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Ethanol and Energy Security

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ABSTRACT

I propose a framework to evaluate the impact of ethanol on energy security from an economic perspective. In this model, economic energy efficiency maximizes a social or governmental objective function with respect to energy price levels and shocks. This tradeoff can entail raising expected energy prices while lowering price volatility. I develop a theoretical model showing ethanol's potential to lower overall fuel price volatility and estimate this relationship with both structural and reduced form approaches. I show that ethanol does not substantially lower U.S. gasoline price volatility or insulate gasoline prices from oil shocks in the absence of a binding quantity mandate. Ethanol can lower gasoline price volatility under a binding mandate, but this comes at substantial expected cost. In sum, ethanol is not an effective way to mitigate world oil price shocks and does not substantially enhance US energy security.

Section I: Introduction and overview

On May 3 2012, Secretary of Agriculture Tom Vilsack visited the Biofuels Center of North Carolina where he said “the Obama Administration has an 'all-of-the-above' [approach] to promoting domestic energy security, and increasing the percentage of ethanol to be blended with gasoline will help boost economic growth while lessening the nation's dependence on foreign oil” (USDA 2012). Vilsack’s statement was typical, with several distinct elements:

1) A high-level U.S. official stressed the importance of energy security,
2) He framed energy security was framed as an economic issue,
3) He emphasized that ethanol can promote economic energy security.

Proponents of ethanol use such as Vilsack suggest that it can increase domestic production of fuels: by refining domestically grown corn into ethanol and using that for transportation fuel, Americans will face lower energy prices, be insulated from shocks to world oil markets and lessen the financial transfers to foreign nations. While the military security literature has addressed physical supply continuity considerations (DoD 2011), the simulation literature has largely addressed ethanol’s potential equilibrium impact on energy prices and terms of trade (Meyers et al. 2010), and a huge macroeconomic literature has explored the impact of oil shocks on the macroeconomy (Kilian 2008, Bernanke, Gertler and Watson 1997, Hamilton 1983, Sexton, Wu and Zilberman 2011), our understanding of ethanol’s ability to mitigate oil shocks and thus potentially contribute to economic energy security is limited.[1]

This paper makes several contributions to the literature. First, I introduce a new framework for modeling energy security in economic terms. While this is certainly not a complete framework for analysis of energy security issues, I believe it is a key element underlying US policy debates. Second, I demonstrate the theoretical possibility that an ethanol

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[1] Hamilton (1983) noted that “[all] but one of the U.S. recessions since World War II have been preceded … by a dramatic increase in the price of crude petroleum”. For example, in the 1956 Suez Canal crisis, total world oil production fell by 10.1%. This shortfall lasted for approximately 4 months, but lead to an 18% decrease in US exports and subsequent recession. A variety of causal pathways have been proposed. Energy is an input into production, so an increase in its price would be associated with a decrease in production. On the demand side, consumers’ short-run demand elasticity for energy is low. Energy use is largely associated with long-term decisions such as housing and vehicle choice. If consumers continue purchasing energy at higher prices, purchases of other goods much fall. A third suggested pathway that an increase in energy prices can drive up official inflation statistics, which leads to contractionary monetary policy (Bernanke et al 1997). More recently, Sexton et al (2011) suggest that oil shocks can lower housing values in outlying areas by driving up commuting costs, which can destabilize financial institutions that are highly dependent on housing prices.

mandate, or a mandate for the construction of ethanol refining capacity, could lower the gasoline price volatility that US consumers face and insulate consumers from oil price shocks. Finally, I show that ethanol does not effectively lower gasoline price volatility or insulate against oil shocks in the current U.S. economic environment.

In this paper I first discuss previous literature and the context. Section II develops a theoretical model of how the ethanol mandate and blend wall can affect the price and quantity of ethanol on the blending market and how this affects retail gasoline prices. Section III adapts the theoretical model for estimation and places the model in the context of recent years, showing that neither the mandate nor the blend wall have been binding for short-term production decisions. Section IV discusses both structural (panel) and reduced form (GARCH-X) estimation and estimation results. A series of policy analyses such as the tradeoff between cost and volatility and a calculation of the expected benefits of containing shocks follow in section V, while section VI offers policy conclusions and directions for future research.

Literature review

A long series of papers pioneered by James Hamilton make the case that oil price shocks can cause recessions (Hamilton 1983, Hamilton 2003, Mork 1989, Bernanke et al. 1997, Kilian and Murphy 2010, Gronwald 2008, Nordhaus 2007). This has spawned a huge literature examining whether this is still the case, channels of causation, and the magnitude of the effect. One robust conclusion seems to be that both price levels and shocks to prices impact the macroeconomy. Hamilton (2003) offers an overview of the literature, in particular noting that oil shocks can shift or defer consumer purchasing decisions for durable goods such as housing. Bernanke, Watson, and Gertner (1997) instead attribute much of the macroeconomic effects of oil shocks to central bank policy. Kilian and Murphy (2010) distinguish between supply shocks, demand shocks, and speculative behavior, and suggest that repeated unforeseen demand shocks drove the mid-2000's increase in oil prices.

