I document below. That is, facing little incentives to introduce low-emission alternative vehicles, carmakers reacted by introducing high-emission alternative ones. As they were eligible for the rebate, alternative vehicles became more attractive to consumers than their regular counterparts. Since the dominant alternative vehicle can run on both gasoline and ethanol, and a substantial share of consumers purchases the cheapest fuel, those high-emission vehicles benefiting from the rebate were often fueled with gasoline.

[1] For instance, subsidies were awarded to hybrid and electric vehicles in the US and Canada, sales tax was reduced in China and Brazil and stimulus/scrappage programs were launched in France, Germany, Italy Spain, the United Kingdom and the US in 2008 and 2009. Given its design, the Swedish GCR is closer in spirit to the US hybrid subsidy (see Beresteanu and Li 2011) than the "Cash for Clunkers" stimulus program.

[2] Monthly figures reached 39 and 25 percent respectively. For perspective, Beresteanu and Li (2011) document that hybrid electric vehicles commanded a market share of 2.15 percent in the US in 2007.

[3] Anecdotal evidence suggests that the skew towards renewables (ethanol in particular) was inspired by Brazil, whose CO2 emissions per unit of fuel consumption in road traffic are 20 percent below the world average (IEA 2011a).

[4] The choice of threshold seems to come from the 1994 EEA Treaty, which created the European Economic Area and originally set a target of 120 gCO2/km by 2005 (later relaxed to 130 gCO2/km by 2012) and aimed at cutting carbon emissions by 20 percent by 2020 compared to the levels of 1990.

Empirical Strategy To estimate the causal effect of the impact of the GCR on CO2 emission levels of alternative as compared to regular vehicles, I take advantage of the unanticipated character of the policy. That is, since the GCR treats regular and alternative fuels asymmetrically, I employ difference-in-differences (DD) techniques to assess the effects of the policy. The idea of the GCR was made public and discussed by the Swedish Parliament in March 2007. The policy was launched in April 2007, at which point all model-year 2007 vehicles had already been launched.[5] The policy seems to have caught carmakers by surprise and, even if they had anticipated some such policy, it is unlikely that they had enough information to strategically adjust emission settings of their 2007 product lines accordingly.

I take advantage of the institutional setting of the automobile industry to disentangle short- from long-run effects of the policy. That is, while carmakers' product lines (choice sets facing the consumer) for model-year 2007 were defined *before* the inception of the policy, those for model-year 2008 (and onwards) were defined *after* the policy was introduced. As a result, following the inception of the policy carmakers were unable to re-engineer their vehicles in 2007, so one would naturally expect to see only their 2008 product lines accounting for the GCR in some way. Building on the institutional setting, I focus on both the *short-run* effect of the GCR, which goes from April to December 2007 whereby only consumers react to the policy,[6] and a *long-run* effect from January 2008 whereby carmakers adjust their product lines and consumers react to both the policy (as in the short-run) *and* the new choice set.

Main Findings I estimate the causal effect of the GCR on supply- and sales-weighted (i.e. registration-based) emissions of alternative and regular vehicles. That is, using data on all models available on the market, the supply-side analysis captures the re-design of product lines whereas the combination of supply and demand effects gives sales-weighted data an equilibrium interpretation.

Had the aim of the policy been merely to increase the adoption of green cars, it would have been considered a success. However, I document below that one by-product of the GCR is that CO2 emission levels of alternative vehicles benefiting from the program *increased* in a non-trivial way with respect to those able to run on *regular* (fossil, i.e. diesel and gasoline) fuels. That is, the asymmetric treatment of regular and alternative green cars had profound effects on the relative CO2 emission levels (thus fuel economy) of regular and alternative vehicles following the introduction of the GCR. Specifically, it induced carmakers to adjust their product lines accordingly, resulting in higher emission vehicles running on alternative fuels *vis-à-vis* those running on regular ones. What is more, since the leading alternative green cars are FFVs, it opens the possibility for motorists to arbitrage across fuels; in fact, I show that most FFV owners do arbitrage across fuels and purchase the cheapest fuel (not necessarily the renewable one) resulting in increased air pollution levels. In sum, the paper provides evidence that both carmakers and consumers reacted to the policy in ways that worked against its very objectives

Focusing on the supply-side, I document how carmakers took advantage of the lax regulation towards alternative cars and reacted by offering larger, high-emission, vehicles running on alternative fuels. In fact, my results point to a roughly 7 gCO2/km increase in emissions starting from model-year 2008.[7] When decomposing this effect into separate ones for model-years 2008 and 2009, I obtain insignificant estimates for the former and significant ones in the range 10-15 gCO2/km for the latter.

[5] In fact, since new product lines are typically launched in the late fall, model-year 2007 vehicles were in the middle of their production cycle.

[6] Although carmakers cannot re-design their vehicles in the short-run, one cannot rule out responses in other dimensions, e.g. marketing initiatives.

[7] This amounts to about 4 percent of the emissions for the median 2008 car model.

This result provides evidence that carmakers have reacted to the policy in less than two years after its inception.

Looking at sales-weighted emissions, I find evidence of a short-run effect between the inception of the program and the rolling out of the 2008 product lines whereby consumers respond by purchasing alternative vehicles emitting *less* CO2 than their regular counterparts: this decrease in emission levels of alternative as compared to regular vehicles is in the range 7-9 gCO2/km, even after controlling for fuel prices. The long-run effect of the policy, which accounts for carmakers adjusting their product lines suggests that consumers reacted to the enlarged choice set and were more likely to purchase high-emission vehicles running on alternative fuels.[8] What is more, when this long-run effect for year 2008 onwards is decomposed into separate ones for years 2008 and 2009, I obtain insignificant estimates for the former and statistically significant in the range 4-6 gCO2/km for the latter, thus suggesting a strengthening effect over time. This finding is in line with a vast literature looking at demand for automobiles, according to which consumers value characteristics such as size (a proxy for comfort) and horsepower (Berry, Levinsohn and Pakes 1995, Goldberg 1995).

At the root of the problem lies the lax treatment enjoyed by alternative fuels, in particular the dominant gasoline-ethanol FFV. Reasons why FFVs commanded the lion's share among alternative vehicles include the similarity with the standard Otto cycle technology (of which it is a derivative) and the well-developed retail network for ethanol, as opposed to, say, CNG (compressed natural gas), which is only available in parts of the country. As a result, FFV owners are able to arbitrage across fuels and reduce the running costs of their vehicles.

To illustrate the potential adverse effects of relying on FFVs, I gauge the fuel switching behavior among FFV owners combining a structural model of fuel choice and a recent exogenous shock to fuel prices. Following the 2008 recession and the sudden drop in oil prices, gasoline became cheaper than ethanol in energy-adjusted terms causing the monthly volume sales of ethanol to plummet by about 73 percent. When taking the model to data, I find that a small share of FFV owners (11-18 percent) fuels only with ethanol. In contrast, while a moderate fraction of FFV owners (6-43 percent) fuels only with gasoline, the majority of FFV owners (46-77 percent) arbitrages across fuels, in spite of pocketing the value of the rebate. That is, following a policy designed to reduce emissions and promote oil independence via a monetary transfer to purchasers of green cars, a substantial share of these very cars were high-emission vehicles running on the cheaper fossil fuel instead of the renewable alternative.

The effects of fuel switching on air pollution are potentially dramatic in that life-cycle CO2 emissions by FFVs increase by over 80 percent whereas emissions of pollutants such as NOx and particulate matter (PM) increase by about 21 and 46 percent, respectively.[9]

In sum, the paper provides evidence consistent with the view that the GCR was not much more than a transfer to consumers purchasing FFVs. More generally, its findings highlight the margins policymakers should take into account when designing environmental policies aimed at the transport sector. Moreover, these findings are not restricted to ethanol, but should hold to any alternative to the established fossil fuels. This is important because while road transport is already responsible for about 20 percent of the CO2 emissions generated by fuel consumption worldwide (IEA 2011a), transport fuel demand is set to grow some 40 percent by 2035 and the number of passenger cars worldwide is set to double to almost 1.7 billion in the same period, thanks to the growth of emerging

[8] Within the first year of the GCR, the number of gasoline and diesel cars on the market qualifying as green increased from 10 and 33 to 18 and 48, respectively, whereas the number of FFVs increased from 18 to 44 – see Table 2 for details.

[9] Local air pollutants such as nitrogen oxides (NOx) and particulate matter (PM) are not GHGs, but are known to harm human health.

economies (IEA 2011b).

Related Literature This is the first paper to investigate a green car policy with a broad impact on the automobile market and a focus on alternative fuels. The papers most closely related to this one are Knittel (2011) and Sallee and Anderson (2011). Knittel (2011) performs a long-run analysis of the US automobile industry and points to consumer preferences driving changes in vehicle characteristics. Here, I both identify the mechanism by which consumers and carmakers react to the GCR and document that such changes materialize earlier than one may expect (see also Li, Timmins and von Haefen 2009). As in Anderson and Sallee (2011), I show that carmakers explore a regulatory loophole. Additionally, I show how the reactions of both firms and consumers jointly work against the very objectives of the policy. As in Greenstone (2002), the paper benefits from an arguably clean identification strategy to argue that product characteristics endogenously change following the GCR.

More broadly, the paper also relates to other streams of the literature. First, it relates to work by Busse, Silva-Risso and Zettelmeyer (2006) and Sallee (2011b) who both document how consumers tend to capture subsidies, especially if they are salient.

Second, the paper contributes to the burgeoning literature on policies directed towards the transport sector, notably the automobile industry, see for instance Adamou, Clerides and Zachariadis (2011), Beresteanu and Li (2011), Chandra, Gulati and Kandlikar (2010), Li, Linn and Spiller (2011), and Miravete and Moral (2009).

Third, by focusing on fuel choice of FFV owners, the paper relates to the literature on the interaction between fuel and car markets, as in Borenstein (1993), Busse, Knittel and Zettelmeyer (2009), Li, Timmins and von Haefen (2009) and Klier and Linn (2010). In contrast with the bulk of the established literature, I document how fuel switching among FFV owners occurs rapidly due to the particular technology in place. Moreover, by calibrating a structural model of fuel choice for an entire market the paper contributes to research on the choice between fossil and renewable fuels as in Anderson (2012), Corts (2010) and Salvo and Huse (2012). However, contrary to what happens in the US, where Corts (2010) documents a low market penetration of ethanol due to a "chicken-and-egg problem", i.e. the lack of fueling infrastructure which hinders the dissemination of renewable fuels, and *vice-versa*, Sweden has a well-developed network of fueling stations where ethanol is readily available. Infrastructure availability is, however, a necessary, but not sufficient condition for the adoption of renewable fuels, given the ability of FFV owners to arbitrage across fuels.

Finally, by focusing on the effects of fuel switching on air pollution, and by providing estimates of the shares of different consumer types when it comes to fuel choice, the paper relates to research on air quality in economics, see Chay and Greenstone (2003), Davis (2008), Auffhammer and Kellogg (2011), and complements recent research in the natural sciences on the effects of ethanol on air quality, see Jacobson (2007).

2 Institutional Background

Despite its small size in absolute terms, the Swedish passenger car market in the mid-2000s is comparable to larger European ones such as the French and German when looking at ownership on a *per capita* basis. In contrast with the variety of brands on the market, the commonplace view of the average family car being a Volvo wagon is not too far from reality in the country, as are the slightly older fleet and the larger (and likely less fuel-efficient) vehicles circulating, as reported in Table 1. For instance, back in 2008 the average Swedish car was 9.5 years old and 39.1 percent of the fleet was aged above 10 years, numbers significantly worse than those for France and Germany.

More generally, while within the European Union (EU) passenger cars are responsible for about 12 percent of the overall emissions, within Sweden this share is a much higher 19 percent (Commission of the European Communities 2007). In fact, Sweden lags significantly behind most EU 25 countries, with estimated CO2 emissions only lower than those of (poorer countries) Estonia and Latvia (EFTE 2009). Reducing emissions from passenger cars is thus essential for Sweden to meet EU-wide environmental goals.

TABLE 1 ABOUT HERE

Green Car Rebate Sweden has been an early backer of renewable technologies in the transport sector, with the adoption of ethanol-fueled buses in its larger cities, and by generating governmental demand for ethanol cars since the 1990s, when the Ford Focus was first marketed in the country (Volvo and Saab introduced their FFV models only in 2005). Moreover, Sweden has been importing ethanol since the early 2000s and boasts a well-established distribution network in place whereby over 50 percent of fueling stations supply at least one renewable fuel in 2009, typically ethanol.

With the aim of reducing both GHG emissions and oil dependence, in April 2007 the Swedish government introduced a rebate scheme to promote environmentally friendly vehicles. Following the fall 2006 elections, a new government was formed which came to power later that year and proposed the GCR. The program, which was passed in Parliament and announced to the public in March 2007, effectively starting in April 2007, consisted of a rebate of 10,000 SEK (Swedish *krona*) to private individuals upon the purchase of a new green car. As the SEK/$ exchange rate was 6.984 and 7.650 at the inception and at the end of the program, respectively, this amounts to $1,300-1,500, or about 6 percent off the price of a new 2009 VW Golf 1.6 FFV. The GCR was initially scheduled to operate between April 2007 and December 2009. However, in fall 2008 it was made public that the program would end early on June 30 2009 (Ministry of the Environment 2008a). Thus, although its end was anticipated, it is unlikely that product lines for 2009 were designed having in mind that the GCR was to end in June 2009.

