Is Arbitrage Tying the Price of Ethanol to that of Gasoline? Evidence from the Uptake of Flexible-Fuel Technology

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Brazil is the only sizable economy to date to have developed a homegrown ubiquitously-retailed alternative to fossil fuels in light road transportation: ethanol from sugar cane. Perhaps unsurprisingly, the uptake of flexible-fuel vehicles (FFVs) has been tremendous. Five years after their introduction, FFVs accounted for 90% of new car sales and 30% of the circulating car stock. We provide a stylized model of the sugar/ethanol industry which incorporates substitution by consumers, across ethanol and gasoline at the pump, and substitution by producers, across domestic regional and export markets for ethanol and sugar. We argue that the model stands up well to the empirical co-movement in prices at the pump in a panel of Brazilian states. The paper offers a case study of how agricultural and energy markets link up at the very micro level.

> "This car will be an effective fuel price regulator." Fernando Damasceno, Chief Engineer at the Brazilian unit of autoparts firm Magneti Marelli, an early innovator in flexible-fuel vehicle technology

The Energy Journal, Vol. 32, No. 3.

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We wish to thank João A. Abreu (Shell), Severin Borenstein, Fabio Brás (Fenabrave), Leemore Dafny, Richard Friberg, Shane Greenstein, Sylvio Lima, Valdner Papa (Fenabrave), Simone Pasianotto (Sindipeças), Leonardo B. Rocha (International Sugar Organization), Claudia Rodrigues (Denatran), Sarquis J. B. Sarquis, Deise Schiavon (Magneti Marelli & "Circulating Fleet Study Group"), Dan Spulber, Scott Stern and Edson Zanetti (Fenabrave) for comments and/or for facilitating access to data. An online appendix, available from the authors' websites, provides further details on data sources and treatment. We are very grateful to Sergio Goldbaum and to Fernanda Lima who contributed to a substantially different earlier version. We also thank the editor and the referees for their insightful comments. All errors are our own.

1. INTRODUCTION

In recent years, supply insecurity in the oil industry, as well as mounting concern over carbon emissions, have led advanced economies such as the United States, Japan and Sweden to set ambitious goals for increasing the use of biofuels in their transportation systems. In particular, private and public funding in the ethanol business has soared, as the renewable fuel can be produced from home-grown crops or acquired in a nascent world trading market, enabling a country to diversify its energy sources. What makes ethanol further attractive in the minds of policymakers is that it can readily be burned in conventional car engines (or in minor adaptations of these engines), thus “piggy-backing on the existing gas station network” (U.S. Senator Lugar, 2006). Most recently, enthusiasm with biofuels has been tempered somewhat by the “food price scare” of 2007/8, in which sharp increases in the price of farm products were attributed—thanks to an emerging biofuels industry—to the spike in oil prices.[1]

Against this backdrop, we consider the world’s longest established industrial biofuels venture: the Brazilian sugar/ethanol industry, which transforms sugar cane (the country’s third largest crop) into sugar or ethanol for sale in domestic and export markets. Pure ethanol, or “E100”, has powered Brazilian passenger cars on a large scale since the early 1980s. For many years, ethanol-powered cars had single-fuel capability and competed against similarly single-fuel gasoline-powered cars in the car market. Starting in May 2003, thanks to a technological shift (a dramatic drop in the cost of car electronics) and the ubiquitous retailing of ethanol alongside gasoline throughout the country (a legacy of the 30-year experimentation with ethanol), global auto firms replaced the single-fuel cars they had previously sold in Brazil with dual-fuel ones, known as “flexible-fuel vehicles”. FFVs, also referred to as “flex”, run on any blend of ethanol and gasoline in the tank. By 2008, nine out of every ten new cars sold in Brazil were FFVs, and FFVs accounted for almost one-third of the country’s active car stock (the average age of cars in the fleet is 9 years, Sindipeças 2009). FFV motorists can costlessly arbitrage across the prices of ethanol and gasoline at the pump. Given the lower energy content (fuel economy) of ethanol relative to gasoline, pricing parity in $ per mile traveled occurs when the per-liter price of ethanol approximately equals 70% of the per-liter price of retailed gasoline, i.e., $p^e/p^g \approx 0.7$. This relative price threshold, below which ethanol is cheaper per mile traveled, is regularly explained in the media, including on the radio (which Brazilian motorists, often stuck in traffic, spend many hours listening to).[2] In the state

1. See, for example, Peñaranda and Rupérez Micola (2009) and references therein. Higher agricultural prices have fueled a vigorous “food-versus-fuel” debate. To select some examples from the press, the New York Times (2006), reported that “a change is under way that experts say will tightly tie the price of crops to the price of oil: ethanol plants are multiplying”, while the Economist (2007) claimed that “the price of biofuels has risen to that of petrol, and the price of corn and crude oil, the main feedstocks for the two, have converged”.

of São Paulo, the country's leading sugar cane producer and where ethanol has typically been priced below the 70% gasoline-price threshold, the increasing penetration of FFVs had by mid 2009 resulted in ethanol's share of car miles traveled exceeding that of gasoline.

This paper's contribution is twofold. First, we develop an open-economy stylized model of Brazil's sugar/ethanol industry which we believe captures its essential features. We model the industry as exercising market power in domestic regional sugar and ethanol markets and acting as a price-taker in export markets (in which buyers face many more substitution possibilities). We assume that the price of gasoline, effectively set by the central government through the state-controlled oil company Petrobras (a vertical monopolist all the way from exploration to refining), is largely exogenous to the local sugar/ethanol industry.[3] We assume that when ethanol is priced below (resp. above) the gasoline-parity threshold in a given local market, FFV motorists choose ethanol (resp. gasoline), leading to a kink (if not a highly elastic segment) in the ethanol demand curve.

The simple model predicts that, for a range of world sugar prices (international trading in ethanol is incipient) and a range of marginal costs (incurred in producing and delivering ethanol to the local pump), the price of ethanol should "tie" with, and be driven by, the energy-equivalent price of gasoline, i.e., $p^e = 0.7p^g$; further, prices should increasingly co-move as the penetration of FFVs in the car fleet continues to rise. The model also explains why ethanol prices can exceed the gasoline-parity threshold, $p^e > 0.7p^g$, prompting FFV motorists to switch to gasoline; for example, in temporal markets in which the net export price of sugar[4] is sufficiently strong (and thus the opportunity cost of selling ethanol locally is high), or in regional markets that are distant from sugar plantations (and similarly costly to serve). On the other hand, when net export prices for sugar and marginal costs for ethanol are both low enough, ethanol prices can dip below the gasoline-parity threshold, $p^e < 0.7p^g$. Ours is a model of how agricultural and energy—"agrienergy"—markets link up at a very micro level.

The second contribution is to provide an empirical analysis of domestic ethanol prices that is broadly consistent with the central prediction of the model,

2. To provide an example, a leading online news provider informed that "for switching (from gasoline to ethanol) to make financial sense, the price of ethanol should amount to at most 70% of the price of gasoline" (http://economia.uol.com.br/ultnot/infomoney/2007/11/09/ult4040u8011.jhtm; parenthesis added; UOL in 2007). Observing a rally in ethanol prices (which industry observers attributed to strong world sugar prices after a weak harvest in India), even President Lula recently (January 21, 2010) instructed motorists: "If you find a liter of ethanol priced above 70% that of gasoline that is because ethanol is expensive. In that case, it is best to settle for gasoline" (http://oglobo.globo.com/economia/mat/2010/01/22/lula-aconselha-consumidor-colocar-gasolina-caso-encontre-preco-do-alcool-abusivo-915685773.asp).

3. We do not attempt to explain the government's objective function. But we conjecture that gasoline prices in the long run track world oil prices, and in the short run are influenced by the electoral calendar and shielded from exchange rate volatility.

4. This is the world sugar price net of the export trade cost (which includes the transport cost from the sugar/ethanol mill to the port of exit).

namely that as the penetration of FFVs grows, the price of ethanol should increasingly covary with the price of gasoline. Our analysis is based largely on a panel of ethanol and gasoline prices collected at the pump in each of Brazil's 27 states over the period July 2001 to September 2009 (recalling that FFVs were introduced in 2003). We describe the domestic fuel price series in light of variation in world prices for sugar and crude oil and swings in the country's exchange rate. We note that while the price of ethanol relative to gasoline at the pump averages 69% in our panel, there is considerable cross-sectional variation. We then borrow an empirical test from the trade literature to show that the ethanol-to-gasoline price ratio has become less volatile in the later half of the sample relative to the first half. Finally, we apply multivariate time series models used widely in empirical macroeconomics (and used somewhat in the industrial organization of energy markets) to test for statistical causality between domestic fuel prices. We find strong evidence of "instantaneous causality" between gasoline prices and ethanol prices, which suggests that shocks affecting the two fuels' prices are contemporaneously correlated. We also find some evidence that gasoline prices "Granger-cause" ethanol prices, suggesting that gasoline prices have explanatory power for future ethanol prices. In sum, we take a significant cross-effect of gasoline prices on ethanol prices (and less so the other way round) as offering guarded support for our model of the sugar/ethanol industry.[5]

The plan of the paper is as follows. Section 2 describes Brazil's experience with ethanol in road transportation, which has paved the way for the FFV. Section 3 presents a stylized model of the sugar/ethanol industry that considers the impact of arbitrage at the pump. Section 4 contains the empirical analysis of prices. Section 5 concludes.

2. BRAZIL'S EXPERIENCE WITH ETHANOL IN ROAD TRANSPORTATION

Ethanol-powered cars were introduced in Brazil back in 1979, four years after the (then military) government launched the sugar-cane-based National Ethanol Program, the *Proálcool*.[6] With four-fifths of the country's oil consumption being imported, the Proálcool's central aim was to reduce the country's dependence on increasingly-expensive foreign energy supplies, by substituting ethanol for gasoline used in light road transportation. Ethanol consumption would

5. We are cautious in reading too much from our empirical analysis, as it is limited largely to prices. Though this approach has been widely used in different literatures, one may wish to interpret the exercise by way of a statistical exploration, or at best as offering suggestive evidence in support of our model of the industry. Estimating the model structurally, with regional-and-time markets switching between regimes (e.g., as in Salvo 2010), would require richer data, such as quantities demanded and supplied across the many markets, and is left for future research.

6. Unless noted otherwise, institutional information is drawn from Shikida (1998), Tasca (2002), Bacchi et al (2004), Baccarin (2005), Lima (2006), Nass et al (2007), Anfavea (several years), MME (several years), and references therein.

increase in two ways: (i) by raising the proportion of ethanol (from 10% to around 20%) mixed in with regular gasoline for use in the conventional gasoline-dedicated car engine[7] and, more innovatively, (ii) by powering cars newly equipped with an ethanol-dedicated engine.[8] Brazil was the world's largest sugar cane producer and a large sugar exporter, and, following several years of weak and volatile world sugar prices, the government also hoped that the program would provide some support to the country's powerful sugar industry.