The macroeconomic literature on the importance of energy prices prompts the question of how agricultural markets and policies impact energy markets. There have been several strands of literature examining the impact of ethanol policies or the interaction of ethanol and oil markets. The largest literature has consisted of large-scale simulation models of the US agricultural sector which take world energy prices as exogenous inputs (Babcock 2008). These models have played an important role in policy analysis, for example by forming the basis of the EPA's analysis of the Renewable Fuels Standard (EPA 2010). Related literature adds endogenous feedback to energy markets. This work shows that ethanol policy design does have substantial effects on the biofuels markets and agricultural land use but has limited impacts on broader energy markets (Thompson, Meyer and Westhoff 2009, Whistance, Thompson and Meyer 2010, Khanna et al. 2011).

There are also a number of analytic models of ethanol and energy markets. Harry de Gorter and David Just develop an analytical model of the interaction of a mandate and subsidy (de Gorter and Just 2009). Like de Gorter and Just, Hertel and Beckman also show that if an ethanol quantity mandate is binding, oil shocks do not propogate through to food markets (Hertel and Beckman 2011). However, ethanol prices can then become more volatile because they are no longer damped by the less-volatile fuel prices. Other research considers the market equilibrium with flex-fuel vehicles, and show that increasing the amount of ethanol used in the primary gasoline market can drive up prices for E85 (transportation fuel comprised of 85% ethanol and 15% petroleum blendstock), reducing demand for flex fuel vehicles and increasing overall oil use (Qiu et al. 2011). However, these papers are typically based on plausible parametrizations instead of estimated values.

Structural econometric work largely focuses on long-term equilibrium relationships and expected price levels. This literature has had mixed results, with some papers finding that ethanol lowers retail gasoline prices by as much as $0.89 per gallon, while other work finds no statistically robust effects (Du and Hayes 2009, Knittel and Smith 2012). Researchers have examined the relationships between volatility in ethanol and oil prices with financial time-series techniques, finding that price levels and volatility do propogate between energy and agricultural markets because ethanol links them (Serra, Zilberman and Gil 2011, Zhang et al. 2009). This method is excellent for estimating volatility in existing markets. However, it cannot answer questions about future ethanol markets under a strong mandate, which require a structural approach.

A broader literature tries to develop the idea of energy security. One strain work comes from policy and political science communities in addition to economics. Michael Levi offers an excellent overview of energy security from a political science perspective, discussing the impacts of energy security concerns on international relations (Levi 2010). Economists typically focus more directly on direct costs or other economic implications (Brown and Huntington 2010). Some authors have tried to calculate the direct military expenditures related to maintaining international oil shipments (Leiby 2008). Others have described an “oil premium” , using the framework of an externality (Parry and Darmstadter 2003).

From the literature, we know that fuel prices and shocks matter for energy security, that ethanol can impact expected energy prices, and that the market and regulatory structure around ethanol industry impacts how oil prices propogate through related markets. We do not yet know how oil price shocks impact ethanol markets, how ethanol markets impact oil price shocks, or how these impacts vary with policy decisions.

Background on Ethanol Markets and Regulation

U.S. ethanol is produced from corn and other feedstocks, primarily from corn and in the Midwest. High shipping costs of inputs require refineries to locate near the corn fields. Ethanol is then shipped across the country by train and tanker truck. It is not shipped via pipeline because ethanol, unlike oil, will corrode pipelines if the pipeline has previously been used for oil. At rail terminals it is shipped via truck to blending terminals near the point of final sale where it is combined with oil derived blendstock, typically called RBOB, and distributed to retail gasoline stations in the form of finished gasoline.

Ethanol is blended into gasoline for two purposes: as an oxygenate to enhance octane and reduce carbon monoxide formation, and as an energy source. Increased blending of ethanol as an oxygenate came with the phaseout of MTBE during 2000-2006. Oxygenates such as MTBE and ethanol make gasoline burn more completely, increase fuel octane, lower emissions, and prevent engine knocking. MTBE was preferred due to its lower cost. However, the discoveries that MTBE has broadly contaminated drinking water supplies and is carcinogenic lead to MTBE bans in a number of states and a switch to using ethanol as an oxygenate.