Crucially, the policy caught carmakers by surprise: carmakers typically launch product lines once a year, which requires them to plan their overall strategy well in advance. In the Swedish market, where this happens late in the fall, the product lines for model-year 2007 had been launched in late 2006 and were already in the middle of their production cycle. As a result, although carmakers could respond to the GCR via, say, advertising, they were only able to re-engineer their products, e.g. change product lines, alter vehicle design, for model-year 2008, an institutional feature to be used in the empirical strategy below.

Green Car Definition For the purposes of the GCR, the definition of a green car depends on compliance with certain emission criteria and on the type of fuel(s) the car is able to run on (SFS 2007). Cars running on regular fuels (fossil fuels such as gasoline and diesel) qualify as green cars provided they emit no more than 120 gCO2/km, whereas cars able to run on alternative fuels such as ethanol, gas and electricity do qualify provided they consume up to the gasoline-equivalent of 9.2 l/100km (liter per 100km), the gas-equivalent of 9.7m3/100km or less than 37 kWh/100km, respectively.[10]

Although the thresholds defining regular and alternative fuel cars are expressed in different units (gCO2/km and l/100km) the CO2 emissions and fuel efficiency measures are highly negatively correlated: for vehicles marketed in Sweden, the correlation between CO2 emissions (in gCO2/km, the

[10]Emissions of 120 gCO2/km correspond to a fuel consumption of about 5 liters of gasoline or 4.5 liters of diesel per 100 km (or 75.7 and 84.1 mpg, respectively). Besides being applied to individual cars rather than to a brand-level sales-weighted average as in the US CAFE standard, at the equivalent of about 193 gCO2/mile this emission threshold is more stringent than the 250 gCO2/mile CAFE standard to take effect from 2016 in the US.

measure typically used within the EU) and mpg (miles per gallon, the measure typically used in the US) is -0.92, with the threshold for alternative fuels being equivalent to approximately 220 gCO2/km (for perspective, the 2012 Porsche 911 Carrera emits 205 gCO2/km).[11] All in all, the threshold defining alternative green cars is substantially more lenient than the one defining regular ones.

Fuels The dominant fuel among alternative ones is ethanol, with gas (which encompasses compressed natural gas or CNG, liquefied natural gas or LNG, and liquefied petroleum gas or LPG; in what follows I refer to gasoline-gas hybrids as gasoline/CNG vehicles) and electric alternatives also available but commanding slim market shares. Ethanol (also known as E85, a 85-15 blend of ethanol and gasoline, where the latter works as a lubricant and helps starting the engine), a fuel made from renewable raw materials such as sugar cane or cereals (notably corn), is the dominant renewable fuel in Sweden. The environmental benefits of ethanol depend on how it is produced, with sugarcane bringing the highest environmental gains. Ethanol life-cycle CO2 emissions, i.e. those considering also the emissions generated during its production and distribution, are approximately 55 percent lower than those of gasoline (Swedish Consumer Agency 2011). Ethanol does however emit other pollutants (see Section 6).

Typically, cars running on alternative fuels are also able to operate using a regular fuel – usually gasoline – and either ethanol, gas or electricity (thus often being referred to as hybrids). Given their ability to seamlessly drive with any combination of ethanol and gasoline which are stored in the same tank, gasoline-ethanol cars are called FFVs (flexible-fuel vehicles). The price of a FFV is slightly higher than that of a comparable gasoline model, but used FFVs trade at similar prices than comparable captive gasoline models.

While the seamless switch between fuels avoids lock-in problems resulting from incipient retail networks of a newly-established renewable fuel, it also allows owners of FFVs to arbitrage across fuels: ethanol has a lower energy content than gasoline, thus resulting in a higher ethanol consumption per distance traveled, with an implied price parity (no-arbitrage relation) of $p_e \simeq 0.7p_g$. As a result, despite receiving a 10,000 SEK rebate upon the purchase of a FFV, nothing prevents the owner of a FFV from driving his automobile as if it was a captive gasoline car.

From the carmaker's perspective, introducing a FFV version of an existing model is a cheap and trivial task. All that is required is a sensor that detects the mix between ethanol and gasoline from the exhaust pipe fumes and sends a message to the vehicle's electronic central unit (ECU), which then adjusts the engine settings accordingly. Cost estimates of the operation are in the range $100-200, roughly 10 percent of the value of the rebate. (See Anderson and Sallee 2011 and Salvo and Huse 2012 for details).

3 Data

I combine a number of datasets, from administrative-based registration data to publicly-available car characteristics, fuel data and air pollutants. The details are as follows.

Car Characteristics Product characteristics are obtained from the consumer guides *Nybilsguiden* (New Car Guide) issued yearly by The Swedish Consumer Agency (Konsumentverket). For every car model available on the Swedish market the information available includes characteristics such as fuel type, engine power and displacement, number of cylinders, number of doors, gearbox type, fuel

[11] In other words, regulation of fuel economy and emissions is almost equivalent, see Anderson, Parry, Sallee and Fischer (2011).

economy (city driving, highway driving and mixed driving, with testing made under EU-determined driving cycle and expressed in liters per 100 kilometers, or 100 cubic meters per km for CNG cars), CO2 emissions (measured in gCO2/km under EU-determined driving conditions and mixed driving), vehicle tax and list prices.

Car Registrations Car registration data is from *Vroom*, a consulting firm. The data on privately owned vehicles is recorded at the monthly frequency from January 2005 to December 2009. An observation is a combination of year, brand, model, engine size, fuel type, and a green car indicator.

Fuel Data I use market level data for fuels recorded at the monthly frequency at the national level. Recommended retail fuel prices for gasoline, diesel and ethanol are obtained from the biggest distributors in Sweden, OKQ8 and Statoil. Gasoline companies do not provide actual prices which vary by region and even by station. Also at the national level I use quantities sold for gasoline, ethanol and diesel obtained from the Swedish Petroleum Institute (SPI). Given the recent introduction of alternative prices, ethanol and CNG prices are available from January 2005 and January 2007, respectively.

Air Pollutants I use emissions data from a number of sources. First, exhaust CO2 emissions are obtained from the Swedish Consumer Agency. I use life-cycle carbon emission data from the Swedish Transport Authority. Finally, I also use data comparing exhaust pollutants emitted by gasoline- and ethanol-fueled vehicles from the US EPA (Environmental Protection Agency) and Yanowitz and McCormick (2009).

Combining Datasets I merge characteristics and registration datasets to estimate the effect of the GCR on CO2 emissions of newly-registered vehicles. One important issue arising when combining registration and characteristic datasets is that the former is observed at a more aggregate level than the latter. Despite being more aggregated than the car characteristics, this level of aggregation still allows identifying quite accurately the version of a model that was purchased and, critically, to match this information with product characteristics, especially CO2 emissions and fuel economy.[12] Reassuringly, since the original source of the data is administrative and vehicle taxes are based on both fuel and engine and/or CO2 emission information, any aggregation biases should be minimal. This is especially so for green cars: given the relatively small number of green versions (typically one or two per model), aggregation issues for these models essentially vanish.

4 Descriptive Analysis

The recent developments in the Swedish car market can be summarized in four stylized facts. I start by documenting that, as opposed to previous findings for the industry elsewhere, carmakers react swiftly to the policy and introduced a number of green car models already in model-year 2008, i.e. months after the GCR was introduced. This finding can be explained by at least two factors, namely the previous availability of low-emission gasoline and diesel engines within a number of brands (or groups) and the ease with which a carmaker can turn a gasoline vehicle into an FFV.

Second, I show that among alternative car models introduced during the sample period, the majority consist of FFVs. Again, this can be attributed to the ease with which carmakers can

[12] I have also manually checked fuel economy and CO2 emissions of different versions of the same model sharing the same fuel, engine and green car indicator in *Nybilsguiden*.

turn gasoline vehicles into FFVs, but also to the favorable treatment enjoyed by alternative fuels as compared to regular ones.

Third, I focus on sales-weighted figures and show that FFVs gained market share at the expense of regular, high-emission vehicles. This finding is rationalized by the fact that consumers value characteristics such as size and power (Goldberg 1995, BLP 1995), which FFVs are typically endowed with. Given the similarity between gasoline vehicles and FFVs in both the technological and characteristic space dimensions, consumers naturally tend to prefer a larger FFV rather than an equivalent captive gasoline car (or a smaller regular vehicle), especially if the renewable version is offered with a rebate. Moreover, the fact that owners of FFVs can arbitrage across fuels and thus reduce operating costs as compared to captive gasoline cars is also of importance (see Section 6).

Finally, I describe how the GCR affected average CO2 emissions of alternative cars in comparison to regular ones. Given the asymmetric treatment by the GCR towards regular and alternative fuel segments, emission levels for alternative vehicles tend to increase in comparison to those of regular ones. In particular, I stress the difference between short-run (calendar year 2007) and long-run (calendar year 2008 onwards) effects of the policy on sales-weighted CO2 emissions. In the former case, only consumers were able to react to the policy, whereas in the latter carmakers are also allowed to adjust their product lines by re-engineering their vehicles.

Swift product introduction in the green car segment A number of interesting findings emerge when looking at the supply-side data disaggregated by fuel segment – see Table 2. When looking at the market as a whole, both average and median CO2 emission levels seem to decrease during the 2004-2009 period. For instance, by inspecting the quartiles of the overall distribution of CO2 emissions, there seems to be a reduction of about 20 gCO2/km throughout the sample period.

TABLE 2 ABOUT HERE

While the number of brands and models on the market as a whole increased marginally (less than 10 percent), the changes in the low emission segment (that is, cars emitting less than 120 gCO2/km) were marked: the number of brands (models) operating in this particular fuel segment increased from 13 (46) in 2007 to 17 (69) in 2008 and 22 (89) in 2009.

The above numbers suggest carmakers did react swiftly on both the extensive (entering a fuel segment) and intensive (offering a new product in a fuel segment already entered) margins during the sample period. This swift reaction is in stark contrast with those in Li, Timmins and von Haefen (2009), according to which (focusing on the reactions to increasing gasoline prices) supply side reactions are likely to take several years to materialize, suggesting a sizable difference between short- and long-run effects. It is however in line with findings in Sallee and Slemrod (2011) for the US and Canadian markets as well as evidence provided by the EFTE (2009), which supports the view that advances in the diesel technology resulted in a substantial decrease in CO2 emissions while fixing or increasing the horsepower of a given engine within a *two-year period*.[13] A likely explanation for this swift reaction is that product introduction in the FFV and low-emission segments typically occurred via the introduction of new variants (fuel segments) of models already launched in the Swedish market in their gasoline and/or diesel versions. That is, product introduction is typically performed via variants, e.g. as an FFV version of an existing gasoline version, and not via a new vehicle or platform.

[13]EFTE (2009) documents decreases in CO2 emissions in the range 17-27 percent for a sample of models while either fixing or increasing their engine horsepower.

Among alternative fuel vehicles, new models are primarily FFVs Table 2 shows that, starting from 2 models marketed in 2004 (two versions of the Ford Focus), the number of FFV models market increased to 17 in 2007, 44 in 2008 and 66 in 2009. The number of brands offering FFVs also increased substantially, from 3 in 2007 to 10 in 2008 and 12 in 2009. The effect of the GCR on the number of brands and models offering CNG- and electric-based vehicles was less dramatic, partly due to the limited CNG retail network (concentrated in the southern part of the country), but likely also, as anecdotal evidence suggests, to the fact that electric cars are still seen as poor value for money by Swedish consumers.

FFVs gained market share at the expense of regular, high-emission, vehicles The pattern of sales-weighted market shares is reported in Figure 1, which shows how high-emission regular vehicles lost market share to low-emission regular ones and especially FFVs following the GCR. In fact, while the market share of high-emission regular vehicles dropped from 92.1 percent in December 2006 to 84.6 and 72.4 percent in December 2007 and 2008, respectively, FFVs increased their market share from 6.4 percent in December 2006 to 9.9 and 19.8 percent in December 2007 and 2008, respectively. Low-emission regular vehicles increased their market share in a less pronounced way, from 1 percent in December 2006 to 4.8 percent in December 2007 and and 6.2 percent in December 2008, while CNG and electric hybrid vehicles consistently commanded less than 1 percent of the market during the sample period.

FIGURE 1 ABOUT HERE

Other than the number of models introduced, the rise of FFVs can be attributed to the similarity between the FFV and the standard gasoline technologies (namely the Otto four stroke engine) as well as the well-established ethanol retail network. As a result, in the eyes of the average consumer, conditional on purchasing a model available on both FFV and gasoline versions, the choice was between a gasoline version (as before) and its FFV version, which was slightly more expensive but sold at a rebate and which allowed its owner to arbitrage across fuels, thus enabling potentially lower operating costs.[14]

Asymmetric treatment leads to asymmetric reactions in CO2 emission levels Sales-weighted CO2 emissions of regular and alternative fuel cars are reported in Figure 2. Prior to the GCR, emission levels of both categories share a downward trend. Although emissions of regular vehicles are higher than those of alternative ones, this relation begins to change starting from 2008: alternative vehicles now experience an upward trend in emission levels. To appreciate why this may have happened, note that with the inception of the policy in April 2007, high-emission regular vehicles (those emitting more than 120 gCO2/km) became relatively more expensive than both (i) low-emission regular cars; and (ii) alternative cars. The caveat is that, for 2007, carmakers did not adjust their product lines i.e. the choice set facing consumers was kept fixed. As a result, conditional on purchasing a new car, consumers were more likely to switch to either alternative cars (typically larger, high-emission, cars) or downsizing to low-emission regular cars. Thus, this resulted in higher sales-weighted emissions for FFVs and lower ones for regular cars as a whole, as reported in Panel A.

