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 over 25 percent market share in the new vehicle market, an effect of unprecedented scale if compared to recent policies incentivizing the purchase of fuel-efficient vehicles. By awarding vehicles satisfying certain emission criteria a rebate, but giving alternative fuel vehicles (AFVs, those able to run on alternative fuels) a more lenient treatment than regular fuel vehicles (RFVs, those able to run only on gasoline and diesel), the GCR created a regulatory loophole which led carmakers to increase the emissions of AFVs as compared to RFVs. This paper examines the impact of regulation on market developments comparing CO2 emissions (and fuel economy) of AFVs and RFVs. Once carmakers adjust their product lines to the policy, CO2 emissions of AFVs increased significantly as compared to those of RFVs, thus undermining the very objectives of the GCR.

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

Keywords: Automobiles; Emissions; Environmental policy; Alternative fuel vehicles; Flexible-fuel vehicles; Fuel economy; Greenhouse gases; Regulation; Alternative fuels; Renewable fuels.

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1 Introduction

Economists have been interested in the interplay between regulation and market outcomes since at least 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, thanks to increased data availability and advances in econometric methods.[1]

The transport sector has been the target of regulatory initiatives in a number of countries in recent years, amid the ever growing concern with greenhouse gases (GHGs) and the quest for oil independence.[2] In addition to its importance to the GDP of many countries, the prominence of the transport sector is justified because, first, road transport is already responsible for about 20 percent of the CO2 emissions generated by fuel consumption worldwide (IEA 2011a) and, more importantly, because transport fuel demand is set to grow by 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 economies (IEA 2011b). Unfortunately, however, policies aimed at the transport sector have typically not applied widely enough to affect a large fraction of the new vehicle market (Sallee 2011a), itself a small share of the car fleet.

This is the first paper to analyze a policy aimed at the automobile industry which had a broad impact on the new car market, the Swedish Green Car Rebate (GCR); while similar policies managed to affect market shares in single digits, vehicles benefiting from the GCR (*green cars*) commanded an unprecedented market share of 26.5 percent in 2008, the first calendar year after its inception, as compared to a pre-GCR market share of 6 percent in 2006.[3]

In addition to being broad, another crucial feature of the GCR is its embracing of *alternative fuels*, arguably inspired by policies adopted in Brazil, where thanks to ethanol the CO2 emissions per unit of fuel consumption in road transport are 20 percent below the global average (IEA 2011a). Promoting alternative fuels comes hand-in-hand with the promotion of *alternative fuel vehicles* (AFVs) – those able to operate using alternative fuels, such as Gasoline/CNG and Gasoline/Electric hybrids but, most prominently, Gasoline/Ethanol vehicles, the so called *flexible-fuel vehicles* (FFVs).

By combining the increased market shares of green cars and the lower carbon intensity of ethanol as compared to fossil fuels, the GCR was arguably bound to be a success. However, what seems to be the lack of understanding of the technologies being incentivized resulted in two important drawbacks of the policy. First, the very definition of what a green car consists of induced carmakers to produce high-emission AFVs instead of low-emission RFVs (*regular fuel vehicles*, those able to run using only fossil fuels, eg. gasoline and diesel). That is, while RFVs were required to emit no more than 120 gCO2/km (47 mpg running on gasoline) to qualify as green cars, the threshold for AFVs was set to the equivalent of about 220 gCO2/km (25.5 mpg running on gasoline).[4] This regulatory

[1] 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.

[2] 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, which was implemented before the global crisis and was an environmental program, is closer in spirit to the US hybrid subsidy than the "Cash for Clunkers" stimulus program.

[3] For perspective, Beresteanu and Li (2011) document that hybrid electric vehicles commanded a market share of 2.15 percent in the US in 2007 following a similar program.

[4] These figures are equivalent to, respectively, ratings 10 (the highest) and 7 according to the EPA Fuel Economy and Environmental label introduced in 2011. The corresponding figures for diesel are 51.7 mpg and 28.2 mpg, respectively.

loophole was duly explored by carmakers and consumers alike: following the GCR, CO2 emissions of AFVs increased markedly as compared to those of RFVs in both supply and registration data (see Figure 2). That is, carmakers reacted by increasing CO2 emissions (equivalently, reducing fuel economy by increasing engine power and/or engine size) of AFV models available pre-GCR and/or by introducing new variants of existing gasoline models, eg. a (higher emission) FFV version of a captive gasoline vehicle.[5] The reaction in the AFV camp was swift, with the action happening mostly in the FFV segment; this is so because the FFV technology piggy-backs on the Otto cycle technology used in gasoline vehicles. Moreover, given the lax treatment dispensed to AFVs, essentially every FFV qualified as a green car; being available at roughly similar prices than their captive gasoline counterparts, the FFV segment thus experienced the increase in market shares apparent in Figure 1.

Second, since the dominant AFVs are FFVs, which can seamlessly switch between gasoline and ethanol, and a substantial share of consumers purchases the cheapest fuel, those high-emission FFVs benefiting from the rebate were often fueled with gasoline, which emits more CO2 than ethanol. In fact, fuel switching by FFV owners is apparent even from aggregate data, as witnessed by a dramatic drop of over 70 percent in country-wide ethanol sales following the 2008 drop in international oil prices (see Figure 3). That is, FFVs were also attractive to consumers for providing lower operating costs than their captive gasoline counterparts and fuel choice becomes yet another dimension policymakers should account for in policy design.

The empirical analysis of the paper closely follows the above narrative and proceeds in two steps. First, I compare CO2 emissions and fuel economy of AFVs and RFVs using a difference-in-differences (DD) estimator for both supply (all products marketed within a year) and registration (all products sold within a year) data. As suggested in Figure 2, CO2 emissions of AFVs and RFVs share a common, downward, trend pre-GCR, a policy unanticipated by market participants.[6] Following the GCR's inception, while CO2 emissions in the RFV segment continued their pre-policy trend, reflecting the time it takes to develop a new powertrain (if at all, for a market as small as the Swedish one), the trend of CO2 emissions in the AFV segment experienced a swift and stark reversal, trending upwards instead, thanks to the loophole created by the asymmetry in the GCR emission thresholds.[7]

Having established the importance of FFVs in the Swedish market, I propose a stylized structural model of fuel choice by FFV owners, which I bring to data of the Swedish fuel market. To gauge the effect of fuel switching, I calibrate the model to data of the period around the sharp decline in oil prices in connection with the 2008 global crisis, an arguably exogenous event.

The results unequivocally support the findings suggested by the descriptive analysis. Using supply

In what follows, I refer as low-emission (high-emission) vehicles to those emitting up to (more than) 120 gCO2/km. Emissions of 120 gCO2/km amount to consumption of about 5 liters of gasoline or 4.5 liters of diesel per 100 km. While being applied to individual cars rather than to a brand-level sales-weighted average as in the US CAFE standard, the lower emission threshold is also more stringent than the 250 gCO2/mile (156.25 gCO2/km) CAFE standard to take effect from 2016 in the US.

[5] I document how the former effect dominates the latter in Section 6.

[6] 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. 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. 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. Although carmakers cannot re-design their vehicles in the short-run, one cannot rule out responses in other dimensions, e.g. marketing initiatives, but see Section 2 for why prices are unlikely to adjust, at least in the short-run.

[7] I could not find any evidence of conversions (retrofits) pursued by private individuals or garages. On top of requiring some specific knowledge, skills and equipment, eg. adjustment of compression ratios, any vehicle warranties would become null and void in case of such a conversion, making it unattractive, at least for relatively new vehicles.

data (each marketed model receives an equal weight), the benchmark results point to a 21.5 gCO2/km increase in emissions (or a 4.2 mpg decrease in fuel economy), which corresponds to 11 percent of the emissions of the median 2006 vehicle, an effect which is robust to the addition of controls and alternative definitions of treatment and control groups. When decomposing this effect into separate ones for model-years 2008 and 2009, the paper documents how the responses of carmakers strengthened over time following the inception of the GCR.

Using registration data, I obtain an insignificant effect for calendar year 2007, when consumers faced pre-GCR product lines, and a 24.6 gCO2/km increase in emissions (or a 6.1 mpg decrease in fuel economy), which corresponds to 12.5 percent of the emissions of the median 2006 vehicle, again an effect which is robust to the addition of controls and alternative definitions of treatment and control groups. These findings are in line with a vast literature looking at the automobile industry, eg. Berry, Levinsohn and Pakes (1995), Goldberg (1995), according to which consumers are willing to pay for characteristics such as size (a proxy for comfort) and horsepower, which highly correlate with CO2 emissions and fuel economy.