Since 2005, the minimum blending amount has been set by a national quantity mandate. This mandate was set by the Energy Policy Act of 2005 and raised by the Energy Independence and Security Act of 2007. These laws required that US gasoline include 4 billion gallons of ethanol in 2006, increasing to 12.6 billion gallons of ethanol in 2011. The standard also includes mandates for other advanced biofuels such as cellulosic ethanol and requires a total of 36 billion gallons of biofuels in 2022, comprised of a mixture of traditional corn-based ethanol and other fuels. The actual compliance instrument is known as a Renewable Identification Number, or RIN. A RIN is a unique identifier for each gallon of ethanol produced. Compliance is achieved by requiring gasoline refiners and importers to hold a certain number of RINS for each gallon of gasoline blendstock they produce or import.[2] If a party is required to blend ten gallons of ethanol in a given year, operationally they have to acquire ten RINS for that year. If more ethanol is produced in a given year than is required, RINs can be banked for compliance the next year.[3] This means that the actual biofuel production in any given year may be higher or lower than the statutory mandate.

Blenders also face a 10% limit on the amount of ethanol that can be in any gallon of finished gasoline. This is known as the "blend wall". There are two major reasons for the blend wall. First, vehicle manufacturers have expressed concern about damage to engines from ethanol blends above 10%. Second, finished gasoline with medium blends of ethanol (between approximately 20% and 80%) evaporates more volatile organic chemicals than low or high blends. Volatile organic chemicals can have both short- and long-run human health effects in the local area. Thus ethanol use has been capped at 10%.[4]

Blenders have discretion on how much ethanol to add as long as they are at or above the mandate and below the blend wall. Ethanol has energy that can be used to power vehicles, so within this range ethanol and petroleum-based blendstock are substitutes.

Source of Volatility

There are three primary channels for ethanol to lower finished gasoline price volatility. First, adding ethanol capacity in essence flattens the total supply curve for finished gasoline. An increase in demand can be met by both increased oil-based fuel or ethanol-based fuel. Alternatively, a shock to the supply of oil-based fuel from one source could be met with

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[2] Ethanol imports are also eligible to produce RINS, while ethanol exporters must surrender them. This ensures that RINS reflect actual ethanol blended into gasoline in the U.S. – ethanol produced domestically and exported does not count towards the mandate.

[3] A maximum of 20% of the mandate can be met with banked RINS. This suggests the convergence of RIN prices across different RIN vintages may be limited if the total surplus of RINS in a year is more than 20% of the next year's mandate.

[4] The EPA has recently increased the limit to 15%, but blends between 10 and 15% are not yet in broad use. The limit was 10% during my period of study.

increased supply from both other oil sources or ethanol. This channel depends on the slope of the ethanol supply curve and on ethanol producers being legally able to increase production – on there not being a binding ethanol quantity cap.

Ethanol could also lower fuel price volatility by portfolio diversification. Supply-side variation in oil blendstock prices is dominantly driven by variation in international crude oil markets. Changes in world crude prices arise from demand changes, from geopolitical events, and from industry characteristics. Oil industry supply infrastructure (such as refineries and wells) is characterized by high fixed costs, long lead times, and low variable costs. This means that periods of high prices can lead to overinvestment in supply, causing a crash in prices. Ethanol supply volatility is instead primarily driven by its input corn prices. Corn is traded on world grain markets but primarily grown in the Midwestern United States and thus highly exposed to American weather patterns. If ethanol has less supply-side volatility than oil blendstock, then increasing ethanol use and decreasing oil blendstock use would lower aggregate supply side volatility. Ethanol can lower volatility even if it is more volatile as long as the supply side shocks are sufficiently uncorrelated. Table 1 shows the correlations between the basic fuel input goods. While it first seems that corn and oil prices are strongly correlated, this is largely due to demand side effects. When corn is instrumented with weather to focus on the relationship between exogenous inputs, we see that the correlation between corn and crude prices is less than 0.3, and between other input goods is lower.

The third way ethanol could potentially lower finished gasoline price volatility is volumetrically. If the ethanol blend rate is fixed, then a change in oil prices will not result in a change in ethanol prices because the ethanol price. An ethanol quantity constraint decouples the ethanol and oil blendstock prices. This means that an increase in crude oil prices only increases a portion of the finished gasoline. The larger the fixed ethanol blend rate, the larger the impact of this volumetric factor if there is a binding quantity cap.

Section II: Theoretical Model

Economic Energy Security

Energy security is represented as a mean-variance value function taking into account the economy's exposure to energy prices and energy shocks. This could be a risk-averse function of GDP or a regret-minimizing function of a decision-maker's political goals, or a combination of both. Both energy price shocks and energy price levels can have negative macroeconomic consequences, so an optimal energy policy should take into account both of these factors.