Judged in terms of sales, the early years of the Proálcool were a roaring success. By 1984, ethanol-dedicated engines accounted for more than 80% of new passenger car sales nationwide, with gasoline-fueled cars falling below 20%. By 1987, as Figure 1 indicates, ethanol consumption had reached that of gasoline. This was achieved through a variable combination of (i) subsidies, such as low-interest loans, for (largely private-sector) infrastructure (i.e., sugar cane plantations, ethanol mills, fuel distribution and retailing, R&D for agriculture and car engine systems); (ii) guaranteed purchases of ethanol, by the state oil company Petrobras, at a wholesale price floor; (iii) lower producer and consumer taxes for ethanol fuel and ethanol-powered cars (including registration tax), relative to gasoline; and (iv) a ceiling for the price of ethanol relative to gasoline at the pump.[9] Whereas 97% of the 1977/78 sugar cane harvest had been transformed into sugar (for domestic and export markets), by 1984/85 ethanol was being produced from as much as 48% of the sugar cane harvest (which itself had roughly doubled in comparison to the 1977/78 harvest thanks to increased acreage and crop yields). (For perspective, only 20% of the U.S. corn harvest of 2006 was diverted to ethanol production.)

The impetus behind the ethanol program began to fade in the late 1980s. With world oil prices falling and oil fields being discovered off the Brazilian coast, the government's enthusiasm for curbing gasoline consumption began to wane. World sugar prices were on the rise, putting pressure on domestic ethanol prices[10], and a heavily-indebted government was less willing to foot the bill (say via unit subsidies) to assure supply of ethanol at the pump at the prevailing official price ceiling relative to gasoline. While in the early years the (per-liter) retail price of ethanol relative to gasoline had remained below the 70% threshold, more than fully offsetting ethanol's lower mileage per liter, by 1989 the relative price

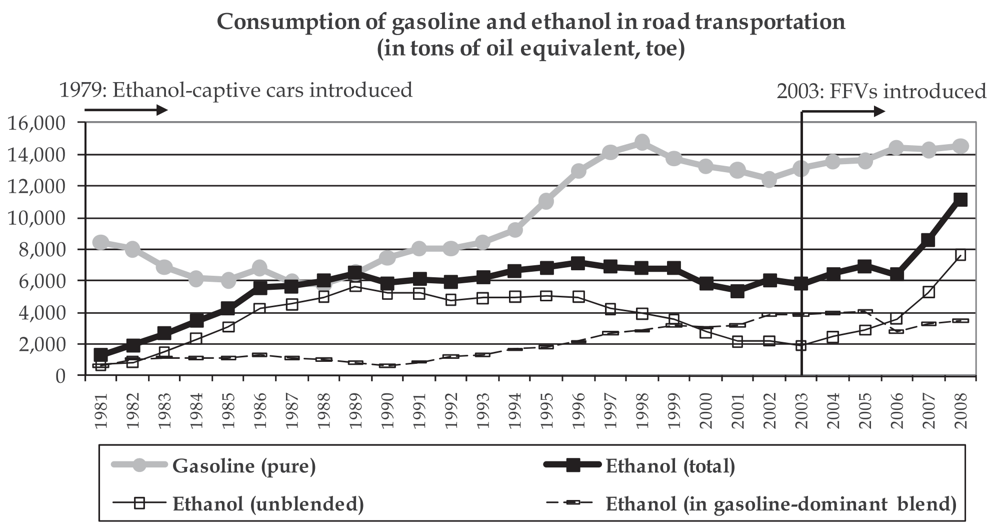
7. To this day, gasoline retailed in Brazil includes a low proportion of ethanol (e.g., one-fifth by volume, or E20)—throughout the paper we refer to these gasoline-dominant blends simply as gasoline.

8. These ethanol-captive cars (like FFVs a generation later, discussed below) have run on unblended E100 ethanol (bar a residual 4% water content, thus known as "hydrated" or "hydrous" ethanol). In the U.S., by contrast, the ethanol fuel currently being introduced is actually a blend containing 15% gasoline, i.e., E85, due to the colder weather.

9. Relatedly, Borenstein (1993) analyzes the U.S. experience of switching from leaded to unleaded gasoline, where price incentives for adoption of the new single-fuel technology (i.e., unleaded-fuel cars whose catalytic converters would be damaged by leaded gasoline) were largely absent.

10. See the model of Section 3.

Figure 1: Evolution of gasoline and ethanol consumption in Brazil's road transportation, in tons of oil equivalent (toe), over the period 1981 to 2008. Ethanol consumption is broken down into unblended ethanol (which has fueled ethanol-dedicated cars and, more recently, flexible-fuel vehicles) and as an additive to gasoline (which has fueled-dedicated gasoline cars and FFVs). Source: MME (several years).



of ethanol had reached the 75% mark, steadily increasing to 85% over the next decade. Sales of ethanol cars plummeted, compounded by news of "locked in" car owners fuming at the occasional ethanol supply shortages. Compared to an all-time high 96% share in 1985, ethanol-captive cars accounted for less than 10% of new car sales by 1994. By the late 1990s, ethanol consumption amounted to barely one-half that of gasoline (Figure 1).

The vast infrastructure of ethanol production and distribution assets that had been built in the 1980s managed to survive the Proálcool's downturn in the 1990s thanks to the slow decay of ethanol-captive cars in the fleet. Because the fleet is a stock rather than a flow, ethanol remained ubiquitously retailed across the country (i.e., virtually all fueling stations sell ethanol in addition to gasoline). This helped to pave the way for the widespread introduction of flexible-fuel vehicles from 2003. Since flex engines could burn any blend of gasoline and ethanol (with the tank not having to be run dry to switch to the other fuel), FFV owners were now in a position to costlessly arbitrage across the prices of gasoline and ethanol in the fuels aftermarket (and maintenance costs were similar to those of single-fuel cars). The speed of adoption of the flex motor paralleled that of its ethanol-dedicated counterpart almost 25 years earlier, but this time round carmakers quickly transitioned their models to the flex version alone, rather than offering flex alongside a conventional gasoline-only version, and at broadly equivalent prices.[11] By the first quarter of 2007, FFVs already accounted for as much as 85% of new car sales nationwide. At the end of 2008, the composition of Brazil's passenger car fleet (22 million, including SUVs) was 57% gasoline-only, 12% ethanol-only, and 30% flex.[12] As a result of car manufacturers soon offering models in the flex version alone, the uptake of the FFV has occurred at similar rates across the different regions of the country (and regardless of cross-sectional variation in the price of ethanol relative to gasoline, presented below). The early 2000s was a time in which world oil prices were again on the rise, and the world price of sugar had weakened compared to the 1990s. Importantly, by the late 1990s, the government was no longer interfering with (producer and consumer) prices of ethanol: the ethanol supply chain had by then been deregulated.

3. CONCEPTUAL FRAMEWORK

We begin by considering how the introduction of the FFV impacts the demand for ethanol. We then provide a stylized model of the vertical sugar cane-sugar/ethanol industry which predicts that, as the penetration of the flex engine grows, the equilibrium price of ethanol should increasingly move with the price of gasoline.

3.1 The Advent of Flex: Consumer Arbitrage in Fuel Markets

Passenger car engines are of three types: gasoline-only, ethanol-only, or flex, indexed by g, e and f respectively. In a given local market, the number of active cars by fuel type is given by a vector $n=(n^g,n^e,n^f)$. Each car (engine) $j\in\{g,e,f\}$ is owned by a different consumer, thus there are $\sum_j n^j$ consumers. The average mileage per liter of fuel on which engine j runs is given by α^j. For simplicity, we (i) assume that a flex engine burning ethanol (resp. gasoline) has the same fuel economy as an ethanol-only (resp. gasoline-only) engine (i.e., the FFV is fully "backward compatible"), and (ii) assume away variation in α^j across consumers within engine type (owing to, say, differences in car models, patterns of city relative to highway driving, or vehicle maintenance).

A consumer's problem, conditional on her ownership of car type j, is given by

11. In June 2006, for example, Volkswagen announced that its Brazilian subsidiary would only produce FFVs (Forbes 2006). With the collapse in the price of electronics, a carmaker's cost upcharge in equipping a model with a flex engine relative to a single-fuel one is about 100–150 US$ (Corts 2010), possibly not worth the cost of carrying different engines. In the U.S., carmakers have also begun equipping models with flex engines. Corts (2010) notes that, because of the limited availability of (E85) ethanol in retail fueling stations and the fact that flex cars and gasoline-captive ones are priced similarly, many U.S. flex car owners are unaware that their engine also runs on ethanol.

12. We calculated these shares from Sindipeças' (2009) estimates. The use of other fuels such as diesel and natural gas in passenger cars is minimal.

$$\max_q U(q_{transp}, q_{outside})$$
$$\text{s.t. } p_{transp} q_{transp} + q_{outside} \leq y$$

where y is income, q_{transp} denotes the quantity of miles of personal transportation the consumer chooses at the expense of the numeraire outside good (i.e., $q_{outside}$ is money spent on all other goods), and the price per mile traveled equals

$$p_{transp} = \begin{cases} p^j/\alpha^j & \text{if consumer } i \text{ owns car type } j \in \{g,e\} \\ \min(p^g/\alpha^g,\ p^e/\alpha^e) & \text{if consumer } i \text{ owns car type } f \end{cases}$$

where p^g and p^e are unit (i.e., per-liter) prices of gasoline and ethanol, respectively, at the pump. We assume away any variation in the way an FFV owner arbitrages across (normalized) differences in the prices of gasoline and ethanol, due to environmental, "home bias" or driving preferences;[13] we comment on this assumption below.