The results from the fuel choice model suggest 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.[8]

In sum, the above findings are consistent with the view that the GCR was not much more than a transfer to consumers purchasing FFVs. More generally, the findings highlight the margins policymakers should take into account when designing environmental policies aimed at the transport sector. Importantly, such findings are not restricted to ethanol, but should hold to any alternative to the established fossil fuels.

At the root of the problem lies the lax treatment enjoyed by AFVs, in particular the dominant gasoline-ethanol FFV, likely due to the lack of understanding of the technology. In addition to the similarity to the standard Otto cycle technology (of which it is a derivative), reasons why FFVs commanded the lion's share among AFVs include the fuel-switching enabled by the technology, and the well-developed retail network for ethanol as opposed to say, CNG, whose retail network is concentrated in the Southwest of the country. As a result, FFV owners are able to arbitrage across fuels and reduce the operating costs of their driving.

The paper relates to different branches of the literature. The closest paper to this one is Anderson and Sallee (2011), which shows how carmakers explore a regulatory loophole arising from the CAFE standard. Another closely related paper is Knittel (2011), which performs a long-run analysis of the US automobile industry and points to consumer preferences as being the drivers of changes in vehicle characteristics. Here, in addition to documenting how the GCR created a loophole, I show how the reactions of both firms and consumers jointly work against the very objectives of the policy, unveiling the role of technology and identifying the mechanism by which consumers and carmakers react to the GCR.

The paper also contributes to the burgeoning literature on policies directed towards the transport

[8] Local air pollutants such as nitrogen oxides (NOx) and particulate matter (PM) are not GHGs, but are known to harm human health, thus being classified as criteria pollutants by the US EPA.

sector, notably the automobile industry, see for instance Beresteanu and Li (2011), Chandra, Gulati and Kandlikar (2010), Huse and Lucinda (2013), Li, Linn and Spiller (2011), and Miravete and Moral (2009).

By focusing on fuel choice decisions made by 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 to 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) and Salvo and Huse (2013).

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 research in the natural sciences on the effects of ethanol on air quality, see Jacobson (2007).

2 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 to 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 whereby over 50 percent of fueling stations supply at least one alternative fuel since 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.[9]

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) –RFVs– qualify as green cars provided they emit no more than 120 gCO2/km, whereas AFVs, ie. 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 liter/100km, the gas-equivalent of 9.7m3/100km or less than 37 kWh/100km, respectively.

Although the thresholds defining RFVs and AFVs are expressed in different units (gCO2/km and liter/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 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 AFVs being equivalent to approximately 220 gCO2/km (for perspective, the 2012 Porsche 911 Carrera emits 205 gCO2/km).[10] All in all, the threshold defining alternative green cars is substantially more lenient than the one defining regular ones. Anecdotal evidence suggest that this was a way the newly-formed government managed to get the support of the Green Party.

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, AFVs 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

[9] Interestingly, and in contrast with stylized facts for other markets, there does not seem to be evidence of bunching at the 120 gCO2/km threshold, likely due to the size of the Swedish market. In fact, the figures for low-emission gasoline and diesel vehicles do not seem to change by much from 2006 (or earlier, in the case of gasoline) to 2009.

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

with any combination of ethanol and gasoline which are stored in the same tank, gasoline-ethanol cars are called FFVs (flexible-fuel vehicles).[11] 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. Importantly, Sweden being a small market, car dealers keep very low inventory levels, so much so that typically one has to order a car a few months in advance and make a deposit, which results in very few episodes of sales or rebates from the part of carmakers and/or dealers and stable prices within a model-year (see Huse and Koptyug 2013 for details).[12]

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 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 straightforward task. All that is required is a sensor which 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 *Konsumentverket*, the Swedish Consumer Agency. 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 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

[11] FFVs have a long tradition in the auto industry; for instance, Henry Ford thought that biofuels were the "fuel of the future" and believed ethanol would become the most commonly used fuel source. In fact, Ford's vision of mass biofuel consumption began with his Model T, which was a FFV from the original design (National Geographic 2007). However, the decreasing cost of oil extraction and the US prohibition meant that most Model Ts were run on oil-derived petrol (The Telegraph 2008). Nowadays, FFVs command a substantial share of the car fleet in Brazil and the US.

[12] In particular, I could not find any evidence that either carmakers or car dealers were taking advantage of the policy by raising vehicle prices, be it anecdotally or conducting news searches.

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 fuels, 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.[13] 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

In this Section, I first document the development of market shares of different fuel segments in the Swedish car market in the period around the GCR. Then, I examine the evolution of CO2 emissions of AFVs and RFVs using both supply and registration data.

When looking at market shares, the striking finding is that 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 RFVs lost market share to low-emission RFVs and, most importantly FFVs, following the GCR. In fact, while the market share of high-emission RFVs 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 RFVs increased their market share in a less pronounced way, from 1 percent in December 2006 to 4.8 percent in December 2007 and 6.2 percent in December 2008, while CNG and electric hybrid vehicles never commanded more than 1 percent of the market during the sample period.

FIGURE 1 ABOUT HERE

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 in the country. In the eyes of the average consumer, conditional on purchasing a model available in both FFV and gasoline variants, the choice was between a captive gasoline version and its FFV

[13] 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*.

version, which was slightly more expensive but sold at a rebate due to the GCR, and which allowed its owner to arbitrage across fuels, thus enabling lower operating costs.[14]

A crucial finding worth mentioning is the development of average CO2 emissions of AFVs and RFVs during the sample period, which will guide the empirical analysis below. Both supply- and registration-based figures are reported in Figure 2, see Panels A and B, respectively; in the former, all marketed vehicles are given uniform weights when computing the average CO2 emissions whereas in the latter, those weights are given by their market shares. In either graph, emission levels of AFVs and RFVs share a common, downward, trend prior to the GCR, with emission levels of RFVs being somewhat higher than those of AFVs.

However, starting from model-year 2008, the average CO2 emissions of AFVs experience a dramatic change, resulting in an upward trend in emission levels in both supply and registration data. There are two ways such a change can materialize.[15] First, carmakers could have *tinkered* with products existing *prior to the GCR* by increasing emission levels of AFVs and/or decreasing emission levels of RFVs, in order to make them eligible for the rebate. In practice, this can be achieved via changes in the chips governing the electronic central unit (ECU) of most vehicles or by changing the powertrain with which a given variant is equipped.

FIGURE 2 ABOUT HERE

Second, carmakers could introduce new products such as a (previously non-existent) FFV variant of an existing model. Given the incentive structure of the GCR, it is rather plausible that new products were more likely to emit less than 120 gCO2/km conditional on being RFVs, but not necessarily so in the case of AFVs due to the asymmetry in the definition of what a green car consists of. As I discuss below, the effects of the GCR on emissions and fuel economy can be thought of as a composition of the tinkering effect described above with the effect of product introduction following the policy.

The findings documented in Figure 2 suggest that both carmakers and consumers acted in ways that resulted in increases in average CO2 emissions of new vehicles. Alternatively, one could argue that both groups took advantage of the loophole provided by the GCR, thus working against its very objectives. That is, faced with vehicles similar to existing captive gasoline ones, sold at a rebate and allowing lower operating costs, a non-trivial share of consumers voted with their feet against high-emission RFVs flocking towards their alternative – mostly FFV – counterparts.

5 Econometric Analysis

5.1 Empirical Strategy

Setup I focus on the effect of the GCR on CO2 emission levels and fuel economy of newly-purchased AFVs as compared to RFVs. To do so, I estimate specifications of the form

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

[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).

[15] I have also examined a third alternative, according to which carmakers have pursued price adjustments of vehicles benefiting from the GCR. While *within* a year vehicle prices are fixed, since a new car is typically ordered from the car dealer and taking between four weeks and four months to be delivered (see Huse and Lucinda 2013), price changes *across* years are minimal. I thus argue that the change in sales-weighted CO2 emissions are driven by (a subset of) characteristics typically treated as exogenous in the demand literature.