Consider a policymaker faced with choosing a parameter ψ which represents the aggregate national ethanol capacity and implications for both the expected price and volatility of fuels. The policymaker is maximizing a value function V, which may include income, risk aversion, environmental and distributional concerns. Exposure to shocks is measured as volatility, later measured as variance.

$$\begin{aligned}&\max_{\psi} V(P_{Energy}, Vol(P_{Energy}))\\ &s.t.\\ &P_{Energy} = p(\psi)\\ &Vol(P_{Energy}) = v(\psi)\end{aligned} \tag{1.1}$$

Taking our first order condition, we see that

$$\frac{dE[V(P_{Energy}, Vol(P_{Energy}))]}{d\psi} = \frac{dV}{dP_{Energy}}\frac{dP_{Energy}}{d\psi} + \frac{dV}{dVol(P_{Energy})}\frac{dVol(P_{Energy})}{d\psi} \tag{1.2}$$

Setting the first order condition equal to zero suggests an optimality condition for the policymaker's choice of ψ

$$\frac{dE[V]}{dP_{Energy}}\frac{dP_{Energy}}{d\psi} = -\frac{dE[V]}{dVol(P_{Energy})}\frac{dVol(P_{Energy})}{d\psi} \tag{1.3}$$

Equation (1.3) shows that the policymaker faces a tradeoff between prices and volatility in choosing ψ, and that the optimal choice depends on the relative impacts of prices and volatility on the macroeconomy. Referring back to our literature review, the macroeconomic literature has focused on the direct impacts of energy prices and volatility (our $\frac{dE[V]}{dP_{Energy}}$ and $\frac{dE[V]}{dVol(P_{Energy})}$ terms). The simulation literature has told us a lot about the impact of ethanol on expected energy prices (our $\frac{dP_{Energy}}{d\psi}$ term). However, few have empirically studied the impact of ethanol on energy price volatility (our $\frac{dVol(P_{Energy})}{d\psi}$ term). I characterize this term for consumer finished gasoline prices.

Theoretical Model

Finished gasoline sold at the retail pump is a combination of ethanol and petroleum blendstock. If I assume that retail sales are competitive and costless, the price of gasoline P^G is a linear combination of the ethanol price P^E and petroleum blendstock price P^B.[5] This is described in equation (1.4)

$$P^G = \alpha P^E + (1-\alpha)P^B \tag{1.4}$$

where α is the blend ratio $\frac{E}{G}$ and G is the total quantity of finished gasoline.

Ethanol producers supply a quantity of ethanol E as a function of the ethanol price P^E, available ethanol capacity K, and exogenous supply shifters X. These supply shifters include input prices and available capital. The quantity of ethanol supplied is constrained to be within the statutory range $\left[\underline{E}, \overline{E}\right]$.

$$\begin{aligned} &E = f(P^E, K, X) \\ &s.t. \\ &\underline{E} \le E \le \overline{E} \end{aligned} \tag{1.5}$$

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[5] I show that costly retail does not affect my volatility calculations in Appendix 1.

Ethanol substitutes for petroleum blendstocks, so the ethanol price is set in equilibrium with the price of the petroleum blendstock P^B unless the mandate or blend wall bind:

$$P^E = \begin{Bmatrix} f^{-1}(\underline{E}) & if & E = \underline{E} \\ P^B & if & \underline{E} < E < \overline{E} \\ f^{-1}(\overline{E}) & if & E = \overline{E} \end{Bmatrix} \tag{1.6}$$

From equation (1.6), we see that an oil price spike will only increase ethanol prices, and thus send a signal to increase ethanol production, potentially mitigating the price spike, if neither the mandate nor the blend wall are binding. If the mandate is binding, ethanol production is independent of RBOB prices.

However, if the blend wall is binding and oil prices increase (decrease), the finished gasoline quantity will decrease (increase). This will lower (raise) the blend wall because it is defined as a percentage of the quantity of finished gasoline. This will lower (raise) the ethanol price, partially mitigating the shock to oil prices.

Renewable Identification Numbers, or RINs, are the basic compliance unit for the ethanol mandate. A blender can comply by either blending a gallon of ethanol or by purchasing excess RINS from another blender who over-complied. A blender purchasing ethanol is actually purchasing both a unit of physical ethanol for blending and resale, and a unit of compliance with the mandate. Thus if the mandate is binding, RINs will trade at the difference between ethanol and RBOB prices. If the mandate is not binding, there will be more RINs available than gasoline blenders demand and the price will fall to zero (net of transactions costs). Alternatively if the ethanol blending cap, or blend wall, is binding, the price of ethanol will be the price necessary to induce that maximum level of production. The RIN price reflects the tightness of the mandate (de Gorter and Just 2009).

