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

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February 2012

Abstract

Aiming at oil independence and lower greenhouse gas emissions, in 2007 Sweden introduced the Green Car Rebate, according to which newly-purchased vehicles satisfying certain emission criteria were eligible for a rebate. The lax treatment enjoyed by alternative (renewable) fuels as compared to regular (fossil) ones induced carmakers to introduce a number of high-emission alternative models, notably flexible-fuel vehicles (FFVs), which gained market share at the expense of high-emission regular vehicles. Building on the exogeneity of the policy, I quantify the change in CO2 emissions of alternative cars – these decrease only until carmakers react and adjust their product lines to the policy, providing consumers with an expanded choice set. I also propose a structural model of fuel choice of FFV owners and find evidence that fuel arbitrage is prevalent when calibrating it to market data, resulting in an 85 percent increase in lifecycle CO2 emissions following the 2008 oil price drop.

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

Keywords: CO2 emissions; Ethanol; Environmental policy; Flexible-fuel vehicles; Fuel economy; Governmental policy; Greenhouse gases; Renewable fuels.

*Preliminary, comments welcome. I thank Tobias Olsson for making data available, participants at the SSE Empirical Micro Workshop for feedback and Nikita Koptyug for detailed comments.

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1 Introduction

Oil supplies most of the energy in transportation worldwide. Burning oil releases greenhouse gases (GHG) into the atmosphere which are instrumental in driving climate change. The implications of GHG emissions such as CO2, the predominant GHG linked to global warming, have been much debated in recent times, but local air pollutants such as nitrogen oxides (NOx) and particulate matter (PM) are also well-known to harm human health. Among the main polluters is road transport, which is responsible for about 20 percent of the CO2 emissions generated by fuel consumption worldwide (IEA 2011a). What is more, while transport fuel demand is set to grow by 40 percent by 2035, 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). Within the European Union (EU) passenger cars are responsible for about 12 percent of the overall emissions while within Sweden this share is a much higher 19 percent due to one of the most fuel-devouring car fleets on the continent (Commission of the European Communities 2007). Reducing emissions from passenger cars is thus essential for Sweden to meet EU-wide environmental goals.[1]

Environmental Policy This paper investigates the causal effect of an environmental policy launched by the Swedish government on CO2 emissions and fuel economy (mpg). Reducing oil consumption in transportation involves increasing fuel economy standards of the means of transport and/or investing in alternative fuels and technologies for the transportation sector – the Swedish "Green Car Rebate" (GCR) introduced in April 2007 combines both.[2]

The objectives of the GCR were twofold, namely promote the reduction of GHG emissions of newly-registered cars and reduce oil dependence. These aims were to be achieved through a rebate given to individuals purchasing environmentally friendly cars, the so called *green cars*.[3]

Compared to other policies worldwide, the GCR has two distinguishing features of note. First, its general character – in contrast with what typically happens in North America and elsewhere (see Sallee 2010), where no existing policy has applied widely enough to affect a large fraction of the new vehicle market. Second, the focus on alternative (renewable) fuels to tackle both GHG emissions and oil dependence.[4]

The GCR defined green cars according to which fuels a vehicle is able to run on and on how much CO2 it emits. While cars able to run only on fossil fuels such as gasoline and diesel – the so called *regular fuels* – were considered green cars provided they emitted no more than 120 gCO2/km, those able to run on *alternative fuels* (ethanol, gas and electricity) were given a more lenient treatment.

Had the objective of the policy merely been the dissemination of green cars, especially those able to run on alternative fuels, the GCR could be considered a success: from its introduction in 2007 to 2008, the number of green car models available on the market increased from 73 to 120, of which 54 were alternative green cars. When it comes to FFVs (flexible-fuel cars), the leading alternative cars

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

[2] Parry, Harrington, and Walls (2007) provide a thorough review of externalities associated with road transport and gasoline consumption, as well as a discussion of policy instruments.

[3] The rebate consisted of a transfer of 10,000 SEK to private individuals upon the purchase of a "green car". The SEK/USD exchange rate was 6.984 and 7.650 at the inception and at the end of the program, respectively, thus varying in the range USD 1,300-1,500. The value of the rebate corresponds to 6-7 percent off the price of a new VW Golf 1.6.

[4] Anecdotal evidence suggests that the skew towards renewables was inspired by Brazil, whose CO2 emissions per unit of fuel consumption in road traffic are 20 percent below the world average (IEA 2011a). It then comes as no surprise the fact that Sweden has based its policies on ethanol.

which can seamlessly switch between gasoline and ethanol, the number of models offered grew from 18 to 44 and the sales-weighted market shares grew from about 4 to 16 percent from 2006 to 2008.

The asymmetric treatment of regular and alternative green cars had profound effects on the relative CO2 emission levels – and thus fuel economy – between regular and alternative vehicles following the introduction of the GCR. More specifically, it induced carmakers to adjust their product lines accordingly resulting in larger, high-emission, vehicles running on alternative fuels *vis-à-vis* those running on regular ones. Moreover, and contrary to previous evidence, carmakers reacted swiftly to the new policy. What is more, since the leading alternative green cars are FFVs, motorists not only can, but actively do, arbitrage across fuels and purchase the cheapest fuel – not necessarily the renewable one – resulting in increased air pollution levels.

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

I also take advantage of the institutional setting of the automobile industry to disentangle short- and long-run effects of the policy. More specifically, while carmakers' product lines (consumer choice sets) for model-year 2007 were defined *before* the inception of the policy, those for model-year 2008 (and onwards) were defined *after* the policy was introduced. That is, following the inception of the policy, carmakers were unable to re-engineer their vehicles accordingly in 2007, so one would naturally expect to see only their 2008 product lines accounting for the GCR in some way. Building on the institutional setting, I focus on both the *short-run* effect of the GCR, which goes from April to December 2007 whereby consumers – but not carmakers – react to the policy, and a *long-run* effect starting from January 2008 whereby carmakers adjust their product lines and consumers react to both the policy (as in the short-run) *and* the new choice set they face.

Main Findings I start by examining the pattern of overall CO2 emissions and fuel economy (measured in mpg) over the sample period 2004-2009. In spite of the evidence of decreasing emissions (equivalently, increasing fuel economy) over the period, I do not find evidence that it has been triggered by the GCR. In fact, the robust finding across all specifications is that this trend seems to have started before the policy.

I then estimate the causal effect of the GCR on supply- and demand-side emissions and fuel economy of alternative as compared to regular vehicles. That is, using data on all models available on the market, I estimate supply-side effects of the policy, while registration information allows me to estimate sales-weighted – thus demand-side – effects of the GCR.

Focusing on the supply-side, I show descriptive and econometric evidence of how carmakers took advantage of the lax regulation towards alternative cars and reacted quickly by offering larger, high-emission, vehicles running on alternative fuels. In fact, my most conservative specification estimates a roughly 7 gCO2/km increase starting from model-year 2008 (approximately 4 percent of the emissions of the median 2008 car model), even after controlling for model-fuel-segment fixed-effects. When

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

decomposing this into separate effects for model-years 2008 and 2009, I obtain an insignificant estimate for the former and a significant one of roughly 10 gCO2/km for the latter (about 5.5 percent of the emissions of the median car model that year). This result provides evidence that carmakers have reacted to the policy in less than two years after its launch. Although at a faster pace, this is consistent with findings for the US, where Sallee (2010) and Sallee and Slemrod (2011) document how carmakers tended to react to CAFE standards by designing car-like vehicles to classify as trucks.

Looking at the demand-side, I find evidence of a short-run effect whereby consumers purchased green cars available on the market (typically low-emission vehicles) between the inception of the program (April 2007) and the rolling out of the 2008 product lines (roughly December 2007), which considerably expanded the available choice set.[6] The most conservative specification finds the short-run effect to be about -3.60 gCO2/km (or 0.31 mpg), even after controlling for model-fuel-segment fixed-effects.

The long-run effect of the policy, which accounts for carmakers adjusting their product lines is, however, suggestive that when faced with this enlarged choice set, consumers promptly reacted and were more likely to purchase the high-emission vehicles running on alternative fuels, which my most conservative specification estimates to be about 3 gCO2/km (or -0.5 mpg).

When this long-run effect for model-year 2008 onwards is decomposed into separate ones for model-years 2008 and 2009, the corresponding estimates are 2.68 and 3.75 gCO2/km, respectively, suggesting an increasing effect over time. Although at a different pace, this finding is consistent with Knittel (2011), according to which changes in US vehicle characteristics were driven by consumer preferences and the vast literature looking at demand for automobiles, according to which consumers value characteristics such as size (a proxy for comfort) and horsepower (Berry, Levinsohn and Pakes 1995, Goldberg 1995).

At the root of the problem lies the favorable treatment enjoyed by alternative fuels, in particular the dominant gasoline-ethanol FFV. FFVs can seamlessly switch between gasoline and ethanol (which are stored in the same tank) and allow their owners to arbitrage across fuels. The main reason why FFVs commanded the lion's share among alternative vehicles has to do both with the similarity with the standard Otto cycle technology (of which it is a derivative) and the well-developed retail network of ethanol, as opposed to, say, CNG (compressed natural gas), which is only available in parts of the country.

To illustrate the potential adverse effects of relying on FFVs, I gauge the fuel switching behavior among FFV owners combining a structural model of fuel choice and a recent exogenous shock to fuel prices. Following the 2008 recession and the sudden drop in oil prices, gasoline became cheaper than ethanol in energy-adjusted terms causing the monthly volume sales of ethanol to plummet by about 70 percent. To both rationalize and quantify the fuel switching behavior among FFV owners, I propose a stylized structural model of fuel choice. When taking the model to data, I find that for reasonable sets of parameter values a moderate share of FFV owners (17-41 percent) fuels only with ethanol. In contrast, while a small fraction of FFV owners (2-15 percent) will fuel only with gasoline, over half (57-81 percent) of FFV owners arbitrage 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 one.

The effects of fuel switching on air pollution are potentially dramatic in that lifecycle CO2 emissions by FFV owners increase by 85 percent, and emissions of NOx, particulate matter and carbon

[6] Within the first year of the GCR, the number of gasoline and diesel cars on the market qualifying as green increased from 10 and 33 to 18 and 48, respectively. The number of FFVs increased from 18 to 44 while the number of gas and electric hybrids went from 12 to 10, see Table 2 for details.

monoxide increase by 16, 36 and 18 percent, respectively. In sum, there is substantial evidence that the GCR was not much more than a transfer to purchasers of FFVs.

Related Literature This is (to my knowledge) the first paper to investigate a green car policy with a broad impact on the automobile market and a focus on alternative fuels. The paper most closely related to this one is perhaps Anderson and Sallee (2011), which looks at the incentives faced by carmakers when deciding to offer FFVs in the US market exploring a loophole in CAFE standards. In addition to the research cited above, the current relates to four streams of the literature. First, by disentangling the reactions of consumers and carmakers, and by pointing to the quick reaction of the latter, the paper contributes to the burgeoning literature on policies directed towards the transport sector, notably the automobile industry, see Adamou, Clerides and Zachariadis (2011), Beresteanu and Li (2009), Chandra, Gulati and Kandlikar (2010), Li, Linn and Spiller (2011), Miravete and Moral (2009), Sallee and Slemrod (2011).

Second, by focusing on the fuel choice of FFV owners, the paper relates to the literature focusing on the interaction between fuel and car markets, as in Borenstein (1993), Busse, Knittel and Zettelmayer (2009), Li, Timmins and von Haefen (2009), Linn and Klier (2007), and Sallee (2011).

Third, by calibrating a structural model of fuel choice for an entire market (as opposed to focusing on state-level data or micro data for a sample of consumers), the paper contributes to research on the choice between fossil and renewable fuels as in Anderson (2011), Corts (2010) and Salvo and Huse (2011, 2012). Contrary to what happens in the US, where Corts (2010) documents a low market penetration of ethanol due to a "chicken-and-egg problem", i.e. the lack of fueling infrastructure which hinders the dissemination of renewables, and vice-versa, Sweden has a well-developed network of fueling stations where ethanol is readily available. Infrastructure availability is, however, a necessary, but not sufficient condition for the adoption of renewable fuels, given the ability of FFV owners to arbitrage across fuels.

Finally, by focusing on the effects of fuel switching on air pollution and 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) and Davis (2008), and complements recent research in the natural sciences on the effects of ethanol on health, see Jacobson (2007) and Yanowitz and McCormick (2009).

The outline of the paper is as follows. Section 2 provides an overview of the market while Section 3 describes the datasets used. Sections 4 and 5 perform descriptive and econometric analyses of the policy whereas Section 6 provides a stylized structural model of fuel choice for FFV owners which allows me to back out the shares of different consumer types. Section 7 quantifies implications of fuel switching for air quality and the final section concludes.

2 Institutional Background

Despite its small size in absolute terms, the Swedish passenger car market in the mid-2000s is comparable to larger European countries such as France and Germany when looking at ownership on a per capita basis. In contrast with the variety of brands on the market, the commonplace view of the average family car being a Volvo wagon is not too far from reality in Sweden, 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 9.4 years old and 39.1 percent of the fleet was aged above 10 years, numbers significantly worse than those for France and Germany. 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). Sweden does however fare better than the US in terms of fuel economy: while the average fuel economy of the latter increased from 29.5 to 32.9 mpg in the period 2004-2009, in Sweden it improved from 31.2 to 38.7 mpg in the same period (see details below).

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 in 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 a well-developed distribution network whereby over 50 percent of fueling stations supply at least one renewable fuel in 2009, typically ethanol.

With the aim of reducing GHG emissions and reduce oil dependence, in April 2007 the Swedish government introduced a rebate scheme to promote environmentally friendly cars. Following the fall 2006 elections for the Swedish Parliament, a new government was formed which came to power later that year and proposed the GCR. The GCR program, which was passed in Parliament and announced to the public in March 2007, effectively starting in April 2007, consisted of a 10,000 SEK rebate off of the price of a newly purchased car.[7]

Crucially, the policy caught carmakers by surprise: carmakers typically launch product lines once a year, which requires carmakers to plan their overall strategy e.g. product positioning, advertising, 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, carmakers were only able to adjust their product lines only for model-year 2008, an institutional feature to be used in the identification strategy below.