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 or fuel economy, measured in miles per gallon, mpg), Γ denotes the period during which the GCR was in place, $\aleph$ denotes the set of treated subjects, namely AFVs, the indicator $1\{A\}$ takes on value one if the event A holds, and x_{it} is a set of controls.[16] Given the unexpected character of the policy, I make use of difference-in-differences (DD) techniques focusing on estimates of δ. I estimate the effects separately for supply and registration data.

Supply-side Data In the supply-side analysis, 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-GCR responses into one effect for each of these two years.

Registration Data When using registration data, 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 potential adjustments in the choice set (product lines) following the policy. That is, more than comparing CO2 emission levels or mpg of AFVs vs. RFVs 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 react to the policy, 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.

Standard Errors 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.[17] 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).

[16] Both CO2 emissions and fuel economy (typically in liters/100km) are obtained under ideal conditions, eg. constant speed, and routinely reported by carmakers (via, eg. the *Nybilsguiden*). Note that CO2 emissions are inversely related to mpg, with a correlation of -0.92 in the data. In turn, the relation between CO2 emissions and gpm – gallons per mile – is linear, with a correlation coefficient of 0.98.

[17] 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.

5.2 Identification

Identification of the DD estimator relies on a combination of statistical and institutional arguments, see Figure 2. As a pre-condition for the DD analysis, I test for the existence of pre-GCR common trends in the CO2 emissions of RFVs and AFVs: this is performed for both supply and registration data by estimating a triple difference specification where the effect of interest is measured by the coefficient associated to the interaction of a time trend, a pre-GCR indicator and a treatment group indicator. Since one cannot reject the null hypothesis of a common trend between CO2 emissions of RFVs and AFVs pre-GCR at the 5 percent significance level using neither supply nor registration data, this lends support to the use of the DD estimator throughout the analysis.

Next, recall that the GCR was not only unanticipated but had a very fast implementation (one month), see Section 2 for details. Moreover, its announcement and implementation were already in the middle of the 2007 model-year production cycle (March-April 2007), since product lines had already been launched in late 2006.

Turning to post-GCR trends, CO2 emissions of RFVs tend to behave in a similar manner as compared to the pre-policy period for the rest of the sample period. This is suggestive of a sluggish response to the GCR in the RFV segment, which can be rationalized by the fact that designing/bringing to market a new powertrain takes time, ie. although carmakers are able to marginally change powertrain configurations swiftly via changes in chips governing a vehicle's ECU, a more thorough adjustment consisting of a low-emission engine would be costlier and take time. What is more, Sweden being a small market, the development of a tailor-made powertrain in order for a vehicle to qualify as a green car is unlikely to be a profitable enterprise. For AFVs, however, the trend in CO2 emissions changes dramatically, suggesting not only a quick response in this segment, but also an increase in CO2 emissions of AFVs as a reaction to the policy. This can be rationalized by the fact that turning a captive gasoline vehicle into an FFV – the leading AFV, see Figure 1 and results below – consists of installing a $100-200 (and falling) FFV kit

The increase in CO2 emissions among AFVs (think of FFVs to fix ideas) can occur in either the intensive or the extensive margin, ie. via adjustments in characteristics of existing model-fuel combinations (increasing engine size and/or engine power of an existing AFV, say) or, more likely among brands which already operate in the AFV segment, via the introduction of new model-fuel combinations (a previously non-existent FFV variant of an existing model, say), the latter of which poses a threat to the exogeneity of the AFV indicator in equation (1).

In what follows I devise two strategies to address such concern. First, given the possibility that a set of observable variables that determine the AFV indicator may be correlated with the outcomes, I follow a control function (CF) approach, ie. I introduce a set of control variables in an attempt to approximate the influence of omitted variables in equation (1). These variables are obtained from a set of first-stage probit regressions whereby the AFV indicator (the FFV indicator was also used for robustness) is regressed on a set of variables, including an indicator of whether a carmaker's conglomerate (group) owned an AFV technology the previous year interacted with variables such as lagged sales, an indicator of whether a given model had CO2 emissions in excess of 120 gCO2/km and a GCR dummy, which I label as the *AFV determinants*.[18]

[18] Note that being lagged, these variables are pre-determined with respect do the dependent variables and covariates in equation (1). Using group instead of brand comes from the fact that brands within a group often pool resources, eg. brands VW and Audi within the VW Group share powertrains for the VW Golf and the Audi A4; the findings reported are robust to the use of brand instead of group though. I have also experimented with other variables interacted with ownership of the AFV technologies, but (lagged) sales and CO2 emissions were the ones with some – albeit small – predictive power in probit models (or linear probability models) where the dependent variable was either the AFV or the FFV indicator. While the CO2 emissions indicator directly relates to the GCR emissions threshold, sales are

Second, I also estimate specifications considering only the subset of model-fuel combinations available pre-GCR and thus unable to self-select into treatment by construction (see Column 4 of each panel in Table 3 and labeled as "pre-GCR"). That is, one can argue that the *DD estimates using only pre-GCR models provide a lower-bound to the effect of the GCR on CO2 emissions* (or mpg) by considering product line adjustments in the intensive rather than the extensive margin. As I detail below, although the resulting effects are (not surprisingly) milder when compared to those obtained using the full sample, the pre-GCR effects are still significant and within the 95 percent confidence bounds of the full sample estimates, thus suggesting that endogeneity is of limited concern (see also the discussion of the results below).

6 Effect of the GCR on CO2 Emissions and Fuel Economy

This section reports on the effects of the GCR on CO2 emissions and fuel economy of AFVs and RFVs looking separately at supply-side and registration effects.[19] While in the supply-side analysis all marketed products are equally weighted, when looking at registration data products are sales-weighted, giving it an equilibrium interpretation. For every specification, I report the main results in terms of CO2 emissions measured in gCO2/km and (for the sake of comparability with a substantial part of the literature) in terms of fuel economy expressed mpg – the latter are reported within square brackets in Tables 2 and 3. All specifications use data from years 2005-2009.

While the paper mostly focuses on the relative CO2 emission levels (mpg) of AFVs and RFVs, I also contemplate alternative definitions of treatment and control groups. For instance, I also consider specifications where treatment and control groups are, respectively, FFVs (thus a subset of AFVs) and the set of captive gasoline vehicles (upon which the FFV technology piggy-backs). Moreover, since no FFV emits less than 120 gCO2/km in my data, I have also, eg. compared FFVs to the subset of high-emission gasoline vehicles, see the Appendix for robustness checks.

As a pre-requisite for the subsequent analysis, I test for the existence of a common trend between CO2 emissions of AFVs and RFVs prior to the GCR, very much in the spirit of Figure 2. To do so, I estimate a triple difference specification; the effect of interest is measured by the coefficient associated to the interaction of a time trend, a pre-GCR indicator and a treatment group indicator. Since one cannot reject the null hypothesis of a common trend between CO2 emissions of RFVs and AFVs pre-GCR, this lends support to the use of the DD estimator.

6.1 Supply-side Effects

To estimate the supply-side effects of the GCR on CO2 emissions and mpg, I focus on DD coefficients interacting the AFV indicator with an indicator for the period in which the GCR is in place, see Table 2.

TABLE 2 ABOUT HERE

The robust finding across specifications is that, following the GCR, CO2 emissions of AFVs increased as compared to those of RFVs. Without any covariates, Specification 1 in Panel A of Table

typically inversely related to markup, thus proportional to elasticities (in absolute value), and can be thought of as a reduced-form way – however imperfect – of capturing which models would be more impacted by having an FFV version.

[19] When using CO2 emissions as the dependent variable, one may be tempted to use *dollar per mile*-like quantities as covariates; recall, however, that emissions and fuel economy are simultaneously determined.

2 returns DD estimates of 21.48 gCO2/km, or -4.16 mpg, both significant at the one percent level and 11 percent of the emissions of the median 2006 vehicle. Since operating costs are key when considering both the purchase of a vehicle and the development of product lines, I introduce fuel-year fixed-effects to capture fuel price trends over time. Moreover, since carmakers are more likely to introduce AFVs if they had AFVs on offer previously and, if so, are likely to do so strategically, I also introduce *AFV determinants*, ie. interactions between an indicator of whether a group owned an AFV technology the previous year interacted with either (i) lagged sales or (ii) an indicator of whether a given model had CO2 emissions in excess of 120 gCO2/km. Finally, I also interact AFV determinants with a GCR dummy.