I show this graphically in Figure 3 and Figure 4. In Figure 3, I show the impact of an ethanol mandate on the blending market. The length of the x-axis is the total amount of gasoline demanded. While I diagram this as a fixed quantity, that is only for visual simplicity. I will allow the quantity of gasoline demanded to be determined endogenously. The ethanol supply curve is E. The petroleum blendstock supply curve B originates from the bottom-right corner. They intersect at (P*, Q*) which is the efficient market equilibrium. The price will be P*, the ethanol quantity will be Q*, and petroleum blendstock will supply the remainder. If a low ethanol mandate $\underline{E}^1$ is imposed, it will not be binding and will not affect prices or quantities. However, if the mandate is raised to $\underline{E}^2$, meeting the mandate will require increasing production above the efficient level Q*. This will drive ethanol prices up to P_2^E and blendstock prices down to P_2^B. The difference between them will be reflected in RIN prices.

Figure 4 shows the impact of an ethanol cap on the blending market. The supply curves and unconstrained market equilibrium are the same as in Figure 3. If regulators impose a cap $\overline{E}^1$ that is higher than Q*, blenders continue to use Q* gallons of ethanol, the cap will not bind, and prices will not change. However, if the cap is lowered to $\overline{E}^2$, the quantity of ethanol will fall to $\overline{E}^2$ and its price will fall to P_2^E. Petroleum blendstock supply will increase and its price will rise to P_2^B. Blenders would like to use more ethanol because it is cheaper, but cannot because it is not allowed.

Oil blendstock B is produced based on the price of blendstock P^B and the price of crude oil P^O while consumers demand gasoline quantity G, which is a function of the price of gasoline P^G and demand shifters Z.

$$B = g(P^B, P^O, Y) \tag{1.7}$$

$$G = h(P^G, Z) \tag{1.8}$$

I close the model by assuming that markets clear and noting that gasoline, ethanol, and blendstock prices are equivalent if neither the mandate nor the blend wall bind.

$$G = B + E \tag{1.9}$$

$$P^G = P^B = P^E \tag{1.10}$$

I can now solve for the equilibrium gasoline price as a function of the fundamentals that determine the supply and demand curves and solve for the volatility (or variance) of this price. By inverting equation (1.7), I see that

$$P^B = g^{-1}(B, P^O)$$

From equation (1.9) we know that B = G – E, G is a function of demand. Thus

$$P^B = g^{-1}(G - E, P^O) \tag{1.11}$$

The only endogenous variable in equation (1.11) is the price of oil blendstock P^B, which is equal to the price of finished gasoline P^G. The price of gasoline and its variance can thus be expressed in terms of exogenous supply and demand parameters and covariates.

$$P^G = p(K, P^O, X, Y, Z) \tag{1.12}$$

$$Var(P^G) = Var(p(K, P^O, X, Y, Z))$$

Section III: Econometric Model

I now adapt my theoretical model for estimation. The amount of ethanol available for blending scales with the available production capacity. The amount of ethanol available in each location i is assumed to be a fixed share of capacity denoted as ν_{4i}. The total ethanol capacity utilization rate is then $\sum_i \nu_{4i}$. The capacity utilization rate is shifted up and down by corn prices P^C, natural gas prices P^N, and ethanol prices which are equal to gasoline prices P^G. Time is denoted with t and ε describes iid unobservable errors.

The quantity of petroleum blendstock supplied is assumed to move with the price of crude oil P^O, the price of gasoline P^G, and a vector of supply shifters Y and an iid unobservable δ. Gasoline demand G is a function of a vector of demand shifters Z, the price of gasoline, and coefficient vectors η and λ. Population and income will serve as demand shifters.

Ethanol supply: $$E_{it} = \nu_0 + K_t * (\nu_1 P^G_{it} + \nu_2 P^N_{it} + \nu_3 P^C_t + \nu_{4i}) + \varepsilon_{it} \tag{1.13}$$

Blendstock supply: $$B = \phi_0 + \phi_1 P^O_{it} + \phi_2 P^G_{it} + Y_{it}\varphi + \delta_{it} \tag{1.14}$$

Demand: $$G_{it} = \eta Z_{it} + \lambda Z_{it} P^G_{it} \tag{1.15}$$

Price equilibrium: $P_{it}^{E} = P_{it}^{R} = P_{it}^{G}$

Note that I omit the ethanol blending credit from equation (1.13). Others have ably studied the impact of the tax credit and shown that it increases production at substantial net cost to the taxpayer (de Gorter and Just 2009). However, it has little variation over my period of study. Appendix 2 shows that including it does not substantially change my results. Appendix 3 shows that the price equilibrium holds.

I can then solve this system for P^{G} in terms of coefficients and observables.

$$P_{it}^{G} = D*(\nu_0 + K_t*(\nu_2 P_{it}^{N} + \nu_3 P_t^{C} + \nu_{4i}) + \varepsilon_{it} + \phi_0 + \phi_1 P_{it}^{O} + Y_{it}\varphi + \delta_{it} - \eta Z_{it}) \tag{1.16}$$

Where $D \equiv \dfrac{1}{(\lambda Z_{it} - K_t \nu_1 - \phi_2)}$.