A consumer's (ordinary) demand for personal transportation $q_{transp}(p_{transp}, y)$ will, under standard assumptions on the utility function, be a smooth and decreasing function[14] of the price of personal transportation p_{transp}, i.e., miles traveled q_{transp} will be given implicitly by

$$\frac{U_1(q_{transp}, q_{outside})}{U_2(q_{transp}, q_{outside})} = p_{transp} = \frac{y - q_{outside}}{q_{transp}}$$

To derive market-level demand for ethanol (the demand for gasoline is derived similarly), consider a consumer who owns a dedicated ethanol engine. Since she cannot arbitrage across price differences, her individual demand in liters of ethanol is

$$q^e(p^e, y; \alpha^e \,|\, \text{consumer } i \text{ owns } e) = q_{transp}(p^e/\alpha^e, y)/\alpha^e$$

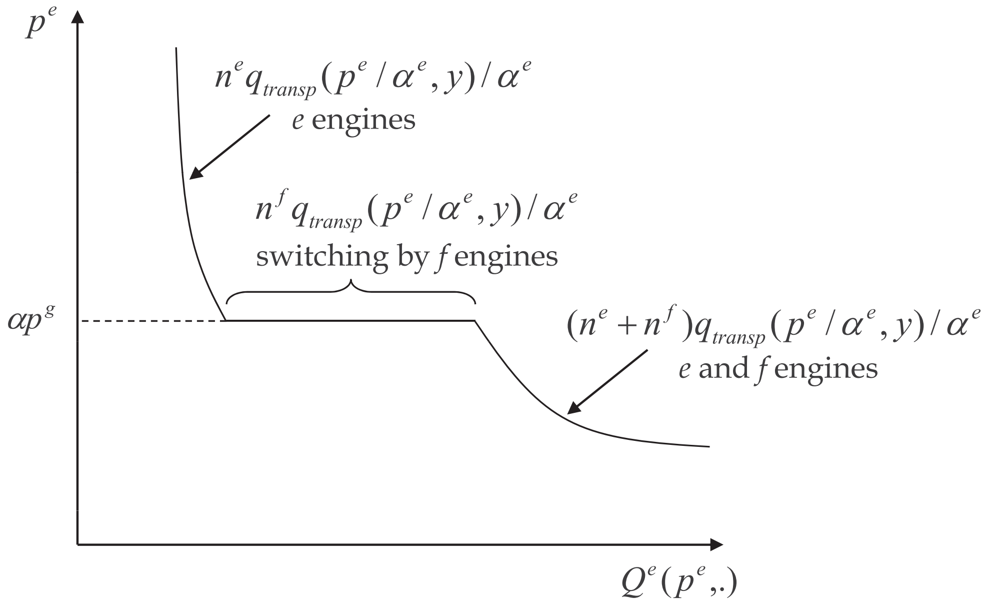
Now consider the owner of a flex engine. Her demand in liters of ethanol is given by

$$q^e(p^e, p^g, y; \alpha^e, \alpha^g \,|\, \text{consumer } i \text{ owns } f)$$
$$= \begin{cases} 0 & \text{if } p^e/p^g > \alpha^e/\alpha^g \\ [0, q_{transp}(p^g/\alpha^g, y)/\alpha^e] & \text{if } p^e/p^g = \alpha^e/\alpha^g \\ q_{transp}(p^e/\alpha^e, y)/\alpha^e & \text{otherwise} \end{cases}$$

13. Similarly, as the relative price jumps around, motorists may exhibit habit formation, or be unable or unwilling to do the cost conversion every time they refuel. See Anderson (2009) for an early study of how FFV owners in certain regions of the U.S. switch between gasoline and ethanol. In current work, we are attempting to infer preferences from choices Brazilian FFV motorists make at the pump (Salvo and Huse 2010).

14. The price elasticity of demand for personal transportation is typically very low. For example, price elasticities of gasoline demand are estimated to be as low as –0.05 by Hughes et al (2008) using recent U.S. data, and at a still low –0.5 by Alves and Bueno (2003) from less recent Brazilian data.

Figure 2: Arbitrage by flex consumers: Aggregate demand for the ethanol fuel variety retailed in a given local market (to include ethanol contained in the retailed gasoline variety, both steep segments would shift to the right, the upper steep segment shifting more than the lower one since the elastic segment would now be shorter).



Aggregating across the distribution of engine types described by n we obtain the aggregate demand function for ethanol in liters:

$$Q^e(p^e,p^g,y;\alpha^e,\alpha^g,n) \\ = \begin{cases} n^e q_{transp}(p^e/\alpha^e,y)/\alpha^e & \text{if } p^e/p^g > \alpha^e/\alpha^g \\ [n^e q_{transp}(p^e/\alpha^e,y)/\alpha^e,(n^e+n^f)q_{transp}(p^e/\alpha^e,y)/\alpha^e] & \text{if } p^e/p^g = \alpha^e/\alpha^g \\ (n^e+n^f)q_{transp}(p^e/\alpha^e,y)/\alpha^e & \text{otherwise} \end{cases} \tag{1}$$

Figure 2 illustrates how aggregate demand for ethanol jumps out by $n^f q_{transp}(p^e/\alpha^e,y)/\alpha^e$ at $p^e = \alpha p^g$, where $\alpha := \alpha^e/\alpha^g$—recall that $\alpha \approx 0.7$.[15] Should

15. Should retailed gasoline fuel contain a (low) proportion of ethanol (e.g., about 20% in Brazil and up to 10% in the U.S.), one can either (i) restrict the interpretation of Figure 2 to include only the retailed ethanol *fuel variety* (E100 in Brazil, E85 in the U.S.); or (ii) "horizontally add" the quantity of ethanol contained in retailed gasoline fuel to Figure 2, thus depicting total demand for ethanol (the upper and lower steep segments of the curve would shift to the right, the upper one shifting more than the lower one as the horizontal segment would now be shorter, reflecting the ethanol component in gasoline).

the relative price threshold at which there is switching between fuels, α, vary across FFV owners, for reasons that we have assumed away above, the demand curve would be smoother, though remain highly elastic around the $0.7p^g$ mark.

3.2 A Stylized Model of the Sugar/Ethanol Industry

Our purpose is to develop a simple model of the current Brazilian sugar/ethanol industry, which buys sugar cane from domestic growers and transforms it into either sugar or ethanol for sale on domestic and export markets.[16] With this end, we make some simplifying assumptions, none of which we believe is wide off the mark in guiding our understanding of how the industry operates. First, we assume that the sugar/ethanol industry exercises market power in domestic markets but much less so on the world market. In other words, we take local sugar/ethanol mills, particularly concentrated compared to more fragmented sugar cane growers upstream, as setting domestic prices.[17] Second, we take the price of gasoline as (largely) exogenous to the sugar/ethanol industry, and set by the government. The central role of the state in Brazil's oil sector is well known. While retail fueling stations have been free to price gasoline since the late 1990s, the government in effect still mandates the price of fossil fuels across the economy through its control at wholesale, namely at Petrobras refineries. One might speculate about the government's objective function,[18] but it seems plausible to argue that the domestic sugar/ethanol industry is one factor among many (obscure) others determining the price of gasoline.

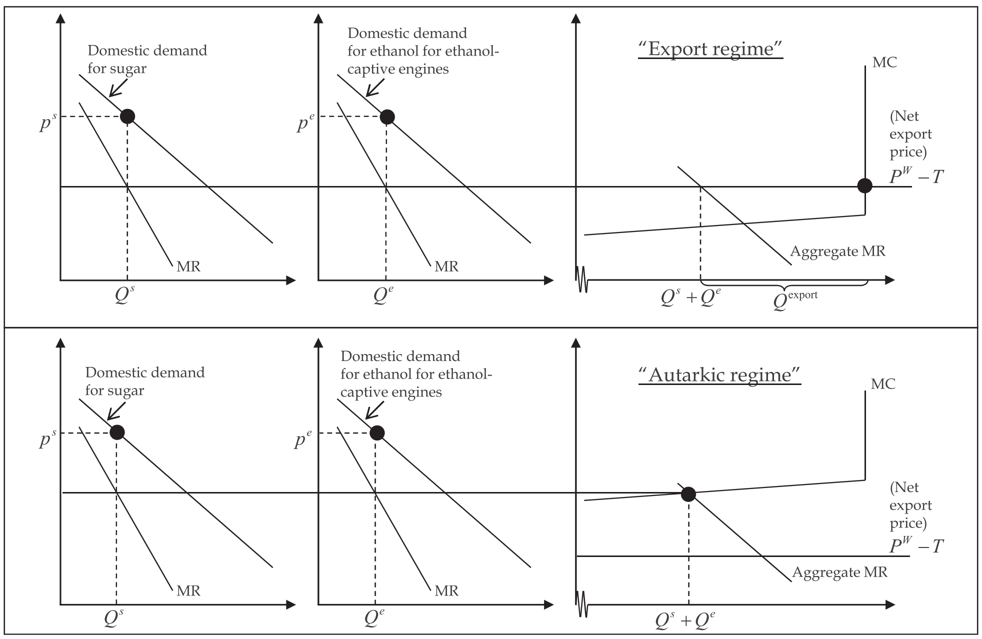
Begin by considering the sugar/ethanol industry around 2001/2002, prior to the introduction of the FFV in 2003, depicted in Figure 3. Given the fixed-coefficient nature of technology, the figure should be read in sugar cane equivalent units. At this point in time, the industry faced captive domestic demand for ethanol by owners of ethanol-only cars (around 20% of the car fleet), in addition to demand for sugar in both the domestic market and the world market. Again, we assume that regional producers act as price-setters on domestic markets and as price-takers on the (much larger) world market, where the relevant export price

16. A ton of sugar cane can either be refined into 130 kg of sugar or distilled into 80 liters of ethanol, approximately. Sugar cane plantations agglomerate around the southeastern state of São Paulo and the northeastern state of Alagoas. Firms in the industry typically run both sugar refining and ethanol distillation operations, most often located in the same mill (and close to the cane plantation, as transporting the raw material is more costly than the finished product). The largest firm, Cosan (accounting for one-tenth of sugar cane processing nationwide, and a larger share in specific local markets), is vertically integrated from farm to consumer packaged sugar, fuel distribution and retail, and export terminals.

17. Brazil's traditional sugar industry has a long history of collectively representing its interests. For perspective, see Genesove and Mullin (1998, 2001) for a historical account of the U.S. sugar industry.

18. For example, it appears that the domestic price of gasoline tracks the world price of oil in the long run, but in the short run is influenced by the political cycle, and shielded from transitory exchange rate shocks. See the empirical analysis of prices below.