FIGURE 2 ABOUT HERE

[14] Although diesel cars have also gained market share in the Swedish market, the evidence of "dieselization" is not as pronounced as in other European countries (see Miravete and Moral 2009).

These findings suggest that both carmakers and consumers took advantage of the loophole provided by the GCR, thus working against its very objectives. This effect can be seen in the data by inspecting CO2 emissions disaggregated at the monthly frequency in Panel B of Figure 2: while average CO2 emission levels change slightly upon the inception of the GCR in April 2007, their change is dramatic once new product lines are rolled out in January 2008 and January 2009, suggesting a compounded effect of supply and demand. That is, faced with a wider choice of vehicles which were similar to the existing ones, sold at a rebate and allowing lower operating costs, a non-trivial share of consumers voted with their feet against high-emission regular vehicles flocking towards their alternative – mostly FFV – counterparts.

5 Econometric Analysis

5.1 Empirical Strategy

Setup I estimate the causal effect of the GCR on CO2 emission levels of newly-purchased vehicles able to operate using alternative (renewable) fuels *vis-à-vis* regular ones. To do so, I estimate specifications of the form

$$y_{it} = \delta 1\{t \in \Gamma\} 1\{i \in \aleph\} + \tau 1\{t \in \Gamma\} + \gamma 1\{i \in \aleph\} + x_{it}^{'}\beta + u_{it} \tag{1}$$

where $t = 1, ..., T$ are time periods, $i = 1, ..., N$ are products, y_{it} is the variable of interest (CO2 emissions, measured in gCO2/km), Γ denotes the period during which the GCR was in place, $\aleph$ denotes the set of treated subjects, namely vehicles able to operate on alternative fuels, the indicator $1\{A\}$ takes on value one if the event A holds, and x_{it} is a set of controls, including fuel prices and model-based fixed-effects. Given the unexpected character of the policy, I make use of difference-in-differences (DD) techniques focusing on the DD estimator given by δ. I estimate the effects separately for the supply and demand sides of the market.

Supply-side Data On the supply side, I assign uniform weights to all car models marketed in a given year, so i indexes car models available on the market, t is measured in years and the indicator $1\{t \in \Gamma\}$ takes on value one starting from year 2008, the first where carmakers were able to react to the GCR by re-engineering their products. The supply-side analysis thus assesses to which extent carmakers adjusted their product lines following the introduction of the GCR. Since carmakers have more time to re-engineer their vehicles in 2009 as compared to 2008, I also estimate specifications where I decompose post-rebate responses into these two effects.

Registration Data When using registration data (i.e., quantifying sales-weighted effects), i indexes a tuple of brand-model-fuel-emissions for each newly-registered vehicle and t is measured in months. With such a data structure, I am able to account for both how consumers react to the GCR and to changes in the choice set (product lines) following the policy. That is, more than comparing CO2 emission levels of alternative vs. regular cars before and after the policy, I take advantage of the institutional setting to distinguish between *short-run* and *long-run* effects of the program. Specifically, I am able to disentangle these effects since consumers respond to the GCR already in 2007 (between April and December 2007) when they face the choice set defined by the 2007 product line; in contrast, carmakers are unable to react to the policy by re-engineering their vehicles still in 2007, meaning that the choice set facing consumers in the short-run is fixed (see Section 2 for discussion). Since it is only with the introduction of the 2008 product line that carmakers are able to effectively change the choice set facing consumers, I replace the indicator $1\{t \in \Gamma\}$ in the baseline specification above with an indicator $1\{t \in \Gamma_{SR}\}$ which takes on value one between April and December 2007 to measure the short-run effects of the policy and another $1\{t \in \Gamma_{LR}\}$ which takes on value one from January 2008 to June 2009 to gauge the long-run effects of the GCR. As carmakers may well respond differently in model-years 2008 (for which they had only months to prepare) and 2009, in some specifications I further decompose the long-run effects into elements $1\{t \in \Gamma_{LR1}\}$ and $1\{t \in \Gamma_{LR2}\}$ taking on value one during calendar year 2008 and the period January-June 2009, respectively.

Inference and Fixed-effects Reported standard errors are clustered at the carmaker (brand) level, for if carmakers aim at adjusting their products according to emissions (equivalently, fuel economy), or if they vary in terms of characteristics that may affect those variables, their errors will be correlated.[15] Clustering at the carmaker level will account for the variation in the correlation across models and within carmaker (see Knittel 2011 for a similar strategy).

FIGURE 3 ABOUT HERE

Throughout the analysis I use two sets of fixed effects, namely model and model-fuel ones, see Figure 3. With model-fuel fixed-effects (see Panel B in Figure 3), the DD estimator is unable to account for the introduction of a new fuel version of an existing product, i.e. a new *variant*, following the GCR. That is, I can only compare the DD effect of the GCR on the versions (tuples brand-model-fuel) of the model available both before and after the introduction of the program, say, the gasoline and diesel versions of the Ford Focus (denoted as G and D in Figure 3). In contrast, with model fixed-effects, the DD estimator does account for the introduction of new variants and, say, the FFV version of the Ford Focus is subsumed among post-GCR observations of the Ford Focus. It then follows that a larger DD estimate when controlling for model rather than model-fuel fixed-effects suggests that product introduction played a role in increasing the effects of the policy on CO2 emissions. While the text highlights only the main results, the Appendix discusses a number of robustness checks.

5.2 Supply-side Effects

To estimate the supply-side effects of the GCR on CO2 emissions, I focus on DD coefficients interacting the indicator of alternative fuel and the one for the period in which the GCR is in place.

Specifications 1-4 and 5-8 in Table 3 report results using model and model-fuel fixed-effects, respectively. All specifications use data from years 2005-2009 and, except for Specifications 1 and 5, control for fuel prices.[16] Additionally, Specifications 8-9 assess the robustness of the results by considering the subsample of vehicles operating on gasoline or ethanol.

TABLE 3 ABOUT HERE

The robust finding across specifications is that, following the GCR, CO2 emissions of alternative vehicles increased as compared to those of regular ones. Using model fixed-effects and without controlling for fuel prices, Specification 1 returns a DD estimate of 15.05 gCO2/km. Operating costs

[15] Intuitively, this amounts to assuming some within-brand correlation among models, consistent with an industry where brands seem to have developed expertise in what concerns market segments, e.g. French carmakers tend to specialize in smaller vehicles whereas German ones tend to target the higher end of the market. In fact, conglomerates such as Volkswagen, Toyota and Honda, have developed portfolios of brands to cater different market segments.

[16] Although one may be tempted to use *dollar per mile*-like quantities, recall that emissions and fuel economy are simultaneously determined.

are however key when considering the purchase of a vehicle, so one should expect carmakers to react to them accordingly: in fact, once fuel prices of diesel, ethanol and gasoline are controlled for, the DD estimate reduces to 6.58 – see Specification 2.

Once post-GCR effects are decomposed into separate ones for years 2008 and 2009, the robust finding is that they strengthen over time, see Specifications 3-4. (to be compared to Specifications 1 and 2, respectively). Besides returning lower estimates, controlling for fuel prices results in an insignificant effect for year 2008, see Specification 4 – this lends support to the view that it took carmakers some time to react to the program.

From the discussion above, model fixed-effects account for the introduction of new products. A related question of interest is to which extent carmakers re-engineered products existing prior to the GCR. In a nutshell, these products were also tinkered with and our estimates based on model-fuel fixed-effects are typically similar to the above. Except for the case not controlling for fuel prices (Specification 5, to be compared to Specification 1), the DD estimates are very similar in magnitudes and significance: while Specification 6 returns a 6.94 gCO2/km DD estimate (as compared to 6.58 for Specification 2), decomposing the effects into years 2008 and 2009 returns an insignificant estimate of 5.39 and a significant (at the 10 percent level) of 10.38 gCO2/km.

Since most of the action in the alternative fuel segment comes from FFVs, one could argue that the right treatment and control groups to be considered are FFVs and gasoline vehicles, which share the same technology. As FFVs essentially piggy-back on the gasoline technology, the choice of a carmaker to launch a FFV version of a given vehicle ultimately amounts to the decision of spending an extra $100-200 in a sensor to detect the gasoline-ethanol mix in the engine; this information is then passed on to the vehicle's electronic central unit which adjusts engine settings according to the fuel mix. Thus, Specifications 8-9 in Table 3 focus on gasoline and FFV vehicles only.

Controlling for fuel prices and model fixed-effects, Specification 8 (to be compared to Specification 4) returns no significant DD estimates for either 2008 or 2009. This finding can be rationalized by going back to Table 2: note that diesel vehicles have experienced a downward trend in the period 2004-2009, with median levels starting at 185.5 gCO2/km and ending at 160 gCO2/km. The results for Specification 9 go back to the standard pattern of strengthening effects over time: a significant effect of 6.02 gCO2/km for 2008 is followed by a 12.02 gCO2/km one for 2009, both of which are statistically significant. What is more, by comparing Specifications 9 and 8, one infers that carmakers have tinkered with emission levels of existing products, i.e. increased emissions of FFVs available on the market pre-GCR as compared to their gasoline counterparts.

All in all, the above findings support the view that lax constraints placed on alternative fuels were duly exploited by carmakers. What is more, when decomposing post-GCR effects into separate ones for model-years 2008 and 2009, point estimates consistently point to a strengthening effect over time.

5.3 Sales-weighted Effects

Sales-weighted DD regressions allow disentangling different effects of the GCR taking advantage of the institutional setting. That is, given the interpretation of equilibrium outcomes one can give to registration data, with knowledge of the market developments one is able infer something about supply- and demand-induced changes in market outcomes. Doing so, I focus on two effects. First, I examine how consumers react to both pre- and post-policy product lines (choice sets), denoted Γ_{SR} and Γ_{LR}. Second, I disentangle "long-run" reactions of carmakers into effects for product lines 2008 and 2009 (denoted by Γ_{LR1} and Γ_{LR2}, respectively) to the policy.

Specifications 1-3 in Panel A of Table 4 report a short-run effect (captured by the interaction of the alternative fuel indicator and the one for months April until December in 2007) and a long-run effect (captured by the interaction of the alternative fuel indicator and one for months between January 2008 and June 2009). Specification 1, which considers the full sample 2005-2009, does not control for fuel prices and uses model fixed-effects, has an insignificant estimate for year 2007 and a significant one of 10.47 gCO2/km for 2008 onwards. These estimates contrast with those of Specification 4, which uses model-fuel fixed-effects and finds insignificant effects throughout. So far, the findings suggest that product introduction starting from 2008 played a role in increasing CO2 emissions of alternative as compared to regular vehicles.

TABLE 4 ABOUT HERE

As consumers are likely to consider operating costs when purchasing an automobile, carmakers may re-engineer their products in response to increases in fuel prices so they become more fuel-efficient. Thus, Specifications 2-3 and 5-6 in Panel A of Table 4 do control for fuel prices. Given the limited availability of CNG data, Specifications 2 and 5 consider a longer sample (2005-2009) restricted to vehicles running on gasoline, diesel and ethanol, while Specifications 3 and 6 consider all fuels for the shorter period 2007-2009. Both qualitative and quantitative results are similar across specifications, in that controlling for fuel prices results in negative and significant estimates for year 2007 and insignificant ones for year 2008 onwards – these emission reductions in the short-run are in the ranges 7.5-8.5 and 6.4-7.3 gCO2/km using model and model-fuel fixed effects, respectively, suggesting that the GCR triggered purchases of (relatively) low-emission alternative vehicles in the short-run but an insignificant one for 2008 onwards, that is, once new product lines hit the market.

Given the few months carmakers had to react to the policy via their 2008 product lines and the longer period to do so via their 2009 one, it is natural to consider them separately, and this is precisely what Specifications 1-6 in Panel B do (each specification in Panel B is directly comparable its Panel A counterpart). Overall, results change in an important way when decomposing 2008 and 2009 (January to June 2009 only, due to the end of the GCR) responses: once fuel prices are accounted for, the short-run effects of the GCR are negative and significant (marginally so for Specification 5), with decreases in the range 7.2-9.1 and 6.2-7.0 with model and model-fuel fixed-effects, respectively (see Specifications 2-3 and 5-6 in Panel B). What is more, these estimates are very similar across Panels A and B. Again, the robust finding is that the short-run effect following the GCR is in the direction of lower CO2 emissions of alternative as compared to regular fuel vehicles.

The long-run responses are very much in line with what one would expect. That is, given the extended period carmakers had to think through the policy and re-engineer their vehicles, DD point estimates are larger for 2009 than 2008 – in particular, this holds for both products existing pre-GCR (see Specifications 5-6) but especially once product introduction is accounted for, as in Specifications 2-3. This is evidence that both consumers and carmakers worked against the objectives of the policy once product lines were given enough time to adjust.

Discussion The above results can be summarized as follows. On the supply-side, the asymmetric treatment enjoyed by renewable and regular fuels leads to asymmetric reactions by carmakers, even after controlling for fuel prices. As a result, DD estimates capturing the causal effect of the GCR on CO2 emissions of alternative *vis-à-vis* regular vehicles are positive and significant.