The variance of P^{G} then measures the volatility. It has three major terms that represent the impact of volatility from ethanol supply volatility, blendstock supply volatility, and diversification between ethanol and oil-based blendstocks respectively.

$$Var(P^{G}) = D^2*(eth + blend + div) \tag{1.17}$$

Where

$$\begin{aligned}
eth &\equiv K^2\nu_2^2 Var(P^{N}) + K^2\nu_3^2 Var(P^{C}) + Var(\varepsilon)\\
blend &\equiv \phi_1^2 Var(P^{O}) + \varphi^2 Var(Y) + Var(\delta)\\
div &\equiv 2K^2\nu_2\nu_3 Cov(P^{N}, P^{C}) + 2K\nu_2\phi_1 Cov(P^{N}, P^{O}) + 2K\nu_3\phi_1 Cov(P^{C}, P^{O})
\end{aligned}$$

I can take the derivative of variance with respect to ethanol production capacity to find out when increasing ethanol production capacity lowers price volatility. We know that the optimal ethanol capacity choice will be when this derivative is negative or zero.[6]

$$\frac{dVar(P^{G})}{dK} = D^2\left(\frac{deth}{dK} + \frac{dblend}{dK} + \frac{div}{dK}\right) - 2Var(P^{G}) \tag{1.18}$$

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[6] If the derivative is positive, that means that increasing capacity increases volatility. Alternatively, lowering capacity would lower volatility. This would also lower costs and would be preferred. Thus a positive derivative indicates a non-optimal capacity level.

Intuitively, increasing ethanol production capacity lowers variance as long as the portfolio diversification effect (the extent to which oil shocks are uncorrelated with corn and natural gas shocks) outweighs the increased exposure to corn and natural gas shocks. Note that if there were no ethanol, the variance would reduce to the variance from blendstock supply factors: of world oil prices P^G, blendstock shifters Y, and unobserved shocks.

Estimation

I estimate the model in levels and first differences with a standard panel instrumental variable approach and with a system GMM approach. While both are consistent, system GMM can improve estimation efficiency and allows the use of predetermined (as opposed to strictly exogenous) instruments. The distinction is that a shock in period t can affect the value of a predetermined variable in later periods, but cannot affect strictly exogenous variables in any period. Gasoline and corn price instruments are discussed below. The system GMM also estimates both the panel and first differences equations simultaneously and uses lagged values as instruments.

Gasoline Price Endogeneity

A key prediction of the model is that the price of gasoline P^G, which appears in both the ethanol and blendstock supply equations, is endogenous. I thus instrument for it in both. In the ethanol supply equation, I instrument for the price of gasoline with the price of crude oil. In the blendstock supply equation, I use the crude price, crude stocks, ethanol production capacity, and ethanol production capacity interacted with corn and natural gas prices.

Corn Price Endogeneity

High levels of ethanol use may drive up corn prices. This phenomenon is known as the “food versus fuel” debate and entails real resource, efficiency, and distributional costs. It also presents an endogeneity problem for estimating my ethanol supply curve (equation). I thus follow the work of Roberts and Schlenker by using weather measures to instrument for corn prices (Roberts and Schlenker 2009). They follow a substantial literature in using current season weather as a supply shifter. They also show that past seasons’ weather can be used as a demand shifter because a low (high) past harvest would lead to lower (higher) grain stocks, thus increasing (decreasing) current demand to replenish stocks.

The Roberts and Schlenker approach relied on annual weather measures to instrument annual average prices. To extend this to monthly data, we first weight state-level monthly heating and cooling degree days with 2003 state-level corn production to generate national monthly heating and cooling degree days as they impact corn producing regions. We then construct each month's average number of total heating and cooling degree days since the start of the growing season for that month of the year, deviation from average for the specific month, and deviation as a percent of the average and instrument for corn prices with both the same and next-month heating and cooling degree percent deviations. Inclusion of next-month weather allows for forward-looking agents. Because many of the same areas are used to grow winter wheat in the winter, this approach effectively instruments grain prices year-round. Figure 8 shows the actual and predicted corn prices.

The ethanol mandate and blend wall

This section shows that the ethanol mandate has not been binding on short-term production decisions (as opposed to long-term infrastructure capacity investment decisions) and that the blend wall was not binding during the period of analysis. This means that the supply curves of equations (1.13) and (1.14) hold.

