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Is arbitrage tying the price of ethanol to that of gasoline? Evidence from the uptake of flexible-fuel technology

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THE CENTER FOR THE STUDY
OF INDUSTRIAL ORGANIZATION
AT NORTHWESTERN UNIVERSITY

Working Paper #0093

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

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Abstract

As much of the world goes searching for alternative sources of energy to oil, Brazil's three-decade experience in developing a successful substitute for gasoline merits attention. Brazil is the only sizable economy to date to have developed a ubiquitously distributed alternative to oil-based fuels in road transportation: ethanol from sugarcane. Perhaps unsurprisingly, the uptake of flexible-fuel (dual-fuel) vehicle technology has been tremendous. We provide a stylized model of the vertical sugar industry which incorporates arbitrage by producers, across domestic and export markets for ethanol and sugar, and arbitrage by consumers, across ethanol and gasoline at the pump. We show that the model stands up well to the empirical covariation in prices over 30 years. In particular, owing to the increasing penetration of flexible-fuel vehicles, consumer arbitrage is tying the retail price of ethanol to that of gasoline. Of relevance to the current “food-versus-fuel” debate, the outward shift of the ethanol demand curve, at price levels where traditional gasoline consumers arbitrage, may lead to higher sugar prices, thanks to substitution in demand (gasoline and ethanol) and in supply (sugar and ethanol).

Keywords: Ethanol, gasoline, sugar, biofuels, food prices, commodity prices, food-versus-fuel debate, arbitrage, export price floor, price convergence, flexible-fuel vehicles

JEL classification: F19, L11, Q11, Q42

“This car will be an effective fuel price regulator.” Fernando Damasceno,
Chief Engineer at the Brazilian unit of autoparts firm Magneti Marelli

“Switching to an ethanol-based transportation system, by adapting new cars to run on an ethanol-gasoline blend with inexpensive, off-the-shelf flexible fuel technology and piggy-backing on the existing gas station network, would be both good policy and a great bargain for the American consumer.” U.S. Senator Richard G. Lugar, then Chairman of the Senate Foreign Relations Committee (in an open letter to the editor of the Wall Street Journal, published on 02/13/2006, p.A17)

1 Introduction

In recent years, higher prices and supply insecurity in the oil industry, coupled with mounting concern over global climate change, have rekindled the search for alternative sources of energy. Nuclear power is back on the agenda even in countries that once shunned it. Investments to improve technology that harnesses solar or hydrogen energy are soaring. Analysts report that grain prices are under pressure as growing demand for biofuel feedstocks competes with food over the use of land. Ethanol, in particular, is an expanding industry. Countries such as Japan and Sweden are increasingly importing ethanol to reduce their dependence on oil. In the U.S., reference to ethanol has become commonplace in the president’s annual State of the Union address, as the country considers the viability of adopting ethanol as a substitute for gasoline in transportation. According to the New York Times (2006), “a change is under way that experts say will tightly tie the price of crops to the price of oil: ethanol plants are multiplying”.

Against this backdrop, this paper examines the behavior of prices during Brazil’s 30-year experience with ethanol in road transportation. In particular, we analyze the impact of the “Flexible-Fuel Vehicle” (FFV), introduced in 2003. Ethanol has been used as an alternative to gasoline in powering Brazil’s cars since 1979. Until 2003, cars that ran on ethanol had ethanol-dedicated engines; conditional on a consumer buying an ethanol car (a longer term decision), ethanol producers faced captive demand in the fuels aftermarket. With the widespread introduction of flexible-fuel, or dual-fuel, vehicles in 2003, consumers can now arbitrage across price differences in gasoline and ethanol—both ubiquitously distributed—at the pump, as they can fill the tank with any blend of gasoline and ethanol. The country produces ethanol from sugar cane, in contrast to the U.S. which (currently) uses corn, a considerably less efficient source (Marris 2006). As such, sugar and ethanol are substitutes in supply, both transformed from sugar cane at fixed coefficients. Further, Brazil being a major sugar exporter, the domestic sugar industry arbitrages across price differences in its domestic and foreign markets.

The question we address is whether, in a world where the acquisition of “flexibility” in the primary car market makes fuel switching costless in the aftermarket, the price of sugar-cane ethanol ties up with the price of gasoline. Brazil is the only sizable economy to date to have developed a widely distributed biofuel substitute for fossil fuel in road transportation, and to have widely introduced a multiple-fuel vehicle. (The U.S., in contrast, has as yet limited distribution of both ethanol at the pump and the FFV.) We conjecture that the Brazil’s experiment is indicative of the future path of world prices for biofuel feedstocks, should an international market develop and individual and industrial customers acquire the ability to arbitrage. Indeed, the Economist (2007) claims that already, at an international level, “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”.

We model a domestic sugar/ethanol industry that acquires sugar cane in a competitive factor market and exercises market power in its domestic ethanol and sugar output markets, price-discriminating across the two, while acting as a price-taker on the international sugar market. Prior to the introduction of the flexible-fuel vehicle, our simple structural model predicts that domestic ethanol prices should covary tightly with domestic sugar prices, by virtue of (i) income shocks that move both domestic demand curves (for ethanol and sugar), (ii) supply shocks that move the (common) marginal cost curve (e.g. a poor harvest), and (iii) the level of an export price floor (for sugar) which may bind in equilibrium.

Following the introduction of the flexible-fuel vehicle in 2003, the model predicts that domestic ethanol prices should (increasingly) covary with the domestic price of gasoline. As of 2003, the adoption of flexible-fuel technology has introduced a kink in the domestic demand curve for ethanol. Noting the higher fuel economy (mileage per gallon) of gasoline relative to ethanol, the ratio of prices per gallon that equalizes cost per mile traveled is given by (price per gallon of ethanol p^e) : (price per gallon of gasoline p^g) $\simeq 70\%$. For ethanol prices below the threshold price $0.7p^g$, ethanol is demanded by owners of flex cars as well as owners of the many earlier ethanol-dedicated cars that are still running. For ethanol prices above this threshold, and abstracting away from consumers’ mistakes and environmental preferences, ethanol is demanded only by owners of ethanol-dedicated cars. This price threshold is broadly the same across car models, given the common software-based technology adopted by carmakers (and introduced originally by autoparts firm Magneti Marelli, among others). The price threshold is also fairly well known among consumers—it was even communicated by the carmakers in their advertising campaigns¹. While the uptake of flex has been fast—85% of new cars sold in

¹To provide a random example, an article in the household finance section of a leading online news provider informs 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).

the first quarter of 2007 were flex—the share of flex in the stock of cars naturally grows more gradually, as new cars need to displace old cars—at the end of 2006, flex accounted for 9% of the nationwide fleet of passenger cars. Our stylized model predicts that for a “sufficiently large” share of flex in the fleet and a “moderate” marginal cost of supplying ethanol, the price of ethanol will lie at (or below) the kink set by the price of gasoline. In particular, the covariation between retail prices of ethanol and gasoline should be high. Going forward, the model also predicts that growing demand for ethanol, because of substitution in the demand for gasoline at equilibrium price levels, and substitution in the supply of sugar, will put pressure on sugar prices, bar a sizable technology shock.

We then conduct an empirical analysis of prices to verify whether pricing behavior is consistent with the predictions of our model. In the spirit of the international pricing literature, our purpose is to verify whether data on prices, collected from a large variety of sources, bear the hypotheses out. (For a survey of this—trade and macro—pricing literature, and how it informs on the magnitude of trade costs of arbitrage, see Anderson and van Wincoop 2004).² In the “pre-flex period” covering the 1980s and 1990s, we indeed find that domestic ethanol prices were highly correlated with domestic sugar prices. In particular, when world sugar prices were high such that the domestic industry was constrained by an export price floor, as in the 1990s, we confirm that domestic ethanol and sugar prices moved in step with the world price of sugar. In contrast, when world sugar prices were depressed such that the domestic industry was setting domestic prices based on domestic demand and supply conditions alone (i.e. the export arbitrage constraint was slack), as in the 1980s, we find weak correlation between the world sugar price and domestic (ethanol and sugar) prices. We also document that despite ethanol production accounting for 50% of the sugar cane harvest by 1985, growing farming acreage and mechanization in the field helped keep domestic sugar prices subdued.

In the recent “post-flex period”—the focus of our empirical analysis—we slice the disaggregated data (a panel of monthly local market prices) in a number of ways to uncover evidence that, as the share of the dual-fuel engine in the car fleet grows at the expense of single-fuel engines, the price of ethanol is increasingly tying up with the retail price gasoline. We find that the price of ethanol relative to gasoline has been falling of late, particularly in local markets where the marginal cost of supplying ethanol is expected to be lower, proxied by the market’s distance from sugar cane plantations. (We observe $p^e < 0.7p^g$ more often in these lower cost markets relative to higher cost markets: this may, naturally, owe directly to cost, but is also consistent with the consumer arbitrage story.) We adapt Engel and Rogers’ (1996) relative price volatility measure to product

²Collecting further data (such as quantities, demand and supply shifters, etc) across the different product and geographic markets, would allow one to *estimate* the structural model. Though certainly commendable, this lies beyond the present paper’s scope. Instead, we choose to focus on pricing data, verifying their consistency with stylized predictions of the model.

(rather than spatial) markets and find that the price volatility of ethanol relative to gasoline in the 2004-2007 period is significantly lower than in 2001-2004. Estimates of vector autoregression (VAR) models provide (i) overwhelming support for instantaneous causality between the price of ethanol and the price of gasoline, and (ii) evidence in many local markets of the price of gasoline Granger-causing the price of ethanol, but not the other way round, consistent with the dominant size of the gasoline (oil) market relative to that of ethanol (sugar cane).

The plan of the paper is as follows. Section 2 describes Brazil’s experience with ethanol in road transportation. Section 3 presents a stylized structural model of the sugar cane – sugar/ethanol industry that considers the impact of arbitrage in the fuels aftermarket. Section 4 describes the data, whose consistency with the predictions of the stylized model is verified in the empirical analysis of Section 5. Section 6 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 (Alcohol) Program. With increasingly-expensive imports accounting for 80% of the country’s oil consumption (MME 2006), the “Proalcool” aimed to reduce the country’s dependence on foreign energy supplies by substituting ethanol for gasoline, for usage in light road transportation. Ethanol consumption would 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 established gasoline-dedicated car engines³ and, more innovatively, (ii) by powering cars with ethanol-dedicated engines⁴. Brazil being the world’s largest sugar cane producer, and a leading sugar exporter, the government also hoped that the program would provide some support to the vertical sugar cane – sugar industry, following several years of volatile and weak international sugar prices (Baccarin 2005, Lima 2006).

The early years of the Proalcool were a roaring success. By 1984, ethanol-dedicated engines accounted for more than 80% of new car sales nationwide, with gasoline-fueled cars corresponding to only 20% (Anfavea 2006). By 1987, as Figure 1 indicates, consumption of ethanol had reached that of gasoline (MME 2007). 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

³Such gasoline-dominant blends, which include a low proportion of (“anhydrous”, or quasi-pure) ethanol, are known as “gasohol” (or, e.g., G80/E20). We refer to these blends simply as gasoline.