Controlling for fuel prices and AFV determinants yields a DD estimate of 28.47 gCO2/km or -13.89 mpg – see Specification 2 –, both significant at the one percent level. Further introducing interactions between AFV determinants and a GCR dummy hardly changes the results, see Specification 3.[20]

Since most of the action in the AFV segment comes from FFVs, one could argue that the right treatment and control groups to be considered are, respectively, FFVs and captive 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.[21] Thus, Specifications 4-5 focus on two sub-samples of the data: while the former considers only Gasoline and FFV vehicles, the latter considers only Gasoline and Electric and CNG hybrids. While Specification 5 returns estimates which are not only small but also insignificant, those of Specification 4 are very close to those of Specification 1: at 16.23 gCO2/km or -2.57 mpg, both of which are significant at the five percent level, they imply that 75 percent (=16.23/21.48) of the AFV-RFV increase in CO2 emissions in the supply-side comes from FFVs as compared to captive gasoline models. That is, the combined role played by diesel, CNG and electric vehicles amounts to just 25 percent of changes in CO2 emissions.

Once post-GCR effects are decomposed into separate ones for years 2008 and 2009, the robust finding is that these responses strengthen over time, see Panel B (each column in Panel B is to be compared to the corresponding one in Panel A); this can be attributed to the extra time carmakers had to react when planning their model-year 2009 product lines. In particular, while there is mixed evidence that the effects for model-year 2008 are significant, those for model-year 2009 are significant and very close to each other, regardless of the controls used. What is more, the sub-sample results obtained in Panel A, according to which the post-GCR developments mostly happen in the FFV segment, follow through in this case.

All in all, the above findings support the view that lax constraints placed on AFVs 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 from the part of carmakers. Finally the results also show that the reactions to the GCR seem to have concentrated in the FFV segment.

[20]Note also that introducing these controls considerably improves the explanatory power of the specifications, as measured in terms of the CO2 emission regressions R-squared, from one to over 14 percent, and even more so for mpg regressions.

[21]In addition, to protect against corrosion, the conversion requires an extra coating of all parts in contact with the fuel, since ethanol contains water. There are also some fixed, conversion, costs to be considered, as carmakers need to calibrate engine settings, eg. the engine's compression ratio, before launching an FFV version derived from a captive gasoline model.

6.2 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 to 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 decompose "long-run" effects of the policy into separate ones for product lines 2008 and 2009, denoted by Γ_{LR1} and Γ_{LR2}, respectively.

All specifications in Panel A of Table 3 report a short-run effect (captured by the interaction of the AFV indicator with an indicator for the period April-December/2007) and a long-run effect (captured by the interaction of the AFV indicator with an indicator for the period January 2008 until June 2009). Specification 1, which does not have any controls, has an insignificant estimate for year 2007 and a significant one of 24.60 gCO2/km (-6.08 mpg) for 2008 onwards, which amounts to 12.5 percent of the emission levels of the median 2006 vehicle.

As both consumers and carmakers are likely to consider operating costs when purchasing and designing an automobile, respectively, Specifications 2-3 do control for fuel prices via fuel-time fixed-effects. Qualitatively, the short- and long-run affects are similar to those for Specification 1, even though the long-run estimates become milder as more controls are introduced, eg. emissions increase by 19.22 gCO2/km and fuel economy decreases by -3.77 mpg for Specification 3. The significant increases in emissions (decreases in fuel economy) from model-year 2008 suggests that once product lines were adjusted, consumers went for less fuel-efficient vehicles.

TABLE 3 ABOUT HERE

The above findings beg the question of where these product line adjustments are coming from. By comparing Specifications 1 and 4, one can infer the role of adjustments in the intensive vs. extensive margins. Interestingly, since by using only the products available pre-GCR one is by construction not allowing any kind of selection into treatment, the results in Specification 4 provide a lower bound to the effects of the GCR, ie. an estimate of the intensive margin of the GCR effects. Qualitatively, these effects are similar and one cannot reject the null of equality of effects at the 5 percent significance level, but at 16.75 gCO2/km – or -4.04 mpg – the estimates based only on the products available pre-GCR are (not surprisingly) somewhat milder than those in Specification 1. In fact, back-of the-envelope calculations based on the point estimates of Specifications 1 and 4 suggest that the bulk of the adjustment in product lines – roughly 70 percent – is due to adjustments in the intensive margin (adjustment of characteristics of, say, an AFV already available pre-GCR) rather than in the extensive margin (introduction of new products, ie. model-fuel combinations, in particular in the AFV segment). This evidence is consistent with the view that there is limited scope to think about contamination of the treatment group due to self-selection into treatment, ie. endogeneity of the AFV dummy.

Finally, sub-samples of Gasoline and FFVs (Specification 5) and Gasoline, CNG and Electric vehicles (Specification 6) yield estimates in the spirit of those for the supply-side, namely implying that the bulk of post-GCR changes do happen in the FFV segment. In particular, point estimates for Specification 5 are about 95 percent of those obtained for the full sample as compared to 75 percent when looking at the supply-side, which suggests that consumers played an active part in flocking towards (high-emission) FFVs, as already apparent when from Figure 2.

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 ones, it is natural to consider those two effects separately, and this is precisely what Specifications 1-6 in Panel B do (each specification in Panel B is directly comparable to its Panel A counterpart). Overall, the results show that the effects of the GCR on CO2 emissions and fuel economy are insignificant in the short-run and strengthen over time when it comes to the long-run: these may or may not be significant for 2008, but are significant throughout for 2009, eg. 32.44 gCO2/km (-7.88 mpg) as per Specification 1. As before, the results are robust to the inclusion of controls and alternative definitions of treatment and control groups.

The long-run responses are very much in line with what one would expect. That is, given the extended period carmakers had to think things through and re-engineer their vehicles, and consumers had to understand the GCR's features, results in DD point estimates are larger for 2009 than 2008. More specifically, while 2008 estimates may or may not be significant, all of the 2009 DD estimates are statistically significant. As before, confining the analysis to those models available pre-GCR results in somewhat lower point estimates, but the qualitative results are unchanged. In particular, the evidence suggests that consumers were only too keen to purchase high-emission AFVs made available by carmakers via adjustment of their product lines in the intensive or extensive margins. In sum, this findings suggest agents working against the very objectives of the GCR.

6.3 Discussion

The above results beg the question of where precisely the variation in the data identifying the DD estimates is coming from, ie. the mechanism by which CO2 emissions increase in AFVs as compared to RFVs. 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. (From Table A1, no FFV emitted less than 120 gCO2/km during the sample period in the data.)

On the supply-side, the asymmetric treatment enjoyed by AFVs and RFVs 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 AFVs *vis-à-vis* RFVs are positive and significant. Moreover, back-of-the-envelope calculations suggest that most of the reactions by carmakers were in the intensive margins, ie. re-engineering existing models rather than introducing new variants.

Using registration data, the first robust finding has to do with the distinction between short- and long-run effects. In the short-run, when facing product lines introduced prior to the GCR, not much happens when comparing AFVs and RFVs. However, carmakers react to the new regulation and adjust their product lines accordingly; while reactions may or may not be statistically insignificant for year 2008, whose product line is introduced a few months after the GCR is put in place, 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, once carmakers adjusted their product lines to the new policy, thus providing consumers with an adjusted choice set, consumers were more likely to purchase these vehicles tinkered with –typically an FFV– in detriment of a high-emission RFV. Importantly, note that the effects of product introduction looking at sales-weighted data are always larger than those obtained using supply-side data, suggesting the importance of consumer reactions to the policy. Intuitively, this can be rationalized by the fact 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 7 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 (2013) 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 vehicles.)

7 Fuel Choice by 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. 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.

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 3.[22] In contrast to 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 3. 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 premium becomes negative, in October 2008, ethanol sales plummet, suggesting that fuel arbitrage is substantial among FFV owners.[23] 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 most fuel stations supply at least one alternative fuel (second only to Brazil worldwide), typically ethanol.

FIGURE 3 ABOUT HERE

7.1 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

[22] 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.

[23] 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.

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.[24] 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 3B. 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.

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 4 ABOUT HERE

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

The aggregate demand function for ethanol, which is depicted in Figure 4, 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).

Needless to say, this is a highly-stylized, short-run model. That is, it assumes away important issues such as heterogeneity in vehicle-kilometers travelled, kilometres-per-liter, and the rebound effect, mostly due to the lack of data. Note, however, that 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.