First consider the ethanol mandate. I start by directly comparing the quantity of ethanol to the mandate. Figure 5 shows US ethanol consumption (blue solid line), the statutory mandate (green dashed line), and the amount of ethanol needed to meet the compliance obligation – the mandate minus banked RINs (red dotted line). I construct the actual compliance obligation by assuming that all allowances which can be banked and used later are. The compliance obligation is then the statutory mandate minus the lesser of the previous year's excess production or 20% of the cap.

In particular, the 2006 compliance obligation was the statutory mandate because it was the first year of the program and there were no banked allowances. Actual 2006 use was 4.8 billion gallons, 800 million gallons above the mandate of 4 billion. The 2007 mandate was 4.7 billion gallons, but 800 million 2006 RINS could be used in 2007, so the actual 2007 compliance obligation was 3.9 billion gallons. Production in 2007 was 6.5 billion gallons, 2.6 billion above the compliance obligation. Because the 2008 cap was 9 billion gallons and banked RINS can meet at most 20% of the cap, 1.8 billion 2007 RINS could be used in 2008 and the net compliance obligation was 7.2 billion gallons.

Ethanol use has been at least 21 percent above the level needed for compliance in every year and on average 34 percent above the compliance level. Without banking, the mandate would have been binding in 2008 and nearly so in 2009, but considering banking ethanol use has been at least 22% above the compliance level every year and has averaged 34% above this level.

Not only was the mandate not short-run binding in my sample, but the blend wall was also non-binding. Ethanol consumption does seem to have neared the blend wall in many areas in the summer of 2011, which is after my study period. This suggests that oil price increases in that period would lead to ethanol quantity decreases (as opposed to increases) because they would lead to decrease in the quantity of gasoline demanded, which would lead to a decrease in the total quantity of ethanol that could be blended. In principle this is a testable question, however using aggregated data from a single season would not be a robust test because the blend wall applies to every gallon of finished gasoline.

Data

I use monthly PADD-level data from 2004-2010.[7] Monthly wholesale gasoline prices, refiner acquisition costs for crude, and international crude benchmarks are from the Energy Information Administration (EIA) and are in dollars per gallon. Ethanol blending quantity and total gasoline quantity in thousand barrels per day are also from the EIA. Natural gas prices are from also EIA.

Due to concerns about potential endogeneity of corn and crude prices, in some specifications I instrument for each. I instrument for corn prices with weather measures. Weather data is from the National Climactic Data Center. They provide state-month level average heating and cooling degree days. The cooling degree days measure for a single site on a single date is the daily average temperature in Fahrenheit minus 65, truncated at zero. If the daily average temperature is 77, that would be 12 cooling degree days, whereas a daily average temperature of 50 would be zero cooling degree days. Heating degree days are 65 minus the

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[7] PADDs, or Petroleum Administration for Defense Districts, are a standard way of dividing the country into regions to measure transportation fuel use. The five PADDs are the East Coast, Gulf Coast, Midwest, Rocky Mountains, and West Coast. I include a map of the PADDS in Appendix 5.

daily average temperature, again truncated at zero. A daily average temperature of 50 would then be 15 heating degree days, whereas a temperature of 77 would be zero. These single site-date measurements are then spatially averaged and aggregated to monthly levels. I instrument for PADD-level crude prices with international crude benchmarks, WTI and Brent crude. Corn prices are monthly averages of the spot price from the S&P GSCI index on the Chicago Mercantile Exchange.

National ethanol production capacity data is from the Renewable Fuels Association, the professional association of ethanol producers. 90 percent of U.S. ethanol is produced in PADD 2. It is then shipped throughout the United States, largely by rail. Thus PADD-level capacity and production data would not accurately measure our market.

All prices are in 2010 dollars. Table 4 shows summary statistics for key variables. Key prices over time are shown in Figure 6 and Figure 7. The economic crash of 2008 jumps out in all prices, but there is also other variation in each. In particular, gas prices spiked in 2006 but have remained low with the onset of unconventional production. Corn prices remained in the early period, but spiked during the food crises of 2006-2007, 2008, and 2011-12 (largely beyond my study period). Figure 8 shows corn prices and predicted corn prices based on weather variables. Crude oil and finished gasoline prices also fluctuated throughout the period, largely moving together. Note that weather largely explains corn price movements in the early part of my analysis while ethanol production was low, but does not fully explain the price spike at the end of 2011 when ethanol production was high. Figure 9 shows nationwide US ethanol blending. Note the dramatic increase with RFS in 2006 and continued increase over time.

Prices for gasoline, natural gas, and corn are demeaned for the ethanol supply equation. This means that their coefficients represent the change in PADD-level utilization rate from a one dollar change in price. The change in total utilization rate is then 5 times the coefficient, because there are five PADDs.

For the reduced form time-series estimation I use national monthly data from the same sources from 1986-2010. GARCH-X models can be computationally unstable and have better convergence properties with a long time period than with a shorter panel, and the full panel is not available for this longer period.