⁴Ethanol-dedicated engines have typically run on (unblended) ethanol containing 4% water (thus referred to as “hydrous” ethanol).

and retailing, R&D for automotive technology); (ii) lower sales and registration taxes for ethanol-powered cars; (iii) guaranteed wholesale purchases of ethanol at a (wholesale) price floor by the state-owned oil company Petrobras⁵; (iv) retail price ceilings for ethanol relative to gasoline; and (v) lower sales taxes on ethanol vis-à-vis gasoline (Tasca 2002)⁶. While 97% of the 1977/78 sugar cane harvest had been transformed into sugar (for the domestic and export markets), by 1984/85 ethanol mills were acquiring as much as 48% of the sugar cane harvest (which had roughly doubled in comparison to the 1977/78 harvest). (For perspective, only 20% of the U.S. corn harvest of 2006 was diverted to ethanol production.)

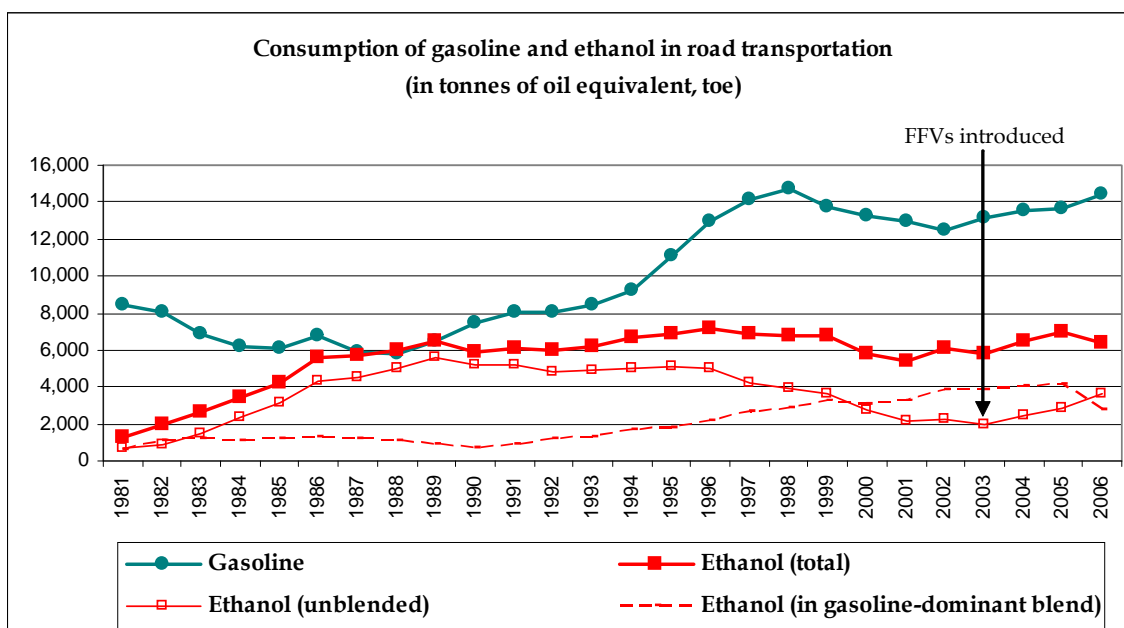


Figure 1: Evolution of gasoline and ethanol consumption in road transportation, in tonnes of oil equivalent (toe). Ethanol consumption is broken down into unblended (fueling ethanol cars and, more recently, flex cars) and as an additive to gasoline (which fuels gasoline cars and flex cars).

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 reducing gasoline consumption began to wane. World sugar prices were on the rise, putting pressure on domestic ethanol prices⁷, 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 (Shikida 1998). While

⁵As such, Petrobras was the residual player in ethanol wholesaling and distribution, competing alongside several private-sector distributors.

⁶Relatedly, 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.

⁷See the model of Section 3.

in the early years the retail price per gallon (liter) of ethanol relative to gasoline had remained below the 70% threshold, more than fully offsetting ethanol’s lower mileage per gallon, by 1989 the relative price of ethanol (official or otherwise) had reached the 75% mark, steadily increasing to 85% over the next decade (MME 2006). With headlines showing “locked in” ethanol-car owners fuming at the occasional supply shortages at the pump, sales of ethanol cars plummeted. Compared to an all-time high 96% share of the light-vehicle primary market (new passenger cars including SUVs) in 1985, ethanol-powered 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 Proalcohol’s downturn in the 1990s thanks to the slow decay of ethanol cars in the fleet—a stock rather than a flow. This helped to pave the way for the widespread introduction of cars with dual-fuel or flexible-fuel engines in 2003. “Flex” engines are flexible in that they can run on either a gasoline-dominant blend or an ethanol-dominant blend, unlike gasoline-dedicated and ethanol-dedicated engines which must run on one or the other. Owners of flexible-fuel vehicles are thus in a position to costlessly arbitrage across the prices of gasoline and ethanol in the fuels aftermarket (and maintenance costs are similar to those of gasoline-only cars). The speed of adoption of the flex motor paralleled that of its ethanol-dedicated counterpart almost 25 years earlier, though this time round carmakers were soon offering their models in the flex version only, and at prices broadly equivalent to those of the earlier gasoline-only versions. In June 2006, for example, Volkswagen declared that its Brazilian subsidiary would only produce flex cars (Forbes 2006). By the first quarter of 2007, flex accounted for as much as 85% of new car sales nationwide. At the end of 2006, the composition of Brazil’s aggregate passenger car fleet (27.8 million) was 76.5% gasoline-only, 14.7% ethanol-only, and 8.7% flex⁸. Possibly as a result of car manufacturers soon offering models in the flex version alone, the uptake of flex occurred at similar rates across the different regions of the country. 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 attempting to interfere with retail (and wholesale) prices of ethanol. The ethanol industry had by then been deregulated.

3 Theoretical framework

We begin by considering how the introduction of the flexible-fuel vehicle impacts the demand for ethanol. We then provide a stylized model of the vertical sugar cane –

⁸The use of other fuels such as diesel and LPG in passenger cars does not exceed 0.2% of the fleet. We calculated these proportions from Fenabreve data—see Section 4.

sugar/ethanol industry which predicts that, as the penetration of the flex engine grows, the equilibrium price of ethanol is increasingly tying up 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 is given by a vector $\mathbf{n} = (n^g, n^e, n^f)$. Each car (engine) $j \in \{g, e, f\}$ is owned by a different consumer i , so that there are $\sum_j n^j$ consumers. The average mileage per gallon (mpg) of fuel on which engine j runs is given by α^j . For simplicity, we (i) assume that a flex engine running on ethanol (resp. gasoline) will have the same fuel economy as that of an ethanol-only (resp. gasoline-only) engine, and (ii) assume away variation in α^j across consumers i (owing to, say, differences in ownership of car models, patterns of city relative to highway driving, or vehicle maintenance). (Also for simplicity, we do not index the region-and-time specific market: α^j might vary according to the composition of fuel blends and technology.)

Representative consumer i ’s problem, conditional on her ownership of car type j , is given by

$$\max_q U(q_{transp}, q_{outside})$$

$$\text{s.t. } p_{transp}q_{transp} + q_{outside} \leq y$$

where y is income, q_{transp} denotes the quantity of miles of personal transportation chosen by consumer i at the expense of the numeraire outside good, and where the price per mile of personal transportation 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 the prices of the gasoline- and ethanol-dominant blends, respectively, per gallon of fuel at the pump. Notice that, again for expositional purposes, we assume away any variation in the way a flex car owner arbitrages across (normalized) differences in the prices of ethanol and gasoline (due, say, to differences in environmental or social preferences); we comment on this assumption below. (We also ignore any intertemporal arbitrage through consumer stockpiling, e.g. filling up the tank before it is empty, given an expectation that prices are rising.)

Consumer i ’s (ordinary) demand for personal transportation $q_{transp}(p_{transp}, y)$ will, under standard assumptions on the utility function, be a smooth and decreasing func-

tion⁹ of the price of personal transportation p_{transp} , i.e. q_{transp} , in miles of personal transportation, will be given implicitly by

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

Now let us derive the aggregate ordinary demand function for ethanol. (The demand for gasoline can be derived analogously.) Begin by considering a consumer who owns a dedicated ethanol engine. Given that she cannot arbitrage across price differences, her individual demand in gallons of ethanol is given by

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

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

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

Aggregating across the distribution of engine types given by $\mathbf{n} = (n^g, n^e, n^f)$ we obtain

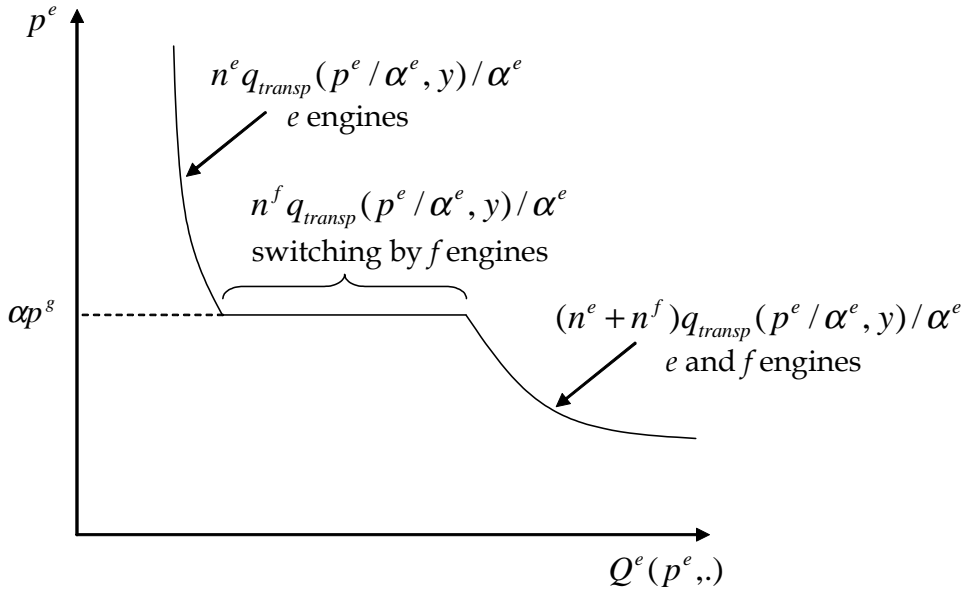


Figure 2: Arbitrage by flex consumers: Aggregate demand for ethanol in a given local market

⁹The 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 (2007) using recent U.S. data, and at a still low -0.5 by Alves and Bueno (2003) from less recent Brazilian data.

the aggregate demand function for ethanol in gallons¹⁰:

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

Notice that aggregate demand for ethanol jumps out by $n^f q_{transp}(p^e/\alpha^e, y)/\alpha^e$ at $p^e = p^g \alpha$, where $\alpha := \alpha^e/\alpha^g$ —see Figure 2 (recall that $\alpha \approx 0.7$). Should the relative price threshold at which there is switching between fuels, α , vary across flex owners, for reasons that we have assumed away above, this flat segment of the aggregate demand curve would be replaced by a series of downward steps (and, as the number of different values for α grows, the downward-sloping curve would become smooth).