Green Car Definition For the purposes of the GCR, the definition of a green car depends on compliance with certain emission criteria and on the type of fuel(s) the car is able to run on (SFS 2007). Cars running on regular fuels (fossil fuels such as gasoline and diesel) qualify as green cars provided they emit no more than 120 gCO2/km, whereas cars able to run on alternative fuels such as ethanol, gas and electricity do qualify provided they consume up to the gasoline-equivalent of 9.2 l/100km, the gas-equivalent of 9.7m3/100km or less than 37 kWh/100km, respectively.[8]

Although the thresholds defining regular and alternative fuel cars are expressed in different units (gCO2/km and l/100km) the CO2 emissions and fuel efficiency measures are highly negatively correlated: for vehicles marketed in Sweden, the correlation between CO2 emissions (in gCO2/km, the measure typically used within the EU) and mpg (miles per gallon, the measure typically used in the US) is -0.90, with the threshold for alternative fuels being equivalent to approximately 240 gCO2/km (for perspective, the 2012 Porsche 911 Carrera emits 205 gCO2/km).[9] All in all, the threshold defining alternative green cars is substantially more lenient than the one defining regular ones.

[7]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).

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

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

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) 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 lifecycle 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 (more on this below).

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

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

From the carmaker's perspective, introducing a FFV version of an existing model is a cheap and trivial task. All that is required is a sensor that detects the mix between ethanol and gasoline from the exhaust pipe fumes and sends a message to the vehicle's electronic central unit (ECU), which then adjusts the engine settings accordingly. Cost estimates of the operation are in the USD 100-150 range, roughly 10 percent of the value of the rebate. (See Anderson and Sallee 2011 and Salvo and Huse 2012 for details).

3 Data

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

Car Characteristics Product characteristics are obtained from the consumer guides "Nybilsguiden" (New Car Guide) issued yearly by The Swedish Consumer Agency (Konsumentverket). For every car model available on the Swedish market the information available includes characteristics such as fuel type, engine power and displacement, number of cylinders, number of doors, gearbox type, kerb weight, 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 gas 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 was generously provided by *Vroom*, a consulting firm. The data on privately owned vehicles is recorded at the monthly frequency from January 2004 to December 2009 which I aggregate to the yearly frequency. An observation is a combination of year, brand, model, engine size, fuel type, an indicator for green car and initially the zip code of the car owner, which I aggregate to the national level.

Fuel Data I use market level data for fuels recorded at the monthly frequency at the national level. Recommended retail fuel prices for gasoline, diesel and ethanol are obtained from the biggest distributors in Sweden, OKQ8 and Statoil. Gasoline companies do not provide actual prices which vary by region and even by station. Also at the national level I use quantities sold for gasoline, ethanol and diesel obtained from the Swedish Petroleum Institute (SPI). Finally, I also use monthly sugar and oil prices from the World Bank database.

Air Pollutants I use emissions data from a number of sources. First, exhaust CO2 emissions are obtained from the Swedish Consumer Agency, the same source providing the vehicle characteristics. I use lifecycle 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 use the car characteristics dataset to estimate "supply-side effects", which uniformly weighs all models available on the market. For instance, I investigate the causal effect of the GCR on CO2 emissions and mpg of regular and alternative fuels based on how carmakers adjusted their product lines to the new policy.

I also merge characteristics and registration datasets to estimate "demand-side effects" by constructing sales-weighted CO2 emissions and mpg. 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 precise version of a model that was purchased and, critically, to match this information with product characteristics, especially CO2 emissions and fuel economy.[10] 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 describe a number of stylized facts of how the GCR affected the Swedish car market. First, I describe how the GCR affected average CO2 emissions of alternative cars in comparison to regular ones on both the supply and demand sides. Given the asymmetric treatment towards different fuels, emission levels for alternative cars tend to increase in comparison to those of regular ones. I also describe the difference between short-run (calendar year 2007) and long-run (calendar year 2008 onwards) effects of the policy on the demand side. In the former case, only consumers were able to react to the policy, whereas in the latter carmakers are also allowed to adjust their product lines.

Second, I document that as opposed to previous findings for the industry elsewhere (see Li, Timmins and von Haefen 2009), carmakers react swiftly to the policy and introduced a number of green models already in 2008, i.e. months after the GCR was introduced. This finding can be explained by at least two factors, namely the previous availability of low-emission gasoline and diesel engines within a brand or group and the ease with which a carmakers can turn a gasoline vehicle into a FFV.

[10] 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 the New Car Guide finding negligible differences, if at all.

Third, I focus on alternative cars and show that alternative cars are primarily FFVs, which are typically larger, high-emission cars. Again, this can be attributed to the ease with which carmakers can turn gasoline vehicles into FFVs.

Fourth, I focus on the demand-side and show that FFVs – the most successful type of green car – gained market share at the expense of regular, high-emission vehicles. This finding is rationalized by the fact that consumers value characteristics such as size and power (Goldberg 1995; BLP 1995). Given the similarity between gasoline vehicles and FFVs in both the technological and characteristic space dimensions, consumers naturally tend to prefer a larger FFV rather than an equivalent captive gasoline car or a smaller gasoline or diesel vehicle, especially if this vehicle is offered with a rebate.

Finally, I show that contrary to previous findings in other markets, see Salle and Slemrod (2011), the evidence of bunching in the Swedish market is weaker, i.e. low-emission cars do not necessarily tend to cluster just below the threshold defining low-emission green cars.

Asymmetric treatment leads to asymmetric reactions Focusing on the supply-side, prior to the GCR both regular and alternative fuel vehicles were on a downward trend in what concerns CO2 emissions, as shown in Panel A of Figure 1, which reports average supply-side CO2 emissions (each model on the market is given the same weight, 1/N). Interestingly, until 2007 the trends were roughly parallel and average CO2 emissions of alternative fuel vehicles were 25-30 gCO2/km lower than those of regular fuel ones.

Following the GCR and the more lenient treatment given to alternative fuels, their trend reversed and became upward-sloping: starting from about 170 gCO2/km in 2007, emissions increased to about 183 and 186 gCO2/km in 2008 and 2009, respectively, while emissions of regular cars were essentially stable from 2007 to 2008 and resumed the downward trend in 2009.

FIGURE 1 ABOUT HERE

On the demand-side, Panel B in Figure 1 reports sales-weighted CO2 emissions of regular and alternative fuel cars, showing that there is not as clear a trend as on the supply side. Prior to the GCR, emission levels of regular cars are higher than those of alternative ones, but this relation begins to change from 2007. With the inception of the policy in April 2007, high-emission regular cars (those emitting more than 120 gCO2/km) became relatively more expensive than both (i) low-emission regular cars; and (ii) alternative cars. The caveat is that, for 2007, carmakers did not adjust their product lines i.e. the choice set facing consumers was kept fixed. As a result, conditional on purchasing a new car, consumers were more likely to switch to either alternative cars (typically larger, high-emission, cars, see below) or low-emission regular cars, which implied higher sales-weighted emissions for the former group and lower sales-weighted emission for regular cars as a whole.

The increase in CO2 emissions is amplified from 2008, once carmakers adjusted their product lines: the number of low-emission regular cars (both gasoline and diesel) increased from 43 in 2007 to 66 in 2008 and 87 in 2009 whereas the number of alternative cars –the majority of which are FFVs– increased from 30 in 2007 to 54 in 2008 and 83 in 2009 –see Table 2.

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

TABLE 2 ABOUT HERE

While the overall number of brands and models on the market increased marginally (less than 10 percent in both cases), the changes in low emission cars (those emitting less than 120 gCO2/km) were marked: the number of brands (models) operating in this particular niche increased from 8 (20) in 2004 to 13 (46) in 2007, 17 (69) in 2008 and 22 (89) in 2009. These numbers suggest carmakers did react swiftly on both the extensive (entering a market) and intensive (offering a new product) margins due at least in part to the GCR. This finding is in stark contrast with those in Li, Timmins and von Haefen (2009), according to which (focusing on reaction to increasing gasoline prices) supply side reactions are likely to take several years to materialize, which would suggest a dramatic departure between short-run and long-run effects. It is however along the lines of 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*.[11]

Among alternative fuel vehicles, new models are primarily FFVs, which are typically larger, high-emission cars Table 2 shows that, starting from 2 models marketed in 2004 (two versions of the Ford Focus), the number of FFVs increased to 18 in 2007, 44 in 2008 and 66 in 2009. The number of brands offering FFVs also increased substantially, from 1 in 2004 to 3 in 2007, 10 in 2008 and 12 in 2009. The effect of the GCR on the number of brands and models offering gas- and electric-based vehicles was much less dramatic, partly due to the limited gas retail network (concentrated in the southern part of the country),but likely, as anecdotal evidence suggests, that electric cars are still seen as poor value for money by Swedish consumers.

One particularly striking feature when looking at emission levels in Table 2 is the consistent upward trend among FFVs: average CO2 emission levels increased from 165 gCO2/km in 2004 to 184 in 2007, 194 in 2008 and 195g CO2/km in 2009 and a rightward shift when looking at the quartiles of the distribution. Interestingly, no FFV emits less than 120 gCO2/km.

FFVs gained market share at the expense of regular, high-emission vehicles The pattern of sales-weighted market shares reported in Figure 2 shows how high-emission regular vehicles lost market share to low-emission regular ones (plummeting from 94.65 percent in 2006 to a 77.64 percent in 2008), but especially FFVs following the policy. In fact, FFVs were the main gainers following the GCR reaching 16.10 percent of registrations in 2008, while gas and electric vehicles never commanded more than 1 percent of the market. This might be due to a number of factors besides product introduction, such as the similarity between the FFV and the standard gasoline technologies and the well developed ethanol retail network. In particular, although diesel cars have 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).

FIGURE 2 ABOUT HERE

There is evidence of improvement in fuel economy and emission levels of new cars, though not necessarily due to the Green Car Rebate On the supply side, Panels A and B in Figure 3 suggest a long-run trend in the improvement of fuel economy and emission levels among the models marketed in Sweden, but this effect does not seem to have been triggered by the GCR. For instance, although the third quartile of the distribution seems to have decreased following the

[11] 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.

inception of the policy, first quartile and median CO2 emissions look stable for the period 2007-9. Fuel economy figures provide a similar intuition, with only slight changes in the quartiles of the mpg distribution following the GCR.

FIGURE 3 ABOUT HERE

Sales-weighted emission levels and mpg reported in Panels C and D of Figure 3 suggest a milder trend than what the supply-side suggests. In Panel C, the first and third quartiles look flat over time whereas median CO2 emissions seem to follow a long-run downward trend. Again, there is no clear evidence of lower emission levels following the GCR.

TABLE 3 ABOUT HERE

Finally, I compare fuel economy of Swedish and US new passenger cars to assess the policy in a broader context.[12] Although one would ideally want to compare mpg distributions, when pursuing this analysis I am constrained to use data available for both countries. I thus compare sales-weighted average fuel economy measured in mpg for both countries in the period 2004-9. For the US, Table 3 reports mpg for passenger cars at the aggregate level and for both domestic and imported passenger cars using data from BTS (2011). Overall, the period 2004-9 witnessed a 11.5 percent increase in mpg, with the lion's share of the improvement – 17.8 percent– coming from imported cars.

For Sweden, Table 3 reports sales-weighted mpg for both the overall market and for passenger cars only. Given the low market penetration of light-trucks in the Swedish market, these measures are very similar. The first thing to note is that the overall improvement in fuel economy for the period 2004-9 is 23.9 percent (24.0 percent for passenger cars), thus twice the one observed in the US – this corresponds to a year-on-year growth rate of 4.4 percent in the period 2004-9 (4.2 percent in 2007-9). Moreover, while the gap between Swedish and US average fuel economy figures for passenger cars was 1.7 mpg in 2004, it widened to 4.2 mpg in 2007 and 5.5 mpg in 2009. These findings suggest that notwithstanding any shortcoming the policy might have, the GCR resulted in improvements in terms of fuel economy.

FIGURE 4 ABOUT HERE

There is limited evidence of bunching Among low-emission vehicles, both average and median emissions increased towards the 120 gCO2/km threshold. However, as reported in Figure 4, interquartile ranges tend to widen from 2007, especially for gasoline models. These findings are confirmed when plotting histograms separately for years 2004-9 for both gasoline and diesel vehicles. Although the number of low-emission gasoline models increases, one is almost as likely to find models emitting 110 gCO2/km as 120 gCO2/km. For low-emission diesel models the evidence of bunching is stronger, with a mode at 120 gCO2/km, as suggested by the box plot.

[12]In this analysis I use the US as a benchmark, for it is the most studied market worldwide. Results in Knittel (2011) show that fuel economy in US-sold passenger vehicles is essentially stagnant in the period 1980-2004 (due to a mere 6.5% overall improvement), while average horsepower and weight of cars and light duty trucks increased substantially.

5 Econometric Analysis of the Green Car Rebate

5.1 Overall Emission and Fuel Economy Levels: 2004-2009

I start by assessing the overall pattern of fuel economy and CO2 emissions over time for the entire sample period. To do so, I regress sales-weighted CO2 and mpg on year fixed-effects and (i) model; (ii) model-segment; or (iii) model-fuel segment fixed-effects, reporting the results in Table 4. While the definition of individual fixed-effects in other areas of economics looks natural, e.g. one fixed-effect per subject in labor market studies, this is not exactly the case here. Had I used model fixed-effects defined by the name of a particular model e.g. "Focus 1.8 FFV Ambient Station Wagon" (thus being effectively model-fuel-segment-engine fixed-effects), the resulting regression model would not have enough degrees of freedom. This happens due to, e.g. frequent changes in names of models, adjustment to product lines due to changes in engines etc. I thus experiment with alternatives (i)-(iii) above and consistently find specifications with model-fuel-segment fixed-effects to be nearly saturated as witnessed by the high R-squared of the associated regressions.