Using registration data, the first robust finding has to do with a distinction between short- and long-run effects. In the short-run, when facing product lines introduced prior to the GCR, consumers respond by purchasing alternative vehicles emitting *less* CO2 than their regular counterparts. However, carmakers react to the new regulation and adjust their product lines accordingly: while the reaction is statistically insignificant for year 2008, whose product line is introduced a handful of months after the GCR, it is positive and significant for year 2009, suggesting that the combined actions of consumers and carmakers were detrimental to the aims of the program once choice sets were adjusted. That is, faced with a restricted choice set with relatively few high-emission alternative vehicles – typically FFVs – consumers were more likely to purchase low-emission alternative vehicles. However, once carmakers adjusted their product lines to the new policy, thus providing consumers with an enlarged choice set, consumers were more likely to purchase these newly-introduced vehicles –typically an FFV– in detriment of a high-emission regular-fueled vehicle.

The above results beg the question of where precisely the variation in the data identifying the DD estimates is coming from. To fix ideas, consider a car model for which both gasoline and FFV versions are available prior to the GCR. On the supply side, given elastic demands and rebates to the order of 7 percent for FFVs and low-emission gasoline cars, carmakers would opt for a larger version for its FFV version as compared to the gasoline one – in the limit, an FFV version emitting more than the threshold emissions level as compared to a gasoline version below the same threshold. (Recall from Table 2 that no FFV emitted less than 120 gCO2/km during the sample period in the data.)

On the demand-side, note that consumers have a preference for size (comfort) and engine power, even if environmental concerns arguably have been playing an increasing role in recent times. Moreover, a significant share of consumers understands the option value provided by an FFV (see Section 6 for further evidence). Finally, the very cars offering this option value were available at a rebate. As a result, what one sees is a skew towards FFVs within models offering both the gasoline and FFV options, thus generating a response in the associated sales-weighted regressions. (See Huse and Lucinda (2012) for a structural model of the Swedish car market and further evidence of how FFVs benefited from the asymmetric treatment dispensed to regular and alternative fuels.)

6 Fuel Choice of FFV Motorists

The majority of vehicles running on alternative fuels in the Swedish market is made of FFVs, which can operate on both gasoline and ethanol. Ethanol was tax-exempt at its inception, which resulted in far lower prices when compared to those of other fuels, see Figure 4. Although widely available throughout Sweden only from January 2005, ethanol was already available of over half of the fueling stations by 2009. Gasoline, diesel and CNG prices in turn are higher and more volatile than ethanol's. What's more, the prices of these three fuels endured an upward trend from early 2007 to about mid-2008, dropping only as a result of the global economic crisis.

FIGURE 4 ABOUT HERE

The pattern of ethanol sales has grown hand-in-hand with that of FFVs for most of the period 2004-2009, see Panel A in Figure 5.[17] In contrast with previous findings, e.g. Borenstein (1993), which document that fuel switching occurs over the course of years among owners of captive cars, owners of FFVs seem to have switched almost instantaneously to price incentives following the 2008 drop in oil prices. This shock quickly affected domestic prices and resulted in ethanol becoming more expensive than gasoline in energy-adjusted terms already in October 2008, see Panel B in Figure 5. While the full line in Panel B again depicts ethanol sales, the dashed one depicts the energy-adjusted price premium of gasoline over ethanol - that is, given the lower energy content of ethanol as compared to gasoline, prices are reported per energy unit. As soon as the gasoline price

[17] Consistent with the previous analysis and the data available, in this section I focus on light-duty vehicles able to run on combinations of ethanol and gasoline.

premium becomes negative, in October 2008, ethanol sales plummet, suggesting that fuel arbitrage is substantial among FFV owners.[18] This swift reaction implies that Swedish consumers seem to account for the option value provided by FFVs and promptly exercise it. This can be attributed to a relatively well-developed retail network in Sweden (as opposed to what happens in the US, see also Corts 2010) where about 60 percent of fuel stations supply at least one renewable fuel (second only to Brazil worldwide), typically ethanol.

FIGURE 5 ABOUT HERE

6.1 Model

To quantify the extent to which consumers arbitrage across fuels, I propose a stylized model where arbitrageurs and fuel-lovers coexist. The model aims at rationalizing the empirical evidence and allows quantifying the extent of fuel-switching using only market-level data (see Salvo and Huse 2011 for a model focusing on FFV and captive ethanol owners). The main assumption has to do with the coexistence of three consumer types, namely ethanol-lovers, gasoline-lovers and fuel arbitrageurs. This assumes away the fact that distinct consumers have different willingness-to-pay for fuel and can moreover err in their fuel arbitrage calculations. It is however a pragmatic compromise to quantify fuel switching using the aggregate data available. (Salvo and Huse 2012 provide evidence supporting departures from perfect substitution, i.e. that a non-trivial share of motorists does not arbitrage across fuels and should ideally be taken into account in such a model, whereas Anderson 2012 documents willingness-to-pay for ethanol.)

Engine j's (average) fuel economy is given by kpl_j (kilometers per liter on fuel j) and in what follows I assume away (i) variation in kilometers driven *per capita* and kpl across consumers; (ii) variation in distance driven and fuel economy over time and across regions; (iii) any dynamic considerations.[19] This consists of a very stylized setting ignoring differences in characteristics of the car model owned by a consumer, variations in driving patterns, time variation in the fuel, engine technology and fuel purchases due to stockpiling and price expectations, but good enough to capture fuel switching, the salient feature in the data as per Figure 5B. Consumer i solves

$$\max_{q} U_i(q_{trans}, q_{out})$$

$$s.t.\ p_{trans}q_{trans} + q_{out} \leq y$$

where y is income, q_{trans} is the quantity of personal transportation (in kilometers) consumed by consumer i and q_{out} is the outside good.

Under standard assumptions on the utility function,

$$\frac{U_{i1}(q_{trans}, q_{out})}{U_{i2}(q_{trans}, q_{out})} = \frac{y - q_{out}}{q_{trans}}$$

Passenger car engines are endowed with the FFV technology and consumers populating the economy are of one among three types depending on whether the FFV owner is an arbitrageur, purchases only ethanol or only gasoline – their types is denoted by the parameter $\theta = (\theta_a, \theta_e, \theta_g)$, where the subscripts denote arbitrageurs, ethanol- and gasoline-lovers, respectively.

[18] For reference, median ethanol, gasoline and energy-adjusted ethanol prices are 8.6, 12.2 and 11.6 SEK/liter, respectively, making a drop in the price premium from roughly +2 to -2 SEK/liter substantial.

[19] One kpl amounts to approximately 2.35 mpg, since 1 mile equals 1.609 km and 1 gallon equals 3.78 liters.

Each car is endowed with a single flexible-fuel engine and owned by a different consumer indexed by i and the FFV fleet at period t is of size $N_t = \sum_{j=a,e,g} N_{jt}$. That is, N_t consumers own FFVs at period t and they occur in shares $\sigma = (\sigma_a, \sigma_e, \sigma_g)$, $\sum_{j=a,e,g} \sigma_j = 1$,so one can write $N_t = \sum_{j=a,e,g} \sigma_j N_t$. Dropping time subscripts to save on notation, the demand for ethanol by consumer of type θ_e (ethanol-lover) is given by

$$q_e^{\theta_e}(p_e, y, kpl_e) = q_e(p_e, y, kpl_e | i \in \theta_e) = \frac{q_{trans}(p_e/kpl_e, y | i \in \theta_e)}{kpl_e}$$

and that of consumer type θ_a (fuel arbitrageur) is

$$\begin{aligned} q_e^{\theta_a}(p_e, y, kpl_e) &= q_e(p_e, y, kpl_e | i \in \theta_a) = 0 \text{ if } p_e/p_g > k := kpl_e/kpl_g \\ &= \left[0, \frac{q_{trans}(p_g/kpl_g, y | i \in \theta_a)}{kpl_e}\right] \text{ if } p_e/p_g = k \\ &= \frac{q_{trans}(p_e/kpl_e, y | i \in \theta_a)}{kpl_e} \text{ if } p_e/p_g < k \end{aligned}$$

where p_e and p_g are the retail prices per liter of ethanol and gasoline, respectively and the price-per-kilometer of personal transportation for consumer θ_a is given by $p_{trans} = \min\{p_g/kpl_g, p_e/kpl_e\}$.

FIGURE 6 ABOUT HERE

The aggregate demand function for ethanol, which is depicted in Figure 6, is given by

$$\begin{aligned} Q_e(p_e, p_g, y, kpl_e, kpl_g, N) &= N\sigma_e q_e^{\theta_e}(p_e, y, kpl_e) \text{ if } p_e/p_g > k \\ &= \left[N\sigma_e q_e^{\theta_e}(p_e, y, kpl_e), \sum_{\tau=a,e} N\sigma_\tau q_e^{\theta_\tau}(p_e, y, kpl_e)\right] \text{ if } p_e/p_g = k \\ &= \sum_{\tau=a,e} N\sigma_\tau q_e^{\theta_\tau}(p_e, y, kpl_e) := Q_e^{\theta_e} + Q_e^{\theta_a} \text{ if } p_e/p_g < k \end{aligned}$$

consisting of (i) an interval whenever ethanol and gasoline energy-adjusted prices are equivalent; (ii) the demand of ethanol-lovers only whenever ethanol is dearer than gasoline; and (iii) the demand of both ethanol lovers and arbitrageurs when ethanol is cheaper than gasoline (always in energy-adjusted terms).

6.2 Implementation

In an ideal setting one would want to estimate the above fuel choice model using data on fleet size and estimating fuel demand conditional on whether the price regime is $p_e/p_g \lesseqgtr k$. To do so, one would then estimate a switching regression model accounting for price endogeneity. Here, however, I assume a more pragmatic approach since my interest is merely to gauge the extent of fuel switching among FFV owners.

I assume that each motorist drives χ kilometers per month and kilometerage is price-inelastic, i.e. the rebound effect is assumed away.[20] This allows obtaining vehicle-kilometers traveled at month t,

[20] Recent research by Small and van Dender (2007) and Hughes, Knittel and Sperling (2008) finds not only that the price elasticity of the demand for gasoline is very inelastic, but that it has also become significant more so in recent years. Faced with the possibility to switch between fuels, one would expect the price elasticity of fuel (gasoline and

$vkt_t^{\theta_i}$ for consumer type $i = e, g, a$. (Given that fuel lovers are typically found to be less than half of FFV owners in the results below, assuming away the rebound effect can be seen as less of a stringent assumption.)

Fuel demand of consumer θ_g is given by $q_g|\theta_g = vkt_t^{\theta g}/kpl_g$, the one of consumer θ_e is given by $q_e|\theta_e = vkt_t^{\theta e}/kpl_e$ and that of consumer θ_a is $q_f|\theta_a = 1\{p_{et}/p_{gt} > k\}vkt_t^{\theta_a}/kpl_g + 1\{p_{et}/p_{gt} < k\}vkt_t^{\theta_a}/kpl_e$,where f equals e or g if p_{et}/p_{gt} is less than or larger than k, i.e. arbitrageurs will demand ethanol or gasoline depending on whether $p_e/p_g \lesseqgtr k$.

To obtain market demands for bot gasoline and ethanol, let Q_{et} and Q_{gt} be the volume sales of, respectively, ethanol and gasoline at month t and $\widetilde{q}_G$ the volume sales of gasoline to owners of captive gasoline cars. One can thus write

$$\begin{aligned} Q_{et} &= \frac{\sigma_e \chi N_t}{kpl_e} \\ Q_{gt} &= \frac{\sigma_g \chi N_t}{kpl_g} + \frac{\sigma_a \chi N_t}{kpl_g} + \widetilde{q}_G \end{aligned}$$

if $p_{et}/p_{gt} > k$ and

$$\begin{aligned} Q_{et} &= \frac{\sigma_e \chi N_t}{kpl_e} + \frac{\sigma_a \chi N_t}{kpl_e} \\ Q_{gt} &= \frac{\sigma_g \chi N_t}{kpl_g} + \widetilde{q}_G \end{aligned}$$

if $p_{et}/p_{gt} < k$. That is, ethanol-lovers purchase ethanol regardless of its relative prices whereas gasoline-lovers and owners of captive gasoline cars always purchase gasoline. However, fuel arbitrageurs switch between gasoline and ethanol according to price incentives.

Now assume the existence of only two sets of price vectors, $E - cheap$ and $E - dear$, which are observed at months t' and t'', respectively. By looking at ethanol sales only it is possible to identify σ_e and σ_a by solving the above system and obtaining

$$\sigma := (\sigma_a, \sigma_e, \sigma_g) = \left(\frac{kpl_e}{\chi N_{t''}} \left(Q_{et'}^{E-cheap} - Q_{et''}^{E-dear} \right), \frac{kpl_e}{\chi N_{t'}} Q_{et'}^{E-cheap}, 1 - \sigma_e - \sigma_a \right)$$

As a result, the share of arbitrageurs is increasing in fuel economy (kpl_e) and demand sensitivity $\left(Q_{et'}^{E-cheap} - Q_{et''}^{E-dear} \right)$ while decreasing in kilometerage (χ).

One could also take a stand on the components of $\widetilde{q}_G$ and proceed in a similar way, but given the substantial heterogeneity in the captive gasoline car fleet, i.e. the different kilometerage and fuel economy patterns of old and new vehicles, the assumptions made for the more homogeneous FFV fleet would require a further reality stretch which would not necessarily add value to the exercise.