3.2 A stylized model of the sugar cane – sugar/ethanol industry

Our point of departure is the 1980s and 1990s, the “pre-flex period” during which the sugar industry faced captive domestic demand for ethanol by owners of ethanol-dedicated cars, in addition to demand for (refined) sugar in both the domestic market and the international market. Consider Figure 3. Given the fixed-coefficients nature of technology in transforming sugar cane into either sugar (in refineries) or ethanol (in distilleries), this figure should be read in sugar cane equivalent units. (1 ton of sugar cane produces either 100 kg of sugar or 80 liters of ethanol, approximately.) Since marginal cost increases in output, sugar and ethanol are substitutes in supply. We posit that the sugar industry exercised domestic market power and equated marginal revenue in each domestic market to marginal cost, thus price discriminating across the two domestic markets (sugar and ethanol) and its international market (sugar), where it acted as a price-taker. By sugar industry exercising market power, we specifically mean sugar refineries and ethanol distilleries¹¹, rather than the more fragmented sugar cane growers upstream and distributors and consumers downstream. To the extent that the government materially affected prices on the industry’s domestic sales, we assume that this was done largely via unit subsidies. Given the government’s interest in fostering ethanol, particularly during the 1980s when international oil prices were high, any apparent wholesale price controls would effectively have accommodated the industry’s preferences (Baccarin 2005).

Figure 3 suggests that, with captive ethanol demand, what drove domestic prices for ethanol and for sugar— p^e and p^s respectively—were domestic demand and supply

¹⁰See Anderson (2006) for a derivation with a similar flavor, where flex car owners in certain regions of the U.S. switch between gasoline and E85 ethanol (an ethanol blend containing 15% gasoline).

¹¹Firms in the industry—e.g. Cosan, to name one—typically run both sugar refining and ethanol distillation operations, most often located in the same mill.

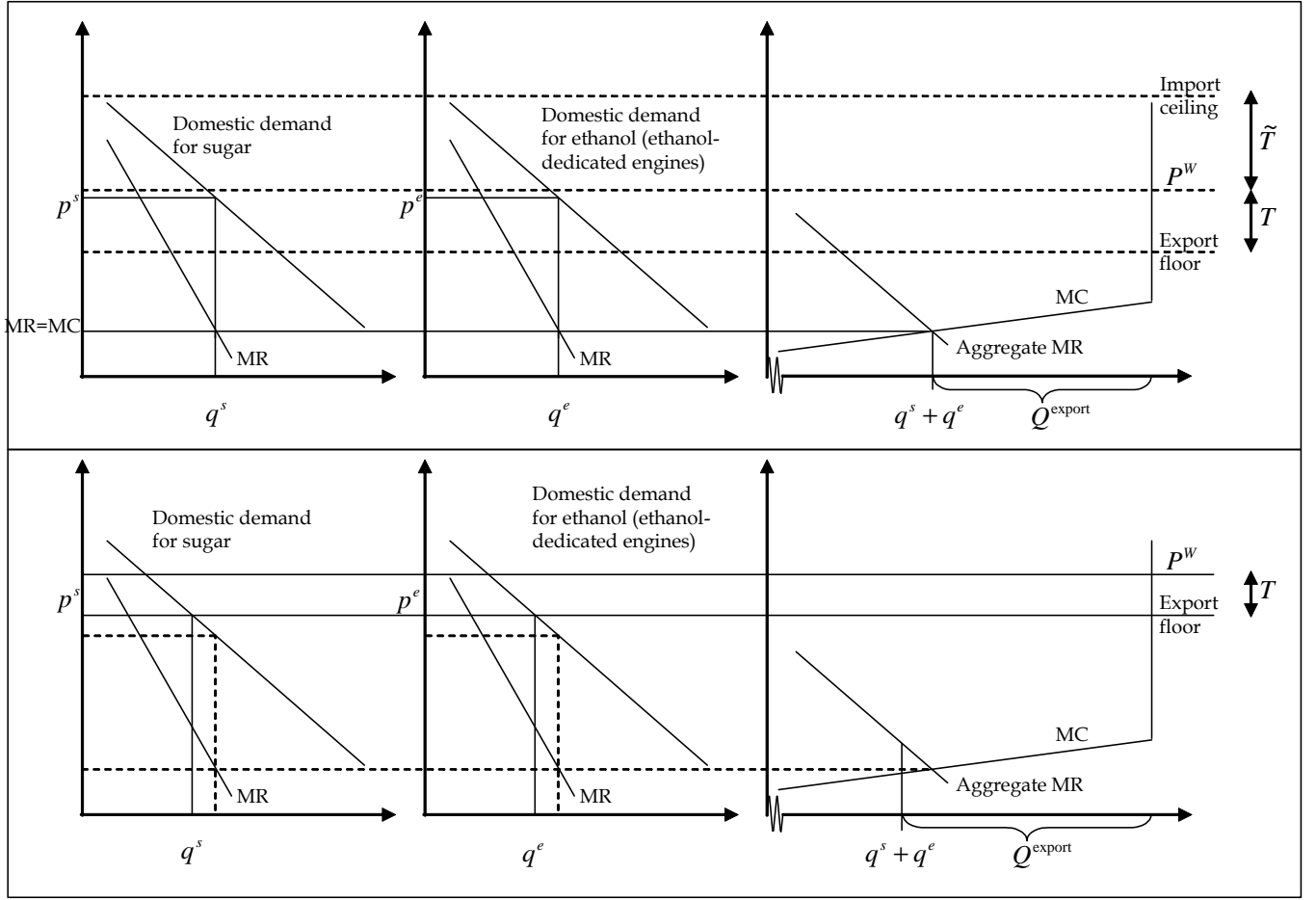


Figure 3: Domestic sugar and ethanol (wholesale) markets in the “pre-flex period”. Top panel: Domestic outcomes unconstrained by low sugar export prices, as in the 1980s. Bottom panel: Domestic outcomes constrained by high sugar export prices, as in the 1990s.

conditions in the industry, as well as an export price floor, equal to the world price of sugar P^W discounted by the outbound trade cost T . Specifically, the covariation in domestic prices would depend on either of two situations, characterized by the level of the sugar export price floor: (i) low $P^W - T$, illustrated in the top panel of the figure, and (ii) high $P^W - T$, in the bottom panel of the figure.

In the first situation, low (net) export prices would have little bite on domestic ethanol and sugar prices, as in the mid 1980s¹². Assuming that fluctuations in the world sugar price did not correlate with either of the two domestic demand curves or with the domestic marginal cost curve (or that any such correlation was relatively low), then domestic ethanol and sugar prices should not covary with the world price of sugar. The

¹²We find evidence of this in Section 5. In this period, in addition to a sufficiently low P^W , we posit that export trade costs T were relatively high in view of the inefficiency of Brazil’s then publicly-managed ports. For perspective, in the early 1980s, exports (in the form of sugar) accounted for only around 20% of sugar cane production. High inbound trade costs \tilde{T} also ensured that the price ceiling set by imports $P^W + \tilde{T}$ did not constrain domestic prices.

industry would set domestic prices based on domestic demand and supply conditions alone: p^e and p^s should covary tightly on account of, say, income shocks that moved both domestic demand curves, or supply shocks that moved the marginal cost curve (a poor harvest due to dry weather, say).

In the second situation, high export prices would constrain domestic prices p^e and p^s , as in the late 1980s and 1990s¹³. In setting domestic prices, the industry would now arbitrage across domestic markets and the strengthened international sugar market. Unlike the first situation, domestic ethanol and sugar prices should move in step with the world price of sugar.

In either of these two situations which characterize the pre-flex period, to the extent that domestic demand and supply shocks, as well as the world price of sugar, displayed low correlation with the world price of oil, there should be low covariation between the price of oil and domestic prices for ethanol and sugar. We summarize the above considerations in Proposition 1.

Proposition 1 (*“Pre-flex period”*) *The domestic ethanol price p^e covaries tightly with the domestic sugar price p^s due to common supply shocks, correlated demand shocks or a binding export price floor. Whether domestic prices p^e and p^s covary with the world sugar price P^W depends on the level of the export price floor, $P^W - T$, as follows:*

- (i) *For low $P^W - T$, $\text{Corr}(p^e, P^W)$ and $\text{Corr}(p^s, P^W)$ are low (assuming that domestic demand and supply shocks are uncorrelated with P^W),*
- (ii) *For high $P^W - T$, $\text{Corr}(p^e, P^W)$ and $\text{Corr}(p^s, P^W)$ are high (and positive).*

Further, the correlation between domestic prices p^e and p^s and the world price of oil should be low, to the extent that the latter does not significantly move domestic demand and marginal cost curves, nor the export price floor.

The 2000s saw the advent of the dual-fuel flexible engine. We label this the “post-flex period”. Recall that by 2006, the composition of Brazil’s passenger car fleet was 76.5% gasoline-only, 14.7% ethanol-only, and 8.7% flex, with the latter eating away at the former two. Recall also that, since the late 1990s, the government was no longer attempting to control ethanol prices. We argue that for an increasing range of realizations of demand and supply shocks, the price of ethanol should now covary with the price of gasoline, thanks to substitution in demand between ethanol and gasoline. The

¹³Starting around this time, domestic demand was also depressed, and trade was being liberalized, further lifting the export price floor. Between 1989 and 1999, sugar export quantities grew eightfold. See Baccarin (2005). Bacchi et al (2004) discuss the politics of trade behind $p^s < P^W = p^s + T$.

domestic demand curve for ethanol in Figure 4 now incorporates the ability of flex car owners to arbitrage across (retail) ethanol prices p^e and gasoline prices p^g , introducing a flat segment of length proportional to the share of flex cars in the fleet.¹⁴ From (1), for $p^e > \alpha p^g$, ethanol is demanded only by the share of ethanol-dedicated car owners, with flex car owners switching to gasoline at (or above) this price threshold. (We now ignore the sugar export price floor, since we posit that this no longer constrained domestic prices as in the 1990s, thanks to high world oil prices and lower world sugar prices, as we show in the empirical analysis of Section 5.)