TABLE 4 ABOUT HERE

MPG Regressions For the mpg regressions, the long-run pattern of year fixed-effects suggests an improvement in terms of fuel economy. More precisely, year fixed-effects tend to follow a J-pattern , with an inflection point between years 2006 and 2007 for Specification 1 and between 2005 and 2006 for Specifications 2 and 3 in Table 4. The results for Specification 3 indicate that, within a model (say, a Ford Focus) there is an improvement in 5.20 mpg from 2004 to 2009, with very similar results for Specification 2, which uses model-segment fixed-effects (say, the Ford Focus station wagon). There is an improvement of 2.05 mpg (comparable to the improvement in the unconditional average fuel economy in the US for the period 2005-2009 –see Table 3) even in the more conservative Specification 1 using model-fuel-segment fixed-effects, and the null hypotheses of equality of both pre- and post-policy fixed effects are rejected at the one percent significance level throughout.

CO2 Emission Regressions For the CO2 emission regressions, the long-run pattern of year fixed-effects signals overall improvements according to Specifications 4-6 in Table 4.

For model and model-segment fixed-effects (Specifications 5 and 6) this pattern is monotonic, downward-sloping, whereas for model-fuel-segment fixed-effects (Specification 4) the pattern resembles an inverted J-pattern, though here the inflection point is between years 2005 and 2006. The reduction in CO2 emissions controlling for model and model-segment is substantial, reaching roughly -18.5 gCO2/km in the period 2004-2009.

Controlling for model-fuel-segment, the effect is a smaller -4.09 gCO2/km which is statistically significant at the one percent level. Again, the null hypotheses of equality of both pre- and post-policy fixed effects is rejected at the one percent significance level.

All in all, despite the evidence of improved fuel economy and emission levels in the period 2004-9, there does not seem to be compelling evidence that these improvements were triggered by the GCR.

5.2 Effect of Environmental Policy on Emissions and Fuel Economy

5.2.1 Empirical Strategy

I estimate the causal effect of the treatment to alternative (renewable) fuels *vis-à-vis* regular ones on the CO2 emission levels and fuel economy of newly-purchased Swedish vehicles following the GCR.

The baseline specification takes the form

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

where $t = 1, ..., T$ are time periods, $i = 1, ..., N$ are car models, y_{it} is the variable of interest (mpg or CO2 emissions) and $\aleph$ denotes the set of car models running on alternative fuels qualifying for the rebate. The indicator $1\{i \in \aleph\}$ takes on value one if the observation is a treated subject whereas x_{it} is a set of controls, such as time and model-based fixed-effects. Given the unexpected character of the policy, I make use of difference-in-differences (DD) techniques focusing on the DD estimator given by δ. The model can be estimated using ordinary least squares and all standard errors are clustered at the brand level.[13]

I estimate the effects separately for the supply and demand sides of the market. On the supply side I assign uniform weights to all vehicles available on the market to assess to which extent carmakers adjusted their product lines following the introduction of the GCR. I thus compare the relative fuel economy and CO2 emission levels of alternative vs. regular cars before and after the policy was introduced. That is, the indicator $1\{t \geq t^*\}$ takes on value one in the baseline supply-side specification starting from model-year 2008.

On the demand side I assign weights to the models according to their sales, thus accounting for how consumers react to the policy and changes in the choice set, i.e. new product lines following the policy. Besides comparing the relative fuel economy and CO2 emission levels of alternative vs. regular cars before and after the policy, I also take advantage of the institutional setting in the Swedish car market to estimate short- and long-run effects of the policy. This distinction arises due to the fact that consumers respond to the GCR already in 2007 (between April and December 2007) to the choice set defined by the 2007 model-year product line and then again to the adjusted choice set defined by product lines for model-year 2008 and onwards. That is, in the baseline specification I define an indicator which is equal to one between April and December 2007 to measure the short-run effects of the policy and another which is equal to one from January 2008 onwards fo gauge its long-run effects.

Estimation of mpg regressions provides a broader context to evaluate the policy –in particular, the use of sales-weighted mpg allows comparing the Swedish and US markets.

5.2.2 Supply-side Effects

To estimate the supply-side effects of the GCR on fuel economy and CO2 emissions I focus on the DD coefficient interacting the indicators of alternative fuel and years 2008 onwards. Specifications 1-3 reported in Table 5 use model-fuel-segment, model-segment and model fixed-effects, respectively.

TABLE 5 ABOUT HERE

All DD coefficients are positive and statistically significant, thus supporting the view that lax constraints placed on alternative fuels were readily exploited by carmakers. Controlling for model, the increase in CO2 emissions of alternative vehicles in comparison to regular ones is a substantial and statistically significant 15.38 gCO2/km, as reported in Specification 3. Controlling for model-segment,

[13] 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, both European and Japanese conglomerates, e.g. Volkswagen, Toyota, Honda, have openly developed their portfolios of brands to cater different market segments.

the increase is very similar at 14.45 gCO2/km. At 6.87 gCO2/km even after controlling for model-fuel-segment fixed-effects, Specification 1's DD estimate is the most conservative one, corresponding to a nearly 5 percent increase of emissions if looking at the average vehicle.

Specifications 4-6 in Table 5 decompose the original DD coefficient into two, namely 2008 and 2009 effects. For Specifications 5-6, the effects in the range 10-12 gCO2/km are both positive and statistically significant. Moreover, being in the range 16-18 gCO2/km, the increase in emissions in 2009 are roughly 50 percent higher than the 2008 ones, suggesting that carmakers continuously adjusted their product lines to take advantage of the lax constraints placed towards alternative cars *vis-à-vis* regular ones. Specification 4 suggests a slightly different –and more conservative– picture, with an insignificant effect for 2008 and a significant one of 9.61 gCO2/km for 2009. Intuitively, this implies a more sluggish response from the part of carmakers, yet a significant one less than two years after the inception of the policy. The null of equality of 2008 and 2009 effects is soundly rejected for all of Specifications 4-6, lending further support to the view that care makers' reactions strengthened over time.

5.2.3 Demand-side Effects

Sales-weighted DD regressions allow disentangling two effects of the policy, namely short- and long-run ones, whereby consumers react to pre- and post-policy product lines (choice sets), respectively. Specifications 1-3 in Table 6 thus report a short-run effect captured by the interaction of an indicator of alternative fuel and another for year 2007 and a long-run effect captured by the interaction of an indicator of alternative fuel and one for years 2008 onwards.

TABLE 6 ABOUT HERE

Estimates for Specifications 2-3 are positive, significant and suggest at least a sevenfold increase of long- over short-run effects, thus highlighting the importance of the new choice set to the increase in CO2 emissions of alternative cars. The more conservative estimates coming from Specification 1 do however indicate a -3.59 gCO2/km decrease of CO2 emissions with respect to pre-policy levels in the short-run and a 3.06 gCO2/km increase in the long-run, again suggesting that once carmakers adjusted their product lines consumers readily took advantage of the enlarged choice set.

Table 6 also reports Specifications 4-6, which decompose the long-run effect into 2008 and 2009 ones (LR1 and LR2, respectively). Short-run responses for Specifications 4-6 are essentially the same as those for Specifications 1-3, while the long-run effects suggest a strengthening effect of the effect over time, all of which are positive and statistically significant. Moreover, the null hypotheses of equality of both long-run effects and equality of short- and long-run effects are all rejected at the 1 percent significant level. Summing up, the most conservative Specification 1 indicates a negative effect -3.62 gCO2/km on emissions of alternative cars in the short-run and increasing long-run effects of 2.68 and 3.75 gCO2/km which more than offset the early reductions, all of which are statistically significant.

TABLE 7 ABOUT HERE

Results for fuel economy essentially mirror those for CO2 emissions and are therefore just briefly discussed. Specifications 2-3 in Table 7 indicate statistically significant lower mpg estimates for alternative cars in both the short- and long-run whereas the more conservative Specification 1 reports an improvement in fuel economy in the short-run which is more than offset in the long-run, i.e. once the 2008 product lines are rolled out. Decomposing long-run effects into LR1 and LR2 (2008 and 2009, respectively) ones provides mixed evidence regarding the strengthening effect observed for CO2 emissions – while Specifications 5-6 suggest that this effect is still present, with values of about 3 mpg for 2008 and about 4 mpg for 2009, one cannot reject the null of equality of the long-run effects for Specification 4, of about 0.50 mpg.

Summary of Findings The above results can be summarized as follows. First, there is a distinction between short- and long-run effects. That is, faced with a restricted choice set with relatively few high-emission alternative vehicles – typically FFVs – consumers were more likely to purchase low-emission alternative vehicles. However, once carmakers adjusted their product lines to the new policy, thus providing consumers with an expanded choice set – constituted by an increasing number of high-emission alternative vehicles – consumers were more likely to purchase these newly introduced alternatives. The robust effect across all specifications is that the net effect of the policy is that of increased emissions for alternative cars with respect to regular ones.

Second, while there is mixed evidence that the supply side reactions started already in 2008, the first year with adjusted product lines, the evidence from the demand side is robust: long-run sales-weighted effects pointing towards higher CO2 emissions and lower mpg, thus suggesting that lax regulation for alternative fuels resulted in higher emissions for alternative fuels relative to regular ones.

The results above beg the question of where precisely the variation in the data is coming from. To fix ideas, consider a car model for which both gasoline and FFV versions are available, such as a Ford Focus or one of the Volvo models. On the supply side, the way the GCR was designed induced carmakers to adjust their product lines in a way that, even within a model-fuel-segment, e.g. Ford Focus hatchback, when faced with a choice of engines, carmakers would opt for a larger one for the FFV version as compared to the gasoline one – in the limit, a gasoline version emitting less than 120 gCO2/km and *always* a FFV version emitting more than the threshold emissions level. (Recall from Table 2 that no FFV emitted less than 120 gCO2/km during the sample period and the first quartiles of the emissions distribution for FFVs were 169, 174 and 177 for years 2007-2009.)

On the demand side, this variation is combined with the way consumers react. First, consumers have a preference for size (comfort) and engine power (although environmental concerns arguably have been playing an increasing role in recent times). Second, a significant share of consumers understands the option value provided by an FFV (see Section 6 for further discussion). Finally, the very cars offering this option value were offered with 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.

6 Fuel Choice of FFV Motorists

FFVs are by far the majority of vehicles running on alternative fuels in the Swedish market. Not surprisingly, the pattern of volume sales of ethanol has grown hand-in-hand with that of FFVs for most of the period 2004-2009, see Panel A in Figure 5.[14] In contrast with previous findings, e.g. Borenstein (1993), which documents 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 being more

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

expensive than gasoline in energy-adjusted terms already in October 2008, see Panel B in Figure 5. The full line in this graph reports the symmetric of the ethanol-to-gasoline price ratio ($-p_e/p_g$), with the corresponding values reported on the right vertical axis. Given the energy content of the fuels, gasoline is cheaper than ethanol whenever the value of this ratio is less than about -0.7, which is what happens starting from October 2008. Given the sharp drop in the price ratio, ethanol volume sales at the national level (measured in thousands of cubic meters by the dashed line) plummet almost instantaneously, suggesting that fuel arbitrage is prevalent among FFV owners. This swift reaction implies that, as opposed to findings for the US (Anderson and Sallee 2010), Swedish consumers seem to account for the option value provided by FFVs and promptly exercise it. This can be attributed to a relatively well-developed retail network in Sweden (as opposed to what happens in the US, see also Corts 2010) where about 60 percent of fuel stations supply at least one renewable fuel (second only to Brazil worldwide), typically ethanol.

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

6.1 Model

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

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.[15] This amounts to 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. Consumer i solves

$$\max_q U_i(q_{trans}, q_{out})$$

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

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

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 consumer types are defined by a parameter $\theta = (\theta_a, \theta_e, \theta_g)$ depending on whether the FFV owner is an arbitrageur, purchases only ethanol or only gasoline, 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, each period, N_t consumers enter the market and purchase FFVs in shares $\sigma = (\sigma_a, \sigma_e, \sigma_g)$, $\sum_{j=a,e,g} \sigma_j = 1$,so one can write $N_t = \sum_{j=a,e,g} \sigma_j N_t$. The demand of ethanol by consumer of type θ_e 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 is

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

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

FIGURE 6 ABOUT HERE

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

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

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

6.2 Implementation

In an ideal setting one would want to estimate the above fuel choice model using data on fleet size and estimating fuel demand conditional on whether the price regime is $p_e/p_g \lesseqgtr k$.[16] To do so, one

[16]More specifically, one could take advantage of the information on *kpl* to introduce heterogeneity into the model *à la* Berry, Levinson and Pakes (1995), i.e. via draws of fuel economy. I leave this interesting topic for future research.

would then estimate a switching regression model accounting for price endogeneity. Here, however, I assume a more pragmatic approach since my interest is 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. This allows obtaining vehicle-kilometers traveled at month t, $vkt_t^{\theta_i}$ for consumer type $i = e, g, a$. The fuel demand of consumer θ_g if 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 $q_f|\theta_a = 1\{p_{et}/p_{gt} > k\}vkt_t^{\theta_a}/kpl_g + 1\{p_{et}/p_{gt} < k\}vkt_t^{\theta_a}/kpl_e$ and 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 $p_e/p_g \lesseqgtr k$.

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

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

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

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

if $p_{et}/p_{gt} < k$.

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

$$
\begin{aligned}
\sigma_e &= \frac{kpl_e}{\chi N_{t'}} Q_{et'}^{E-cheap} \\
\sigma_a &= \frac{kpl_e}{\chi N_{t''}} \left(Q_{et'}^{E-cheap} - Q_{et''}^{E-dear} \right)
\end{aligned}
$$

and $\sigma_g = 1 - \sigma_e - \sigma_a$.

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 cars, 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 $\sigma = (\sigma_a, \sigma_e, \sigma_g)$ 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 can then obtain a candidate σ vector.

6.3 Estimates of Consumer Shares

To quantify the extent of fuel switching in the Swedish market I calibrate the model defining $\sigma = (\sigma_a, \sigma_e, \sigma_g)$.[17] The oil price drop in September 2008 caused by the global recession provides an ideal

[17] 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.

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 and December 2008 ethanol sales, since one could argue that part of the further reduction in ethanol sales from November to December 2008 can be attributed to the arrival of winter and the associated temperature decreases. (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 in winter.)