To quantify the vector of consumer shares σ, I need to make assumptions on kilometerage per month (χ), kilometers driven per liter of ethanol (kpl_e) and obtain estimates of the fleet in both high and low regimes of ethanol prices ($N_{t'}$ and $N_{t''}$, respectively). By plugging in the volume sales of ethanol in the two price regimes I then obtain a candidate σ vector.

ethanol) for FFV owners to be even more inelastic than standard estimates. In contrast, using consumer-level data, Salvo and Huse (2012) find that while a substantial share of Brazilian consumers (about 60 percent) tends to arbitrage across fuels, gasoline and ethanol are not seen as perfect substitutes by many consumers. This finding is likely to be due to the early hiccups of the ethanol technology in the 1980s – thus in stark contrast with the more advanced one employed in Sweden in the 2000s – suggests that price-based policies aimed at switching towards renewable fuels are of non-trivial implementation.

6.3 Shares of Consumer Types

In what follows, I describe the calibration of the model defining $\sigma = (\sigma_a, \sigma_e, \sigma_g)$.[21] The oil price drop in September-October 2008 caused by the global recession provides an ideal situation to do so. First, because one would want months t' and t'' to be as close as possible, since driving patterns have a pronounced seasonal component and there is bound to be measurement error in fleet size data.

Second, because the oil price drop was sudden, substantial and passed through to domestic gasoline prices, thus providing a credible source of exogenous price variation.

Third, because this variation happened when the FFV fleet size was already non-negligible and ethanol was widely distributed across the country.

The data I use are the FFV monthly fleet data from the Swedish Transportation Authority and ethanol monthly volume sales from the Swedish Petroleum Institute (SPI). I set $Q_{et''}^{E-cheap}$ to be the volume of ethanol sold in September 2008, just before the recession started. As for $Q_{et'}^{E-dear}$, I consider both November 2008 ethanol sales. Given the seasonal pattern in fuel demand, calculations were performed after deseasonalizing ethanol sales using month fixed-effects. (For instance, recall that although the difference is minimal, gasoline is less likely to freeze than ethanol, since the latter contains some water. As a result, one can think of motorists being less likely to purchase ethanol as temperatures decrease.)

TABLE 5 ABOUT HERE

The results are reported in Table 5 (see the Appendix for robustness checks). I take a stand on the following variables. First, I assume FFVs drive $\chi = 1500$,1750 or 2000 km/month, depending on the scenario (corresponding to 11250-14900 miles per year). According to the Swedish Transportation Authority, the average Swedish car running on gasoline drives about 15,000 km/year, with new cars driving substantially more. Second, I set $kpl_e = 8$, using $kpl_e = 6, 7, 10$ for sensitivity analysis (thus considering fuel economy in the range 19.1-31.8 mpg of gasoline).[22]

Panel A in Table 5 reports the key parameters in the exercise discussed above whereas Panel B report the shares of consumer types corresponding to each of the six scenarios considered. With a median value of 15.4 percent, the share of ethanol-lovers is not too sensitive to changes in the parameter values: it varies in the range 10.8-18 percent, where the lowest value is obtained for Scenario 4, which has the lowest fuel economy and highest kilometerage among all scenarios considered. With a median value of 19 percent, the share of gasoline-lovers is more sensitive to parameter values, varying in the range 5.5-43.3 percent, and increasing at the expense of ethanol-lovers. Finally, the median share of fuel arbitrageurs is 66.3 percent, with values in the range 45.9-76.5 percent. Despite the sensitivity to parameter values, the robust finding of the exercise is that most FFV owners are fuel arbitrageurs, following closely the developments in fuel prices and purchasing the cheapest one, whereas ethanol-lovers, or environmentally-friendly drivers, represent only a small share of FFV owners in Sweden.

6.4 Implications for Air Pollution

Lifecycle vs. Tailpipe CO2 Emissions The carbon footprint of an automobile can be reported in two ways. The first, which is based on tailpipe (exhaust) emissions follows the EU methodology and

[21] Recently, Holland, Hughes and Knittel (2009) have adopted a similar strategy, numerically simulating a LCFS (low carbon fuel standard) on gasoline and ethanol using parameters based on the US market.

[22] Although these values are arguably on the lower-side of kpl, one has to account for the fact that, given the lower energy content of ethanol as compared to gasoline, kpl_e is roughly 30 percent lower than kpl_g and actual fuel economy is in practice lower than lab measurements provided by carmakers under ideal testing conditions.

is consistent with Sweden's official report to the EU (see EU Directive 80/1268/EEC for details on the testing routine). While this method is appropriate to gauge the effect of improved fuel efficiency in vehicles, it does not take into account the climate benefits of a large proportion of new cars that can also run on ethanol. That is, an alternative way to account for the carbon footprint of a vehicle is to use emissions adjusted for the life-cycle climate benefits of ethanol. The second method of assessing the carbon footprint of a vehicle thus provides a life-cycle perspective of both fossil and renewable fuels, with gasoline and diesel emissions being some 12 percent and 13 percent higher than exhaust pipe emissions, respectively. In other words, a given engine emits less if running on ethanol or gas than gasoline, so one needs to apply a discount factor on gasoline emissions if a FFV is running on ethanol. According to Swedish Consumer Agency (2011), CO2 emissions from the use of ethanol are approximately 55 percent lower than those of gasoline, supporting the view that whenever one switches from ethanol to gasoline, the impact in terms of CO2 emissions can be non-trivial and ultimately jeopardizes the aims of the Swedish policy.

The Effect of Fuel Switching on Air Pollution Besides emitting GHG, of which CO2 and Methane are the best known, combustion engines also emit local air pollutants. By switching from ethanol to gasoline, motorists are (unknowingly) increasing the emissions of some pollutants while decreasing the emission of others. The related literature still seems to be in its early days, with Jacobson (2007) reporting that ethanol is superior to gasoline in terms of CO2 emissions but not local pollutants and Yanowitz and McCormick (2009) providing a compilation of comparative exhaust emissions of gasoline and ethanol using FFVs.

Panel C in Table 5 reports how the switch from ethanol to gasoline by FFV owners impacts the concentration of a number of air pollutants. To construct Panel C, I combine results in Panel B with life-cycle CO2 emissions reported by the Swedish Consumer Agency (2011) and those in Yanowitz and McCormick (2009), which are used by the US EPA (only air pollutants for which the difference in emissions between gasoline and ethanol is statistically significant are included).

Among the eight pollutants considered in Panel C, switching from ethanol to gasoline decreases the concentration of four – namely 1,3-Butadiene, Carbon Monoxide (CO), Formaldehyde and Methane – while increasing the concentration of the remaining four – CO2, Nonmethane Hydrocarbon, NOx and Particulate Matter (PM). Interestingly, the changes are somewhat similar across scenarios for most of the pollutants. Consider for instance the changes in the concentrations of PM, NOx and CO, which are classified as criteria pollutants by the US EPA that is, pollutants for which national standards are set: while the reduction in CO is in the range 16.8-18 percent, the increases in NOx and PM are in the range 20-21.7 and 42.1-50.1 percent, respectively. The pollutant for which the estimates vary most across scenarios is CO2, the main GHG, with increases in the range 79.9-114.5 percent. Given the focus of policymakers on CO2 emissions, fuel switching by FFV owners from ethanol to gasoline paints an overall gloomy picture when it comes to air pollution.[23]

Discussion Stepping back, the results reported in Table 5 suggest a low share of ethanol-lovers,

[23] The above analysis is essentially short-term. Another question worth addressing is the one on the effect of fuel choice on air pollution over the lifetime of an automobile. Performing this long-run exercise would rely on careful modeling of fuel prices and require assumptions on the stability of shares of consumer types over time. While a reduced-form model of fuel prices (or their corresponding first-differences or return series) has a reasonable degree of explanatory power (the R-squared of univariate models is in the range 40-60 percent), the link between car and fuel markets tends to strengthen as the market share of FFVs increases (see Salvo and Huse 2011, who document such a finding for the Brazilian market, where FFVs command over 35 percent of the car fleet). A further complicating factor in the case of sugarcane ethanol, the leading variety used in Sweden, is the relation between the sugar and ethanol markets, see Salvo and Huse 2011 for a joint treatment). As a result, such a long-run analysis – ideally based on a structural model as in, e.g. Bento et al (2009) – is left for future research.

likely to base fuel choice on environmental concerns. A more substantial share of consumers corresponds to gasoline-lovers: these are consumers who potentially received the rebate upon the purchase of a FFV and *never* use the renewable fuel. Finally, most FFV owners are actively using the option value of their FFV and arbitraging across fuels after pocketing the value of the rebate. Although pollution levels may increase or decrease following the switch according to the pollutant considered, the effect on CO2 emissions is clear and points to a substantial increase in its levels.

Concluding Remarks

This paper examines the effects of the Swedish Green Car Rebate, an environmental policy with a broad impact on the automobile market and skewed towards alternative fuels. Specifically, it disentangles the reactions of consumers and carmakers to the program by taking advantage of the institutional setting to compare emission levels of vehicles able to operate using alternative fuels *vis-à-vis* those operating on regular ones.

On the supply-side, carmakers took advantage of the lax regulation enjoyed by alternative fuels and reacted to the policy by offering high-emission alternative vehicles, mostly FFVs.

Looking at registration data, I find evidence of two effects concerning relative emission levels. First, a short-run negative one in the months after the GCR's inception – that is, April-December 2007 – whereby consumers, which were constrained to purchase products that had been on the market prior to the program, tended to purchase alternative vehicles emitting less CO2 than their regular counterparts. Second, a long-run positive effect where – following the reaction of carmakers to the policy – consumers facing an enlarged choice set, i.e. with a larger share of high-emission alternative cars, tended to purchase precisely these models.

The paper also proposes a structural model of fuel choice for owners of FFVs, the leading alternative technology in the Swedish market and a key technology in the dissemination of renewable fuels worldwide. A major share of FFV owners promptly switched from ethanol to gasoline following the 2008 drop in oil prices, which resulted in the plummeting of ethanol sales in the country – when calibrating the model to market level data, I find that the majority of FFV owners are fuel arbitrageurs. As a result, despite investments in fueling infrastructure to increase the retail presence of renewables (notably ethanol) and the 10,000 SEK rebate paid upon the purchase of a green car, fuel switching induced an increase of at least 80 percent in life-cycle CO2 emissions from the part of FFV owners switching fuels. In short, policymakers have been held hostages of the FFV technology thanks to the way regulation was designed.

The above findings – which deliver insights for most alternatives to fossil fuels, not only ethanol – provide a number of policy implications. First, pushing for lower emission thresholds seems to trigger the introduction of low-emission regular vehicles even in the short-run. In fact, the number of low-emission gasoline and diesel vehicles available on the market increased by, respectively, 80 and roughly 50 percent within the first year of the program.

Second, since flexible-fuel technologies essentially piggy-back on existing ones (in this case the Otto cycle engine), they can be used to disseminate the adoption of renewable fuels in general. Moreover, since flexible-fuel technologies do not lock-in consumers to a specific fuel, policymakers can impose common thresholds to regular and alternative fuel vehicles: consumers should – and the evidence provided above suggests that they actively do – switch to FFVs also due to the option value provided by this very technology, i.e. arbitraging across fuels.

Third, although the embracing of renewable fuels will be larger, the more developed their retail network, such network is only a necessary condition for the dissemination of renewables, since arbitrageurs make up a non-trivial share of FFV owners.

Fourth, as a significant number of FFVs hits the road, policymakers can induce motorists to switch to renewable fuels by subsidizing renewables and/or taxing fossil fuels more heavily.

All in all, the findings of the paper show the challenge of policy design in the transportation sector. A good policy has to take different margins into account (intensive, extensive, fuel switching). A gasoline tax (or an increase thereof) should be able to provide right incentives in all these margins, but is unlikely to be politically sustainable in a number of countries, notably the US.

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A Robustness Checks

A.1 Econometric Analysis

For both supply-side and sales-weighted analysis I have experimented replacing model-based fixed-effects with brand and time; time, brand and segment; time-brand; and time-brand-segment fixed-effects. The robust finding is that model-based fixed-effects provide more conservative DD estimates. While the results are reported using for real fuel prices, I have also experimented with nominal prices, obtaining similar results in terms of significance. I have also replaced ethanol prices with the lowest between energy-adjusted ethanol and gasoline prices, which are then interacted with the dummies for FFVs to be used as proxies for the operating costs of an FFV: I obtain estimates with similar magnitudes and statistical significances than the reported ones. I have also re-estimated the DD regressions using a number of subsamples obtaining similar results. Finally, I have estimated all regressions using fuel economy measured in mpg (miles per gallon) as the dependent variable, again obtaining similar results. (The relation between CO2 emissions and gpm – gallons per mile – is linear, with a regression of one on the other rendering an adjusted R-squared of 0.96, whereas the relation between CO2 and mpg is nonlinear with a correlation coefficient of -0.92 in the data.)

Supply-side Analysis While the reported supply-side results use 12-month moving-averages of fuel prices ending in December prior to the launch of a product line, e.g. fuel prices from January to December 2006 for the 2008 product line, the results are robust to changes in the rolling window as well as 12-month moving averages computed until the March, June or September prior to the launch of a product line, e.g. fuel prices from October 2006 to September 2007 for the 2008 product line. The adoption of long moving averages helps wash out seasonal effects likely to appear in time series of fuel prices (and in driving patterns). I have moreover considered variants of Specifications 8-9 in Table 3 which compare FFVs to high-emission gasoline vehicles only (instead of all gasoline vehicles), with results similar to the reported ones.