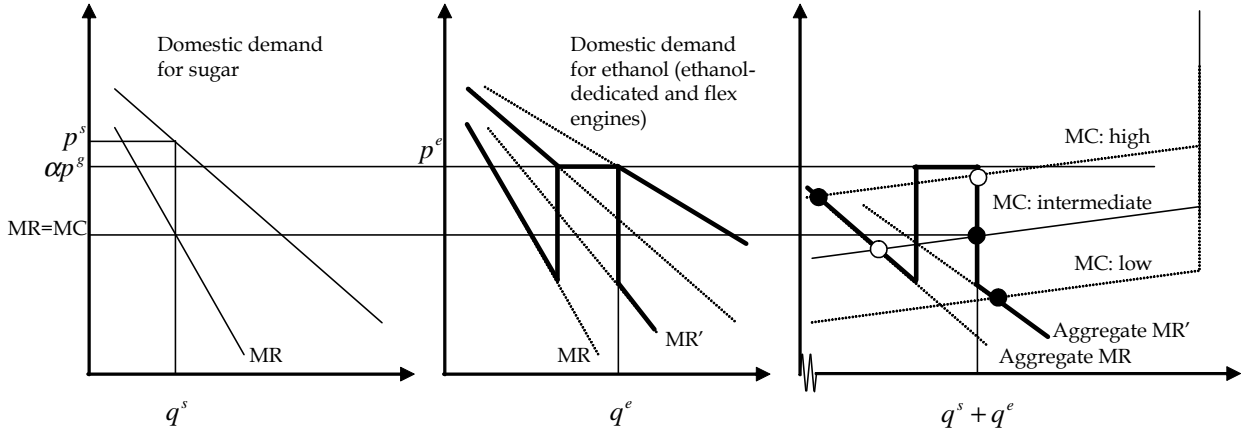


Figure 4: Arbitrage by owners of flexible-fuel cars in the “post-flex period”. Given the the MC schedule labeled “intermediate”, the share of flex cars, and the price of gasoline of the figure, in equilibrium $p^e = \alpha p^g$ (at the kink of the ethanol demand curve). A low p^g , a low flex share (not shown in the figure) or a high marginal cost (shown as the upper schedule in the figure) can tip the equilibrium away from flex consumption of ethanol toward gasoline.

For a “sufficiently large” share of flex, and a “moderate” marginal cost, such as the outcome drawn where the intermediate MC schedule intersects the vertical segment of the aggregate MR schedule, the equilibrium price of ethanol will lie at the kink defined by the price of gasoline, $p^e = \alpha p^g$. (We assume that the price of gasoline is set by the government, via the state-owned oil company Petrobras, based largely on the exogenous world price of oil. We uncover evidence of this in Section 5. Petrobras is effectively a monopolist in the production and refining of oil.) Here, the sugar oligopoly’s marginal ethanol consumer is the flex car owner. Notice that p^e will remain at the kink for moderate fluctuations of the domestic demand and marginal cost curves around this equilibrium. Importantly, p^e will move with the kink as this moves up and down by virtue of fluctuations in p^g . As the penetration of flex grows, the flat segments in the ethanol demand and the aggregate MR curves lengthen: the likelihood that a particular

¹⁴Ethanol prices of interest to us now are those at the pump, given that deregulation of distribution had already occurred (unlike the 1980s and 1990s where, because of government intervention in distribution, we considered producer prices, i.e. in the wholesale market).

realization of exogenous demand and supply covariates 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.)¹⁵ Notice also that when marginal cost is sufficiently low (or, equivalently, when p^g is too high), it may even be the case that $p^e < \alpha p^g$; this outcome is drawn in the figure for the lower MC curve. (In promising American consumers “a great bargain”—see the opening quotes—U.S. Senator Lugar may have had a similar outcome to this one in mind, where $p^e < \alpha p^g$.)

Conversely, if the share of flexible-fuel engines relative to that of ethanol-only is low, or marginal cost is high, we would expect gasoline prices to exert less pressure on ethanol prices. In this situation, the marginal consumer is the owner of an ethanol-only car. It is easy to show that if the share of flex is sufficiently low, or marginal cost is sufficiently high, a monopolist would find it optimal to set $p^e > \alpha p^g$ and sell ethanol only to owners of ethanol-only cars, and not to owners of flex cars. This outcome is drawn in Figure 4 for the upper MC curve.

We can then exploit variation in (i) the penetration of flex engines over time (and possibly across Brazil’s regional markets, i.e. time-and-region-specific markets), and (ii) marginal cost across regional markets due to their differing distance from sugar cane plantations (and thus from sugar/ethanol mills), to verify whether prices are broadly consistent with the above considerations, summarized in Proposition 2.

Proposition 2 (*“Post-flex period”, assuming a low world price for sugar relative to oil*)
As the share of the flexible-fuel engine in the car fleet grows, thus raising the proportion of consumers who arbitrage across price differences in ethanol and gasoline at the pump, the domestic ethanol price p^e increasingly covaries with the domestic gasoline price p^g .

Further, the likelihood that the ethanol price is at or below the gasoline price should be higher in time-and-region-specific markets with higher shares of flex in their car fleets, and low marginal cost, i.e. in such markets we would expect $p^e \leq \alpha p^g$. Conversely, this may not be the case in markets where flex penetration is lower or marginal cost is higher (the “control” group).

Finally, starting at an equilibrium where $p^e \leq \alpha p^g$, notice that as the share of flex increases at the expense of gasoline-only cars, this puts upward pressure on the price of sugar. To see this, let the flat segment of the aggregate MR curve of Figure 4 grow and the (right-hand) vertical segment shift out: unless there is a downward (technology) shock to the MC schedule, equilibrium marginal cost will increase. We thus write:

¹⁵Interestingly, notice that around this “intermediate MC” equilibrium, an increase in p^g and thus an increase in p^e —leading to reduced q^e —may be associated with a *reduction* in the price of sugar p^s (due to substitution in supply). This is counter to claims commonly made by pundits, whereby the domestic price of sugar should trail the domestic price of ethanol.

Corollary 1 *As the share of flex grows, the shifting out of the ethanol demand curve, for $p^e \leq \alpha p^g$, puts upward pressure on the domestic sugar price p^s , thanks to substitution in demand (gasoline and ethanol) and substitution in supply (sugar and ethanol).*

4 Data

Pricing data for this study were pulled together from a variety of sources. As can be expected, the more recent the data, the lower the level of aggregation along either the time or the spatial dimension:

Domestic retail fuel prices A monthly state-level panel of retail prices for gasoline and ethanol (in current local currency Real\$/liter), in the period Jul-2001 through Feb-2007, covering all 27 states of the Brazilian federation, was obtained from the National Agency for Oil (ANP). A monthly city-level panel of retail prices for gasoline and ethanol (in current R\$/liter), in the period Jan-1991 through Feb-2007, covering 11 main cities, was obtained from the Brazilian Institute for Geography and Statistics (IBGE). (A similar city-level panel to that of IBGE, available from ANP for the period Jul-2001 through Feb-2007, essentially replicated the IBGE dataset, validating both datasets.) Prior to 1991, retail prices for gasoline and ethanol (in current US\$/m³) were obtained only at an annual frequency and at an aggregate national level, from the Ministry of Mines and Energy (MME).

Other domestic prices Monthly wholesale prices for (“anhydrous”) ethanol (in current R\$/liter), shipped from mills in the state of São Paulo over the period Jan-1982 through Feb-2007, were obtained from the Association for Sugar Cane Growers (UNICA). A monthly wholesale price index for refined sugar, in the period Jan-1982 through Feb-2007 and at an aggregate national level, was obtained from the Fundação Getulio Vargas (FGV). Producer prices for soyabean (in current R\$/kg), in the same period and national level, were also obtained from FGV. Average monthly exchange rates in current R\$/US\$ were obtained from the Central Bank of Brazil. (We use the average exchange rate across days within each month, rather than end-of-month exchange rates, given the nature of the other monthly pricing data.) A monthly general Consumer Price Index (the “IPCA”), dating back to Jan-1982 and at an aggregate national level, was obtained from IBGE (though alternative general or wholesale price indices, to test robustness, were also collected from FGV).

International prices Monthly oil prices (spot prices of West Texas Intermediate crude oil at Cushing, OK, in current US\$/barrel), for the period Jan-1986 through Feb-2007, were obtained from the Energy Information Administration (U.S. Department of Energy). Prior to 1986, the same WTI price series, though on an annual basis, was obtained from the International Financial Statistics (IMF). (The later monthly EIA series and the earlier annual IFS series were checked for consistency.) A quarterly

(current US\$) export price index for Brazilian sugar dating back to 1981 Quarter 1, compiled by FUNCEX (Center for the Study of Trade), was obtained through Brazil’s Institute for Applied Economic Research (IPEA). An alternative price series for world sugar—International Sugar Agreement (ISA) prices, in US\$ cents/pound—was obtained from the International Sugar Organization (ISO) on (i) an annual basis for the period 1981 through 1990, and (ii) on a monthly basis from Jan-1991 on. (Accounting for the different levels of time series aggregation, the FUNCEX export price index and the ISO price series are highly collinear.) To account for U.S. inflation (see below), a Consumer Price Index (averaged across U.S. cities and all items) was obtained from the Bureau of Labor Statistics (U.S. Department of Labor).

Converting from current prices to constant Dec-2006 prices Domestic prices (or price indices), denominated in current local currency units—the Real\$ (or a multiple of it, in the case of an index), were converted to constant Real\$ using IBGE’s Brazil CPI. Alternatively, where we compare domestic prices with international prices, and thus wish to compute domestic prices in constant US\$ terms, we employ the following two-step procedure: (i) convert current prices in Real\$ into current US\$ terms using current R\$/US\$ exchange rates, and (ii) convert current prices in US\$ into constant US\$ terms using the BLS’s U.S. CPI. International prices denominated in current US\$ units are converted into constant US\$ terms using step (ii) directly.

Other data (state-level characteristics) The amount of sugar cane (in tons) harvested by state and by year was obtained from UNICA. An annual state-level panel of GDP by sector (e.g. agriculture) was obtained from IBGE. The shares of the different types of engines (gasoline-only, ethanol-only, flex) in the passenger car fleet, by state and by year, were calculated from data kindly made available by the National Association of Car Dealers (Fenabrave). Fenabrave keeps track of fleet characteristics based on cumulative new car sales and estimated survival rates, very occasionally checking its figures against state registries of motor vehicles. It has been argued that its estimated survival rates are too high, which would understate the penetration of recent flex technology. (Based on our judgement of the data, we believe that the above-mentioned 8.7% flex share of the aggregate fleet in 2006 might actually be understated by around 2.0%, totaling 10.7%.)

5 Empirical analysis of prices

Guided by the theoretical framework of Section 3, we now analyze the statistical relationship between prices in both the “pre-flex” (1980s and 1990s) and the “post-flex” (2000s) periods, with particular emphasis on the latter. We find that the covariation in prices, and the level of prices, are broadly consistent with the stylized model.

Before proceeding, given its central importance to the story we are recounting, Figure 5 plots the evolution of the world price of raw sugar P^W , at (i) constant ISA annual/quarterly averages in US\$ cents/lb, and (ii) normalized by the world price of crude oil. The picture would be almost identical had we plotted effective export prices for Brazilian sugar.