7.2 Implementation

In an ideal setting one would want to econometrically 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 given the lack of more (disaggregate) data, and 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.[25] This allows obtaining vehicle-kilometers traveled at month t, $vkt_t^{\theta_i}$ 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 both 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

$$
Q_{et} = \frac{\sigma_e \chi N_t}{kpl_e}
$$

[25] Faced with the possibility to switch between fuels, one would expect the price elasticity of fuel (gasoline and 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.

$$Q_{gt} = \frac{\sigma_g \chi N_t}{kpl_g} + \frac{\sigma_a \chi N_t}{kpl_g} + \widetilde{q}_G$$

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.

7.3 Shares of Consumer Types

In what follows, I describe the calibration of the model defining $\sigma = (\sigma_a, \sigma_e, \sigma_g)$.[26] 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

[26] 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.

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 4 ABOUT HERE

The results are reported in Table 4 (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).[27]

Panel A in Table 4 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.

7.4 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 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

[27] 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.

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 4 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.[28]

Discussion Stepping back, the results reported in Table 4 suggest a low share of ethanol-lovers, 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 GCR, an environmental policy which had an unprecedented impact on the automobile market and embraced alternative fuels and vehicles. Specifically, it disentangles the reactions of consumers and carmakers to the program by comparing CO2 emissions and fuel economy levels of alternative and regular fuel vehicles.

Had the aim of the policy been merely to increase the adoption of green cars, it would have been considered a success, since it raised market shares of this segment from 6 percent in 2006 to

[28] 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, when FFVs commanded about 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.

26.5 percent in 2008. However, the paper documents that one by-product of the GCR is that CO2 emission levels of AFVs 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. This so happens because of the asymmetric treatment dispensed to alternative and regular fuel vehicles, whereby the latter received a much stricter treatment than the former to qualify as a green car and be eligible for the $1,500 rebate. Specifically, it induced carmakers to adjust their product lines to this regulatory loophole, which resulted in higher emission AFVs *vis-à-vis* their regular counterparts. What is more, since most FFV owners do arbitrage across fuels and purchase the cheapest between gasoline and ethanol, this is likely to result in increased air pollution levels.

Empirically, I unveil the role of technology and identify the mechanism by which consumers and carmakers react to loophole created by the GCR. On the supply-side, the wedge between CO2 emissions (fuel economy) of AFVs and those of RFVs increased in a non-trivial way following the GCR, especially in model-year 2009.

Looking at registration data, I find evidence of an insignificant effect in the months right 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, did not seem to react to AFVs any differently to RFVs. However, following the introduction of the 2008 and especially 2009 product lines, consumers facing an adjusted choice set were more likely to purchase high-emission AFVs. Importantly, the results point to the predominant role of the intensive (re-engineered versions of products existing prior to the GCR) over the extensive margin (product introduction).

The paper also proposes a stylized 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 bringing the model to 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 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. In short, policymakers have been held hostages of the FFV technology thanks to the way regulation was designed.

The above findings – which provide insights for most alternatives to fossil fuels, not only ethanol – have a number of policy implications. First, 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.

Second, 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.

Third, 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, by highlighting how both carmakers and consumers reacted to the policy in ways that worked against its very objectives, the paper stresses the challenge of policy design in the transport sector. A good policy has to take into account the technologies being regulated and the different adjustment margins (intensive, extensive, fuel switching) involved. A fuel 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.

References

[1] Adamou, A., S. Clerides and T. Zachariadis (2011). Environmental and Economic Effects of CO2-based Automobile Taxes in Germany. Working paper.

[2] Anderson, S. T. (2012). The Demand for Ethanol as a Gasoline Substitute. *Journal of Environmental Economics and Management* 63, 151-168.

[3] Anderson, S., and J. Sallee (2011). Using Loopholes to Reveal the Marginal Cost of Regulation: The Case of Fuel-Economy Standards, *American Economic Review* 101, 1375-1409.

[4] Anderson, S., I. Parry, J. M. Sallee, and C. Fischer (2011). Automobile Fuel Economy Standards: Impacts, Efficiency, and Alternatives. Working paper.

[5] ANFAC (2010). European Motor Vehicle PARC 2008. European Automobile Manufacturer's Association (ACEA).

[6] Auffhammer, M., and R. Kellogg (2011). Clearing the Air? The Effects of Gasoline Content Regulation on Air Quality. *American Economic Review* 101, 2687–2722.

[7] Bento, A., L. Goulder, M. Jacobsen, and R. von Haefen (2009). Distributional and efficiency impacts of increased U.S. gasoline taxes. *American Economic Review* 99, 667-699.

[8] Beresteanu, A. and S. Li (2011). Gasoline Prices, Government Support, and the Demand for Hybrid Vehicles. *International Economic Review* 52, 161-182.

[9] Berman, E. and L. Bui (2001). Environmental regulation and Productivity: Evidence from Oil Refineries. *Review of Economics and Statistics* 83: 498-510.

[10] Berry, S., J. Levinsohn, and A. Pakes (1995). Automobile Prices in Market Equilibrium. *Econometrica* 63, 841-890.

[11] Borenstein, S. (1993). Price Incentives for Fuel Switching: Did Price Differences Slow the Phase-Out of Leaded Gasoline? POWER Working Paper #PWP-010, University of California Energy Institute.

[12] BTS (2011). National Transportation Statistics. Washington, DC, US. Bureau of Transportation Statistics.

[13] Busse, M., C. Knittel and F. Zettelmeyer (2009). Pain at the Pump: The Differential Effect of Gasoline Prices on New and Used Automobile Markets, NBER Working Paper No. 15590.

[14] Busse, M., J. Silva-Risso, and F. Zettelmeyer (2006). $1,000 Cash Back: The Pass-Through of Auto Manufacturer Promotions. *American Economic Review* 96, 1253-1270.

[15] Chandra, A., S. Gulati and M. Kandlikar (2010). Green Drivers or Free Riders? An Analysis of Tax Rebates for Hybrid Vehicles. *Journal of Environmental Economics and Management* 60, 78-93.

[16] Chay, K. Y. and M. Greenstone (2003). The Impact of Air Pollution on Infant Mortality: Evidence from Geographic Variation in Pollution Shocks Induced by a Recession. *Quarterly Journal of Economics*, 2003, 118: 1121-1167.

[17] Corts, K. S. (2010). Building Out Alternative Fuel Retail Infrastructure: Government Fleet Spillovers in E85, *Journal of Environmental Economics and Management* 59, 219-234.

[18] Davis, L. W. (2008). The Effect of Driving Restrictions on Air Quality in Mexico City. *Journal of Political Economy* 116, 38-81.

[19] EFTE (2009). Reducing CO2 Emissions from New Cars: A Study of Major Car Manufacturers' Progress in 2008. Brussels, Belgium. European Federation for Transport and Environment

[20] Goldberg, P. K. (1995). Product Differentiation and Oligopoly in International Markets: The Case of the U.S. Automobile Industry. *Econometrica* 63, 891-951.

[21] Harrington, W., I. Parry and M. Walls (2007). Automobile Externalities and Policies. *Journal of Economic Literature* 45, 374-400.

[22] Heckman, J. J., and V. Hotz (1989). Choosing Among Alternative Nonexperimental Methods for Evaluating the Impact of Social Programs, *Journal of the American Statistical Association* 84, 862-880.

[23] Holland, S. P., J. E. Hughes, and C. R. Knittel (2009). Greenhouse Gas Reductions under Low Carbon Fuel Standards?, *American Economic Journal: Economic Policy* 1, 106-146.

[24] Holland, S. P., Hughes, J. E., C. R. Knittel and N. Parker (2011). Some Inconvenient Truths About Climate Change Policy: The Distributional Impacts of Transportation Policies, NBER working paper.

[25] Holmes, T. (1998). The Effect of State Policies on the Location of Manufacturing: Evidence from State Borders. *Journal of Political Economy* 106: 667-705.

[26] Hughes, J. E., C. R. Knittel and D. Sperling (2008). Evidence of a Shift in the Short-Run Price Elasticity of Gasoline, *The Energy Journal* 29, 113-134.

[27] Huse, C., and N. Koptyug (2013). Bailing On The Car That Wasn't Bailed Out: Bounding Consumer Reactions to Financial Distress. Working paper.