I take a stand on the following variables. First, I assume FFVs drive $\chi = 2,000$ km/month. 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 $kpl_e = 9$ for sensitivity analysis.[18] Third, in some scenarios I also account for ethanol purchases by the public sector: the governmental fleet is a sizable captive source of demand for ethanol across Sweden and should be somehow considered.

TABLE 8 ABOUT HERE

The calibration results are reported in Table 8. The baseline scenario is reported in column 1, whose key assumptions are that (i) the transition from ethanol to gasoline goes from September to December 2008, so that lower winter temperatures had no impact in fuel demand; (ii) yearly mileage is 24,000 km (approximately 15,000 miles); (iii) $kpl_e = 8$. Recall that the volume sales of ethanol collapse from 28.1 million to 8.3 million cubic meters from September to December 2008, a reduction of about 70 percent, so one would expect figures of similar magnitude for the share of arbitrageurs among ethanol users, $\alpha := \sigma_a/(\sigma_e + \sigma_a)$, which is 73.1 percent in the baseline scenario. The vector of consumer type shares is $\sigma := (\sigma_a, \sigma_e, \sigma_g) = (71.7\%, 26.5\%, 1.8\%)$, which implies a low number of gasoline-lovers and a moderate number of ethanol-lovers among FFV owners. The lion's share among FFV owners is made of arbitrageurs, which amount to over 70 percent of FFV owners. All in all, estimates from this baseline scenario imply that only one in every four FFV owners consistently fuels with ethanol.

Scenario 2 accounts for the fact that the public sector uses ethanol and does not switch in reaction to price changes. Here, I assume that the government is responsible for the consumption of 3 million cubic meters of ethanol per month, which amounts to a fleet of 10,000 cars with fuel economy $kpl_e = 10$ driving 36,000 km/year. This amounts to the governmental fleet driving 50 percent more than privately-owned cars and with slightly better fuel economy, since government-owned vehicles tend to be smaller. As a result, the share of arbitrageurs among ethanol users rises to $\alpha = 80.9\%$ and the vector of consumer type shares is $\sigma = (71.7\%, 16.9\%, 11.3\%)$, i.e. there is an increase in the share of gasoline-lovers and a decrease in the one of ethanol-lovers when compared to the baseline.

[18] 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.

Scenario 3 accounts for purchases of ethanol by the public sector and assumes an improved fuel economy of privately-owned vehicles, i.e. $kpl_e = 9$. The share of arbitrageurs among ethanol users is unchanged at $\alpha = 80.9\%$ and the vector of consumer type shares is $\sigma = (80.7\%, 19.9\%, 0.3\%)$, showing the decrease in the share of gasoline-lovers among FFV owners and a slight increase in the shares of both ethanol-lovers and arbitrageurs.

Scenarios 4-6 differ from Scenarios 1-3 in that they consider the transition from ethanol to gasoline to take place between September and November 2008 instead of December 2008. Intuitively, this amounts to attributing the decline in ethanol sales from November to December 2008 entirely to lower temperatures. According to Scenario 4, $\alpha = 58.1\%$ and the vector of consumer type shares is $\sigma = (56.9\%, 40.9\%, 2.2\%)$, which follows from the less dramatic switch from ethanol to gasoline following the oil price drop. Interestingly, however, the share of gasoline-lovers is still a low 2.2 percent. Scenario 5 implies that roughly two-thirds of ethanol users are arbitrageurs and with $\sigma = (56.9\%, 31.1\%, 12.1\%)$ the share of gasoline-lovers increases substantially. Finally, Scenario 6 once again has $\alpha = 64.7\%$ and the vector of consumer type shares is $\sigma = (64.0\%, 34.9\%, 1.1\%)$, thus implying that about two-thirds of all FFV owners are arbitrageurs.

Stepping back, the results reported in Table 8 suggest a low share of gasoline-lovers – in the scenarios reported, less than 15 percent of FFV owners were of this consumer type. These are consumers who potentially received the rebate upon the purchase of a FFV and *never* used the renewable fuel. The range 17-41 percent of ethanol-lovers is considerably wider, mostly due to the inclusion of governmental purchases of ethanol. Alternatively, a moderate fraction of FFV owners uses ethanol on a consistent basis, which is likely to be driven by environmental concerns (see Salvo and Huse 2012 for micro evidence on environmental concerns for the Brazilian market). Finally, the share of consumers classified as arbitrageurs is in the range 57-81 percent; thus, over half of FFV owners are actively using the option value of their FFV and arbitraging across fuels after pocketing the value of the rebate.

7 Implications for Air Pollution

7.1 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 also can run on ethanol (and gas). That is, an alternative way to account for the carbon footprint of a vehicle is to use emissions adjusted for the lifecycle climate benefits of ethanol (and gas). The second method of assessing the carbon footprint of a vehicle thus provides a lifecycle 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.

7.2 Local Air Pollutants

Besides emitting GHG, of which CO2 and Methane are the best known, combustion engines also emit local air pollutants. By switching from ethanol to gasoline, motorists are (unknowingly) increasing the emissions of some pollutants while decreasing the emission of others. The related literature still seems to be in its early days, with Jacobson (2007) reporting that ethanol is superior to gasoline in terms of CO2 emissions but not local pollutants and Yanowitz and McCormick (2009) providing a compilation of comparative exhaust emissions of gasoline and ethanol with small sample sizes for a number of pollutants – see Table 9. For instance, engines running on ethanol emit 1786 percent more acetaldehydes than when running on gasoline based on a sample size of size 92, whereas engines running on ethanol emit 18 percent less NOx based on a sample of size 3.[19]

TABLE 9 ABOUT HERE

7.3 The Effect of Fuel Switching on Air Pollution

To quantify the effect of fuel switching by FFV owners on air pollution, I combine estimates on local air pollutants reported in Table 9 and on CO2 reported by the Swedish Consumer Agency (2011) with shares of consumer types as per Specification 1 in Table 8, thus taking on-board the assumptions leading to the construction of Table 8. Importantly, only air pollutants for which the difference in emissions between gasoline and ethanol is statistically significant are included. The results are reported in Table 10.

TABLE 10 ABOUT HERE

As expected, lifecycle CO2 emissions increase substantially due to the switch from ethanol to gasoline – by 85 percent in this case. The same holds for local air pollutants CO (Carbon monoxide), Particulate Matter, NOx, 1,3-Butadiene and Nonmethane Hydrocarbon. There are also pollutants whose concentrations decrease following the switching, such as Methane, Acetaldehyde and Formaldehyde. Given the focus of policymakers on CO2 and the well-known harming properties of pollutants such as CO and NOx, fuel switching by FFV owners from ethanol to gasoline paints an overall gloomy picture when it comes to air pollution.

Concluding Remarks

This paper examines an environmental policy with a broad impact on the automobile market and a focus on alternative fuels. Taking advantage of the institutional setting, it disentangles the reactions of consumers and carmakers to the policy. On the supply-side, carmakers took advantage of the lax regulation towards alternative cars and reacted quickly to the policy, mainly by offering large, high-emission FFVs.

On the demand-side, I find evidence of two effects. First, a short-run one effect whereby consumers purchased green cars available on the market at the time of the rebate, which are typically low-emission vehicles. Second, a long-run effect whereby – following the reaction of carmakers to the policy – consumers facing an expanded choice set with a larger share of high-emission alternative cars tended to purchase precisely these models.

[19] All measurements reported in Table 9 were performed using the same FFV fueled with ethanol and gasoline. N denotes sample size (number of vehicles tested), p-value refers to the quantity from the paired t-test.

The paper also proposes a new 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 in the country. A major share of FFV owners promptly reacted to price incentives following the 2008 drop in oil prices resulting in the plummeting of ethanol sales in the country – when calibrating the model to market level data, I find that roughly two-thirds of FFV owners are fuel arbitrageurs. As a result, despite investments in fueling infrastructure to increase the retail presence of renewables (notably ethanol) and the 10,000 SEK rebate paid upon the purchase of a green car, fuel switching induced an increase in air pollution, including a substantial 85 percent in lifecycle CO2 emissions, from the part of FFV owners switching from ethanol to gasoline. In short, policymakers have been held hostages of the FFV technology.

The above findings provide a number of policy implications. First, pushing for lower emission thresholds seems to trigger the introduction of low-emission regular vehicles even in the short-run. In fact, the number of low-emission gasoline and diesel vehicles available on the market increased by, respectively, 80 and roughly 50 percent within the first year of the program.

Second, since flexible-fuel technologies (not necessarily ethanol) essentially piggy-back on existing ones, 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 flexible-fuel vehicles due to the option value provided by this very technology, namely arbitraging across fuels, and not due to a rebate.

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

Finally, 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, possibly using a revenue-neutral scheme.

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A Robustness

The results in Section 5 are robust in a number of directions detailed below.

Fixed-effects I have experimented replacing model-based fixed-effects with brand plus time, time plus brand plus segment, time-brand, and time-brand-segment fixed-effects. The robust finding is that model-based fixed-effects provide more conservative estimates.

Fuel prices I have experimented with fuel prices, since these are expected to impact mpg (positively) and CO2 emissions (negatively). More specifically, for each year I have added regressors based on average, median, maximum and interquartile ranges of the corresponding monthly fuel prices, both contemporaneous and lagged. Intuitively one would expect higher fuel prices to induce improved fuel economy (lower CO2 emissions) among newly-registered vehicles (see Busse, Knittel and Zettelmayer 2008 and Li, Timmins, and von Haefen 2009 for evidence on the US market). I re-estimate the results for overall and DD regressions using this new set of variables as additional regressors. The results for mpg and CO2 emissions remain unchanged. In particular, the J and inverted-J relationships for, respectively, mpg and CO2 emissions remain.[20]

Subsamples I also re-estimated the DD regressions using a number of subsamples. The qualitative findings are the same as in the case of the full sample results.

[20] In fact, contemporaneous and lagged fuel price measures load negatively and positively on mpg, respectively (positively and negatively on CO2 emissions, respectively). While lagged price measures load with an unexpected sign, the use of contemporaneous fuel price measures at the yearly frequency does however introduce a consistency problem, since this would imply that car purchases made in January could be influenced by fuel prices in December. Regardless of this finding, signs, magnitudes and statistic significance of coefficients remain.

B Additional Evidence (Not for publication)

Alternative fuel models on the market Figure A1 depicts the number of models running on alternative fuels available on the market in the period 2004-2009. While the trends for gasoline/gas and gasoline/electric barely increase, the one for gasoline/ethanol vehicles (FFVs) shows a stark increase, especially following the GCR, i.e. for model-years 2008 and 2009.

Relation between CO2 emissions and mpg Figure A2 shows the relation between CO2 emissions (in gCO2/km) and fuel economy (in mpg) of vehicles on the Swedish market in the period 2004-2009. The horizontal straight line depicts the 120 gO2/km threshold, so points underneath it emit less than the threshold for regular green cars. Panels A-C in Figure A3 depict the CO2 emissions vs. mpg relation for model years 2007 to 2009.

Mild evidence of bunching Panels A-F in Figure A4 report histograms of the sales-weighted distribution of CO2 emissions for cars running on gasoline for years 2004-2009. Bunching would imply a clustering of observations just below the 120 gCO2/km threshold; for model-year 2008 if there is any evidence of bunching, it is around 110 gCO2/km. Only for model-year 2009, however, is there some mild evidence of bunching, with roughly 2 percent of observations just below the threshold.

Panels A-F in Figure A5 report histograms of the sales-weighted distribution of CO2 emissions for cars running on diesel for years 2004-2009. Prior to the GCR, observations potentially classified as bunching below the treshold make up to roughly 3 percent. Following the GCR, the probability of models just below the 120 gCO2/km threshold is roughly stable at around 3.5 percent.

TABLE 1 ðSummary Statistics of the Swedish Car Market

	Sweden	France	Germany
New passenger car registrations, millions (2007)	4.2	30.4	46.6
Passenger cars per 100 inhabitants (2007)	3.4	3.2	3.8
% Households with a vehicle (2006)	84.5	82	NA
Average car age (2008)	9.4	8.1	8.1
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 cars Ò5 years (2008)	29.0%	33.4%	34.3%
Share of cars 5-10 years (2008)	31.9%	33.0%	31.1%
Share of cars > 10 years (2008)	39.1%	33.6%	34.6%

Note: Based on data from ANFAC (2010), "European Motor Vehicles PARC 2008"

TABLE 2 ðSupplyside Summary Statistics

Fuel		2004	2005	2006	2007	2008	2009
		CO2 Emissions (gCO2/km)					
Total	mean	210.8	210.4	205.5	197.7	198.8	191.4
	se(mean)	1.2	1.2	1.2	1.4	1.3	1.2
	p25	175	172	167	159	161	155
	p50	205	205	197	185	188	181
	p75	239	239	233	223	225	217
	#brands	37	40	40	45	44	40
	#models	1854	1920	2101	1624	1946	2026
Total Ò120g	mean	107.1	106.8	113.6	114.4	113.6	114.1
	se(mean)	3.1	2.9	0.9	1.1	0.9	0.7
	p25	90	90	109	109	109	109
	p50	114.5	113	116	118	116	118
	p75	118	116	119	119	116	119
	#brands	8	8	10	13	17	22
	#models	20	21	40	46	69	89
Gasoline	mean	218.0	218.4	215.4	210.5	212.4	205.9
	se(mean)	1.3	1.4	1.4	1.8	1.7	1.7
	p25	184	182	180	169	173	167
	p50	213	211	207	194	198	193
	p75	246	249	244	238	238	232
	#brands	37	40	40	45	43	39
	#models	1398	1417	1473	1081	1225	1195
GasolineÒ120g	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
	p25	113	113	109	109	109	109
	p50	116	116	111	109	109	112
	p75	119	116	116	113	116	119
	#brands	3	2	4	5	7	12
	#models	10	8	14	10	18	36
Diesel	mean	188.8	188.1	183.0	172.3	174.8	168.4
	se(mean)	2.1	2.0	1.8	1.8	1.6	1.3
	p25	153	153	154	145	148	146
	p50	185.5	187	174	162	169	160.5
	p75	215	216	210	189	193	184
	#brands	28	28	31	32	34	35
	#models	442	491	596	513	667	748
DieselÒ120g	mean	97.1	101.3	114.8	115.8	114.4	115.2
	se(mean)	1.0	1.2	1.4	1.4	4.5	5.2
	p25	90	90	115	116	114.5	112
	p50	90	100	118	119	119	119
	p75	116	116	119	119	119	119
	#brands	5	6	6	11	14	19
	#models	9	12	23	33	48	51
FFV	mean	165.0	198.0	185.4	184.4	194.2	195.1
	se(mean)	0.0	12.2	6.8	4.6	3.7	3.1
	p25	165	150	169	169	174	177
	p50	165	215	172	175.5	184.5	191.5
	p75	165	228	179	206	213	214
	#brands	1	3	3	3	10	12
	#models	2	11	17	18	44	66
FFV Ò120g	#models	0	0	0	0	0	0
Petrol/Gas	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
	p25	150	150	148	136.5	138	144
	p50	213	228	164	157	155	157
	p75	231	215	183	164	160	167
	#brands	5	5	5	5	4	3
	#models	11	11	11	8	5	11
Petrol/Electric	mean	104.0	104.0	147.8	147.8	161.8	171.3
	se(mean)	.	.	23.9	23.9	23.3	21.3
	p25	104	104	106.5	106.5	109	109
	p50	104	104	147.5	147.5	185	188.5
	p75	104	104	189	189	192	219
	#brands	1	1	3	3	3	3
	#models	1	1	4	4	5	6

TABLE 3 ðAverage Fuel Economy of New Passenger Cars

Average Fuel Economy of New Passenger Cars						
	2004	2005	2006	2007	2008	2009
US						
Passenger cars	29.5	30.3	30.1	31.2	31.5	32.9
Domestic passenger cars	29.9	30.5	30.3	30.6	31.2	32.1
Imported passenger cars	28.7	29.9	29.7	32.2	31.8	33.8
Sweden						
Overall	31.0	30.8	31.7	35.4	37.1	38.4
Passenger cars	31.2	31.0	31.9	35.6	37.3	38.7

Note: US data from the Bureau of Transportation Statistics (BTS).