Sales-weighted Analysis Besides the robustness checks noted above I have also estimated sales-weighted specifications using data at the annual frequency and considered lagged fuel prices, again with similar results.

A.2 Calibration of Fuel Choice Model

To the possible extent, the key parameters in Table 5 were chosen so as to provide a meaningful range of parameter values. An important constraint is the adding-up condition requiring consumer shares to sum to one (see Section 6.2), which binds in some cases. Controlling for seasonality in fuel demand results in more conservative results for the share of fuel arbitrageurs – a previous version of this paper not doing so obtained results which were qualitatively similar but with a higher share of fuel arbitrageurs.

TABLE 1 – Summary Statistics of the Swedish Car Market

	Sweden	France	Germany
Passenger car fleet, millions (2008)	4.3	30.9	41.3
Passenger cars per 100 inhabitants (2008)	46.3	49.5	50.4
% Households with a vehicle (2006)	84.5	82	NA
Average car age, years (2008)	9.5	8.3	8.2
Average engine of new cars, in cc (2007)	1,964	1,680	1,863
Average power of new cars, in kw (2007)	105	80	96
% Passenger cars able to run on fuels other than gasoline and diesel (2008)	3.8	0	0.9
Share of cars ≤ 5 years (2008)	29.0%	33.4%	34.3%
Share of cars 5-10 years (2008)	31.9%	33.0%	33.0%
Share of cars > 10 years (2008)	39.1%	33.6%	33.6%

Note: This table is constructed using data from ANFAC (2010). Engine sizes are reported in cubic centimeters (cc).

TABLE 2 – Supply-side Summary Statistics

Fuel		CO2 Emissions (gCO2/km)					
		2004	**2005**	**2006**	**2007**	**2008**	**2009**
Total	mean	210.8	210.4	205.6	199.5	198.8	191.3
	se(mean)	1.2	1.2	1.2	1.5	1.3	1.2
	median	205	205	197	186	188	181
	IQ range	175-239	172-239	167-234	159-226	161-225	155-216.5
	#brands	37	40	39	44	43	40
	#models	1851	1920	2101	1652	1946	2048
Total ≤ 120g	mean	107.1	106.8	113.6	114.4	113.7	114.1
	se(mean)	3.1	2.9	0.9	1.1	0.9	0.7
	median	114.5	113	116	118	116	118
	IQ range	90-118	90-116	109-119	109-119	109-119	109-119
	#brands	8	8	10	13	17	22
	#models	20	21	40	46	69	89
Gasoline	mean	218.0	218.3	215.4	213.0	212.4	206.0
	se(mean)	1.3	1.4	1.4	1.9	1.7	1.7
	median	213	211	207	197	199	193
	IQ range	184-246	182-249	180-244	170-242	173-238	167-232
	#brands	37	40	39	44	42	39
	#models	1395	1417	1473	1108	1227	1207
Gasoline ≤ 120g	mean	116.3	115.3	112.1	111.1	112.1	113.1
	se(mean)	0.8	0.8	0.9	1.0	0.9	1.0
	median	116	116	111	109	109	112
	IQ range	113-119	113-116	109-116	109-113	109-116	109-119
	#brands	3	2	4	5	7	12
	#models	10	8	14	10	18	36
Diesel	mean	188.8	188.1	183.0	172.2	174.8	168.3
	se(mean)	2.1	2.0	1.8	1.8	1.6	1.3
	median	185.5	187	174	162	169	160
	IQ range	153-215	153-216	154-210	145-189	148-193	146-184
	#brands	28	28	31	32	34	35
	#models	442	491	596	514	667	758
Diesel ≤ 120g	mean	97.1	101.3	114.8	115.8	114.6	115.2
	se(mean)	5.2	4.5	1.4	1.4	1.2	1.0
	median	90	100	118	119	119	119
	IQ range	90-116	90-116	115-119	116-119	114.5-119	112-119
	#brands	5	6	6	11	14	19
	#models	9	12	23	33	48	51
FFV	mean	165.0	185.3	185.4	184.4	194.2	195.1
	se(mean)	0.0	6.8	6.8	4.6	3.7	3.1
	median	165	172	172	175.5	184.5	191.5
	IQ range	165-165	169-179	169-179	169-206	174-213	177-214
	#brands	1	3	3	3	10	12
	#models	2	17	17	18	44	66
FFV ≤ 120g	#models	0	0	0	0	0	0
Gasoline/CNG	mean	199.5	198.0	164.4	150.4	147.6	156.9
	se(mean)	12.4	12.2	7.9	6.3	9.7	4.5
	median	213	215	164	157	155	157
	IQ range	150-231	150-228	148-183	136.5-164	138-160	144-167
	#brands	5	5	5	5	4	3
	#models	11	11	11	8	5	11
Gasoline/Electric	mean	104.0	104.0	147.8	147.8	161.8	171.3
	se(mean)	.	.	23.9	23.9	23.3	21.3
	median	104	104	147.5	147.5	185	188.5
	IQ range	104-104	104-104	106.5-189	106.5-189	109-192	109-219
	#brands	1	1	3	3	3	3
	#models	1	1	4	4	5	6

Note: This table reports sample statistics of the distribution of engine CO2 emissions (measured in gCO2/km) disaggregated by fuel and the number of brands and car models present in each fuel segment. For a given year, a model is a combination of brand-model-fuel. Brands within a conglomerate are treated as separate entities. Sample statistics reported are mean emission levels and their standard errors, median emission levels, the interquartile range, the number of brands and the number of models in a given fuel segment.

TABLE 3 – Supply-side Emission Levels

Dep. Var: gCO2/km	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
Sample period:	2005-2009	2005-2009	2005-2009	2005-2009	2005-2009	2005-2009	2005-2009	2005-2009	2005-2009
Fuels:	All	D,E,G	All	D,E,G	All	D,E,G	D,E,G	E,G	E,G
1{post-rebate} x									
1{i∈ℵ}	**15.05****	**6.58***			**6.66****	**6.94***			
	[2.28]	[1.73]			[2.08]	[1.82]			
1{year=2008} x									
1{i∈ℵ}			**11.88***	3.43			5.39	4.39	**6.02***
			[1.92]	[1.11]			[1.56]	[1.37]	[1.75]
1{year=2009} x									
1{i∈ℵ}			**18.27****	**14.61****			**10.38***	8.22	**12.02****
			[2.52]	[2.34]			[1.88]	[1.14]	[2.08]
1{Alt. Fuel}	√	√	√	√	√	√	√	√	√
1{post-rebate}	√	√			√	√			
1{year=2008}			√	√			√	√	√
1{year=2009}			√	√			√	√	√
Fuel-Fuel price interactions		√		√		√	√	√	√
Model FEs	√	√	√	√				√	
Model-fuel FEs					√	√	√		√
N	9686	7695	9686	7695	9686	7695	7695	5160	5160
R-squared	0.760	0.853	0.762	0.854	0.870	0.876	0.876	.857	.864

Note: This table reports estimates of the causal effect of the GCR on engine CO2 emissions (measured in gCO2/km) of alternative as compared to regular vehicles using supply-side data recorded at the yearly frequency. Columns 1-4 compare the effects before and after the GCR using model fixed-effects. Columns 2-3 also control for fuel prices. Columns 5-7 use model-fuel fixed-effects, with Columns 6-7 also controlling for fuel prices. Columns 8-9 compare FFV and gasoline vehicles controlling for model and model-fuel fixed effects. Standard errors are clustered by brand, with t-statistics reported in brackets. A model-fuel combination is given by, e.g. a Ford Focus-gasoline. Significance levels at 10, 5 and 1 percent are denoted by *,** and ***, respectively.

TABLE 4 – Sales-weighted Emission Levels

Panel A: Post-GCR DD Estimates

Dep. Var: gCO2/km	[1]	[2]	[3]	[4]	[5]	[6]
Sample period:	2005-2009	2005-2009	2007-2009	2005-2009	2005-2009	2007-2009
Fuels:	All	D,E,G	All	All	D,E,G	All
$1\{t\in\Gamma_{SR}\} \times 1\{i\in\aleph\}$	-0.41	**-8.50***	**-7.47****	-5.54	**-6.43***	**-7.28****
	[-0.11]	[-1.81]	[-2.09]	[-1.57]	[-1.70]	[-2.49]
$1\{t\in\Gamma_{LR}\} \times 1\{i\in\aleph\}$	**10.47*****	1.36	1.162	1.89	1.69	-0.46
	[4.09]	[0.45]	[0.55]	[0.74]	[0.62]	[-0.33]
1{Alt. Fuel}	√	√	√	√	√	√
1{year=2007}	√	√	√	√	√	√
1{year≥2008}	√	√	√	√	√	√
Fuel-Fuel price interactions		√	√		√	√
Model Fes	√	√	√			
Model-fuel Fes				√	√	√
N	588285	584866	322670	588285	584866	322670
R-squared	0.701	0.856	0.875	0.900	0.900	0.931

Panel B: Post-GCR DD Estimates Disaggregated for Years 2008 and 2009

Dep. Var: gCO2/km	[1]	[2]	[3]	[4]	[5]	[6]
Sample period:	2005-2009	2005-2009	2007-2009	2005-2009	2005-2009	2007-2009
Fuels:	All	D,E,G	All	All	D,E,G	All
$1\{t\in\Gamma_{SR}\} \times 1\{i\in\aleph\}$	-0.44	**-9.11***	**-7.24****	-5.47	-6.21	**-7.03*****
	[-0.12]	[-2.01]	[-2.22]	[-1.55]	[-1.67]	[-3.21]
$1\{t\in\Gamma_{LR1}\} \times 1\{i\in\aleph\}$	**9.01*****	-0.99	-0.61	1.15	0.29	-2.21
	[3.18]	[-0.28]	[-0.19]	[0.34]	[0.08]	[-0.73]
$1\{t\in\Gamma_{LR2}\} \times 1\{i\in\aleph\}$	**14.16*****	**6.04****	**3.71****	**3.86****	**4.17*****	**2.10****
	[4.47]	[2.50]	[2.40]	[2.59]	[2.83]	[2.40]
1{Alt. Fuel}	√	√	√	√	√	√
1{year=2007}	√	√	√	√	√	√
1{year=2008}	√	√	√	√	√	√
1{year=2009}	√	√	√	√	√	√
Fuel-Fuel price interactions		√	√		√	√
Model FEs	√	√	√			
Model-fuel FEs				√	√	√
N	588285	584866	322670	588285	584866	322670
R-squared	0.702	0.857	0.876	0.901	0.900	0.933

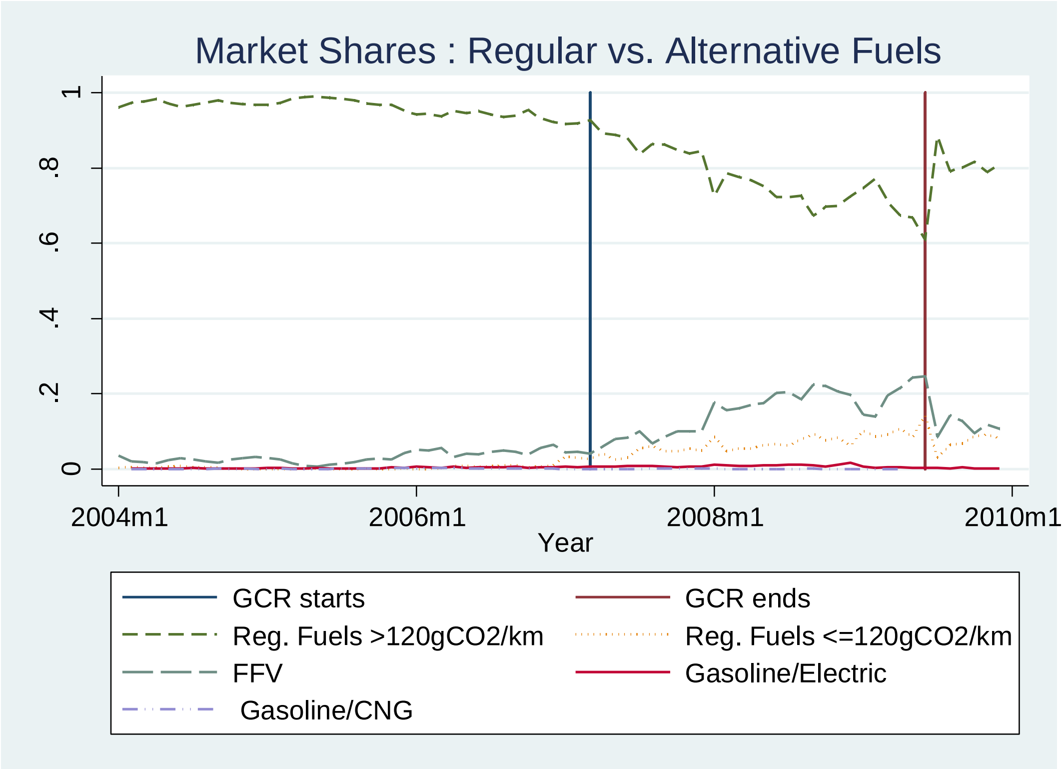
Note: This table reports estimates of the causal effect of the GCR on engine CO2 emissions (measured in gCO2/km) of alternative as compared to regular vehicles using sales-weighted data recorded at the monthly frequency. Columns 1-6 in Panel A compare the short- and long-run effects of the GCR, whereas Columns 1-6 in Panel B decompose the long-run effects of the GCR into separate ones for years 2008 and 2009. Standard errors are clustered by brand, with t-statistics reported in brackets. A model-fuel combination is given by, e.g. a Ford Focus-gasoline. Significance levels at 10, 5 and 1 percent are denoted by *,** and ***, respectively.