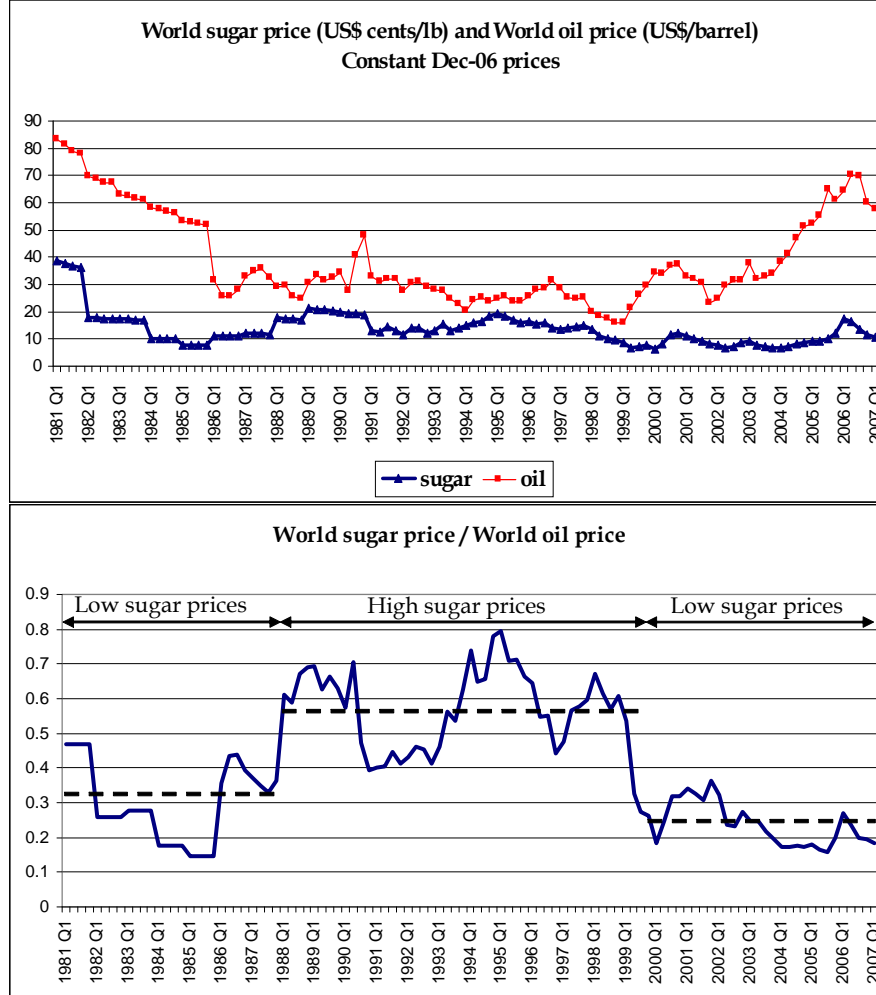


Figure 5: World sugar price (ISA annual/quarterly average) normalized by the world oil price (WTI quarterly average), Constant US\$ (base Dec-06 U.S. CPI)

5.1 The “pre-flex period”: the 1980s & 1990s

The mid 1980s were marked by low world sugar prices (relative to the world price of oil), followed by a decade of high world sugar prices starting around 1988 (Figure 5). Our model predicts that the absence of a binding export price floor for sugar—during most of the 1980s—would result in low correlation between the world price of sugar P^W and domestic prices for sugar p^s and ethanol p^e ; conversely, high export prices—during the 1990s—would lead to the cointegration of P^W and domestic prices. (Here

we refer to wholesale ethanol prices, given the government's control over retail prices in this period. We look at retail prices when we turn to the post-flex period—post deregulation—below.)

We start with the domestic price of sugar. Figure 6 plots the evolution of (constant US\$) wholesale price indices for sugar on the domestic market (p^s) and on the world market (P^W), between 1982 and 1999¹⁶. To the naked eye, it indeed appears that the domestic price of sugar begins to track the world price of sugar more closely from the end of the 1980s. This is confirmed by simple correlation coefficients, reported in the following table along with their significance levels (as a simple falsification exercise, the correlation between the world price of sugar and the domestic price of soyabean—another of the country's leading crops—is also reported):

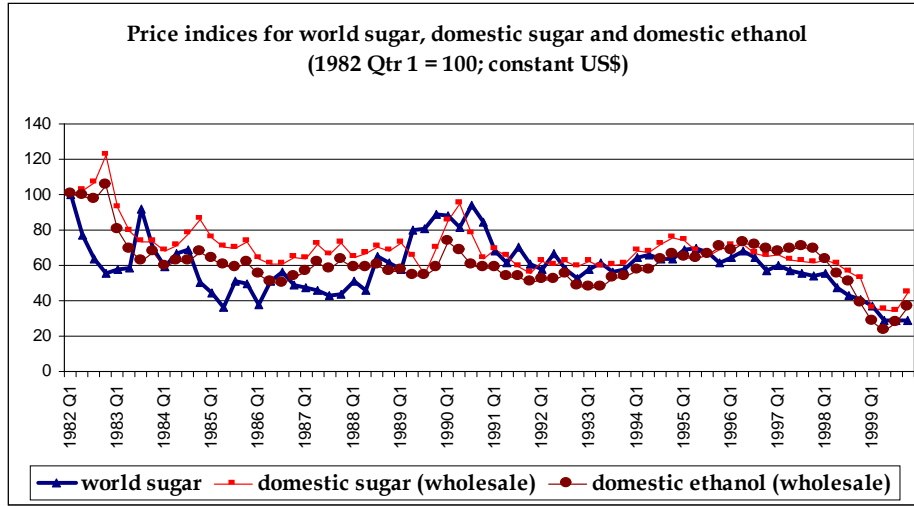


Figure 6: Quarterly price indices for sugar on the world market (P^W), and for sugar (p^s) and ethanol (p^e) on domestic wholesale markets, between 1982 and 1999 (Constant US\$, 1982 Q1 = 100)

	1982 Q1 to 1989 Q4	1990 Q1 to 1999 Q4
$Corr(p^s, P^W)$	0.22 (22%)	0.85 (0.0%)
$Corr(p^{soyabean}, P^W)$	0.37 (3.7%)	0.31 (5.3%)
$Corr(p^s, P^{OIL})$	0.75 (0.0%)	0.31 (5.5%)
No. obs.	32	40

Note: p-values in parentheses

Thus the variation in the domestic price of sugar pictured in Figure 6 and in the table above, seems consistent with Proposition 1 of our stylized model. (The table also reports the correlation between the domestic price of sugar and the world price of oil:

¹⁶We plot world sugar prices as proxied by effective export prices for Brazilian sugar, rather than ISA prices, since the latter are available on a quarterly basis only from 1991.

the non-zero coefficient in the 1980s is probably due to fluctuations in the world price of oil moving the domestic demand and marginal cost curves, as stated in the proposition.)

Of relevance to the current “food-versus-fuel” debate, despite ethanol production consuming half the sugar cane harvest by 1985—recall Section 2—domestic sugar prices actually fell 40% in the early 1980s. Total acreage devoted to the country’s agricultural sector was growing fast, as was farm productivity, thanks to mechanization.

Now turning to the domestic price of ethanol, Figure 6 also plots the evolution of a wholesale price index for ethanol on the domestic market (p^e) against that for sugar on the world market (P^W) in the same period. As with domestic sugar prices, ethanol pricing data appear to bear our hypotheses out: see the correlation coefficients in the table below. Domestic ethanol prices are highly (and significantly) correlated with world sugar prices only in the 1990s. Domestic sugar and ethanol prices remain highly (and significantly) correlated throughout both the 1980s and the 1990s. (Unsurprisingly, the correlation between p^e and world oil prices is similar to that between the latter and p^s .) We again find support for Proposition 1.¹⁷

	1982 Q1 to 1989 Q4	1990 Q1 to 1999 Q4
$Corr(p^e, P^W)$	0.32 (7.9%)	0.69 (0.0%)
$Corr(p^e, p^s)$	0.96 (0.0%)	0.83 (0.0%)
$Corr(p^e, P^{OIL})$	0.75 (0.0%)	0.23 (15%)
No. obs.	32	40

Note: p-values in parentheses

5.2 The “post-flex period”: the 2000s

Proposition 2 states that as the share of the dual-fuel engine in the car fleet grows at the expense of single-fuel engines, ethanol prices will increasingly move in step with gasoline prices. While the government did attempt to fix the relative price of ethanol (to a greater or lesser degree of success) during the 1980s and early 1990s, by the late 1990s price controls in ethanol markets had been removed. This is not true for gasoline, whose prices remain very much under the government’s control¹⁸.

In view of the panel nature of our retail fuel price data—a monthly panel of 27 states between Jul-2001 and Feb-2007 and, earlier to this, a monthly panel of 11 cities between Aug-1994 and Jun-2001—we begin by characterizing each state along two different dimensions: (i) the (recent) penetration of the flex engine in the state’s car fleet, and (ii)

¹⁷As for retail ethanol prices, these are highly correlated with retail gasoline prices (a correlation coefficient of 0.91, not reported) between 1982 and 1999, at which point deregulation occurred and price controls for ethanol at the pump were dropped.

¹⁸In fact, retail gasoline prices have largely been trailing the world price of oil, with a correlation coefficient of 0.82 in the period 2000 Q1 to 2007 Q1.

the supply of sugar cane normalized by a measure of the demand for sugar cane, proxying the extent to which the state needs to acquire ethanol from other states, thus incurring transportation costs. Figure 7 presents these two characteristics for each state. The horizontal axis depicts the share of flex in the car fleet at the end of 2005: for example, this was 5.3% for the state of Pernambuco (PE)—see the right panel. The vertical axis depicts the ratio of a given state’s share of the Brazilian 2002/03 sugar cane harvest to that state’s share of Brazilian GDP in 2003. The state of PE, for example, harvested 4.5% of Brazil’s sugar cane, while accounting for 2.7% of Brazil’s GDP, translating into a $4.5/2.7 \approx 1.7$ “ethanol supply-to-demand ratio”, suggesting that PE was a net seller of ethanol to other states.