TABLE 4 ðOverall Fuel Economy and Emission Levels (Sales-weighted)

2004-2009 data	Dep. var: mpg			Dep. var: CO2 emissions (gCO2/km)		
	[1]	[2]	[3]	[4]	[5]	[6]
1{year==2005}	-0.28***	-0.32***	-0.35***	-0.58***	-0.52***	-0.44***
	[-44.99]	[-17.07]	[-18.40]	[-18.04]	[-6.80]	[-5.69]
1{year==2006}	-0.41***	0.63***	0.60***	0.37***	-3.23***	-3.12***
	[-66.57]	[33.49]	[31.89]	[11.38]	[-42.25]	[-40.73]
1{year==2007}	1.41***	3.78***	3.58***	1.03***	-9.50***	-8.68***
	[215.02]	[193.65]	[187.56]	[30.01]	[-120.85]	[-112.64]
1{year==2008}	1.64***	4.03***	3.94***	-1.23***	-12.57***	-12.11***
	[226.18]	[194.23]	[192.40]	[-32.30]	[-149.53]	[-146.05]
1{year==2009}	2.05***	5.25***	5.20***	-4.09***	-18.53***	-18.33***
	[264.07]	[240.05]	[237.92]	[-100.64]	[-209.78]	[-207.40]
Model FEs			ã			ã
Model-segment FEs		ã			ã	
Model-fuel-segment FEs	ã			ã		
N	554683	554683	554683	557961	557961	557961
R-squared	0.969	0.701	0.698	0.962	0.782	0.779

Note: Standard errors clustered by brand, t-statistics in brackets

* p<0.10, ** p<0.05, *** p<0.01

TABLE 5 ð Supply-side Emission Levels

Dep. var: CO2 emissions (gCO2/km)	2004-2009 data					
	[1]	[2]	[3]	[4]	[5]	[6]
1{yearÓ2008} x 1{Alt. Fuel}	6.87*	14.45***	15.38***			
	[1.75]	[3.55]	[4.16]			
1{year==2008} x 1{Alt. Fuel}				4.32	10.77**	11.88**
				[0.98]	[2.06]	[2.51]
1{year==2009} x 1{Alt. Fuel}				9.61**	16.90***	17.71***
				[2.14]	[3.66]	[4.22]
Alt. Fuel FE	ã	ã	ã	ã	ã	ã
Time FEs	ã	ã	ã	ã	ã	ã
Model FEs			ã			ã
Model-segment FEs		ã			ã	
Model-fuel-segment FEs	ã			ã		
N	11537	11537	11537	11537	11537	11537
R-squared	0.991	0.980	0.983	0.991	0.980	0.983

Note: Standard errors clustered by brand, t-statistics in brackets.
* p<0.10, ** p<0.05, *** p<0.01

TABLE 6 ðSales-weighted Emission Levels

Dep. var: CO2 emissions (gCO2/km)	2004-2009 data					
	[1]	[2]	[3]	[4]	[5]	[6]
1{year==2007} x 1{Alt. Fuel}	-3.59	1.99***	1.22***	-3.62	1.91***	1.15***
	[-32.23]	[7.73]	[4.70]	[-32.46]	[7.43]	[4.45]
1{yearÓ2008} x 1{Alt. Fuel}	3.06***	14.00***	13.73***			
	[27.94]	[58.70]	[57.29]			
1{year==2008} x 1{Alt. Fuel}				2.68***	12.10***	11.68***
				[23.45]	[48.01]	[46.17]
1{year==2009} x 1{Alt. Fuel}				3.75***	16.78***	16.77***
				[30.17]	[63.00]	[62.61]
Alt. Fuel FE	ã	ã	ã	ã	ã	ã
Time FEs	ã	ã	ã	ã	ã	ã
Model FEs			ã			ã
Model-segment FEs		ã			ã	
Model-fuel-segment FEs	ã			ã		
N	557961	557961	557961	557961	557961	557961
R-squared	0.999	0.992	0.992	0.999	0.992	0.992

Note: Standard errors clustered by brand, t-statistics in brackets.
* p<0.10, ** p<0.05, *** p<0.01

TABLE 7 ðSales-weighted Fuel Economy

Dep. var: mpg	2004-2009 data					
	[1]	[2]	[3]	[4]	[5]	[6]
1{year==2007} x 1{Alt. Fuel}	0.31***	-1.45***	-1.25***	0.31***	-1.44***	-1.24***
	[14.43]	[-23.17]	[-19.86]	[14.45]	[-22.95]	[-19.68]
1{yearÓ2008} x 1{Alt. Fuel}	-0.49***	-3.27***	-3.21			
	[-23.55]	[-56.47]	[-55.08]			
1{year==2008} x 1{Alt. Fuel}				-0.49***	-2.92***	-2.82***
				[-22.25]	[-47.69]	[-45.83]
1{year==2009} x 1{Alt. Fuel}				-0.51***	-3.79***	-3.79***
				[-21.28]	[-58.51]	[-58.16]
Alt. Fuel FE	ã	ã	ã	ã	ã	ã
Time FEs	ã	ã	ã	ã	ã	ã
Model FEs			ã			ã
Model-segment FEs		ã			ã	
Model-fuel-segment FEs	ã			ã		
N	554683	554683	554683	554683	554683	554683
R-squared	0.999	0.988	0.988	0.999	0.988	0.988

Note: Standard errors clustered by brand, t-statistics in brackets.
* p<0.10, ** p<0.05, *** p<0.01

TABLE 8 ðConsumer Types in Fuel Choice

	[1]	[2]	[3]	[4]	[5]	[6]
Panel A: Data and Parameters						
t õ	Sept/2008	Sept/2008	Sept/2008	Sept/2008	Sept/2008	Sept/2008
t õ õ	Dec/2008	Dec/2008	Dec/2008	Nov/2008	Nov/2008	Nov/2008
kpl_e	8	8	9	8	8	9
c	2,000	2,000	2,000	2,000	2,000	2,000
N _ t õ	125,699	125,699	125,699	121,417	121,417	121,417
N_t õ õ	110,421	110,421	110,421	110,421	110,421	110,421
Q_E_cheap(t õ)	28,120,000	25,120,000	25,120,000	28,120,000	25,120,000	25,120,000
Q_E_dear (t õ õ	8,314,000	5,314,000	5,314,000	12,426,000	9,426,000	9,426,000
Panel B: Shares of each consumer type						
s_e	26.5%	16.9%	19.0%	40.9%	31.1%	34.9%
s_a	71.7%	71.7%	80.7%	56.9%	56.9%	64.0%
s_g	1.8%	11.3%	0.3%	2.2%	12.1%	1.1%
s_a/(s_e + a)s _	73.1%	80.9%	80.9%	58.1%	64.7%	64.7%

TABLE 9 ðAir PollutantsEmission Reductions from Ethanol Use

Emission Reductions from ethanol use - literature

Variable	**Avg. Change (%)**	**95% Conf. Interval**	**N**	**p-value**
Total Hydrocarbons	-8	[-19,4]	89	0.20
Nonmethane Organic Gas	12	[-56,182]	6	0.43
Nonmethane Hydrocarbon	-10	[-17,-3]	72	0.03**
Benzene	-70	[-82,-50]	6	0.16
1,3-Butadiene	-62	[-83,-13]	6	0.01***
NOx	-18	[-27,-9]	3	0.00***
Particulate Matter	-34	[-98,-2395]	3	0.00***
CO	-20	[-39,4]	93	0.00***
Formaldehyde	63	[51,75]	92	0.00***
Acetaldehyde	1786	[1424,2233]	92	0.00***
Methane	92	[72,114]	86	0.00***

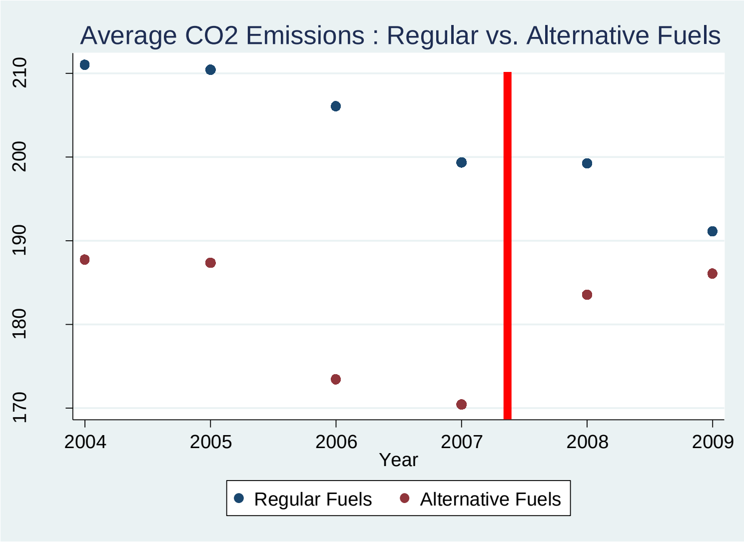
TABLE 10 – Change in Air Pollution due to FFV Owners' Switch from Ethanol to – Sept-Dec/2008

Air Pollutant	Estimated Change in Concentration of Air Pollutant (%)
Lifecycle CO_2	+85.30
Nonmethane Hydrocarbon	+ 7.93
1,3-Butadiene	+112.97
NO_x	+15.63
Particulate Matter	+36.46
CO	+17.79
Formaldehyde	- 27.85
Acetaldehyde	- 69.02
Methane	- 34.59

Note: Estimates in Table 10 combine figures from Table 9 and Specification 1 in Table 8.

FIGURE 1

Panel A: Supply (before-after)



Panel B: Demand (short- and long-run effects)