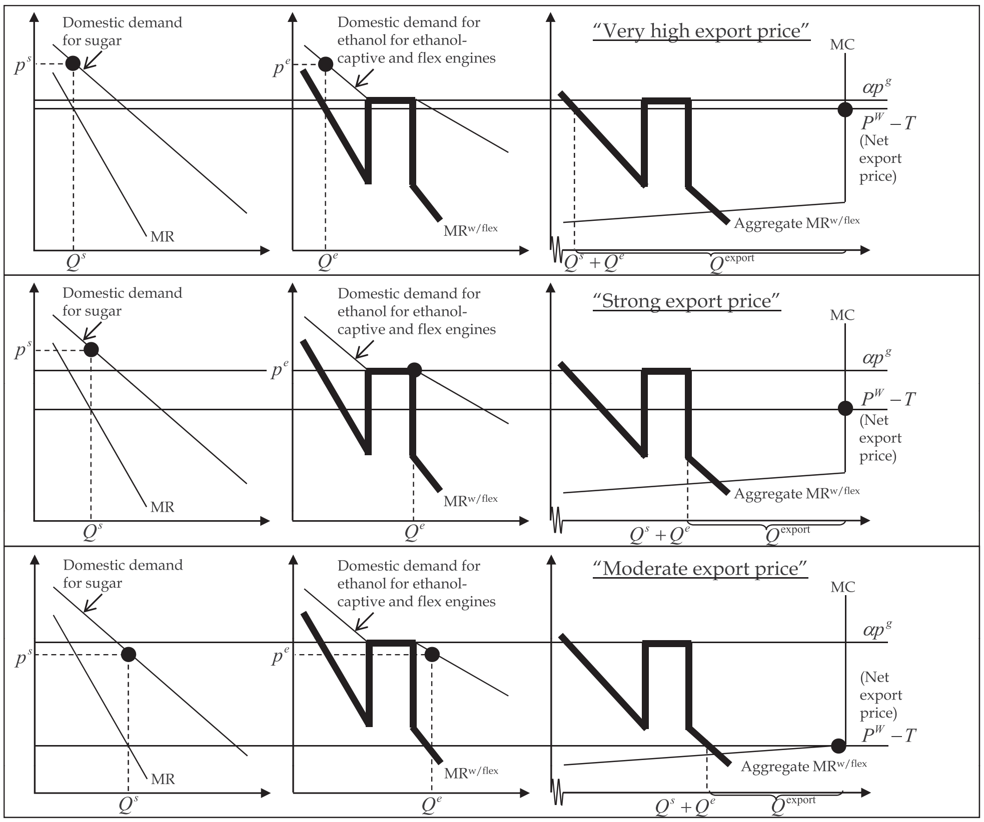
Figure 3: The Brazilian sugar/ethanol industry around 2001/2002, prior to the introduction of the FFV: Local markets for sugar (food consumers) and for ethanol (motorists of ethanol-captive cars, amounting to 20% of the car fleet), and world market for sugar. In sugar cane equivalent units. Upper panel: (the "export regime") Local sugar and ethanol prices determined by local demand conditions and the world price (net of the export trade cost). Lower panel: (the "autarkic regime") Local sugar and ethanol prices determined by local demand conditions and local supply conditions.



is the world price (of sugar) P^W discounted by the export trade cost T.[19] As drawn in the upper panel, labeled "export regime", the industry equates this net export price $P^W - T$ with the marginal revenue in each domestic market (or, equivalently, with the "horizontal aggregate" of the domestic marginal revenue curves), thus determining domestic prices and quantities of sugar and ethanol as well as the export quantity of (predominantly) sugar, respectively marked p^s, Q^s, p^e, Q^e, Q^{export}. Alternatively, should the world sugar price be too depressed, or the export trade cost be too high (e.g., a local market such as a state located far from

19. A Vector Error Correction (VEC) model estimated with world sugar prices and domestic (producer) sugar prices (over the period July 2001 to September 2009, in constant US$ terms; see the online appendix) produced a highly significant cross-effect from world prices to domestic prices and an insignificant effect the other way round (i.e., no significant feedback from domestic sugar prices to world sugar prices). Further details can be provided upon request.

Figure 4: The sugar/ethanol industry after the introduction of the FFV (30% of the car fleet by 2008), drawn for the "export regime". In sugar cane equivalent units. Upper panel: ("very high export price") $p^e > \alpha p^g$. Middle panel: ("strong export price") $p^e = \alpha p^g$. Lower panel: ("moderate export price") $p^e < \alpha p^g$.



a port), relative to the marginal cost schedule MC, the industry would equate marginal cost with aggregate domestic marginal revenue: this "autarkic regime" is drawn in the lower panel of the figure.

Now consider the present sugar/ethanol industry, several years after the introduction of the FFV, depicted in Figure 4. Recall that by 2008, the composition of Brazil's car stock was 57% gasoline-only, 12% ethanol-only, and 30% flex, with the latter eating away at the former two.[20] In each panel of the figure (the three panels corresponding to different export prices, all drawn under the export regime,[21] as described below), the domestic demand curve for ethanol now in-

20. Our estimate of the composition two years earlier (based on estimates obtained from Fenabrave, Sindipeças and Denatran—see below), is 72% gasoline-only, 15% ethanol-only, and 12% flex.

21. We focus our text on the export regime since the industry, at the country level, exports large quantities of sugar (and increasingly ethanol). For perspective, of the sugar cane harvested nationwide in 2006, 15% was supplied to domestic sugar markets, 42% to domestic ethanol (fuel) markets, and

corporates the ability of FFV motorists to arbitrage across ethanol and gasoline prices at the pump. Given the simplifying assumptions we made above, the flat segment of the ethanol demand curve grows in proportion to the penetration of flex cars in the fleet. From (1), for $p^e > \alpha p^g$, ethanol is demanded only by the captive share of ethanol-dedicated cars, with FFV motorists switching to gasoline. This switching explains the shape of ethanol marginal revenue and "aggregate" domestic marginal revenue, indicated by the thick curves.

First examine the middle panel in Figure 4 (labeled "strong export price"), where the net export price cuts through the vertical segment of the (ethanol or) aggregate MR schedule (and lies sufficiently away from the extremes of this vertical segment). For this market realization, the local oligopoly finds it optimal to set the price of ethanol at the gasoline-parity threshold, $p^e = \alpha p^g$, i.e., at the kink in the ethanol demand curve. Notice that p^e will remain at the kink for moderate fluctuations in domestic demand conditions and in the export price (or, similarly, for moderate fluctuations in marginal cost, were marginal cost raised sufficiently that the market were instead in the autarkic regime—not shown in Figure 4). Importantly, p^e will move with the kink as this moves up and down by virtue of fluctuations in p^g.[22]

Next examine the upper and lower panels, in turn. Under a "very high export price", namely at a level sufficiently close to or above the αp^g price threshold, the industry sets $p^e > \alpha p^g$ and sells ethanol only to motorists of ethanol-captive cars (see the upper panel of Figure 4). The industry, unable to price discriminate between ethanol-captive motorists and FFV motorists, faces a trade-off between (i) selling ethanol at a high price only to the former (exporting the balance of the sugar-cane harvest, traditionally in the form of sugar), and (ii) selling ethanol, at the αp^g price threshold, also to FFV motorists (thus exporting less). In this case, the industry chooses (i) and the marginal consumer is the

30% to foreign sugar markets (with exported ethanol fuel accounting for only 4%). However, at the local level, there may be markets for which the autarkic regime, illustrated in Figure 3 but not in Figure 4, is the relevant one. One might think of non-farming states in the remote north of the country, to which sugar/ethanol needs to be shipped from producers close to the coast, yet for these states the world price may still be relevant in the form of an *opportunity* marginal cost. To see this equivalence, notice that a producer (typically close to the coast), on supplying a remote consumer market in the north, will consider the opportunity cost of exporting (shifting up not only MC but also the net export price schedule by the cost of shipping to the market). A more likely candidate for the autarkic regime would be a state located far from a port but with plantations of its own, such as the state of Goiás (here the net export price would shift down, relative to MC, by the cost of reaching the port embedded in T).

22. As the penetration of flex grows further, the flat segments in the ethanol demand and the aggregate MR curves lengthen: the likelihood that a particular realization of exogenous conditions leads to an equilibrium where $p^e = \alpha p^g$ also increases. To see this, notice that the area under the flat segment is increasing in the length of the segment. We provide a numerical example in the appendix.

ethanol-captive car owner.[23] (And notice that over the coming years as the share of ethanol-captive cars in the fleet dwindles to zero—since carmakers quit producing ethanol-captive cars altogether in 2005—the industry may choose not to sell ethanol locally whenever the net export price (or marginal cost) exceeds αp^g.) Finally, in the lower panel (labeled "moderate export price", as we are illustrating with the export regime), where the export price lies below the MR's vertical segment, the industry finds it optimal to undercut the gasoline-parity threshold and sets $p^e < \alpha p^g$.

Remark *For market realizations as illustrated in the middle panel of Figure 4, the price of ethanol at the pump should covary with the price of gasoline. In principle, this can be verified directly in the data by estimating a structural model of the industry, exploiting variation across Brazil's regional markets and over time (e.g., distance from sugar cane plantations, size of the harvest, world sugar prices, distance from a port, growing penetration of FFVs in the fleet, etc) to estimate the different regimes.*

4. EMPIRICAL ANALYSIS OF PRICES

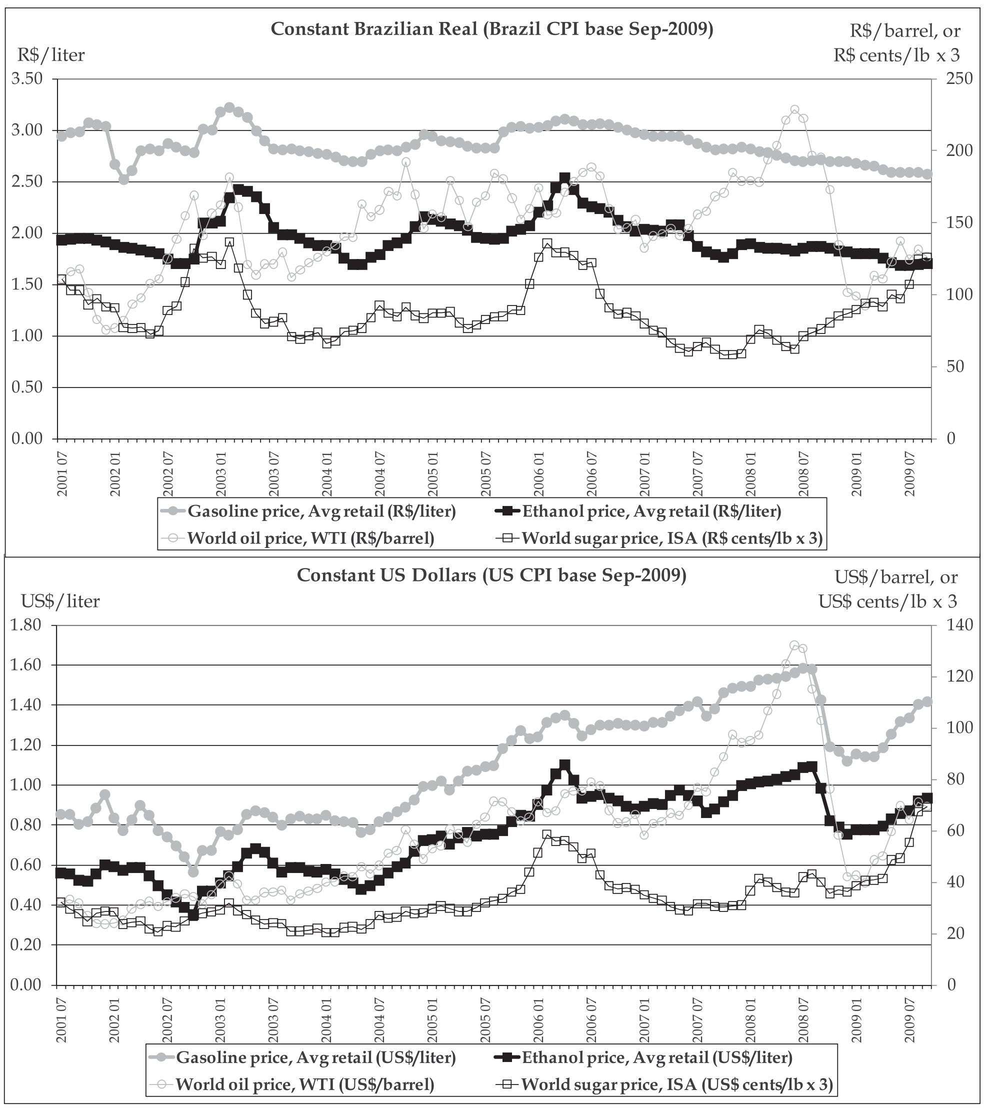
We provide a simple analysis of price variation to verify whether the evidence is broadly consistent with the prediction of the model, namely that as FFV penetration grows, the price of ethanol should increasingly (i.e., conditional on a range of world sugar prices and local marginal costs, per the middle panel of Figure 4) covary with the price of gasoline. We argue that the pricing data does appear consistent with this prediction.[24]