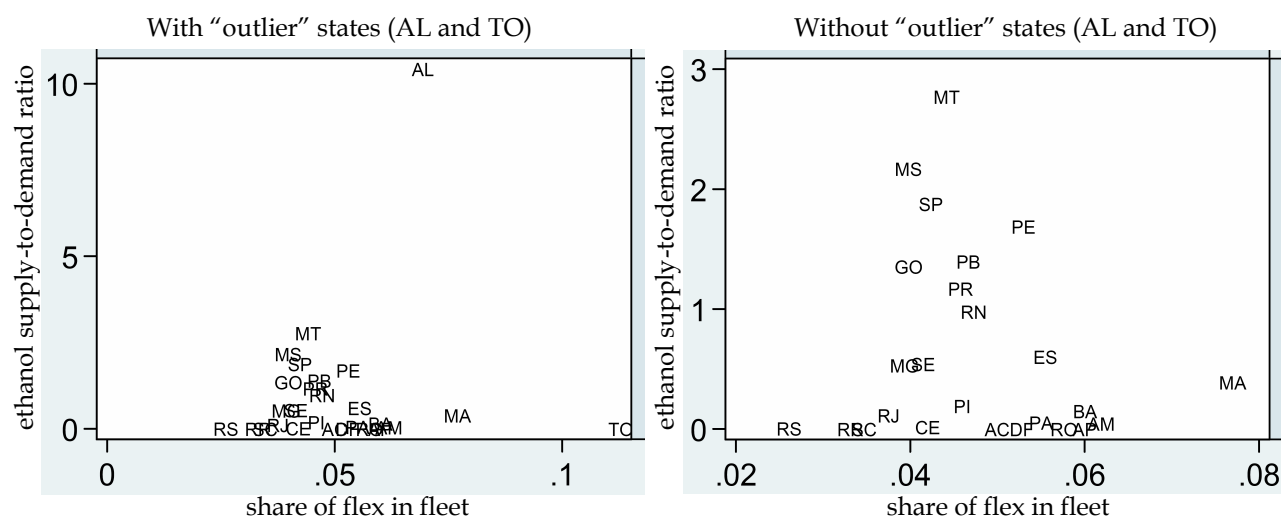


Figure 7: State characteristics: the “ethanol supply-to-demand ratio” (in 2003), against the share of flex in the car fleet (at the end of 2005). Left panel shows all 27 states, right panel excludes two “outlier” states (TO and AL).

Figure 7 indicates that despite the above-mentioned success of the flex engine among new car sales (the flow), in all but one state the share of flex in the car fleet (the stock) is still quite limited: the median flex share at the end of 2005 was only 4.7% of the fleet. Also, there is (unfortunately) little variation in flex shares across states: flex versions appear to be equally successful everywhere, either because of consumer preferences being similar, or because car manufacturers were soon restricting certain models to flex versions only. It is not clear whether with such limited arbitrage to date by the flex consumer, pricing data (through Feb-2007) will already be consistent with Proposition 2—it may be the case that ethanol and gasoline prices will only move in tandem once a higher threshold is reached¹⁹. Figure 7 also indicates that there seems to be no correlation between the uptake of flex technology among car buyers in a state and the extent to

¹⁹In principle, this threshold could be determined if one were to collect further data on the industry (quantities, demand shifters, cost, etc) and then fit the structural model. See note 2.

which that state is an important supplier of ethanol. Again, this is possibly due to the marketing strategy of car makers to limit their offerings of engine types.

Figure 8 (at the end) looks at the relationship between retail ethanol and gasoline prices across the different regional markets, in levels (constant Dec-2006 R\$/liter), and how this has been changing over time. We divide time-and-region-specific markets into 9 similarly-spaced sequential subperiods—subperiod 1: Aug-94 to Nov-95, subperiod 2: Dec-95 to Mar-97, ..., subperiod 9: Oct-05 to Feb-07—and 2 region types, “net buyers of ethanol” (defined as states or cities in states where the ethanol supply-to-demand ratio lies at or below the median of 0.19) and “net sellers of ethanol” (states or cities in states where the ethanol supply-to-demand ratio lies above the median). The figure should be read from the upper left corner to the lower right corner, covering the sequential subperiods, and the 2 region types within each subperiod. In each of the $9 \times 2 = 18$ bins, a “pricing parity” line is drawn: dots—observed price pairs (p^e, p^g) —above this line indicate time-region markets where $p^e > 0.7p^g$ (where $\alpha = 0.7$).

Several features of the pricing data are evident from the scatterplot. First, both retail ethanol and gasoline prices have been increasing between 1994 and 2007: dots move up and to the right. Second, ethanol prices have been increasing by less than gasoline prices: while $p^e > 0.7p^g$ in all early markets (i.e. the cloud of points lies strictly above the parity line), this is not so in later markets. Third, the increase in ethanol prices over time is less pronounced in those regional markets which are net sellers of ethanol (i.e. relative to net buyers of ethanol, over time most points move under the parity line for net sellers of ethanol). Importantly, these markets do not need to source ethanol from beyond state borders and thus probably have lower marginal cost. This might explain why for these markets—net sellers of ethanol in later time periods where flex engines were present—we observe $p^e \leq 0.7p^g$ in most instances compared to markets that are net buyers of ethanol, consistent with Proposition 2.

This is confirmed in the simple OLS regressions of Table 1, which capture (unconditional and conditional) statistical relationships among fuel prices in each of the 9 subperiods. An observation is a time-and-region-specific market. Regressions (I) and (II) project ethanol prices on gasoline prices with no intercept. Compared to earlier markets, ethanol prices in later markets correspond on average to a lower proportion of gasoline prices: 65-72% (2001 on) against 80-85% (1994 to 1998)—see regression (I). Further, ethanol prices in regions that are net sellers of ethanol are $0.06p^g$ lower than in regions that are net buyers of ethanol *but only for later periods*, for the most part of which the flex engine had been introduced—see regression (II). We interpret this finding as being consistent with Proposition 2. While consistent with Proposition 2, we also note that the drop in relative ethanol prices began in 1998/1999, prior to the introduction of the flex engine in 2003. To illustrate, the evolution of prices for a specific region, the

city of São Paulo, is provided in Figure 9. Recall from Figure 5 that around 1998/1999 (i) world oil prices were rising, explaining the increase in gasoline prices, and (ii) world sugar prices were falling, such that the export price floor which had remained high in the 1990s was now falling, explaining the initial drop in ethanol prices across all states. Also, (retail) ethanol markets were being deregulated around this time²⁰.

Regression (III) of Table 1, which includes region fixed effects, suggests that the positive association between (deregulated) ethanol and (regulated) gasoline prices has been strong since late 2002, and this is robust even when controlling for world sugar prices—regression (IV). This is consistent with Proposition 2. Again, Figure 9 provides greater detail for a specific region, including a 24-month moving correlation between ethanol and gasoline prices. In the wake of the government’s diminished role in ethanol markets, the onset of the flexible dual-fuel technology in the early 2000s appears to be making ethanol prices move in step with gasoline prices.

Relative price volatility We partition the 68 time periods over which retail fuel prices are available in the 27 states into two equally-spaced subperiods, an “earlier” subperiod (the 34 months from Jul-2001 to Apr-2004) and a “later” subperiod (the 34 months from May-2004 to Feb-2007). (Recall that controls on ethanol prices had been dropped by 1999.) Within each of these two subperiods $T \in \{\text{“earlier”}, \text{“later”}\}$, and for each of the panel units $l \in \{1, \dots, 27\}$, we compute a measure of relative price volatility, defined à la Engel and Rogers (1996) as:

$$V_{l,T}^{e,g} := std.dev.t \in T \left(\ln \left(\frac{p_{l,t}^e}{p_{l,t}^g} \right) - \ln \left(\frac{p_{l,t-1}^e}{p_{l,t-1}^g} \right) \right) = std.dev.t \in T \left(\ln \left(\frac{p_{l,t}^e/p_{l,t-1}^e}{p_{l,t}^g/p_{l,t-1}^g} \right) \right) \quad \forall l, \forall T \quad (2)$$

where $std.dev.t \in T(x)$ denotes the standard deviation of metric x across the sample of time periods $t \in T$, and metric x is the first difference in the log of the relative price of ethanol. (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 price volatility of ethanol relative to gasoline, conditioning on some variables, in the later subperiod after which flex cars had (largely) been introduced with the earlier subperiod which predates flex technology. Notice that while Engel and Rogers (1996) are concerned with the covariation in prices for the same good across two different locations (i.e. price variation in geographic space, one location relative to the other), we are concerned with the covariation in prices in the same location across two different goods (i.e. price variation in product space, ethanol relative to gasoline). While Engel and Rogers (1996) condition on covariates such as whether a national border is crossed, we condition on

²⁰Falling ethanol prices upon deregulation are consistent with the statement above that any binding price controls during the 1980s and 1990s accommodated the industry’s (joint) preferences.

the two state characteristics of Figure 7, the state’s ethanol supply-to-demand ratio (in 2003) and the share of flex in its car fleet (at the close of 2005).

Column (I) of Table 2 reports results of an OLS regression of the relative price volatility on a dummy variable which takes on the value 1 for observations that correspond to the later subperiod, controlling for the two state characteristics. While the mean of the dependent variable—relative price volatility (or standard deviation) (2)—across the 54 observations (27 states \times 2 subperiods) is .044, volatility is on average (across states) .013 *lower* in the “later” subperiod as compared with the “earlier” one. This is significant not only in terms of magnitude but also statistically, and is consistent with Proposition 2: ethanol prices seem to be increasingly moving in step with gasoline prices—thus relative prices are less volatile—as the penetration of flex engines grows. Despite the limited variation in the penetration of flex across states (recall Figure 7), a 1% higher flex share in a state’s fleet (in 2005), is associated with a statistically significant $0.2/100 = 0.002$ lower price volatility of ethanol relative to gasoline. As for the other state-level control, the coefficient on the ethanol supply-to-demand ratio is insignificant: we might have expected a significantly negative coefficient on the ethanol supply-to-demand ratio. Results, reported in column (II), are robust to replacing the linear functional form of the controls by step functions (i.e. dummy variables defined according to the state’s characteristics relative to the median, as above).

Causality tests We again consider the 68 time periods over which retail fuel prices are available in the 27 states to investigate statistical causality between the prices of the two fuels²¹. For each location $l \in \{1, \dots, 27\}$, we start by taking each of the time series of prices separately—ethanol or gasoline in levels—to determine their order of integration. For those locations where both the ethanol price series and the gasoline price series are stationary (i.e. $I(0)$), we can estimate a vector autoregression (VAR) model to test for causality between p^e and p^g in the Granger sense, as well as instantaneous causality. For those locations where p^e and p^g are non-stationary but where both series have the same (non-zero) order of integration, we can further verify (following Johansen 1991) whether the two series are co-integrated; should this be the case (i.e. p^e and p^g are both $I(1)$, say, and they co-integrate), we can estimate a vector error correction (VEC) model and test for causality using the corresponding VAR representation. (The appendix provides further details of these standard tests.)

Table 3 presents results. Of the 27 states, ADF tests indicate that in 17 states both the ethanol price series and the gasoline price series are stationary (states AP through

²¹Ferreira et al (2007) apply similar tests using aggregate (nationwide) prices for ethanol and gasoline. For an early paper that uses tests of causality among prices to evaluate the possibility of arbitrage across (geographic petroleum) markets, see Slade (1986). In a similar vein, Doane and Spulber (1994) test for an integrated natural gas market across the U.S.