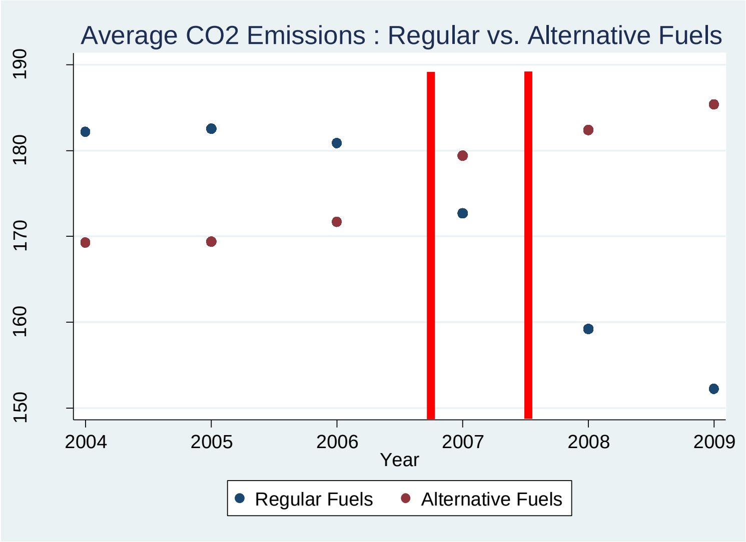
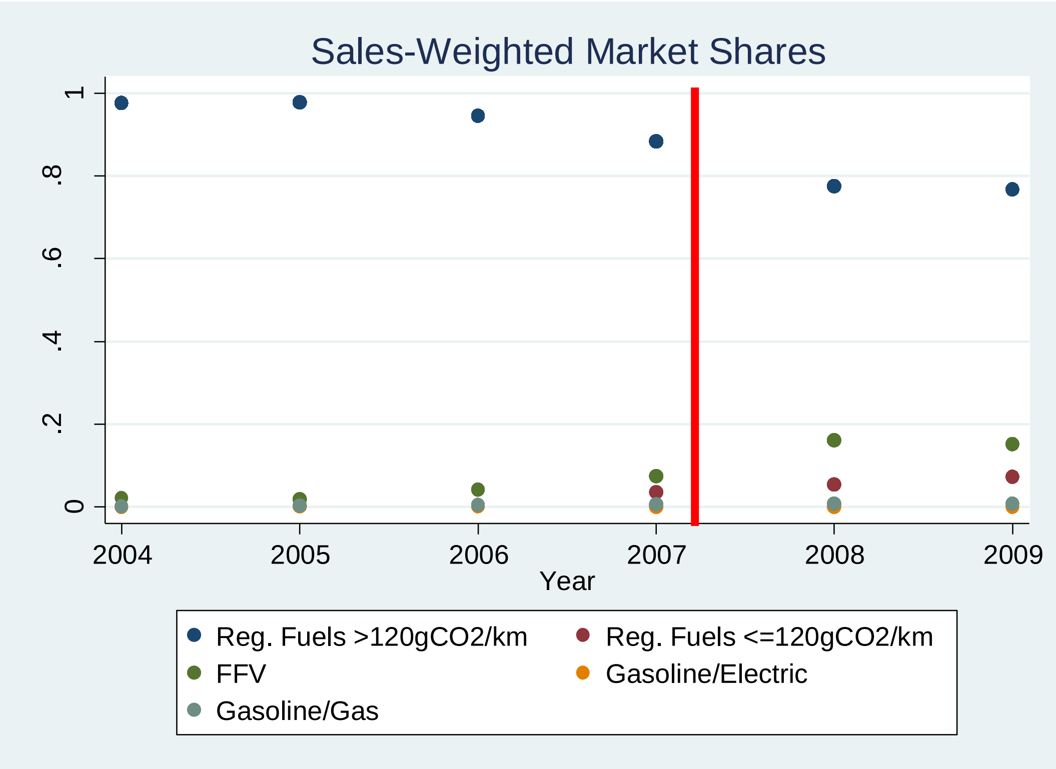
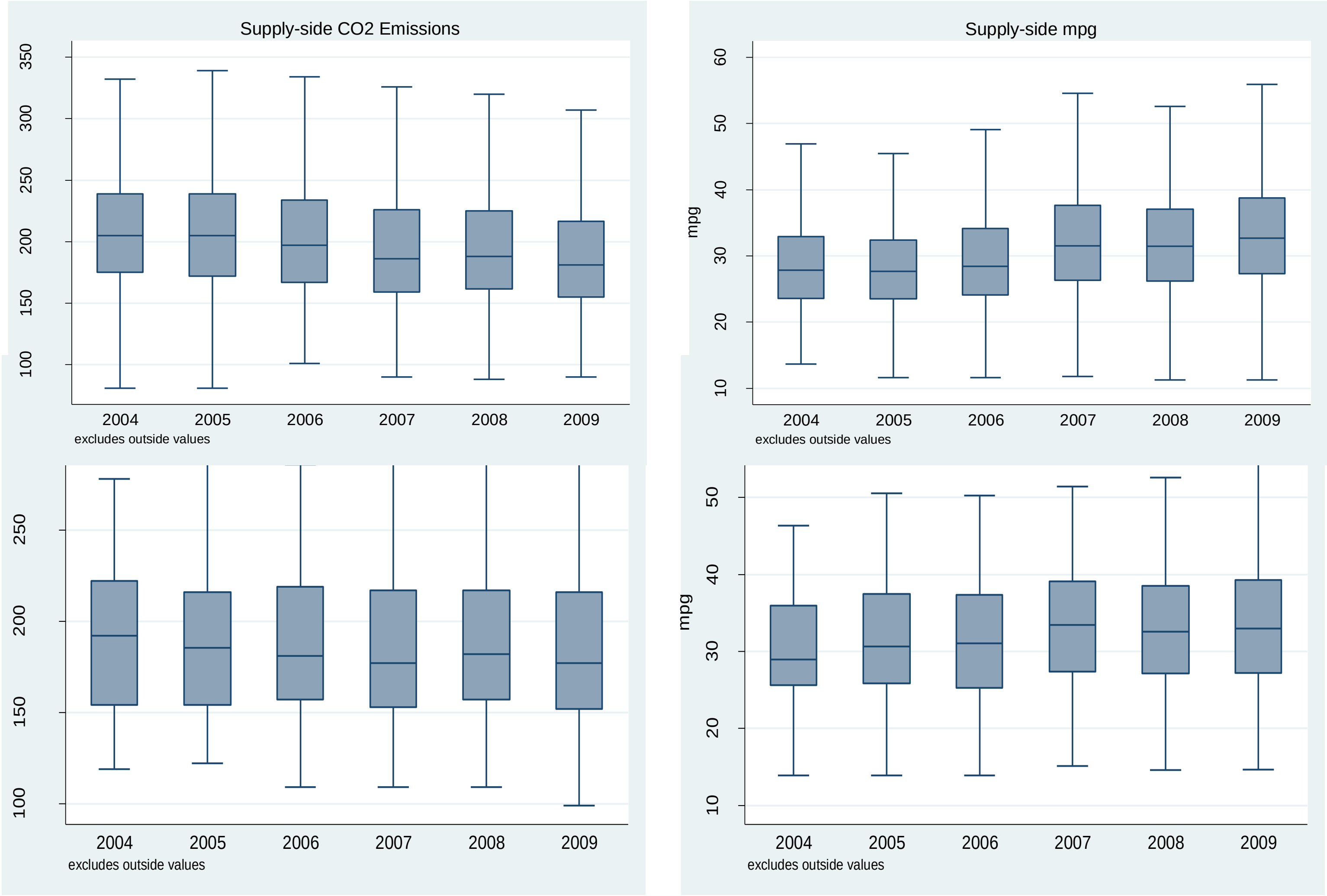


FIGURE 2



Sales-Weighted Market Shares
0
.2
.4
.6
.8
1
2004
2005
2006
2007
2008
2009
Year
Reg. Fuels >120gCO2/km
Reg. Fuels <=120gCO2/km
FFV
Gasoline/Electric
Gasoline/Gas

FIGURE 3



Supply-side CO2 Emissions
350
300
250
200
150
100
2004
2005
2006
2007
2008
2009
excludes outside values
Supply-side mpg
mpg
60
50
40
30
20
10
2004
2005
2006
2007
2008
2009
excludes outside values
250
200
150
100
2004
2005
2006
2007
2008
2009
excludes outside values
mpg
50
40
30
20
10
2004
2005
2006
2007
2008
2009
excludes outside values

FIGURE 4 ðSupplyside CO2 Emissions for Regular Fuel Green Cars

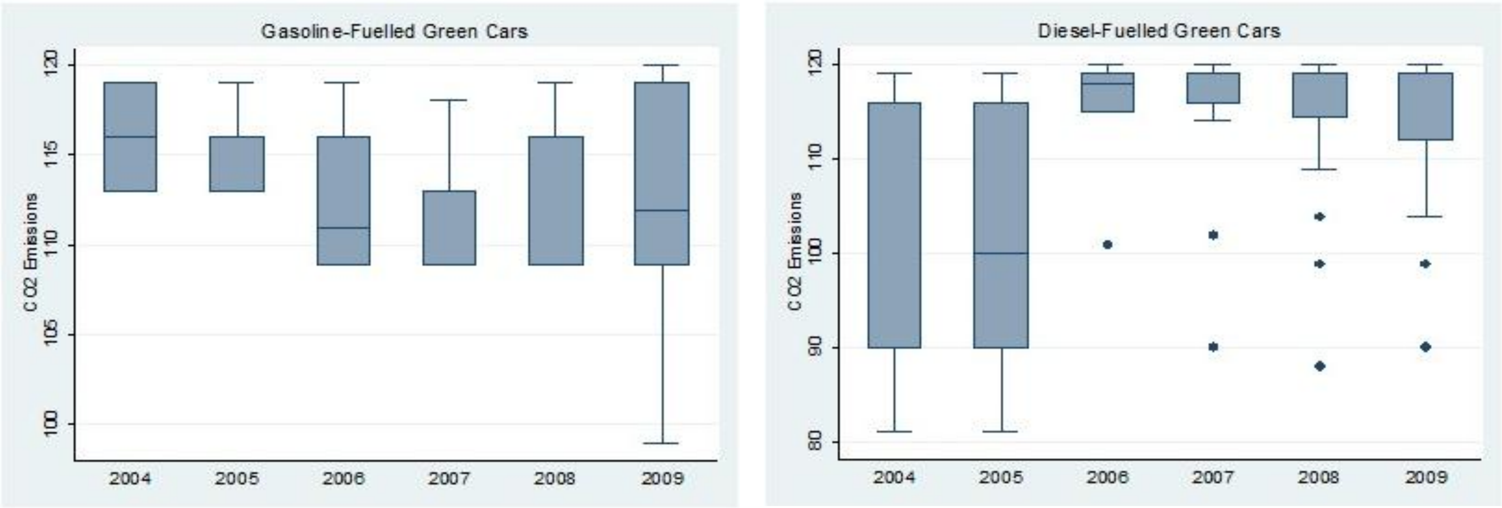
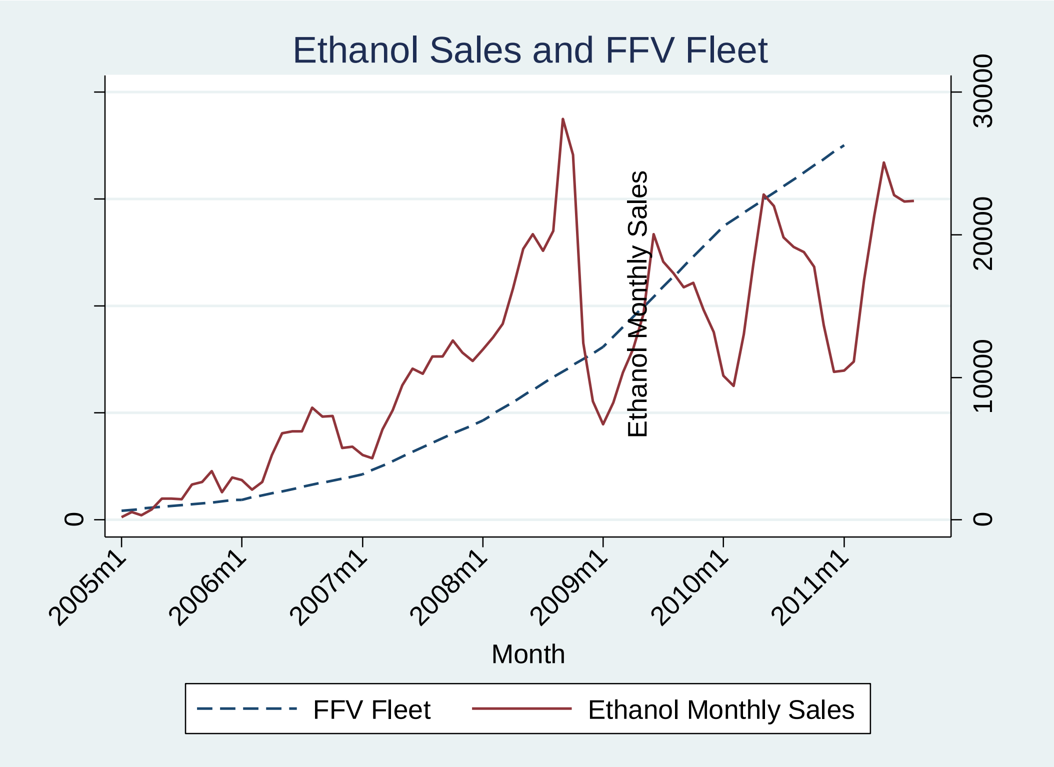


FIGURE 5

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 ethanol-gasoline price ratio.

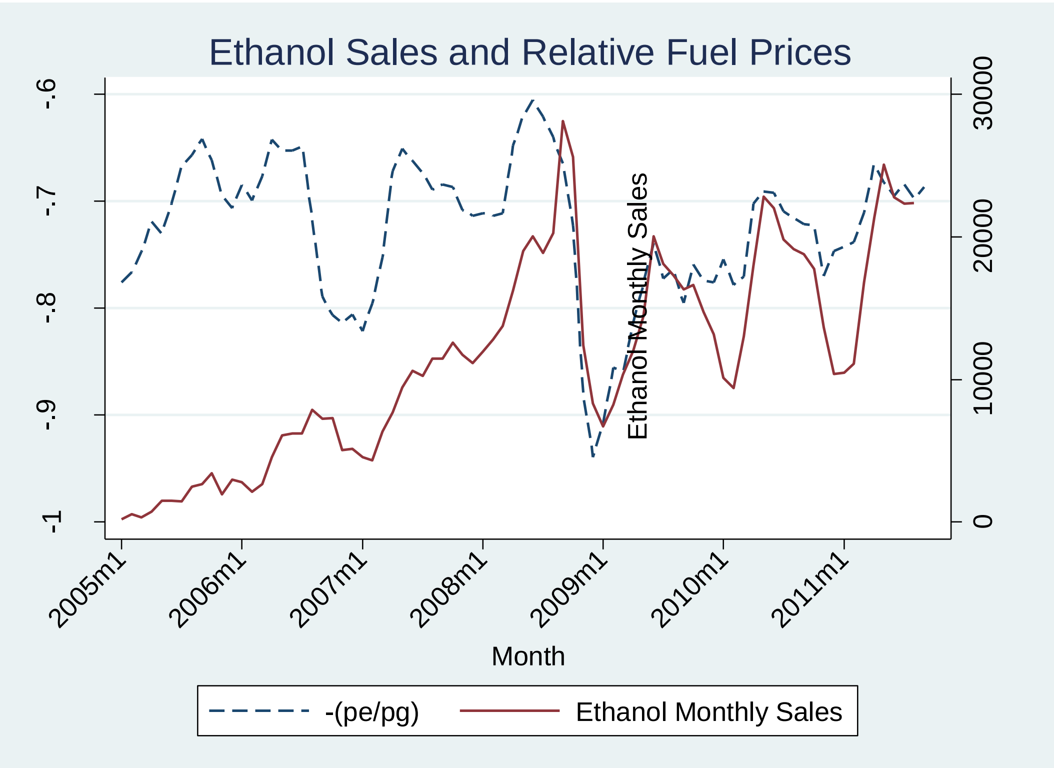
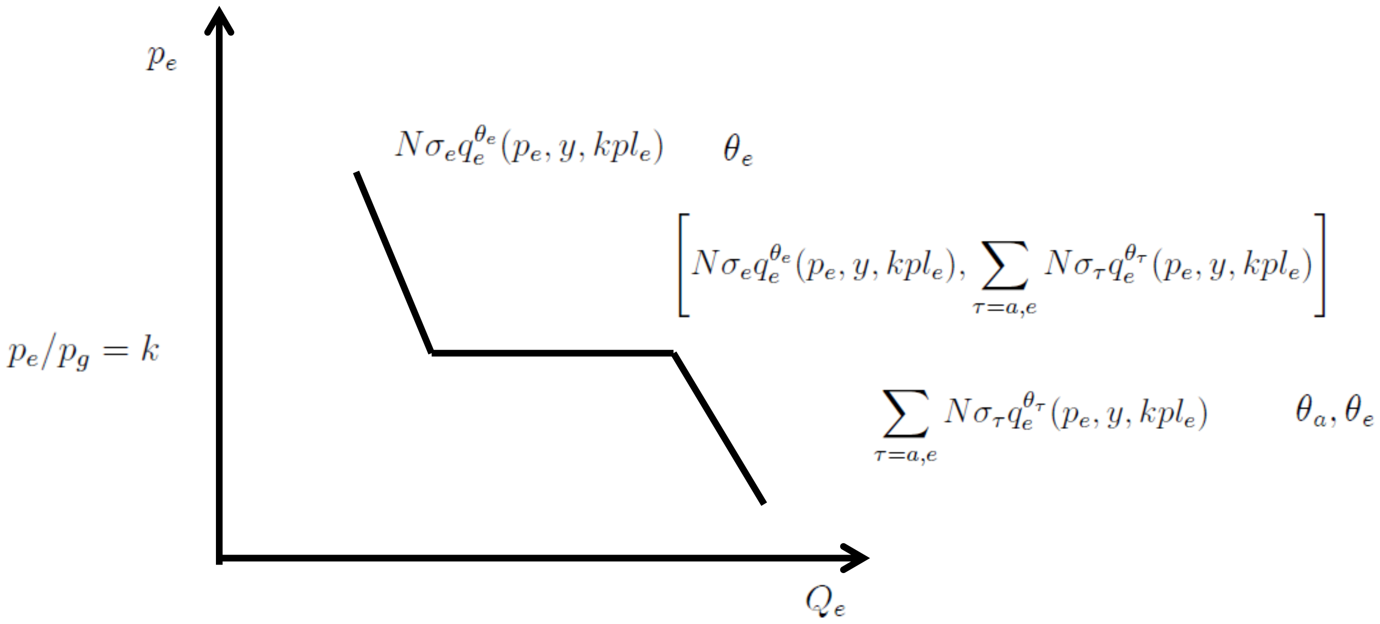