[28] Huse, C. and C. Lucinda (2013). The Market Impact and the Cost of Environmental Policy: Evidence from the Swedish Green Car Rebate. Forthcoming in the *Economic Journal*.

[29] IEA (2011a). CO2 Emissions from Fuel Combustion. Paris, France. International Energy Agency.

[30] IEA (2011b). World Economic Outlook. Paris, France. International Energy Agency.

[31] Jacobson, M. S. (2007). Effects of ethanol (E85) versus gasoline on cancer and mortality in the United States. Environmental Science & Technology 41, 4150-4157.

[32] Kahn, M. E. and E. T. Mansur (2010). How Do Energy Prices, and Labor and Environmental Regulations Affect Local Manufacturing Employment Dynamics? A Regression Discontinuity Approach, NBER Working Papers 16538, National Bureau of Economic Research, Inc.

[33] Klier, T., and J. Linn (2010). The Price of Gasoline and New Vehicle Fuel Economy: Evidence from Monthly Sales Data. *American Economic Journal: Economic Policy* 2, 134–53.

[34] Klier, T. and J. Linn (2012). "New Vehicle Characteristics and the Cost of the Corporate Average Fuel Economy Standard", *RAND Journal of Economics* 43 (1), 186-213.

[35] Knittel (2011). Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector. *American Economic Review* 101, 3368-3399.

[36] Li, S., J. Linn, and E. Spiller (2011). Evaluating "Cash-for-Clunkers": Program Effects on Auto Sales and the Environment, *Journal of Environmental Economics and Management* 65 (2), 175–193.

[37] Li, S., C. Timmins, and R. von Haefen (2009). How Do Gasoline Prices Affect Fleet Fuel Economy? *American Economic Journal: Economic Policy,* 1: 113–37.

[38] Ministry of the Environment (2007). Press release: The Government introduces a green car rebate. Retrieved from http://www.regeringen.se/sb/d/586/a/79866

[39] Ministry of the Environment (2008a). Press release: Klimat- och energisatsningar I budgetpropositionen 2009. Retrieved from http://www.regeringen.se/sb/d/119/a/110590

[40] Miravete, E. J., and M.J. Moral (2009). Qualitative Effects of Cash-For-Clunkers Programs. Working paper UT Austin.

[41] National Geographic (2007). Did You Know?, October 2007. http://ngm.nationalgeographic.com/2007/10/biofuels/did-you-know-learn, accessed January 10, 2014.

[42] Olson, M. (1965). *The Logic of Collective Action: Public Goods and the Theory of Groups*. Harvard University Press.

[43] Peltzman, S. (1976). Toward a More General Theory of Regulation. *Journal of Law and Economics* 19, 211-240.

[44] Sallee, J. M. (2011a). The Taxation of Fuel Economy. *Tax Policy and the Economy* v. 25, Editor Jeffrey R. Brown, NBER: University of Chicago Press, 1-38.

[45] Sallee, J. M. (2011b). The Surprising Incidence of Tax Credits for the Toyota Prius. *American Economic Journal: Economic Policy* 3, 189-219.

[46] Sallee, J. M., and J. Slemrod (2011). Car Notches: Strategic Automaker Responses to Fuel Economy Policy. *Journal of Public Economics* 96(11), pages 981-999.

[47] Salvo, A., and C. Huse (2011). Is Arbitrage Tying the Price of Ethanol to that of Gasoline? Evidence from the Uptake of the Flexible-Fuel Technology, *Energy Journal* 32, 119-148.

[48] Salvo, A., and C. Huse (2013). Build It, But Will They Come? Evidence from Consumer Choice Between Gasoline and Sugarcane Ethanol, *Journal of Environmental Economics and Management* 66, 251-279.

[49] SFS (2005). Lag (2005:1248) om skyldighet att tillhandahalla förnybara drivmedel, Retrieved from http://www.riksdagen.se/Webbnav/index.aspx?nid=3911&bet=2005:1248

[50] SFS (2007). Förordning (2007:380) om miljöbilspremie, Retrieved from http://www.riksdagen.se/Webbnav/index.aspx?nid=3911&bet=2007%3A380

[51] Small, K. A., and K. Van Dender (2007). Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect. *Energy Journal* 28, 25-52.

[52] Stigler, G. J. (1971). The Theory of Economic Regulation. *Bell Journal of Economics* 2, 3-21.

[53] Swedish Consumer Agency (2004-2011). Nybilsguiden.

[54] The Telegraph (2008). Ford Model T reaches 100. http://www.telegraph.co.uk/motoring/news/2753506/Fo Model-T-reaches-100.html, accessed on January 10, 2014.

[55] Trafikverket (2011). Uppdaterade reduktionsvärden för etanol- och gasfordon till bilindex. Retrieved from http://www.trafikverket.se/PageFiles/25435/nov10/04-2011_PM%20uppdaterade%20reduktionsv%C3%A4rden110308.pdf

[56] Whitefoot, K. S., M. Fowlie, and S. J. Skerlos (2013). "Compliance by Design: Industry Response to Energy Efficiency Standards", Working Paper University of California at Berkeley.

[57] Yanowitz, J., and R. L. McCormick (2009). Effect of E85 on Tailpipe Emissions from Light-Duty Vehicles. *Journal of the Air & Waste Management Association* 59, 172-182.

A Robustness Checks

A.1 Econometric Analysis

For both the supply-side and sales-weighted analysis, 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.

Supply-side Analysis I have also estimated versions of the reported specifications using 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 alternative treatment and control groups, eg. comparing 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 the exercise 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, 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.

B Descriptive Statistics

Table A1 provides summary statistics disaggregated by the fuel segment level. 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 A1 ABOUT HERE

The figures for the diesel segment are 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*.[29] However, the descriptive

[29] 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.

evidence in Table A1 and exploratory analysis performed does not lend support to the view that carmakers introduced models whose CO2 emission bunched at the 120 gCO2/km threshold. In fact, the figures for low-emission gasoline and diesel vehicles do not seem to change by much from 2006 (or earlier, in the case of gasoline) to 2009.

Although not representing a major share of the market, notice that average CO2 emissions of Gasoline/CNG and Gasoline/Electric (both of which are AFVs) actually increased following the GCR. Although this finding also holds for FFVs, the most striking feature, however, seems to be the fact that no low-emission FFV was introduced at any time during the sample period, despite the introduction of a number of low-emission captive gasoline vehicles, which share their technology with FFVs.

TABLE 1 – Summary Statistics of the Swedish Car Market

	Sweden	France	Germany
Fleet Size and Penetration			
Passenger car fleet, millions (2008)	4.3	30.9	41.3
Passenger cars per 100 inhabitants (2008)	46.3	49.5	50.4
Share of households with a vehicle (%, 2006)	84.5	82	NA
Average Vehicle Characteristics			
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
Share of passenger cars able to run on fuels other than gasoline and diesel (%, 2008)	3.8	0	0.9
Age Distribution of Car Fleet			
Share of cars $\leq$ 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 Results

Panel A: Post-GCR DD Estimates

Fuels:	[1] All	[2] All	[3] All	[4] FFV,G	[5] G,CNG,El
$1\{y \geq 2008\} \times 1\{i \in \aleph\}$	21.48***	28.47***	27.78***	16.23**	-0.22
	(5.00)	(2.92)	(2.74)	(2.23)	(-0.02)
	[−4.16]***	[−13.89]***	[−13.82]***	[-2.57]**	[0.06]
Fuel-Year FEs		√	√		
AFV Det.		√	√		
AFV Det.×GCR			√		
N	9,686	8,110	8,110	6,594	6,498
R-squared	.012	.143	.147	.007	.011

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

Fuels:	[1] All	[2] All	[3] All	[4] FFV,G	[5] G,CNG,El
$1\{y = 2008\} \times 1\{i \in \aleph\}$	16.66***	34.14	33.91	12.50**	-8.03
	(2.75)	(1.43)	(1.50)	(2.11)	(−0.51)
	[-3.25]***	[−11.40]	[-11.13]	[-2.03]**	[2.06]
$1\{y = 2009\} \times 1\{i \in \aleph\}$	25.86***	28.77***	26.43***	19.85**	5.76
	(5.56)	(3.07)	(2.80)	(2.25)	(0.42)
	[−4.96]***	[−13.79]***	[−13.11]***	[−3.10]**	[−1.32]
Fuel-Year FEs		√	√		
AFV Det.		√	√		
AFV Det.×GCR			√		
N	9,686	8,110	8,110	6,594	6,498
R-squared	.014	.143	.147	.008	.012

Note: This table reports estimates of the effect of the GCR on engine CO2 emissions (measured in gCO2/km) and mpg (point estimates reported within square brackets) of AFVs as compared to RFVs using supply-side data recorded at the yearly frequency. For each panel, Column 1 reports results for the full sample (all fuels, 2005-2009) without any controls. Columns 2 and 3 introduce Fuel-year fixed-effects to account for fuel price trends, determinants of offering an AFV, and their interaction with a GCR dummy. Columns 4-5 are counterpart of Column 1: while Column 4 considers only FFV and Gasoline vehicles, Column 5 considers only Gasoline, CNG and Electric vehicles. Standard errors are clustered by brand, with t-statistics reported in parentheses. Significance levels at 10, 5 and 1 percent are denoted by *,** and ***, respectively. R-squareds of mpg regressions are .014, .277, .282, .007, .019 (Panel A) and .016, .277, .282, .009, .021 (Panel B).