We use a monthly state-level panel of gasoline and ethanol prices at the pump, available for the 99 months from July 2001 to September 2009. Over this period, the National Agency for Oil (ANP) has surveyed a representative sample of retail fueling stations in each of Brazil's 27 states, publishing a mean for every month-state-fuel triple. Prices are provided in current (nominal) *Real* (the local currency, denoted R$) per liter, which we then adjust to constant R$/liter using Brazil's CPI (base Sep-2009). (See the online appendix for further details.) The upper panel of Figure 5 describes the time series variation in average gasoline prices and in average ethanol prices, each average calculated as the arithmetic mean across the 27 states of the Brazilian federation (the vertical axis to the left indicates R$/liter). Also plotted are world prices for crude oil, as proxied by the West Texas Intermediate (WTI) expressed in constant R$/barrel, and world prices for sugar, as proxied by the International Sugar Agreement (ISA) price

23. Alternatively, a lower gasoline price, a lower penetration of flex or (in the autarkic regime) a higher marginal cost can also tip the equilibrium away from flex consumption of ethanol toward gasoline. These comparative statics are not shown in Figure 4, where we illustrate variation in the export price.

24. As mentioned earlier, the limitation is that we do not estimate the structural regime-switch model, in which case the analysis of price variation would be conditioned on (as well as inform) the different regimes across the time-and-region-specific markets—we leave this for subsequent research.

Figure 5: Gasoline and ethanol prices at the pump (averaged across 27 states), World oil price (WTI) and World sugar price (ISA), over the period Jul-2001 to Sep-2009. In the upper panel, prices are expressed in constant R$ per liter (gasoline and ethanol), R$ per barrel (oil), and R$ cents per pound (sugar, scaled up by a factor of 3), Brazil CPI base Sep-2009. In the lower panel, prices are expressed in constant US$ per liter, US$ per barrel, and US$ cents per pound (× 3) respectively, U.S. CPI base Sep-2009. See the online appendix for details. Source: ANP, BACEN, BLS, EIA, IBGE and ISO.



expressed in constant R$ cents/pound (the vertical axis to the right indicates R$/barrel and R$ cents/lb, the latter scaled up by a factor of 3 for convenience). To account for swings in the exchange rate (R$ to the U.S. dollar), the lower panel of Figure 5 reproduces the upper one but expresses all price series in US$, rather than R$, per unit (also at constant prices, U.S. CPI base Sep-2009).

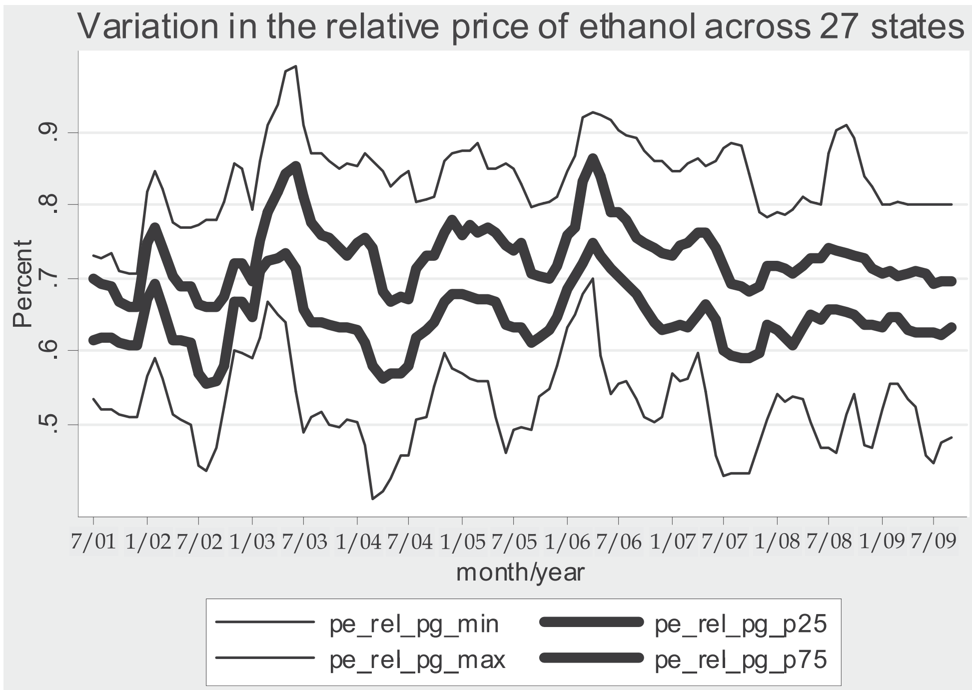
During this period, average gasoline prices have fluctuated about 2.50–3.20 R$/liter, with average ethanol prices fluctuating about a lower 1.70–2.50 R$/liter. At this level of spatial aggregation, (per-liter) ethanol prices have averaged 69% of gasoline prices at the pump, and the two series are tightly correlated, with a correlation coefficient of 0.81 (over 99 months). Domestic gasoline prices, controlled (at wholesale) by the government, appear (to the naked eye) to have roughly tracked the world oil price, but with a considerable lag and with dampened variation: for example, in the lower panel witness the US$ price rises starting around mid 2003 for world oil but only around mid 2004 for domestic gasoline, or notice the mid 2008 price spike in world oil which was muted in domestic gasoline. Examining the world price of sugar in the lower panel (US$ terms), this "export price" appears to have put some pressure on the domestic price of ethanol around early 2006, when the world sugar price peaked at just under 20 US¢/lb (for sugar, divide the scale on the right axis by 3); the comparative static that comes to mind here would be that of moving from a lower to an upper panel in the model of Figure 4.[25]

Rather than report average fuel prices at the pump as Figure 5 does, Figure 6 summarizes their distribution in the cross-section of states. For every month-state pair, we divide the price of ethanol by the price of gasoline; the figure then indicates the maximum, the 75th percentile, the 25th percentile, and the minimum of the distribution of *relative* ethanol prices, p^e/p^g, across the 27 states. For example, for the first month of the sample (July 2001) and across the 27 states, p^e/p^g ranged from a maximum of 73% (the state of Acre) to a minimum of 53% (the state of São Paulo) with an interquartile range, marked with the thick lines, of 70%–61% (thus, since $\alpha \approx 0.7$, at this point of time ethanol tended to be cheaper per mile traveled in most states of the country).[26] A stylized fact suggested by the figure, which we document more carefully below, is that in recent years the price of ethanol has fluctuated less in relation to the price of gasoline, par-

25. The fact that through Sep-2009 a similar rise to 20 US¢/lb in the world sugar price had not yet led to increased domestic ethanol prices in R$/liter was likely due to the higher penetration of flex in the car fleet, as discussed earlier, in addition to the local currency appreciating relative to the U.S. dollar, making exports less competitive (to see this, compare the lower and upper panels of Figure 5).

26. The online appendix provides similar figures to Figure 6 which describe the cross-sectional distribution of *absolute* prices, p^g and p^e (rather than of relative prices, p^e/p^g). It is noteworthy that over the time period, the spatial price dispersion in gasoline (about 0.60 R$/l from max to min) has consistently been markedly lower than in ethanol (about 1.00 R$/l): this probably reflects the presence of non-market forces in gasoline, namely the government's determination to subsidize gasoline in the more remote and less-developed (northern/northeastern) states.

Figure 6: Evolution of the cross-sectional variation in the price of ethanol relative to gasoline at the pump. For each month in the period Jul-2001 to Sep-2009, the minimum, the maximum, and the interquartile range of relative prices across 27 states are shown. Source: ANP.

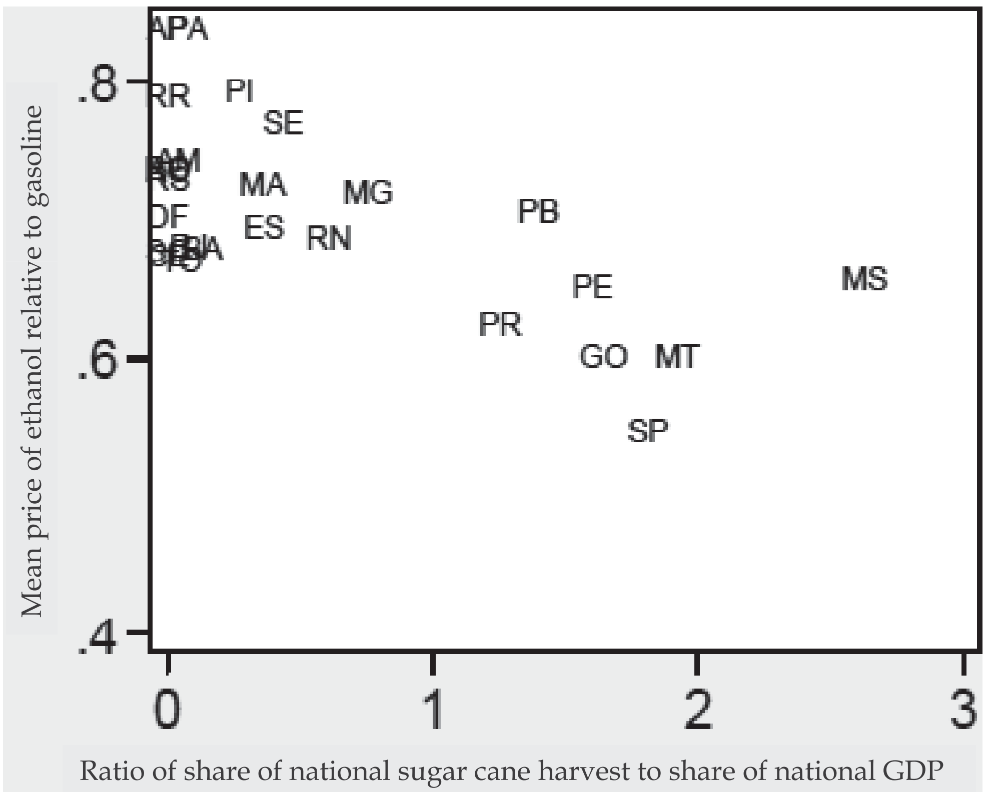


ticularly in states which lie away from the extremes of the cross-sectional distribution of relative prices (to see this, compare the evolution of the thick curves to the evolution of the thin curves). Our model suggests that this may be due, at least in part, to the FFV's growing penetration in every state, to the extent that the incidence of local market equilibrium outcomes as depicted in the middle panel of Figure 4 indeed has increased.