TO). In a further 3 states (states AL through RR), p^e and p^g are both $I(1)$, but only in one of these states (AL) can we reject the null of no cointegration between p^e and p^g . As such, we estimate a VAR model to test for causality in each of 18 states. (We do not perform a joint analysis of prices in the remaining 9 states since p^e and p^g either do not co-integrate or have different orders of integration.) In each of the 18 states, there is strong evidence of instantaneous causality between p^e and p^g . We also find evidence of Granger causality in 11 of the 18 states. Interestingly, while in these 11 states gasoline prices appear to Granger-cause ethanol prices, only in one state do we find ethanol prices Granger-causing gasoline prices. This asymmetric result seems sensible in view of the dominant size of the gasoline (oil) market relative to that of ethanol (sugar cane), in addition to the institutional setting by which the price of gasoline is fixed. We take these findings as further suggestive evidence in support of Proposition 2.

6 Concluding remarks

This paper outlines a theoretical framework for thinking about the covariation in prices in one of the world’s pioneering biofuel industries. We provide a simple structural model where Brazil’s sugar industry arbitrages across domestic and export markets for ethanol (biofuel) and sugar (food), and where consumers arbitrage across ethanol (biofuel) and gasoline (fossil fuel), both widely available at the pump. We find early evidence that the fast-increasing adoption of flexible-fuel technology in the primary car market is tying the price of ethanol to the price of gasoline, as predicted by the theory. We also look back to the 1980s and 1990s, prior to the introduction of the flexible-fuel vehicle, to examine the observed behavior of prices in light of our model. Future research should garner further data on the industry in an attempt to estimate the model, over and above using it to guide an empirical analysis of prices, as we have presently done.

With regard to the food-versus-fuel debate currently being undertaken around the world, the model predicts that, absent a large technology shock as in the 1980s, the booming market in ethanol will put pressure on sugar prices, with ethanol substituting for gasoline on the demand side and for sugar on the supply side. That the level of ethanol additive in regular gasoline, determined by government mandate, has very recently fallen, offsetting the growing market-based demand for (unblended) ethanol by flex cars—notice the 2006 dip in Figure 1—suggests that policymakers are mindful of the “ethanol ripple effect”.²²

²²See, for example, the Wall Street Journal (2007). Brazilian politicians may not have been amused earlier this year by the public outcry sparked by higher tortilla prices in Mexico, which some have linked to the U.S. ethanol boom. Beyond Mexico, the press reports how politicians around the world—including the U.S., China, India and the Philippines—have recently seemed all too eager to be seen checking food prices at the local grocery store.

The U.S. Energy Policy Act of 2005 called for 7.5 billion gallons of ethanol and biodiesel—almost 6% of the nation’s consumption of fuel—to be injected annually into the U.S.’s fuel complex by 2012. The E.U. is drafting similar initiatives (Herrera 2006). Should an international market in biofuels develop, the Brazilian experience with sugar cane ethanol is indicative of how prices of ethanol and agricultural inputs more generally—including land, particularly in view of future wood-based cellulosic ethanol—may increasingly correlate with the price of oil, thanks to substitution both in supply and in demand.

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A Appendix: Causality tests

We start investigating the time series properties of the (constant²³) price series by studying their order of integration, fuel-by-fuel and market-by-market. If, for a given price series, the null hypothesis of non-stationarity of the ADF test²⁴ is rejected, we conclude that the series is $I(0)$: Table 3 indicates that stationary price series are predominant. In case a series is not found to be stationary in levels, we analyze its first difference; for all such series where we performed the ADF test on first differences, we rejected the null of non-stationarity, thus obtaining that the series in levels is $I(1)$.

For those markets where both fuel price series are $I(0)$, we run a VAR in the levels of the variables and test for instantaneous and Granger causality. For those markets where both fuel price series are $I(1)$, we test for cointegration using the Johansen (1991) test. For the case where the two $I(1)$ series co-integrate, we estimate an Error Correction Model and test for instantaneous and Granger causality using the corresponding VAR representation. (Clearly, for the case where the two $I(1)$ series do not co-integrate, we could still test for causality by estimating a VAR in differences.)

A time series Z is said to Granger-cause another time series Y if it can be shown that lagged values of Z provide statistically significant information about future values of Y . In our setting, this corresponds to estimating (assuming stationary price series)

$$\begin{bmatrix} p_t^e \\ p_t^g \end{bmatrix} = \sum_{k=1}^K \begin{bmatrix} \alpha_{11,k} & \alpha_{12,k} \\ \alpha_{21,k} & \alpha_{22,k} \end{bmatrix} \begin{bmatrix} p_{t-k}^e \\ p_{t-k}^g \end{bmatrix} + X_t + \begin{bmatrix} u_t^e \\ u_t^g \end{bmatrix}$$

where X_t corresponds to variables that are exogenous at time t (in particular, seasonal dummies) and K is determined using the Schwarz criterion. In the above specification, p^g does not Granger-cause p^e if, and only if, $\alpha_{12,k} = 0, k = 1, 2, \dots, K$ (this is the null hypothesis). Similarly, p^e does not Granger-cause p^g if, and only if, $\alpha_{21,k} = 0, k = 1, 2, \dots, K$. Intuitively, if the coefficients on lagged variables $\alpha_{21,k}$ are jointly non-significant, then p^e does not have explanatory power for future values of p^g . In our results, we find that parameters $\alpha_{12,k}$ tend to be significantly different from zero for a number of states (i.e. considerable evidence of p^g Granger-causing p^e), whereas parameters $\alpha_{21,i}$ tend to be jointly non-significant (i.e. little evidence of p^e Granger-causing p^g).

Instantaneous causality is characterized by non-zero correlation of the error terms u^e and u^g . The null hypothesis $E(u_t^e, u_t^g) = 0$ is tested against the alternative of non-zero covariance between the two error vectors (see Lütkepohl 1991 for a discussion of causality

²³Unlike the typical macroeconomic study, recall from Section 4 that we analyze real, rather than nominal, prices.

²⁴Throughout our analysis, the optimal number of lags is selected according to the Schwarz criterion. We also acknowledge that the number of time periods is low relative to that wished for by the time series econometrician, with non-trivial implications on testing power.

tests). In our results, we find overwhelming support for instantaneous causality between p^e and p^g .

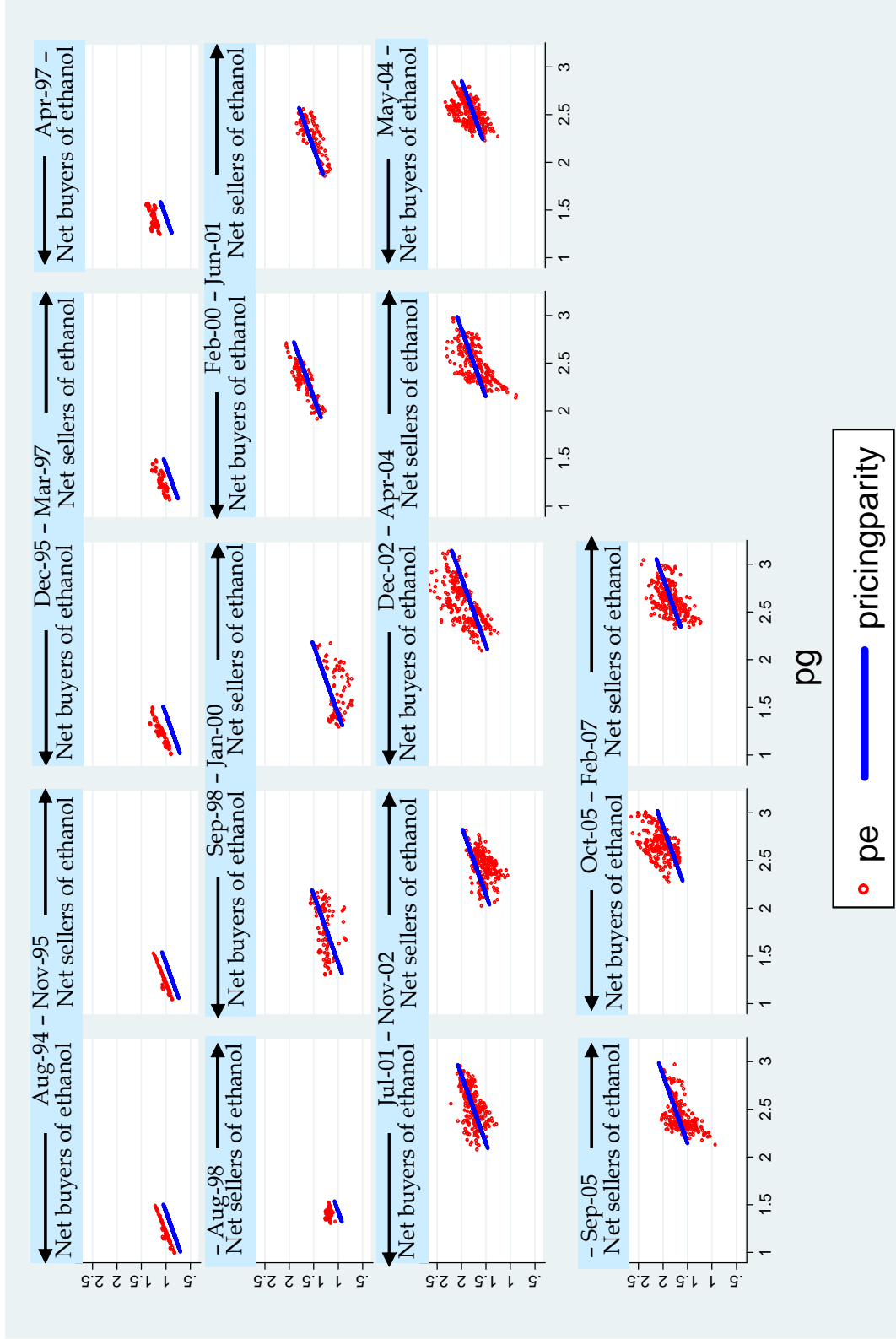


Figure 8: Monthly retail ethanol against gasoline prices (in constant Dec-2006 R\$/liter) in 11 cities (Aug-1994 to Jun-2001) and 27 states (Jul-2001 to Feb-2007). Dots above the “pricing parity” line indicate time-region markets where $p^e > 0.7p^g$ (where $\alpha = 0.7$). For every one of 9 sequential subperiods, regions are divided into net buyers of ethanol (supply-to-demand ratio at or below median) and net sellers of ethanol (supply-to-demand ratio above median).