TABLE 5 – Consumer Types in Fuel Choice and Change in Air Pollution due to FFV Owners' Switch from Ethanol to Gasoline

	[1]	[2]	[3]	[4]	[5]	[6]
Panel A: Scenario parameters						
kpl (running on ethanol) =	6	7	8	6	8	10
χ (kilometres per month) =	1500	1500	1750	2000	2000	2000
Panel B: Shares of each consumer type						
σ_e (ethanol-lovers)	14.4%	16.8%	16.4%	10.8%	14.4%	18.0%
σ_a (fuel arbitrageurs)	61.2%	71.4%	70.0%	45.9%	61.2%	76.5%
σ_g (gasoline-lovers)	24.4%	11.8%	13.6%	43.3%	24.4%	5.5%
Panel C: Change in concentration of air pollutants due to FFV owners' switch from ethanol to gasoline						
CO2	94.1%	106.8%	104.8%	79.9%	94.1%	114.5%
Nonmethane Hydrocarbon	13.2%	13.4%	13.4%	12.9%	13.2%	13.5%
1,3-Butadiene	-42.2%	-40.1%	-40.4%	-45.9%	-42.2%	-39.1%
NOx	20.8%	21.4%	21.3%	20.0%	20.8%	21.7%
Particulate Matter	45.8%	48.6%	48.1%	42.1%	45.8%	50.1%
CO	-17.4%	-17.0%	-17.1%	-18.0%	-17.4%	-16.8%
Formaldehyde	-42.7%	-40.5%	-40.8%	-46.4%	-42.7%	-39.5%
Methane	-54.3%	-50.8%	-51.3%	-60.5%	-54.3%	-49.2%

Note: This table examines the fuel switching behavior of FFV owners following the 2008 oil price drop and its effects on air pollution. All calculations are based on September and November 2008 (corresponding to cheap and dear ethanol months, respectively). Panel A reports the basic assumptions regarding kilometerage (in km/month) and fuel economy (in kilometers/liter, running on ethanol). Kilometerage assumptions used are in the range 11250-14900 miles per year and fuel economy is in the range 19.1-31.8 mpg running on gasoline. Panel B reports the shares of consumer types for each scenario. Panel C reports the percentage change in the concentration of air pollutants for which the equality for ethanol and gasoline is rejected according to Yanowitz and McCormick (2009).

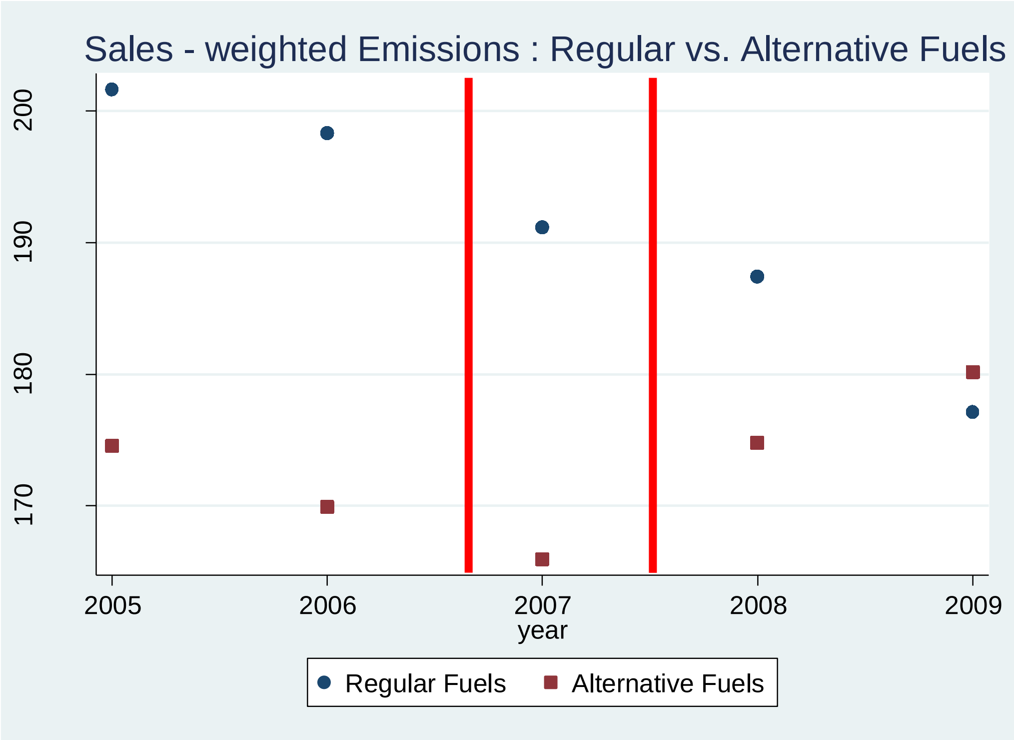
FIGURE 1 – Market Shares Disaggregated by Fuel Segments



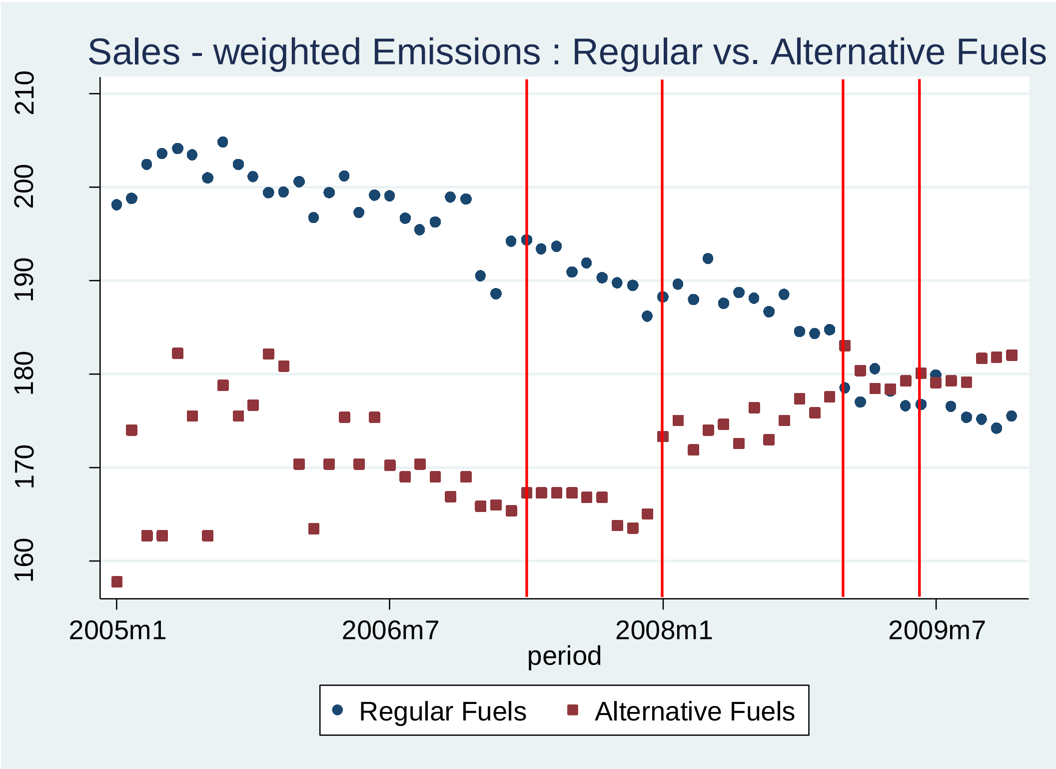
Note: This figure depicts market shares of passenger cars sold to private individuals in the Swedish car market at the monthly frequency disaggregated by fuel segment,, with the vertical bars denoting the start (April 2007) and the end (June 2009) of the GCR. Vehicles running on regular fuels are split into two groups, namely high- and low-emission regular vehicles, depending on whether they emit more or less than 120 gCO2/km. Vehicles able to run on alternative fuels are split into FFVs (gasoline/ethanol), gasoline/CNG and gasoline/electric. The figure shows the decrease in the market shares of high-emission regular vehicles and the increase in those of low-emission regular vehicles and FFVs, the leading alternative vehicle, while showing that the market shares of gasoline/CNG and gasoline/electric vehicles were essentially flat during the GCR period. The figure also suggests the existence of anticipatory effects at the (publicly announced) and of the GCR in June 2009, but no compelling evidence thereof at its start in April 2007.

FIGURE 2 – Sales-weighted CO2 Emissions of Regular and Alternative Fuel Vehicles

Panel A: Sales-weighted CO2 Emissions of Regular and Alternative Fuel Vehicles – Yearly Frequency



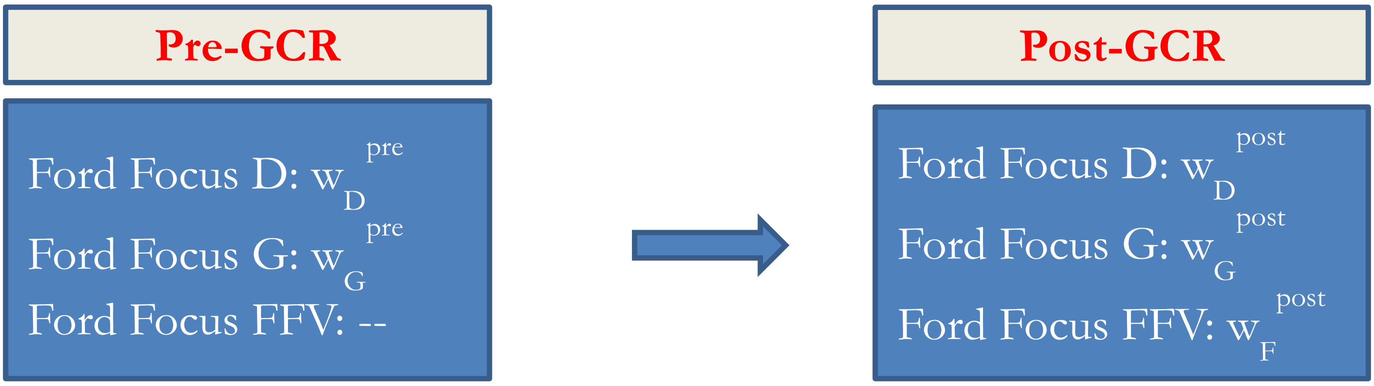
Panel B: Sales-weighted CO2 Emissions of Regular and Alternative Fuel Vehicles – Monthly Frequency



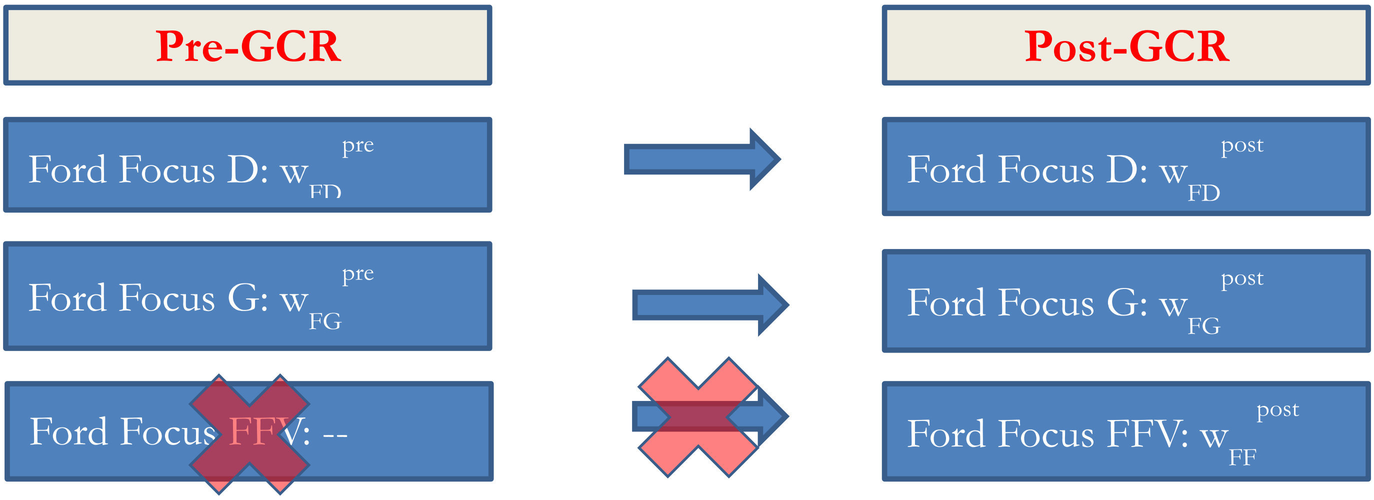
Note: This figure depicts sales-weighted CO2 emissions (measured in gCO2/km) of cars running on regular and alternative fuels. Panel A reports figures at the yearly frequency: the first vertical bar divides the sample into a pre- and post-GCR periods (years 2005-6 and 2007-9, respectively). The second vertical bar divides the post-GCR period into a short-run effect (2007) where carmakers were not able to re-enginer their vehicles and a long-run effect (2008-9) where carmakers were able to adjust their product lines accordingly. The figure suggests that following the GCR there was an increasing trend in the average emissions of alternative vehicles as compared to those of regular ones. Panel B reports figures at the monthly frequency, with vertical bars placed in April 2007 (start of the GCR), January 2008 (new product line), January 2009 (new product line) and June 2009 (end of the GCR). The jaggedness in the early part of the sample is due to the small number of alternative vehicles on the market at the start of the sample period. While the start of the GCR resulted in a small increase in average CO2 emissions of alternative vehicles due to the restricted choice set, the launch of the 2008 and 2009 product lines resulted in a more dramatic effect due to the compounded reactions of carmakers and consumers, as witnessed by the jumps in January 2008 and January 2009.