What might explain the cross-sectional variation in relative ethanol prices? The July 2001 example provides a clue: the southeastern and coastal state of São Paulo, in which ethanol was cheap relative to gasoline, is the country's leading sugar cane producer, whereas the northern and landlocked state of Acre, in which ethanol was dear, is located in the remote Amazon jungle, 1,500 miles from the nearest sugar cane plantation.[27] To further illustrate, Figure 7 plots each state's relative ethanol price (the mean of p^e/p^g over the period Jan-2005 to Dec-

27. As shown in the online appendix (recall the preceding footnote), price dispersion is less pronounced in gasoline thanks to government policy. Thus, cross-sectional variation in p^e/p^g arises primarily from dispersion in p^e.

Figure 7: A state's relative ethanol price against a proxy for its ethanol cost efficiency. The vertical axis plots the state's mean price of ethanol relative to gasoline at the pump over the period Jan-2005 to Dec-2007. The horizontal axis plots the ratio of the state's national share of the sugar cane harvest to the state's national share of GDP (over the period 2005 to 2007). To improve the figure's visibility, the state of Alagoas/AL is omitted (with an economy heavily dependent on sugar cane, the state exhibited a harvest-share-to-GDP-share ratio of 8.7, and a relative ethanol price of 65%). Source: ANP, IBGE and UNICA.



2007) against the ratio of the state's national share of the sugar cane harvest to the state's national share of GDP (using data for GDP from 2005 to 2007 and for three harvesting cycles 2005/6, 2006/7 and 2007/8). The latter metric gives a sense of whether, ceteris paribus (i.e., at equal fuel prices and fleet composition), the state would be a net producer of ethanol (a high harvest-share-to-GDP-share ratio) or a net consumer of ethanol (a low ratio), in which case the state may have to ship ethanol in from afar. For example, the state of São Paulo (a mean p^e/p^g of 55% over that period, marked "SP" in the figure according to its official acronym) accounted for 61% of the country's harvested sugar cane and 34% of the country's GDP, translating into a high harvest-share-to-GDP-share ratio of 1.8;

this would suggest a low marginal cost of supplying the SP market. On the other hand, the state of Acre (a mean p^e/p^g of 74% over that period, marked "AC" but hardly visible in the figure) did not grow the crop, implying a zero harvest-share-to-GDP-share ratio and suggesting a higher (delivered) marginal cost.[28] As one would expect, a negative relationship is evident in the figure: relative ethanol prices tend to be lower in sugar cane growing (and thus sugar/ethanol producing) states. A second (though related) reason behind the negative relationship, other than variation in transport costs, is local tax policy: some producer states such as São Paulo and Paraná (marked "PR") support their local sugar industry by way of lower state sales tax (known as ICMS) on ethanol relative to other states.

Data on the FFV's penetration in *state-level* passenger car stocks are not available. However, one can safely conjecture that FFV shares, relative to single-fuel cars in the active fleet, are higher in states in the north/northeast, since in recent years (i) car stocks have grown at higher rates (and from lower bases) in the less-developed north/northeast relative to the richer southern parts of the country (this is due in part to federal redistribution policy expanded since 2003), and (ii) FFVs have accounted for 90% of new car sales nationwide. To check this, we construct a proxy for state-level FFV penetration based on vehicle registrations (available by state but not by fuel type) and new car sales (available by fuel type).[29] Indeed, our proxy indicates that in 2009 FFVs accounted for 39% of cars in circulation in the north/northeast compared with 32% in the rest of the country. Consistent with this, Fenabrave (2008) reported that cars circulating in the northeast were on average 3 years younger than their southeastern counterparts.

4.1 A Drop in the Volatility of Relative Ethanol Prices

We adapt the relative price volatility measure introduced by Engel and Rogers (1996) to empirically test the point we made in our discussion of Figure 6 above, namely that in recent years the relative price of ethanol appears to have become less volatile. Whereas Engel and Rogers (1996) are concerned with the covariation in prices for one same good across two different locations (i.e., price variation in geographic space, one location relative to the other, such as prices in Chicago relative to Minneapolis for wheat), we are concerned with the covariation in prices in one same location across two different goods (i.e., price variation in product space, such as prices for ethanol relative to gasoline in São Paulo). (See Anderson and van Wincoop 2004 for a discussion of how the international eco-

28. Of course the harvest-share-to-GDP-share ratio is an imperfect proxy for cost efficiency in that, among other reasons, a net consumer state might be able to buy ethanol from a neighboring net producer state (i.e., nearby rather than far away), thus not incurring necessarily high transport costs. But the measure serves for the purpose of illustration.

29. See the online appendix for details and Table 1 (next) for values. We worry less about selection in the car market given the speed with which, starting in 2003, carmakers adopted flex as the only engine available for most models in their portfolios; i.e., conditional on a choice of make-model-year, cars buyers had no choice between gasoline-dedicated or flexible-fuel motors.

nomics literature attempts to infer the trade costs of arbitrage from price variation.)

Partition the 99 monthly time periods over which retail fuel prices are available in the 27 states into two equally-spaced subperiods, an "earlier" subperiod (the 49 months from Aug-2001 to Aug-2005; the measure is based on first differences so we lose an initial month) and a "later" subperiod (the 49 months from Sep-2005 to Sep-2009). This partition is somewhat ad hoc, but two institutional features are worth emphasizing. First, government control of ethanol prices ended only in 1999, so we are restricted to examining market prices over the 2000s. Second, despite FFVs being introduced in 2003, their share of state-level car fleets reached the (plausibly non-negligible) 5% mark only around 2005, providing some justification for the partition into subperiods of equal length. Within each of these two subperiods $T \in \{\text{EARLIER,LATER}\}$, and for each of the panel units $l \in \{1,\ldots,27\}$, we compute a measure of the "relative ethanol price volatility", i.e., the volatility of the ethanol-to-gasoline price ratio, defined as:

$$V^{e,g}_{l,T} := std.dev._{t\in T}\left(\ln\left(\frac{p^e_{l,t}}{p^g_{l,t}}\right) - \ln\left(\frac{p^e_{l,t-1}}{p^g_{l,t-1}}\right)\right)$$
$$= std.dev._{t\in T}\left(\ln\left(\frac{p^e_{l,t}/p^e_{l,t-1}}{p^g_{l,t}/p^g_{l,t-1}}\right)\right) \quad \forall l, \forall T \qquad (2)$$

where $std.dev._{t\in T}(x)$ denotes the standard deviation of metric x calculated over the sample of months $t \in T$, and metric x is the first difference in the log of the relative price of ethanol, $\Delta\ln(p^e_{l,t}/p^g_{l,t})$. The standard deviation is thus used as a measure of volatility. We now have a panel of 27 states over 2 subperiods, and wish to compare the volatility of the ethanol-to-gasoline price ratio in the later subperiod ($V^{e,g}_{l,\text{LATER}}$) with the volatility of the ratio in the earlier subperiod ($V^{e,g}_{l,\text{EARLIER}}$). For example, we compute the volatility of the ethanol-to-gasoline price ratio in São Paulo (SP) state to be .068 in the earlier subperiod (Aug-2001 to Aug-2005), falling to .052 in the later subperiod (Sep-2005 to Sep-2009), amounting to a 23% drop in the measure as defined.[30]

The finding for São Paulo is representative of other states—see Table 1. Comparing the later subperiod to the earlier one, the volatility of relative ethanol prices falls in 25 out of the 27 states. The median change across the 27 states is a 26% drop in volatility. The table also averages these results by way of an OLS regression of $V^{e,g}_{l,T}$ (54 observations, or 2 subperiods $\times$ 27 states) on a dummy variable which takes on the value 1 for observations that correspond to the later

30. To emphasize, consider first differences in the (log of the) price ratio of ethanol to gasoline in the state of São Paulo. (These first differences are the monthly percentage changes in this price ratio, approximately.) The standard deviation over the 49 first differences of the earlier subperiod is .068, compared with a .052 standard deviation over the 49 first differences of the later subperiod.