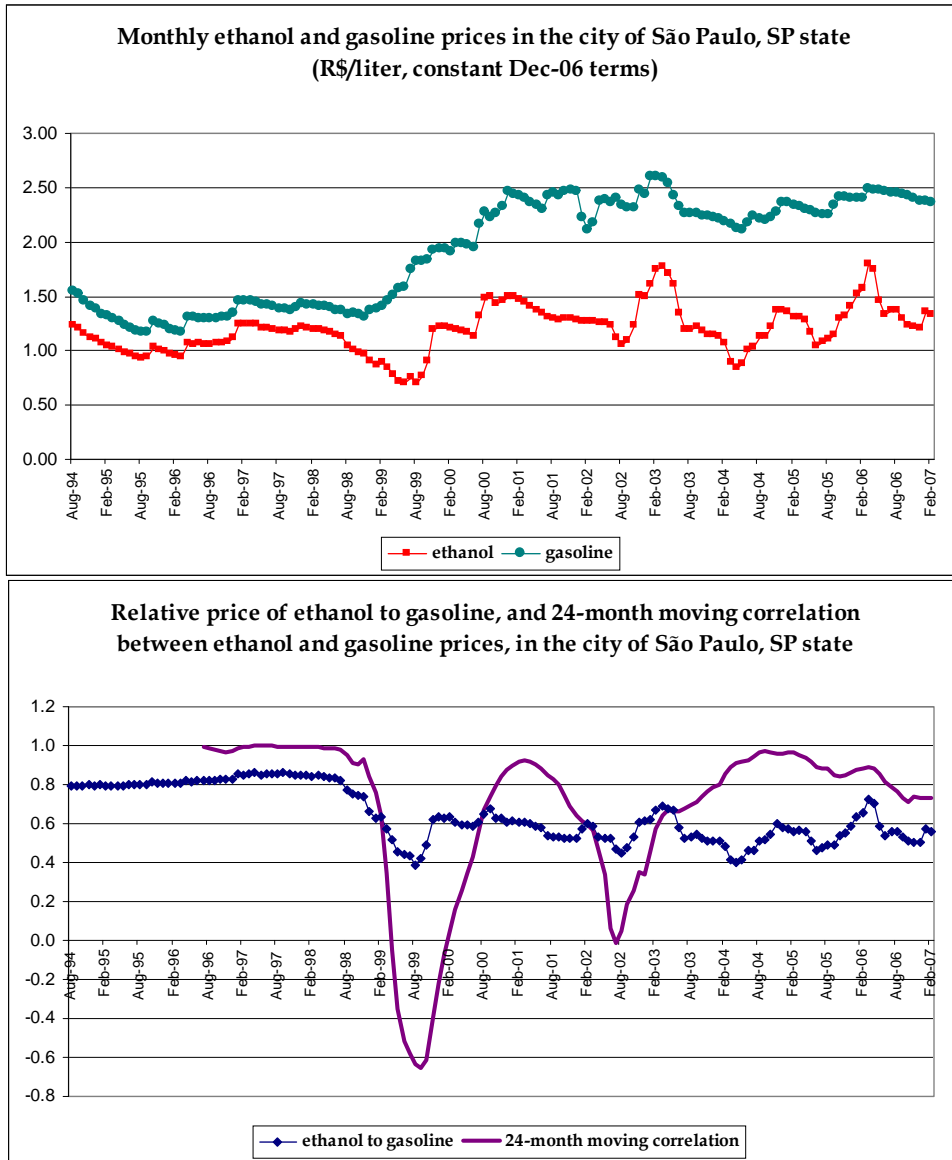


Figure 9: Monthly retail ethanol and gasoline prices, in the city of São Paulo, SP state (R\$/liter, constant Dec-06 terms). The relative price of ethanol to gasoline and the 24-month moving correlation between ethanol and gasoline prices are also shown.

Dependent variable: Ethanol price	No. obs.	Panel units		(I)	(II)	(III)	(IV)
Intercept				N	N		
Region-specific intercepts				N	N	Y	Y
World sugar price				N	N	N	Y
Subperiod 1: Aug-94 to Nov-95	176	11	R^2 :	100%	100%	95%	97%
			Gasoline price:	0.80 *** (0.00)	0.80 *** (0.00)	0.75 *** (0.01)	0.77 *** (0.00)
			Gasoline price * 1(Ethanol supply-to-demand ratio above median):		-0.001 (0.002)		
Subperiod 2: Dec-95 to Mar-97	176	11	R^2 :	100%	100%	97%	97%
			Gasoline price:	0.85 *** (0.01)	0.86 *** (0.01)	0.95 *** (0.04)	0.94 *** (0.04)
			Gasoline price * 1(Ethanol supply-to-demand ratio above median):		-0.022 (0.024)		
Subperiod 3: Apr-97 to Aug-98	187	11	R^2 :	100%	100%	83%	86%
			Gasoline price:	0.84 *** (0.01)	0.86 *** (0.02)	0.47 *** (0.16)	0.52 *** (0.16)
			Gasoline price * 1(Ethanol supply-to-demand ratio above median):		-0.037 (0.023)		
Subperiod 4: Sep-98 to Jan-00	187	11	R^2 :	97%	97%	56%	56%
			Gasoline price:	0.65 *** (0.02)	0.68 *** (0.02)	0.15 *** (0.05)	0.15 *** (0.05)
			Gasoline price * 1(Ethanol supply-to-demand ratio above median):		-0.085 *** (0.025)		
Subperiod 5: Feb-00 to Jun-01	187	11	R^2 :	99%	100%	87%	87%
			Gasoline price:	0.69 *** (0.01)	0.72 *** (0.01)	0.80 *** (0.04)	0.84 *** (0.06)
			Gasoline price * 1(Ethanol supply-to-demand ratio above median):		-0.062 *** (0.022)		
Subperiod 6: Jul-01 to Nov-02	459	27	R^2 :	99%	99%	80%	80%
			Gasoline price:	0.65 *** (0.01)	0.68 *** (0.01)	0.30 *** (0.02)	0.27 *** (0.02)
			Gasoline price * 1(Ethanol supply-to-demand ratio above median):		-0.062 *** (0.016)		
Subperiod 7: Dec-02 to Apr-04	459	27	R^2 :	98%	99%	83%	84%
			Gasoline price:	0.71 *** (0.01)	0.74 *** (0.02)	1.08 *** (0.08)	1.49 *** (0.10)
			Gasoline price * 1(Ethanol supply-to-demand ratio above median):		-0.074 *** (0.024)		
Subperiod 8: May-04 to Sep-05	459	27	R^2 :	99%	99%	87%	87%
			Gasoline price:	0.69 *** (0.01)	0.72 *** (0.02)	1.12 *** (0.06)	1.00 *** (0.07)
			Gasoline price * 1(Ethanol supply-to-demand ratio above median):		-0.068 *** (0.025)		
Subperiod 9: Oct-05 – Feb-07	459	27	R^2 :	99%	99%	70%	75%
			Gasoline price:	0.72 *** (0.01)	0.75 *** (0.01)	1.22 *** (0.17)	1.00 *** (0.14)
			Gasoline price * 1(Ethanol supply-to-demand ratio above median):		-0.067 *** (0.020)		

Note: Standard errors, clustered by region (state or city), in parentheses.

(Two-tailed tests) *** Significant (ly different from zero) at the 1% level; ** Significant at the 5% level; * Significant at the 10% level

Table 1: Statistical relationship between fuel retail prices in each of 9 subperiods. 1(.) denotes the indicator function.

Dependent variable: Relative price volatility, ethanol relative to gasoline		
	(I)	(II)
No. obs.	54	54
Panel units	27	27
R ²	32%	37%
1(Observation corresponds to "later" subperiod)	-0.0127 *** (0.0019)	-0.0127 *** (0.0019)
Ethanol supply-to-demand ratio	0.0003 (0.0007)	
1(Ethanol supply-to-demand ratio above median)		0.0045 (0.0033)
Share of flex in fleet	-0.1936 ** (0.0949)	
1(Share of flex in fleet above median)		-0.0067 ** (0.0032)
Constant	0.0605 *** (0.0052)	0.0521 *** (0.0020)

Note: Standard errors, clustered by region (state), in parentheses.

(Two-tailed tests) *** Significant (ly different from zero) at the 1% level; ** Significant at the 5% level; * Significant at the 10% level

Table 2: Variation in the relative price volatility—ethanol to gasoline—over two subperiods, controlling for state characteristics. 1(.) denotes the indicator function.

State	ADF test of unit root ^{1,2}		Conclusion: The		Cointegration test ³		Estimation of VAR or VEC ¹ : Reject no causality of form:		
	Reject unit root?		two series display:		Order of Integration		Instantaneous		
	Ethanol	Gasoline	Ethanol	Gasoline	Ethanol, Gasoline	Reject no cointegration?	causality	Gasoline->Ethanol	Ethanol->Gasoline
AP	Yes (1%)	Yes (10%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (1%)	Yes (10%)
BA	Yes (10%)	Yes (1%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (1%)	No
CE	Yes (5%)	Yes (1%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (1%)	No
DF	Yes (5%)	Yes (1%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (10%)	No
MS	Yes (10%)	Yes (5%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (5%)	No
PA	Yes (1%)	Yes (10%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (5%)	No
PI	Yes (1%)	Yes (10%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (10%)	No
RN	Yes (5%)	Yes (1%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (5%)	No
RO	Yes (1%)	Yes (5%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (1%)	No
SC	Yes (5%)	Yes (5%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (5%)	No
SE	Yes (10%)	Yes (10%)	Stationarity (both)	Stationarity (both)			Yes (1%)	Yes (1%)	No
GO	Yes (5%)	Yes (1%)	Stationarity (both)	Stationarity (both)			Yes (1%)	No	No
MG	Yes (1%)	Yes (10%)	Stationarity (both)	Stationarity (both)			Yes (1%)	No	No
PR	Yes (5%)	Yes (5%)	Stationarity (both)	Stationarity (both)			Yes (1%)	No	No
RJ	Yes (5%)	Yes (5%)	Stationarity (both)	Stationarity (both)			Yes (1%)	No	No
SP	Yes (5%)	Yes (5%)	Stationarity (both)	Stationarity (both)			Yes (1%)	No	No
TO	Yes (10%)	Yes (5%)	Stationarity (both)	Stationarity (both)			Yes (1%)	No	No
AL	No	No	Unit roots	Unit roots	I(1), I(1)	Yes	Yes (1%)	No	No
PE	No	No	Unit roots	Unit roots	I(1), I(1)	No			
RR	No	No	Unit roots	Unit roots	I(1), I(1)	No			
AC	Yes (5%)	No	Different order of Int.	Different order of Int.					
AM	No	Yes (1%)	Different order of Int.	Different order of Int.					
ES	Yes (5%)	No	Different order of Int.	Different order of Int.					
MA	No	Yes (10%)	Different order of Int.	Different order of Int.					
MT	No	Yes (5%)	Different order of Int.	Different order of Int.					
PB	Yes (5%)	No	Different order of Int.	Different order of Int.					
RS	Yes (10%)	No	Different order of Int.	Different order of Int.					

Note: Number of observations in each of the two state-specific price series is 68 (i.e. monthly retail fuel prices from Jul-01 to Feb-07)

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 (e.g. AL). ADF 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.

Table 3: Testing for causality between the retail prices of ethanol and gasoline in each of the 27 states, over the period Jul-01 to Feb-07.