TABLE 3 – Registration-based Emission Levels

Panel A: Post-GCR DD Estimates

Fuels:	[1] All	[2] All	[3] All	[4] pre-GCR	[5] FFV,G	[6] G,CNG,El
$1\{t \in \Gamma_{SR}\} \times 1\{i \in \aleph\}$	2.65	-7.30	-7.31	2.17	1.88	-10.70
	(0.41)	(-0.72)	(-0.76)	(0.48)	(0.26)	(-0.62)
	[1.48]	[0.93]	[0.89]	[−1.31]	[−1.11]	[2.58]
$1\{t \in \Gamma_{LR}\} \times 1\{i \in \aleph\}$	24.60***	22.35***	19.22***	16.75***	23.46***	1.555
	(5.23)	(4.03)	(2.86)	(3.67)	(4.08)	(0.11)
	[−6.08]***	[−4.74]***	[−3.77]***	[−4.04]***	[−4.97]***	[1.08]
Fuel-Time FEs		√	√			
AFV Det.		√	√			
AFV Det.×GCR			√			
N	588285	522779	522779	499296	469282	421456
R-squared	.055	.151	.164	.034	.048	.062

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

Fuels:	[1] All	[2] All	[3] All	[4] pre-GCR	[5] FFV,G	[6] G,CNG,El
$1\{t \in \Gamma_{SR}\} \times 1\{i \in \aleph\}$	2.65	−7.29	−7.30	2.17	1.88	−10.70
	(0.41)	(−0.72)	(−0.76)	(0.48)	(0.26)	(−0.62)
	[−1.48]	[0.93]	[0.89]	[−1.31]	[−1.11]	[2.58]
$1\{t \in \Gamma_{LR1}\} \times 1\{i \in \aleph\}$	21.12***	16.07*	12.48	13.36**	20.06***	−2.84
	(6.20)	(1.88)	(1.20)	(2.29)	(4.46)	(−0.20)
	[−5.28]***	[−3.32]**	[−2.24]	[−3.19]**	[−4.29]***	[2.14]
$1\{t \in \Gamma_{LR2}\}.1\{i \in \aleph\}$	32.44***	32.86***	30.44***	25.60***	31.67***	17.96
	(3.67)	(3.84)	(3.46)	(5.25)	(3.14)	(1.40)
	[−7.88]***	[−7.13]***	[−6.32]***	[−6.29]***	[−6.61]***	[−3.09]
Fuel-Time FEs		√	√			
AFV Det.		√	√			
AFV Det.×GCR			√			
N	588285	522779	522779	499296	469282	421456
R-squared	.057	.153	.166	.036	.050	.064

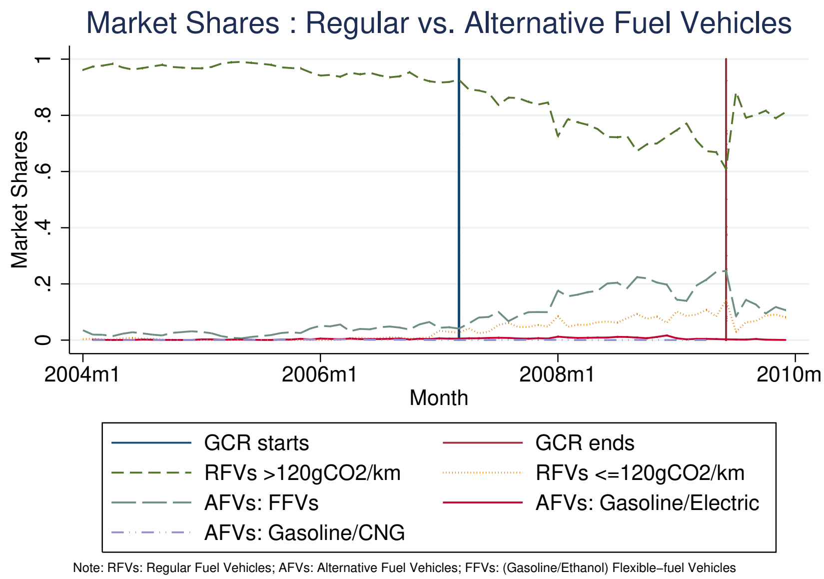
Note: This table reports estimates of the effect of the GCR on engine CO2 emissions (measured in gCO2/km) and mpg (reported within square brackets) of AFVs as compared to RFVs using registration recorded at the monthly frequency. For each panel, Column 1 reports results for the full sample (all fuels, 2005-2009) without any controls. Columns 2 and 3 introduce Fuel-time fixed-effects to account for fuel price trends, determinants of offering an AFV, and their interaction with a GCR dummy. Columns 4-6 are counterparts of Column 1: Column 4 considers only models available pre-GCR (ie. model-fuel combinations launched up to model-year 2006), Column 5 considers only FFV and Gasoline vehicles whereas Column 6 considers only Gasoline, CNG and Electric vehicles. Note that the effects of Specification 4 or Specification 5 in each Panel are contained within the 95 percent confidence interval of the corresponding Specification 1. Standard errors are clustered by brand, with t-statistics reported in parentheses. Significance levels at 10, 5 and 1 percent are denoted by *,** and ***, respectively. R-squareds of mpg regressions are .087, .289, .307, .053, .070, .096 (Panel A) and .089, .291, .309, .056, .073, .099 (Panel B).

TABLE 4 – 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 (km per month)	1,500	1,500	1,750	2,000	2,000	2,000
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 (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 air pollutant concentrations (%)						
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).

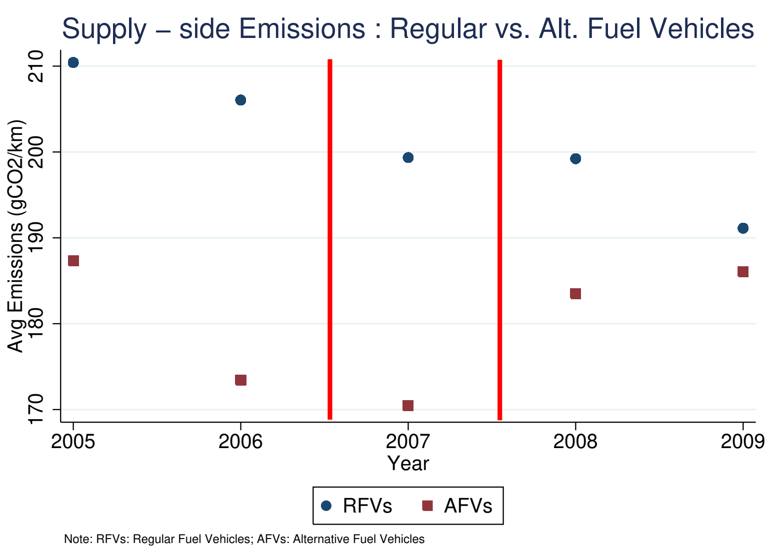
FIGURE 1 – Market Shares Disaggregated by Fuel Segments