Table 1: Volatility of the state-level ethanol-to-gasoline price ratio in two subperiods, EARLIER (Aug-2001 to Aug-2005) and LATER (Sep-2005 to Sep-2009), as defined in the text

	Volatility of the ethanol-to-gasoline price ratio				
State (Region)	"EARLIER": Aug-2001 to Aug-2005	"LATER": Sep-2005 to Sep-2009	Change "LATER" vs. "EARLIER"		Proxy for share of FFVs in circulating car fleet (2009)
AC (North)	0.030	0.022	–0.008	–26%	48%
AM (North)	0.042	0.033	–0.008	–20%	43%
AP (North)	0.043	0.029	–0.014	–32%	52%
PA (North)	0.038	0.021	–0.016	–43%	43%
RO (North)	0.036	0.026	–0.010	–28%	49%
RR (North)	0.049	0.033	–0.016	–33%	48%
TO (North)	0.039	0.036	–0.003	–9%	45%
AL (Northeast)	0.043	0.029	–0.014	–33%	39%
BA (Northeast)	0.042	0.029	–0.014	–33%	40%
CE (Northeast)	0.048	0.031	–0.017	–36%	36%
MA (Northeast)	0.039	0.023	–0.016	–40%	48%
PB (Northeast)	0.038	0.031	–0.007	–19%	40%
PE (Northeast)	0.039	0.038	–0.001	–2%	34%
PI (Northeast)	0.041	0.024	–0.017	–41%	43%
RN (Northeast)	0.054	0.028	–0.026	–49%	42%
SE (Northeast)	0.037	0.019	–0.018	–47%	39%
ES (Southeast)	0.053	0.033	–0.020	–37%	42%
MG (Southeast)	0.043	0.033	–0.010	–23%	36%
RJ (Southeast)	0.047	0.033	–0.014	–29%	28%
SP (Southeast)	0.068	0.052	–0.016	–23%	32%
PR (South)	0.064	0.053	–0.010	–16%	34%
RS (South)	0.049	0.046	–0.003	–6%	29%
SC (South)	0.041	0.032	–0.009	–22%	37%
DF (Centerwest)	0.063	0.047	–0.017	–26%	36%
GO (Centerwest)	0.057	0.065	0.008	15%	41%
MS (Centerwest)	0.041	0.038	–0.003	–8%	36%
MT (Centerwest)	0.040	0.071	0.031	77%	43%
			Median	–26%	

OLS regressions of the subperiod-specific relative ethanol price volatility[1]

	(I)		(II)		(III)	
	Coeff.	Std.Error	Coeff.	Std.Error	Coeff.	Std.Error
1("LATER" subperiod)	–0.010***	(0.002)	–0.008***	(0.003)	0.010	(0.007)
1("LATER" subper) × 1(FFV penetration in upper quartile)			–0.009**	(0.004)		
1("LATER" subper) × 1(state in North/Northeast regions)					–0.027***	(0.007)
1("LATER" subper) × 1(state in South/Southeast regions)					–0.015*	(0.008)
Constant	0.045***	(0.002)	0.045***	(0.002)	0.045***	(0.002)
R-squared	17%		22%		50%	

[1] 54 observations: 27 panel units (states) × 2 subperiods "EARLIER" and "LATER". Standard errors are clustered by state.

*** Denotes significantly different from zero at the 1% level; ** 5% level; * 10% level subperiod, LATER—see regression I at the bottom. While the mean of the dependent variable (i.e., the relative price volatility) across the 54 observations is .044, volatility is on average (across states) .013 lower in the later subperiod as compared with the earlier one. This change is statistically significant: ethanol prices at the pump seem to be increasingly moving in step with gasoline prices—thus relative prices are less volatile—at a time in which the penetration of flex engines grows. The other two regressions exploit any cross-sectional variation in FFV penetration by adding interactions of the LATER dummy with regional variables. In regression II, the drop in volatility is more pronounced in the one-quarter of states with the highest FFV fleet shares, as per our constructed proxy. In a more crude fashion, regression III interacts the LATER dummy with regional indicators (North/Northeast and South/Southeast, the Centerwest being the omitted region), indicating that the drop in volatility is more pronounced in the north/northeast. The p-value of the test of equality between the North/Northeast interaction and the South/Southeast interaction is 0.0034, confirming one's visual inspection (at the top of the table) that states in the north/northeast saw a larger drop in the volatility of the ethanol-to-gasoline price ratio in the later half of the sample (and have accelerated FFV adoption) compared to other regions.

4.2 Co-movement between Ethanol and Gasoline Prices

Another way in which to statistically examine the relationship between fuel prices is to run causality tests. Multivariate time series models (in particular, Vector Autoregressions, VARs) have been widely used in empirical macroeconomics research, particularly in studying the effect of oil shocks (e.g., Hamilton 1983, Hooker 1996, Blanchard and Galí 2008, Kilian 2009). Applications in the Industrial Organization literature include Slade (1986) and Doane and Spulber (1994), both papers testing linkages between spatial energy markets.[31]

We again consider the 99 monthly time periods (Jul-2001 to Sep-2009) over which retail ethanol and gasoline prices are available in the 27 states. In what follows, we briefly explain the tests we conduct (and provide further details in the online appendix). Table 2 summarizes results. We start by determining the order of integration of the price series for every one of $27 \times 2 = 54$ state-fuel pairs (e.g., p^e in the state of São Paulo). (It is worth emphasizing that we examine prices in constant R$/liter, as we want to filter out common economywide inflation shocks: CPI inflation over the sample period has averaged 6.7% p.a.). In the case of 6 states (see rows ES to TO at the top of Table 2), we are able to reject the presence of a unit root for both the ethanol and the gasoline price series, thus concluding that both p^e and p^g for the state are stationary (i.e., I(0)). We then take each non-stationary fuel price series (e.g., p^e and p^g in AC, p^g in AL) and

31. More recently, Ferreira et al (2009) examine linkages between ethanol and gasoline prices in Brazil. They consider producer prices series only until 2006 and in nominal terms (i.e., they do not partial out a common economywide inflationary component). See below.

Table 2: Testing for causality between ethanol and gasoline prices, over the period Jul-2001 to Sep-2009. All rows but the last use prices at the pump. The last row uses producer prices.

	Unit root test$^{(1,2)}$			Cointegration test$^{(3)}$		Estimation of VAR or VEC$^{(1)}$: Reject no causality of form:		
	Reject unit root?							
State	Ethanol	Gasoline	Conclusion: The two series display:	Order of Integration Ethanol, Gasoline	Reject no cointegration?	Instantaneous Causality	Granger Causality Gasoline→Ethanol	Granger Causality Ethanol→Gasoline
Retail prices, R$/liter at the pump:								
ES	Yes (10%)	Yes (1%)	Stationarity	I(0), I(0)		Yes (1%)	Yes (10%)	
GO	Yes (5%)	Yes (5%)	Stationarity	I(0), I(0)		Yes (1%)		Yes (5%)
RJ	Yes (5%)	Yes (10%)	Stationarity	I(0), I(0)		Yes (1%)		
RN	Yes (5%)	Yes (10%)	Stationarity	I(0), I(0)		Yes (1%)	Yes (5%)	
SE	Yes (5%)	Yes (10%)	Stationarity	I(0), I(0)		Yes (1%)	Yes (1%)	
TO	Yes (5%)	Yes (5%)	Stationarity	I(0), I(0)		Yes (1%)		Yes (5%)
AC	No	No	Unit roots	I(1), I(1)	Yes (5%)	Yes (1%)		
CE	No	No	Unit roots	I(1), I(1)	No	Yes (1%)		
DF	No	No	Unit roots	I(1), I(1)	No	Yes (1%)	Yes (1%)	
MA	No	No	Unit roots	I(1), I(1)	No	Yes (1%)		
MG	No	No	Unit roots	I(1), I(1)	No	Yes (1%)		
MT	No	No	Unit roots	I(1), I(1)	No	Yes (1%)		
PA	No	No	Unit roots	I(1), I(1)	Yes (1%)	Yes (1%)		
PB	No	No	Unit roots	I(1), I(1)	Yes (5%)	Yes (1%)		
RO	No	No	Unit roots	I(1), I(1)	No	Yes (1%)		
RR	No	No	Unit roots	I(1), I(1)	Yes (5%)	Yes (1%)	Yes (10%)	
RS	No	No	Unit roots	I(1), I(1)	No	Yes (1%)		
AL	Yes (5%)	No	Diff. order of Int.	I(0), I(1)				
AM	Yes (5%)	No	Diff. order of Int.	I(0), I(1)				
AP	No	Yes (5%)	Diff. order of Int.	I(1), I(0)				
BA	No	Yes (10%)	Diff. order of Int.	I(1), I(0)				

(continued)

Table 2: Testing for causality between ethanol and gasoline prices, over the period Jul-2001 to Sep-2009. All rows but the last use prices at the pump. The last row uses producer prices (continued).

	Unit root test[1,2]			Cointegration test[3]		Estimation of VAR or VEC[1]: Reject no causality of form:		
	Reject unit root?							
State	Ethanol	Gasoline	Conclusion: The two series display:	Order of Integration Ethanol, Gasoline	Reject no cointegration?	Instantaneous Causality	Granger Causality Gasoline→Ethanol	Granger Causality Ethanol→Gasoline
Retail prices, R$/liter at the pump:								
MS	Yes (5%)	No	Diff. order of Int.	I(0), I(1)				
PE	Yes (5%)	No	Diff. order of Int.	I(0), I(1)				
PI	No	Yes (5%)	Diff. order of Int.	I(1), I(0)				
PR	Yes (5%)	No	Diff. order of Int.	I(0), I(1)				
SC	Yes (5%)	No	Diff. order of Int.	I(0), I(1)				
SP	Yes (5%)	No	Diff. order of Int.	I(0), I(1)				
Producer prices, R$/liter at the refinery/distillery gate:								
SP	Yes (1%)	Yes (5%)	Stationarity	I(0), I(0)			Yes (1%)	

Note: Number of observations in each of the two state-specific fuel price series is 99 (i.e., monthly fuel prices from Jul-01 to Sep-09, in constant R$/liter).
(1) Selects the optimal number of lags according to the Schwarz criterion. Significance level in parentheses. (2) Where non-stationarity of the series in levels cannot be rejected, unit root tests on first differences reject non-stationarity at the 1% significance level throughout, indicating series in levels are I(1). (3) Follows the Johansen (1991) procedure.

run unit root tests on their first differences; by rejecting non-stationarity (unit root) in all of these first differenced series, we conclude that all non-stationary series in levels (i.e., the original series) are I(1). In the case of 11 states (see AC to RS in the middle of Table 2), both ethanol and gasoline price series are I(1); further, for 4 of these 11 states, Johansen (1991) tests imply that p^e and p^g cointegrate, suggesting that the two prices move closely together. For the 10 remaining states (see states AL to SP at the bottom of Table 2), p^e and p^g differ in their order of integration (one is I(0), the other is I(1)). The unit root test we adopt is that of Saikkonen and Lütkepohl's (2002), which allows for a level shift at an unspecified time; we find that for an overwhelming proportion of state-fuel pairs the test points to a "structural break" in November 2002. Specifically, a shift in November 2002 is reported in 24 out of 27 ethanol price series and in 20 out of 27 gasoline price series.[32] We also allow for seasonality, which turns out to be significant in most ethanol price series.[33]

In the case of the 17 states for which the ethanol price series and the gasoline price series have the same order of integration (i.e., for states ES to TO p^e and p^g are both I(0), for states AC to RS p^e and p^g are both I(1)), we then estimate the appropriate VAR or Vector Error Correction (VEC) model.[34] (We do not perform a joint analysis of prices in the remaining 10 states since p^e and p^g have different orders of integration.) We are now in a position to test causality of two forms. *There is strong evidence of instantaneous causality between ethanol prices and gasoline prices*: in each of the 17 states, as Table 2 indicates, we are able to reject the absence of instantaneous causality at the 1% significance level, suggesting that shocks affecting the two fuel price series (in constant R$[35]) are

32. The interpretation of this empirical finding is not clear to us. Two relevant events were happening roughly around this time: the introduction of FFVs in May 2003 (would this have impacted ethanol prices as early as November 2002?), and the change in federal administration in January 2003 (would this have impacted gasoline prices?) No matter what the correct interpretation is, the Saikkonen-Lütkepohl test reports these shifts from the data. Also, it is reassuring that an alternative specification in which we do not allow for a structural break (and instead run ADF unit root tests allowing for a trend, which happens to be significant for only a few state-fuel pairs) yields qualitatively similar results to the ones we report in this section.