FIGURE 6



p_e
$N\sigma_e q_e^{\theta_e}(p_e, y, kpl_e)$ θ_e
$\left[N\sigma_e q_e^{\theta_e}(p_e, y, kpl_e), \sum_{\tau=a,e} N\sigma_\tau q_e^{\theta_\tau}(p_e, y, kpl_e)\right]$
$p_e/p_g = k$
$\sum_{\tau=a,e} N\sigma_\tau q_e^{\theta_\tau}(p_e, y, kpl_e)$ θ_a, θ_e
Q_e

ADDITIONAL FIGURES

FIGURE A1

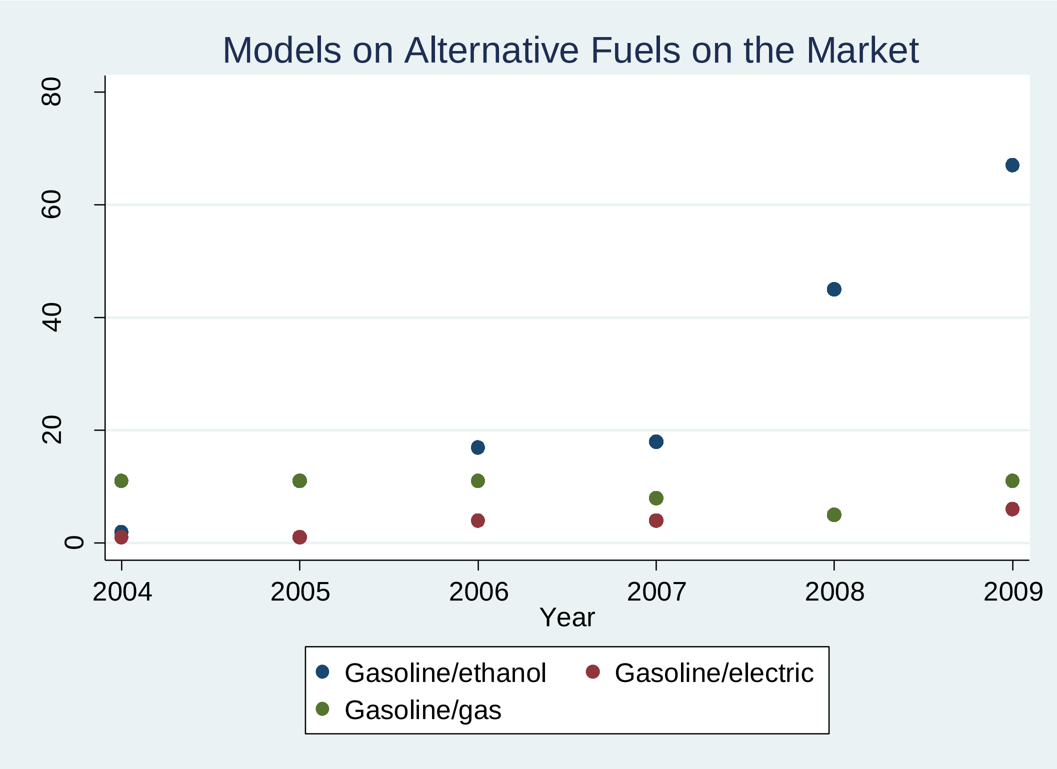
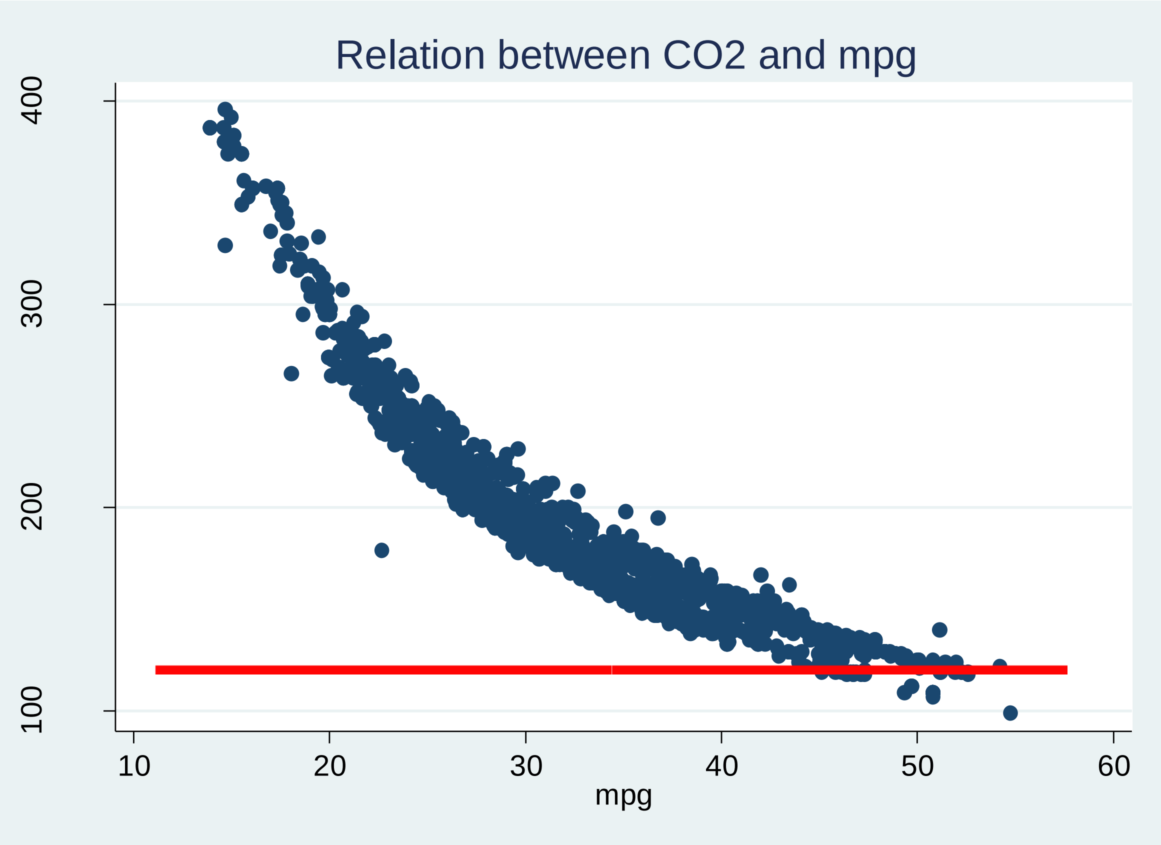


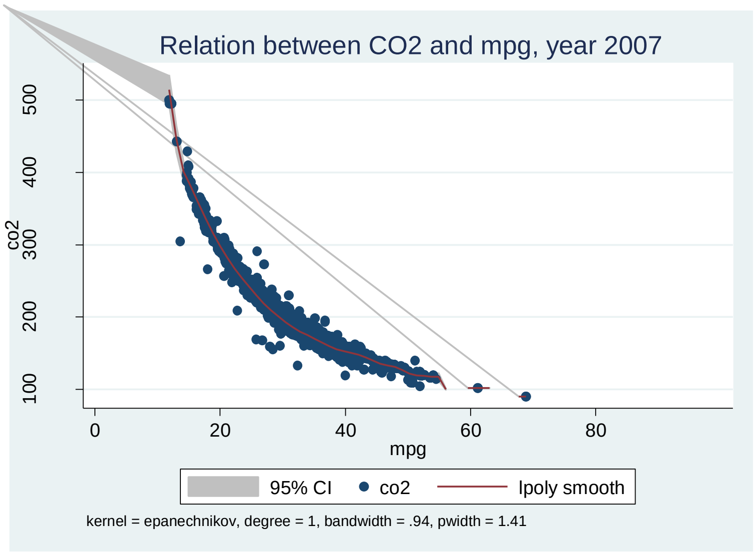
FIGURE A2



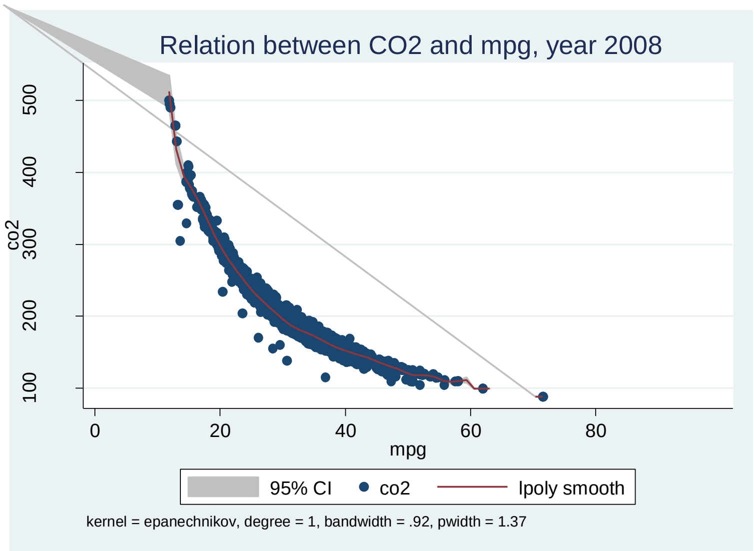
Relation between CO2 and mpg
400
300
200
100
10
20
30
40
50
60
mpg

FIGURE A3

Modelyear 2007



Modelyear 2008



Modelyear 2009

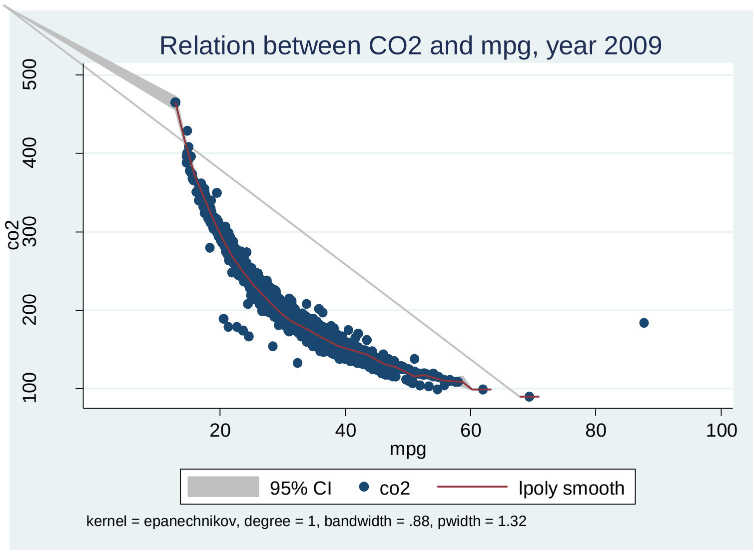
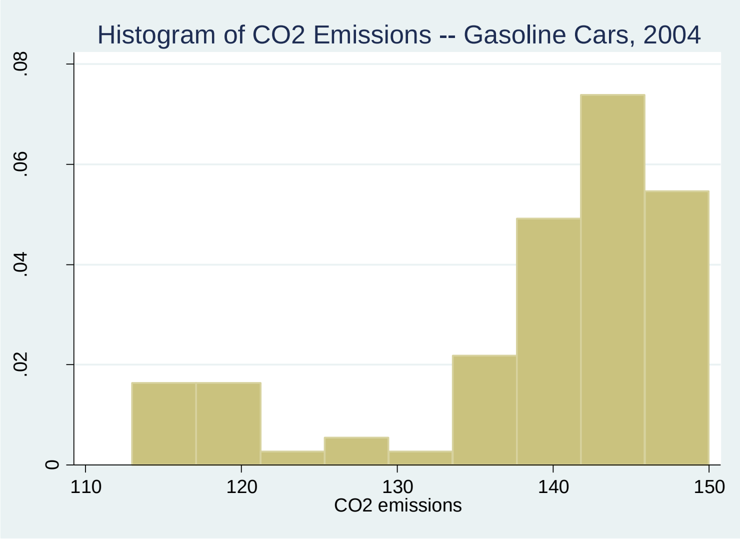
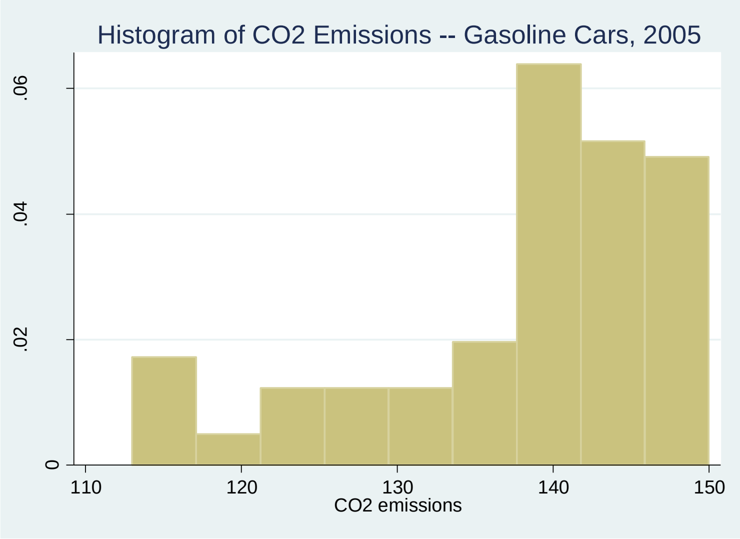