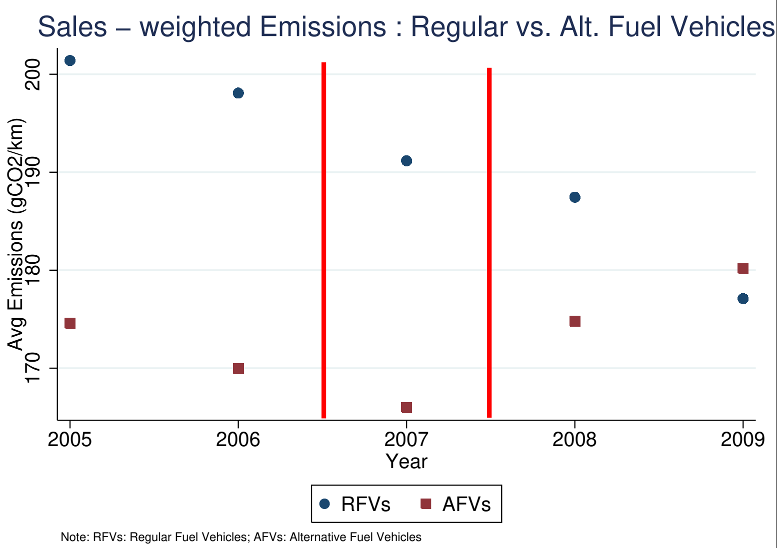
Note: This figure depicts market shares of passenger cars sold to private individuals in the Swedish car market at the monthly frequency disaggregated by fuel segment,, with the vertical bars denoting the start (April 2007) and the end (June 2009) of the GCR. Vehicles running on regular fuels are split 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 (AFVs) 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 AFV, 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) end of the GCR in June 2009, but no compelling evidence thereof at its start in April 2007.

FIGURE 2 – CO2 Emissions of Regular and Alternative Fuel Vehicles

Panel A: Supply-side CO2 Emissions



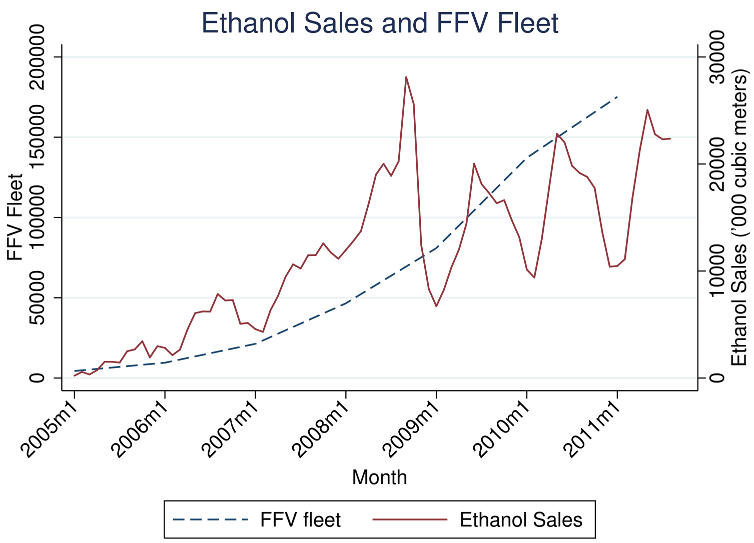
Panel B: Sales-weighted CO2 Emissions



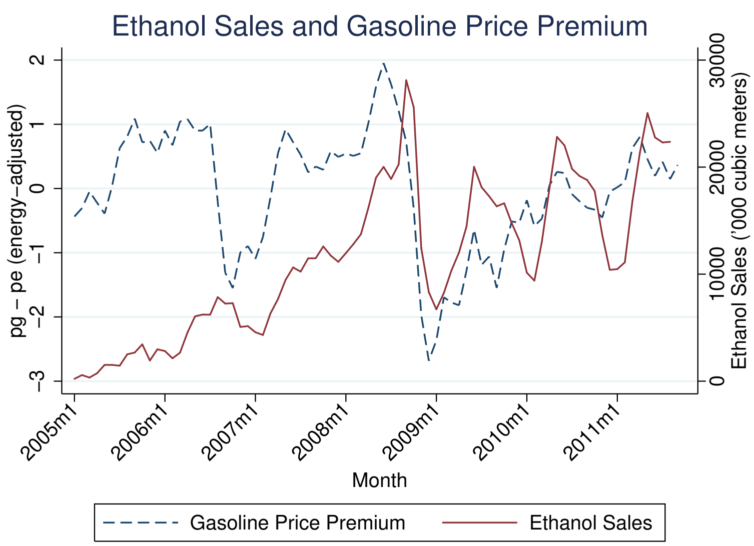
Note: This figure compares supply-side (Panel A) and sales-weighted (Panel B) CO2 emissions measured in gCO2/km of cars running on regular and alternative fuels at the yearly frequency. The first vertical bar in each graph divides the sample into a pre- and post-GCR periods (years 2005-6 and 2007-9, respectively) whereas 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 the existence of common trends pre-GCR, not rejected in the data in either case and, following the GCR, an increasing trend in average CO2 emissions of AFVs as compared to a still decreasing trend for RFVs. While Panel A documents a purely supply-side effect, since all models marketed in a given year are given equal weight, Panel B shows a composition efect between supply and demand, thus having an equilibrium interpretation.

FIGURE 3 – 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)

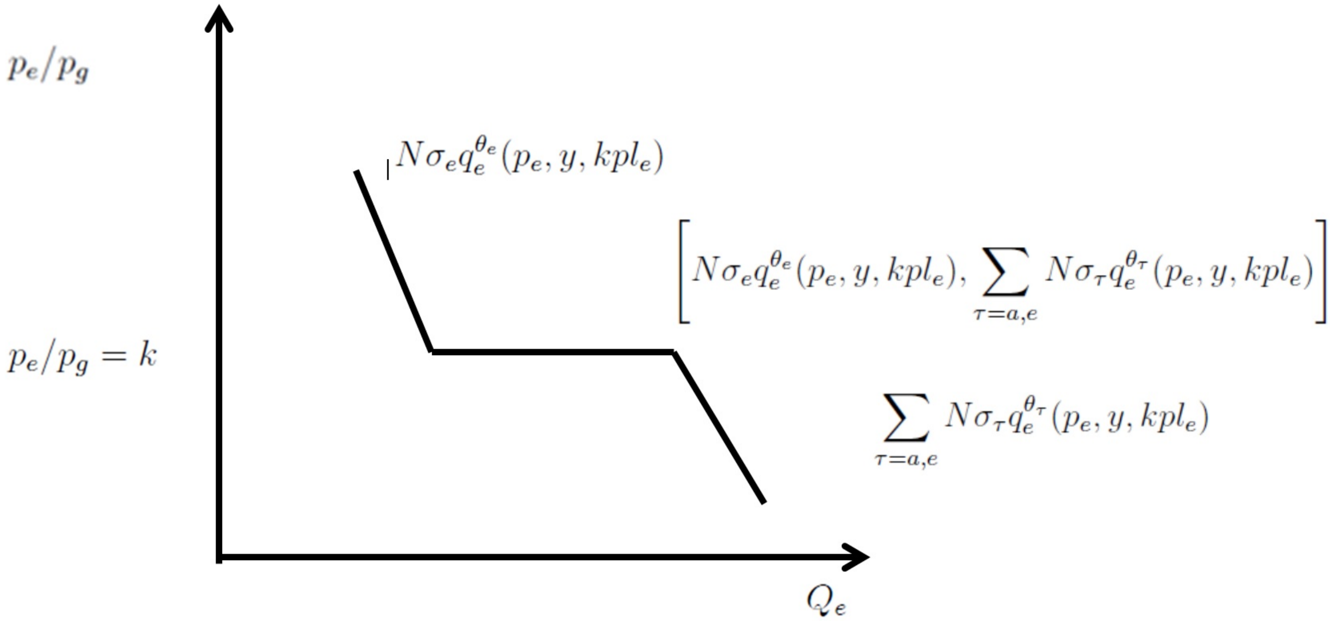


Panel B: Time series of volume sales of ethanol (in ‘000 cubic meters) and energy-adjusted gasoline price premium



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 behavior 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 4 – 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 (pe/pg>k), both ethanol-lovers and fuel arbitrageurs θ_a demand it when ethanol is priced below the parity level (pe/pg<k).

TABLE A1 – 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
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
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
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
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
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
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
FFV ≤ 120g				No models available			
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
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

Note: This table reports sample statistics of the distribution of engine CO2 emissions (measured in gCO2/km) disaggregated by fuel segment. For a given year, a model is a combination of brand-model-fuel. Sample statistics reported are mean emission levels and their standard errors, median emission levels and the interquartile range of emissions.