33. In 25 out of 27 ethanol price series, at least three monthly dummies (from a set of eleven monthly dummies) turn out to be significant. In contrast, for only 6 out of 27 gasoline price series do at least three monthly dummies turn out to be significant.

34. For states where p^e and p^g are both stationary, we estimate a VAR model in levels. For states where p^e and p^g are both I(1) and cointegrate (Johansen 1991), we estimate a VEC model. For states where p^e and p^g are both I(1) but do not cointegrate, we estimate a VAR in differences. Again, see the online appendix for further details (including data).

35. Had we performed the analysis with nominal (rather than real) prices, we would have found even further covariation between p^e and p^g: we would then report evidence of instantaneous causality (all at the 1% level) in 21 (rather than 17) states and evidence of cointegration in 7 (rather than 4) states. Intuitively, macroeconomic inflation shocks can play a role in driving causality. We also note that had we performed the analysis in monthly percentage (real) price changes $\Delta \ln p$, rather than price levels p, we would then report instantaneous causality in all 27 states—see Table 3 for a VAR with this flavor. Results are available upon request.

contemporaneously correlated. We also find some evidence of Granger causality in 7 of the 17 states. Interestingly, only in 2 states do we find ethanol prices Granger-causing gasoline prices, whereas in 5 states there is evidence that gasoline prices Granger-cause ethanol prices (i.e., p^g has explanatory power for future values of p^e).

A concern with the test results we have just reported is that gasoline sold at the pump is actually a blend containing a 20–25% proportion of ethanol by volume (mixed together by fuel distributors downstream to producers and upstream to retail stations, and mandated by government—recall Section 2 and Figure 1). Though this proportion is low, it could be that the causality we identify is, to some extent, spurious. To investigate this, we repeat the tests using the more limited *producer* pricing data that is available: average prices for (pure) gasoline at refineries in the southeastern region of Brazil (which includes the state of São Paulo), and average prices for ethanol at mills in the state of São Paulo.[36] Results are shown in the final row of Table 2, marked "Producer prices". Both producer gasoline and producer ethanol prices series are stationary (unlike the results for the state of São Paulo that used retail prices, displayed two rows above). We do not find evidence of instantaneous causality between the two producer price series; one possible reason is that we are looking at high frequency (monthly) prices which are set upstream to the consumer, and it could take longer than a month for changes in gasoline prices to feed through to changes in ethanol prices at the mill gate. Reassuringly, we do find evidence (at the 1% significance level) that producer gasoline prices Granger-cause producer ethanol prices (and no evidence the other way round).

Finally, we conduct a VAR that controls for world prices of sugar and oil. Instead of estimating a VAR for every state's retail fuel price series, as we did in the causality tests of Table 2, we use—for every month in the sample Jul-2001 to Sep-2009—the arithmetic mean (constant R$) price at the pump (ethanol or gasoline) across the 27 states (recall the upper panel of Figure 5; we also consider world prices in constant R$ terms as shown in that panel). Rather than using price levels p (the series have different orders of integration), we estimate the VAR in the first differences of log prices, $\Delta \ln p$: variables can then be interpreted as monthly percentage (real) price changes.[37] Results are shown in Table 3. For this sample and level of aggregation, the inclusion of world price controls turns out to have an insignificant effect (even including one lag) on monthly proportionate changes in domestic fuel prices at the pump. However, we obtain

36. Recalling footnote 8, we consider "hydrated" ethanol, intended for final sale at the pump as ethanol fuel, rather than the "anhydrous" version that is the additive to gasoline fuel. Again, we work with constant R$/liter, over the period Jul-2001 to Sep-2009.

37. Following Section 3, including the sufficient but not necessary (suggestive) evidence of footnote 19, we model world sugar and oil prices as exogenous. In view of the predominant Nov-2002 break in the earlier Saikkonen-Lütkepohl unit root tests (on the state-fuel-specific price series), we allow for a break in November 2002, but this turns out to be insignificant in the present VAR. As before, we allow for seasonality.

Table 3: Vector Autoregression of domestic retail fuel prices, controlling for (exogenous) world sugar and oil prices. Fuel prices are the means at the pump across the 27 states. Based on first differences in the logarithm of prices (where all prices are in constant R$ terms), over the period Jul-2001 to Sep-2009.

VAR on first differences of log prices, controlling for world prices

	Dependent Variables			
	Ethanol		Gasoline	
	Coeff.	Std.Error	Coeff.	Std.Error
Ethanol_t-1	0.488***	(0.088)	---	---
Gasoline_t-1	0.286***	(0.103)	0.807***	(0.061)
World_sugar_t	---	---	---	---
World_oil_t	---	---	---	---
World_sugar_t-1	---	---	---	---
World_oil_t-1	0.086	(0.064)		

Causality tests

H_0: No instantaneous causality between ethanol prices and gasoline prices
Test statistic c = 12.1954*** p-value Chi-squared(c; 1) = 0.0005

H_0: Gasoline prices do not Granger-cause ethanol prices
Test statistic L = 5.5994** p-value F(L; 1, 186) = 0.0190

H_0: Ethanol prices do not Granger-cause gasoline prices
Test statistic L = 1.8162 p-value F(L; 1, 186) = 0.1794

Note: Series in first differences of log prices, where prices are in constant R$ terms (and domestic fuel prices are averages at the pump across the 27 states). Observations are the 99 months between Jul-01 and Sep-09. Optimal number of lags of endogenous variables selected according to the Schwarz criterion. Variables included in the model but deleted by the Schwarz criterion due to lack of significance denoted by "---". Significance: *** 1% level; ** 5% level; * 10% level.

(i) a significant cross-effect of gasoline prices on ethanol prices (but not the other way round), (ii) evidence (at the 1% level) of instantaneous causality between ethanol and gasoline prices, and (iii) evidence (at the 5% level) that gasoline prices Granger-cause ethanol prices (and no evidence the other way round).

We take the combination of findings as offering guarded support for the predictions of the conceptual model we laid out in Section 3. In the pre-FFV era, prior to 2003, the linkage between gasoline and ethanol prices in the aftermarket was tenuous, necessarily flowing slowly through the primary car market given the captive single-fuel car owner's inability to arbitrage across fuel prices at the pump. Today, with the fast-growing presence of the FFV (30% of the car stock by 2008), there is a direct linkage between the two fuels, with closer substitution between gasoline and ethanol at the pump. Given the nature of institutions, in particular how gasoline prices are mandated by the government, we have argued that one should expect to see the price of ethanol linking up with the price of gasoline for a range of world sugar prices and local marginal costs. In other words, if the opportunity cost of selling ethanol to flex motorists in a particular local market is not too high, the sugar/ethanol industry will set p^e such that it does not exceed αp^g; further, if this opportunity cost is not too low (and noting that fuel demand is inelastic), p^e will be set close to αp^g. In sum, we expect to see co-movement between the series in an increasing number of states before long, as the FFV becomes even more established.

5. CONCLUDING REMARKS

We have provided a framework for thinking about how the price of a biofuel varies at the pump in a country where, uniquely, the availability of both the biofuel and cars that can burn the biofuel are widespread. Our hope is that future empirical work—such as structural estimation of our model of the sugar/ethanol industry, allocating the sugar cane harvest among food and fuel markets, across the many regional and export markets over time—will complement our exploratory analysis of prices.

Our hope is that this line of research will also help guide policy. To cite a very recent example, in the first quarter of 2010, expressing concern about rising prices of (E100) ethanol sold at the pump, Brazil's central government decided to temporarily lower, by 5 percentage points, the proportion of ethanol contained in retailed gasoline; that is, to mandate a change in the composition of "gasoline" from G75/E25 (containing 25% ethanol) to G80/E20 (20% ethanol). According to government officials, the idea was to boost the domestic wholesale supply of ethanol in an attempt to curb the increase in ethanol prices at the pump, given that FFVs now account for one-third of the car fleet. Our simple open-economy model of the industry indicates that to the extent that ethanol price increases were being driven by very high world sugar prices—the highest in over two decades in constant US$ terms—such policy measures would do little to lower the price of ethanol at the pump, as the industry's marginal buyer at this point in time would be the export market (as well as the motorist of aging ethanol-captive cars). Rather, reducing government-mandated procurement of ethanol would tend to boost Brazil's supply of sugar (or ethanol) in the world market.

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APPENDIX: NUMERICAL EXAMPLE: EXPORT REGIME (Figure 4)

Consider a local (time-and-region-specific) market in which the (inverse) demand for sugar is given by $p=10-Q$, the demand for ethanol by ethanol-captive motorists is $p=10-Q$, and the demand for ethanol by FFVs motorists is $p=10-\frac{1}{2}Q$ (i.e., say that FFVs motorists outnumber ethanol-captive ones by two to one, and are otherwise identical). The gasoline-parity threshold $\alpha p^g=8$, and the marginal cost in supplying the local market (with either sugar or ethanol) is given by $MC=2+\frac{1}{5}Q$ if $Q\leq 10$ and arbitrarily large otherwise (i.e., capacity is 10 sugar cane equivalent units). It is straightforward to show that facing a net export price:

1. $P^W-T>4\sqrt{6}-2\approx 7.80$, the industry sets the ethanol price at $p^e=5+\frac{1}{2}(P^W-T)>\alpha p^g$, selling ethanol only to ethanol-captive motorists (as in the upper panel of Figure 4; exports turn out to be $Q^{export}=P^W-T$).
2. $7.80\geq P^W-T\geq 6$, the industry sets $p^e=\alpha p^g=8$, at the kink in the ethanol demand curve, selling ethanol to both ethanol-captive and FFV motorists (as in the middle panel of Figure 4; exports are a lower $Q^{export}=2$).
3. $6>P^W-T(\geq 5)$,[38] the industry sets $p^e=5+\frac{1}{2}(P^W-T)<\alpha p^g$, selling ethanol to both ethanol-captive and FFV motorists (as in the lower panel of Figure 4; exports are an even lower $Q^{export}=2(P^W-T)-10$).

38. When the net export price dips below 5, the industry switches to the autarkic regime. Note that a similar example can be provided, and a figure similar to Figure 4 can be drawn, for the autarkic regime, in which the same three equilibrium outcomes $p^e>=<p^g$ would follow from comparative statics in the marginal cost schedule (keeping the net export price low).