FIGURE A4 ðSales-weighted Distribution of CO2 Emissions of Gasoline Cars

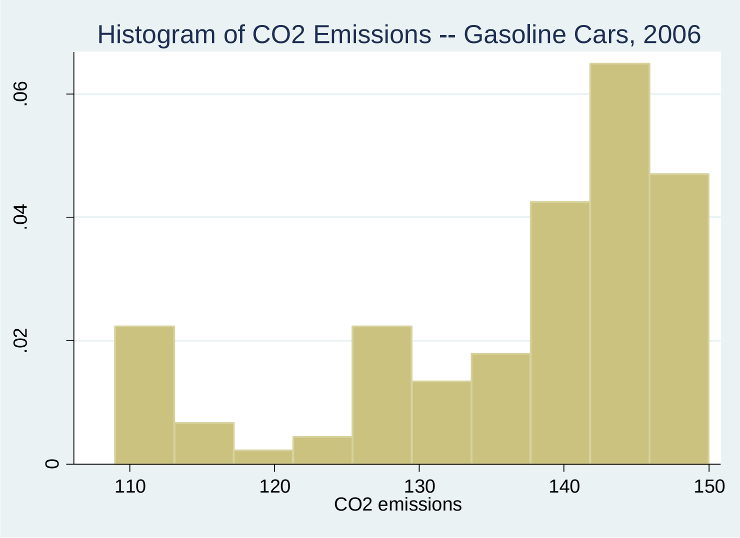
Model-year 2004



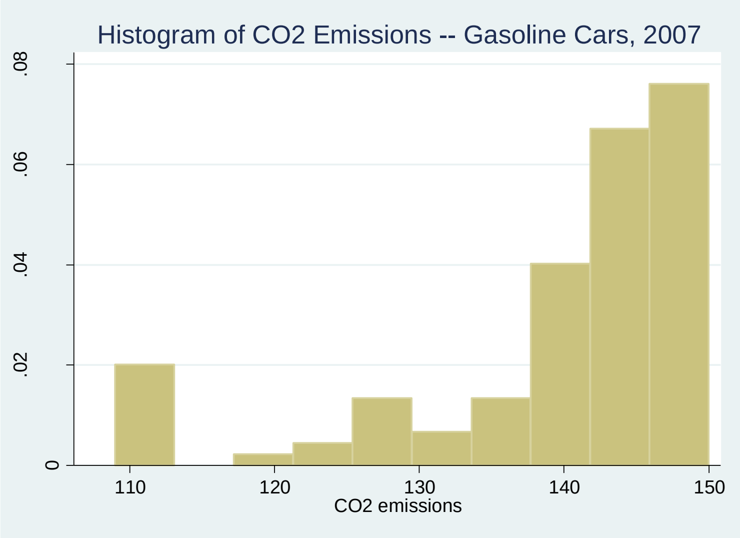
Model-year 2005



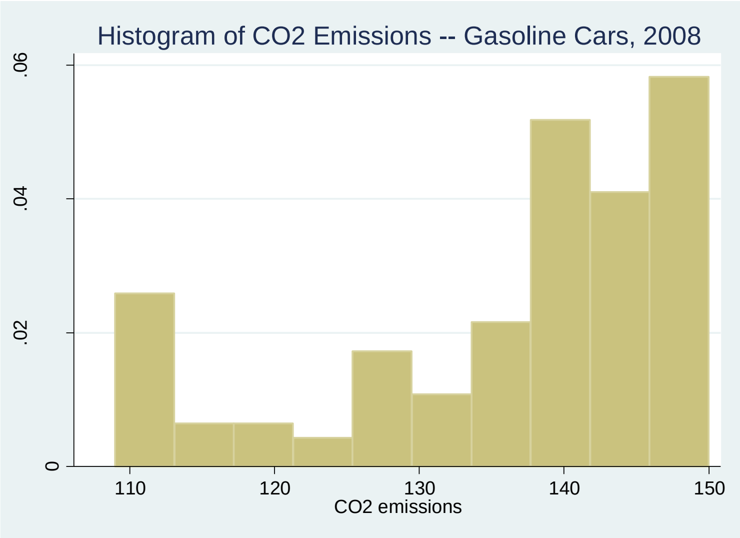
Model-year 2006



Modełyear 2007



Modełyear 2008



Modełyear 2009

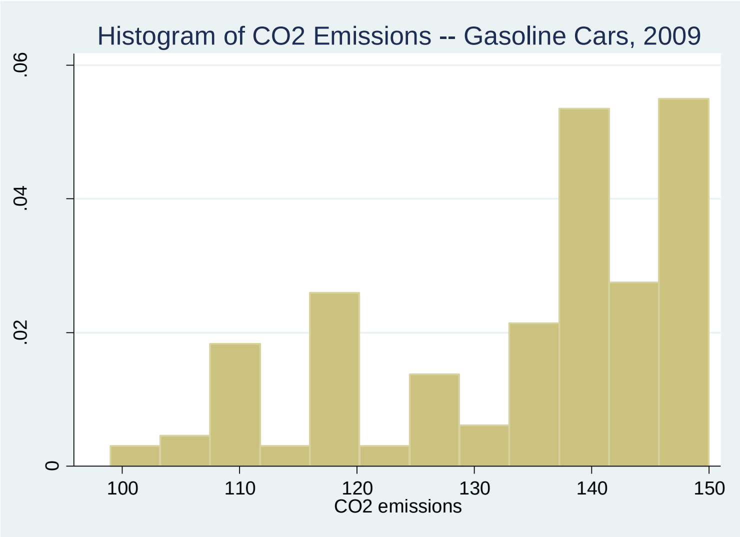
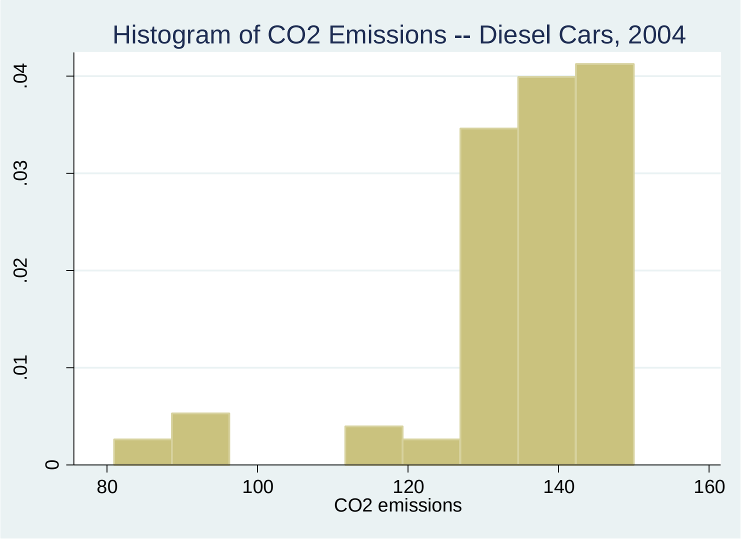
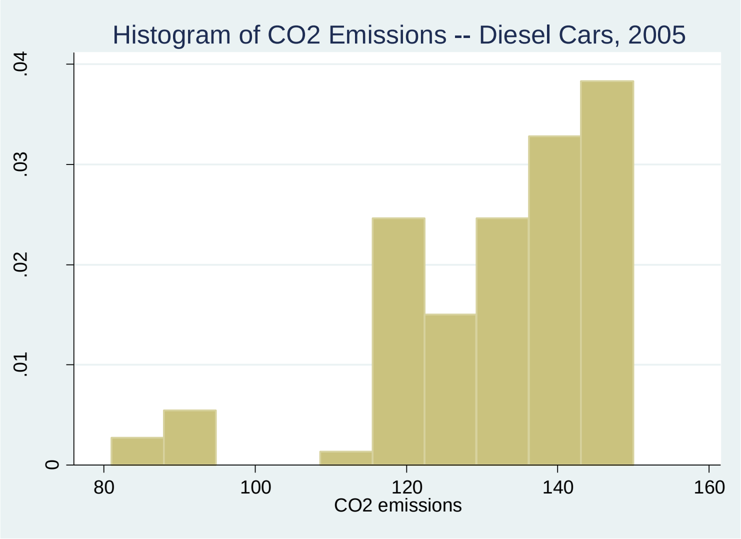


FIGURE A5 ðSales-weighted Distribution of CO2 Emissions of Diesel Cars

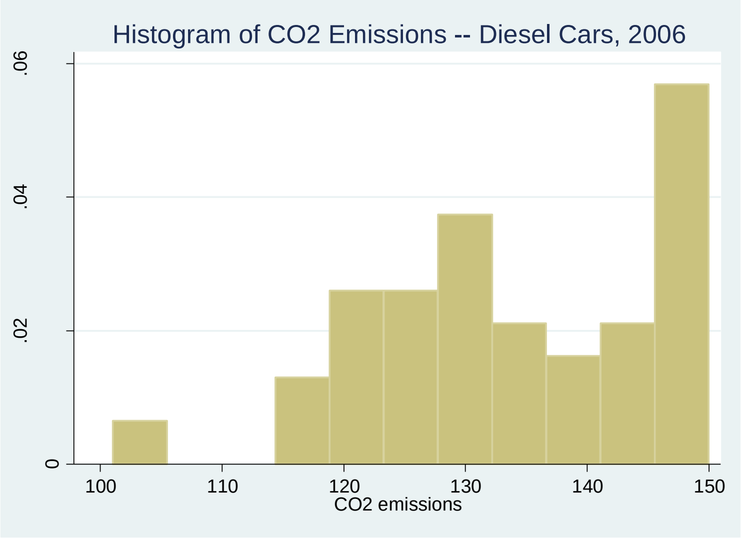
Model-year 2004



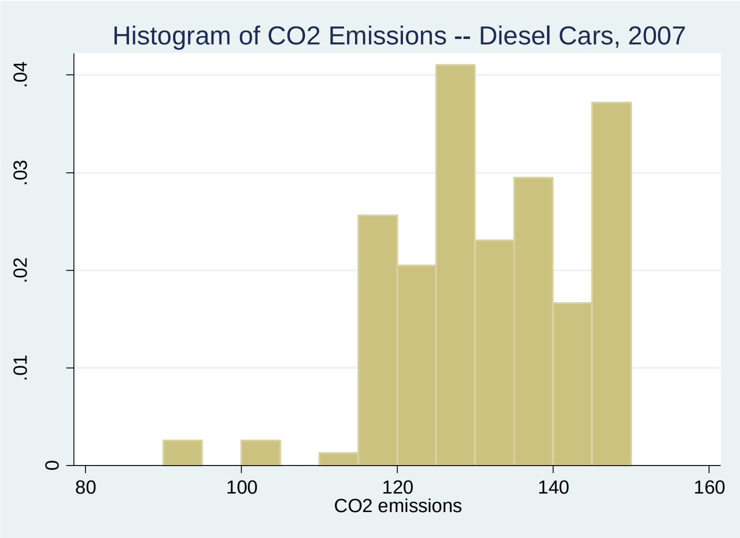
Model-year 2005



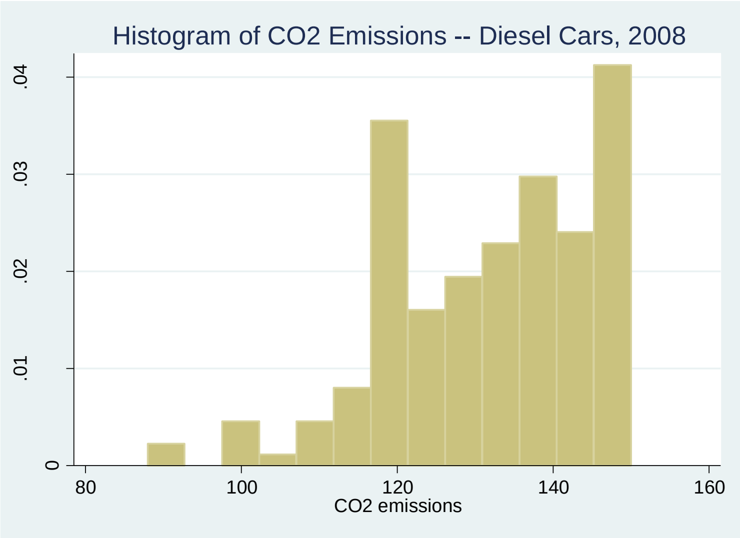
Model-year 2006



Modelyear 2007



Modelyear 2008



Modelyear 2009