FIGURE 3 – Comparison of Fixed-effects

Panel A: Model Fixed-effects

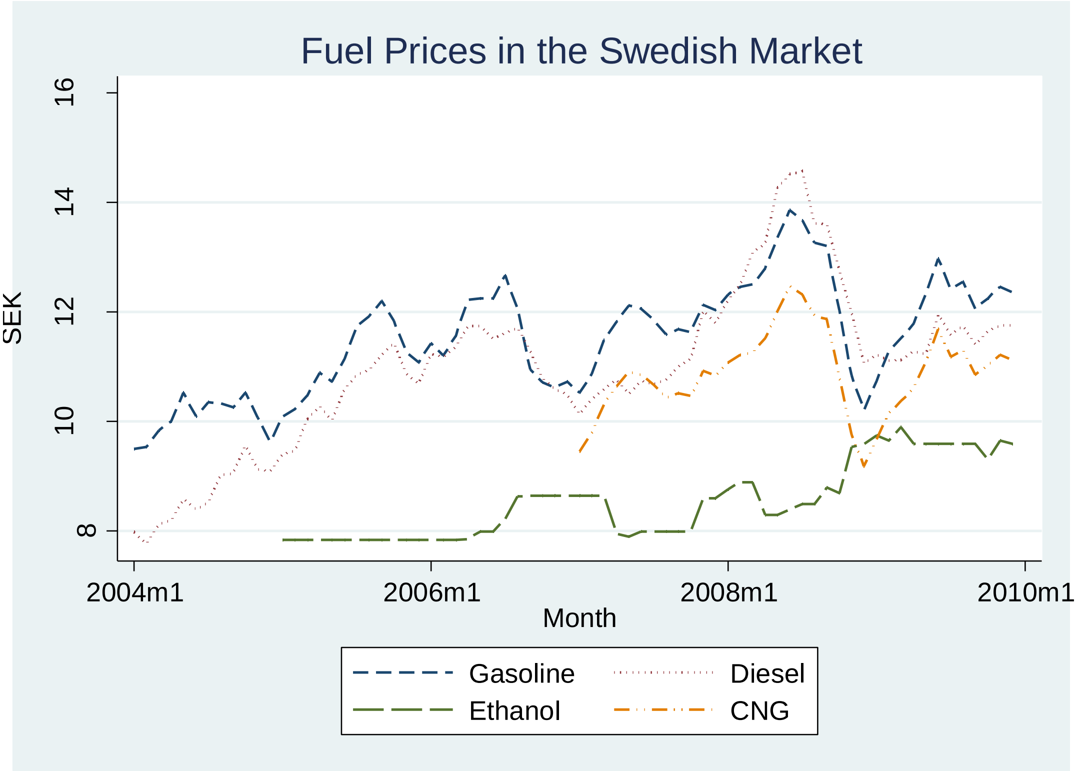


Panel B: Model-fuel Fixed-effects



Note: This figure compares model and model-fuel fixed-effects. In both panels, diesel (D) and gasoline (G) versions of the Ford Focus are available both before and after the introduction of the GCR whereas its FFV version is introduced only after the inception of the program. Model-fuel fixed-effects (shown in Panel B) are unable to account for product introduction, resulting in the dropping of the FFV-related information from the sample. In contrast, model fixed-effects (shown in Panel A) do account for product introduction, with the FFV information being subsumed into the Ford Focus (i.e. model) fixed-effect.

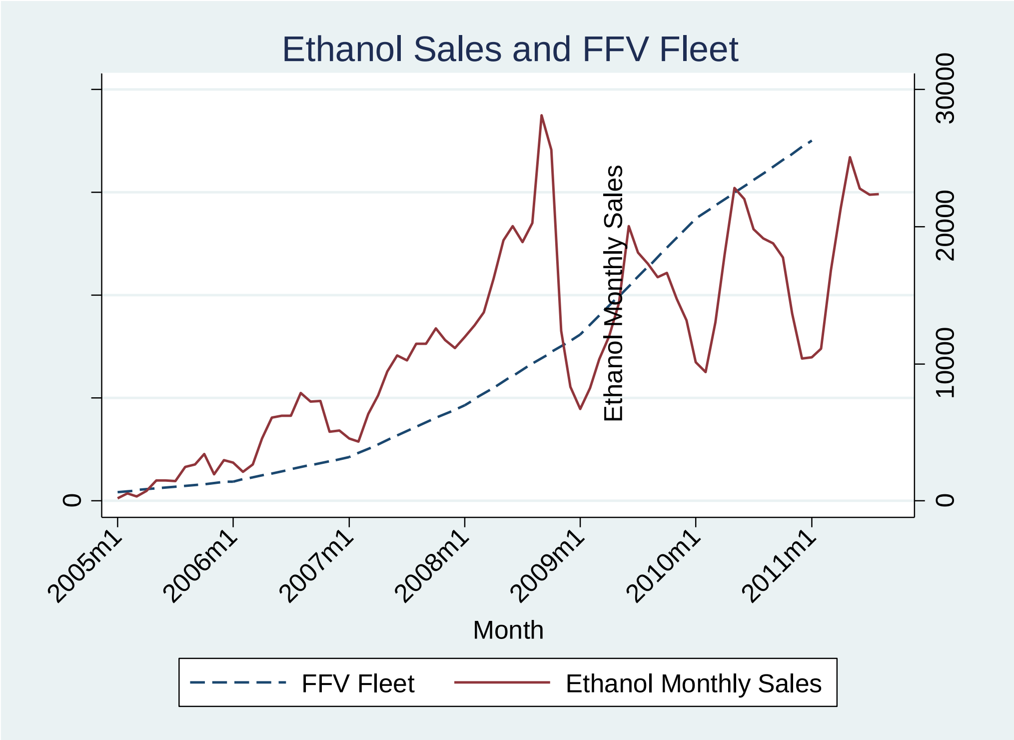
FIGURE 4 - Evolution of Fuel Prices in the Swedish Market



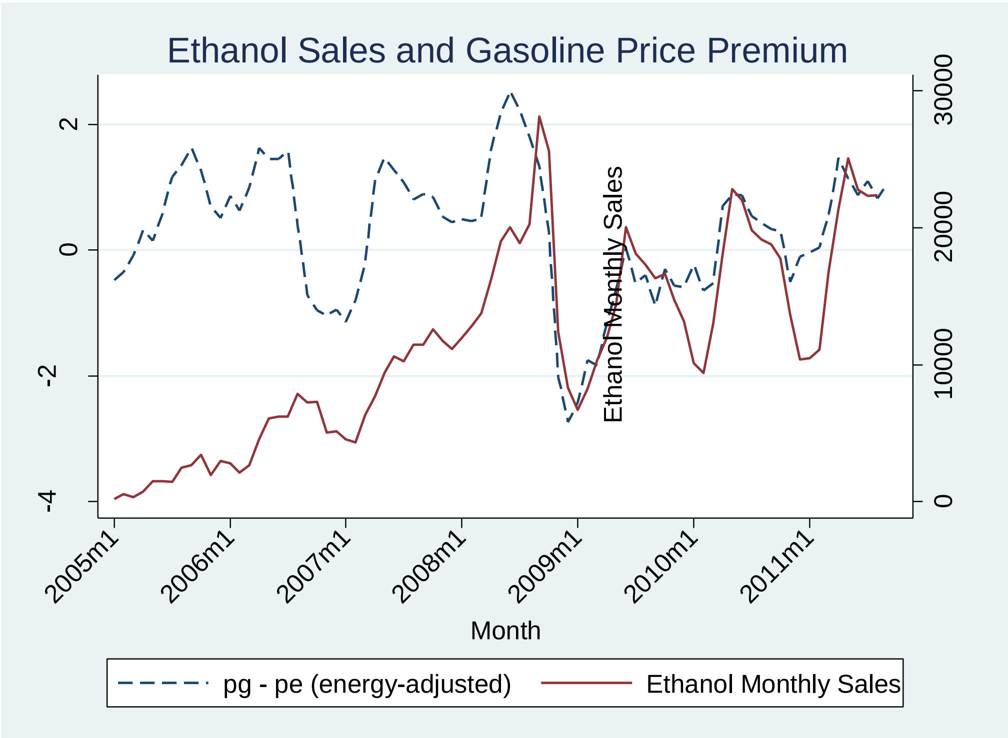
Note: This figure reports nominal fuel prices in the Swedish market reported at the monthly frequency. Prices are measured in SEK/litre for gasoline, ethanol and diesel and SEK/cubic meter for CNG. Data is from the Swedish Petroleum and Biofuels Institute (SPI) and Statoil. Gasoline prices are those for standard gasoline (Gasoline 95). Prices for ethanol are available at the national level from January 2005 and those for CNG from January 2007.

FIGURE 5 – Development of Ethanol Sales, FFV Fleet and Gasoline Price Premium in the Swedish Market

Panel A: Time series of sales of FFVs and volume sales of ethanol (in `000 cubic meters).

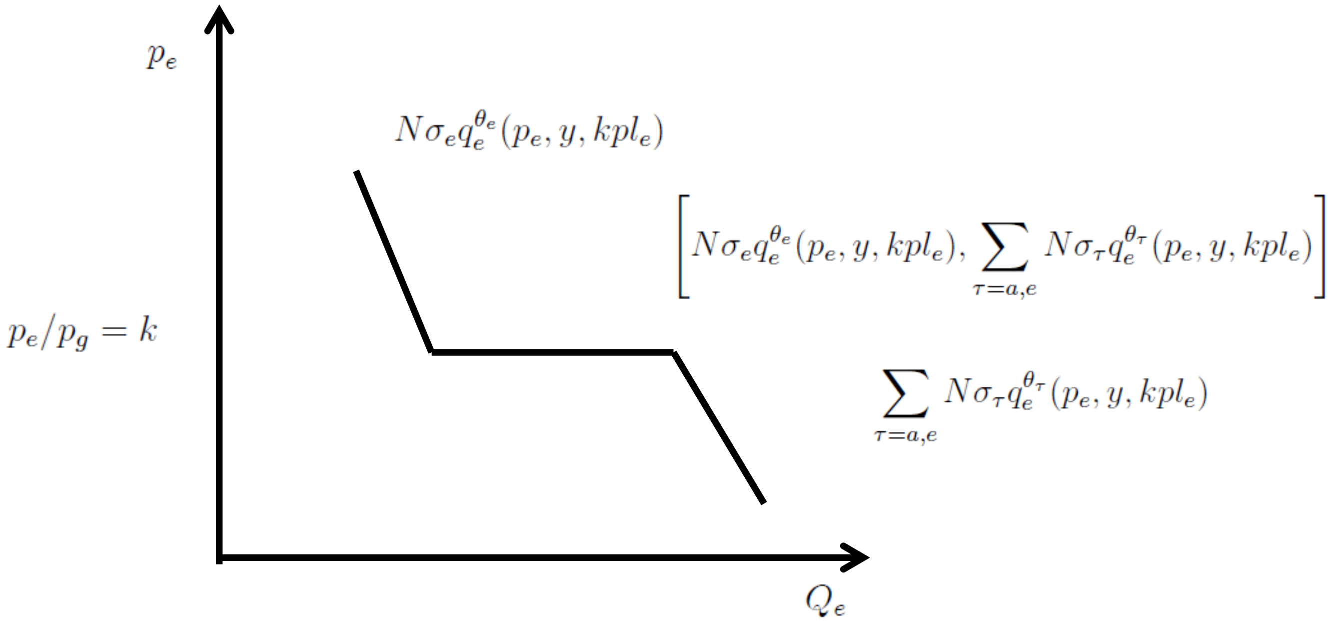


Panel B: Time series of volume sales of ethanol (in `000 cubic meters) and energy-adjusted gasoline price premium.



Note: This figure depicts variables related to the FFV market segment. Panel A depicts ethanol sales and the number of FFVs registered in the Swedish market. While the sales ethanol grew hand in hand with the sales of FFVs for the earlier part of the series, the drop in oil prices in fall 2008 and associated drop in gasoline prices resulted in a drop in the sales of ethanol of roughly 70 percent, due to the fuel switching behaviour of a substantial share of FFV owners. Panel B depicts ethanol sales and the energy-adjusted price premium of gasoline over ethanol, calculated to reflect the energy content of each fuel. The price of gasoline peaks in mid-2008 dropping right afterwards due to the start of the global economic crisis. The price increase of ethanol in late 2008 is essentially seasonal, associated to the sugarcane crop in Brazil and India.

FIGURE 6 – Market Demand for Ethanol



Note: This figure depicts the market demand for ethanol as a function of the ethanol-gasoline price ratio. Consumer type θ_j ($j=a,e,g$) appears as a share σ_j of the population. While only ethanol-lovers θ_e demand ethanol when it is priced above the parity level ($p_e/p_g>k$), both ethanol-lovers and fuel arbitrageurs θ_a demand it when ethanol is priced below the parity level ($p_e/p_g<k$).