Reduced Form Estimation

As a simple robustness check, I also estimate the impact of ethanol capacity on variance directly. I can model gasoline prices as a generalized autoregressive conditional heteroskedasticity process in which the variance of the error term also depends on observed covariates, or a GARCH-X model. This is a two-stage model. The first stage (equation (1.19)) models the price of finished consumer gasoline as a function of the price of crude oil. This is a linear model with a mean zero iid error term (equation (1.20)).

In the second stage, I model the volatility of the unobserved errors from the first stage as a function of past unobserved errors, the variance of past unobserved errors, and past observables as shown in equation (1.21). A positive α and β would indicate volatility clustering – distinct high and low volatility periods in which high volatility tends to follow high volatility, and low volatility follows low volatility. This can be thought of as a continuous version of regime shift models in which variance can be low or high depending on the (possibly endogenously determined) volatility regime. A negative and significant λ_1 would indicate that ethanol production actively reduces gasoline price volatility. I can estimate equation (1.21) by maximum likelihood.

Note that I have changed the functional form relationship between K and variance to be exponential. This is a standard functional form for GARCH-X which is needed for computational reasons (other functional forms can take on negative values) but captures the essential flavor of concavity.

$$P_t^G = \delta_0 + \delta_1 P_t^O + \delta_2 K_t + \varepsilon_t \tag{1.19}$$

$$\varepsilon_t \mid \Omega_{t-1} \sim i.i.d(0, \sigma_t^2) \tag{1.20}$$

$$\sigma_t^2 = \sum_{k=1}^{m} \alpha_k \varepsilon_{t-k}^2 + \sum_{l=1}^{n} \beta_l \sigma_{t-l}^2 + \exp(w + \lambda_1 * K_{t-1} + \lambda_2 * P_{t-1}^O) \tag{1.21}$$

Standard tests suggest a single time period for both ARCH and GARCH terms (m, n = 1).

Section IV: Results

I present results for blendstock and ethanol supply in Table 5 and Table 6, respectively. In Table 5, specifications 1 and 2 show results for a standard panel IV. Crude prices are taken as exogenous, while gasoline prices are instrumented with crude prices, ethanol production capacity, and ethanol production capacity instrumented with weather variables. Specification 3 is a dynamic panel model that uses the same instruments as well as lagged values for more efficient estimation. Specification 4 is a log-log model, so the coefficients represent elasticities.

We see that oil blendstock supply depends on input (crude) prices and output (gasoline) prices.

Table 6 shows ethanol results. Specification 1 is a standard panel IV estimator. Gasoline prices are instrumented with crude prices. Corn prices are instrumented with weather measures. Specification 2 is a dynamic panel data that again uses the same instruments and lagged values to estimate more efficiently. Specification 3 is in logs so the coefficients can be interpreted as elasticities.

To read the ethanol coefficients, first recall that these coefficients are per PADD, while the capacity measure is nationwide and that the coefficients (excluding the constant) represent capacity utilization dates. This means that a K coefficient of 0.198 indicates on average capacity utilization rate of 5*0.198 or 99%. A gasoline price coefficient of 0.143 means that a $1 increase in gasoline prices increases production by 0.0143*5 or 7.15%. This highly inelastic production response is also indicated by the elasticities. The quantity of ethanol blended is primarily driven by the available ethanol production capacity. It is also positively and significantly responsive to crude prices and negatively and significantly responsive to corn prices, although both of these effects are small in magnitude. While point estimates for natural gas price impacts are negative as expected, they are not statistically different than zero across many specifications. This is consistent with a profitable gasoline-corn spread and low other variable costs.

However, the supply response to an increase in crude prices is not large enough to substantively offset the crude price increase. A one dollar exogenous increase in crude prices increases ethanol blending in each PADD by 1.43%. This lowers retail gasoline prices by about 2 cents, for a net price increase of 98 cents.

The gasoline demand equation results (in levels) imply a demand elasticity between -0.17 and -0.20 (for the two specifications), which is generally consistent with recent literature estimates. I estimate this equation primarily to parameterize the shifters which also appear in my volatility calculations and would not suggest that this is the ideal way to estimate the gasoline elasticity.

Table 8 and Table 9 show panel instrumental variable results in first differences. While the point estimates are largely similar, they are less precise and generally not statistically different than zero. Additionally, point estimates of the impacts of ethanol on production are smaller, suggesting that ethanol production takes months to adjust to price shocks.

Reduced form results

Reduced form results are shown in Table 12. Specification 1 measures ethanol with production capacity (as it is written in (1.19)). Specification 2 replaces capacity actual ethanol production. Specification 3 uses ethanol production instrumented with capacity, crude prices, and weather instruments. In each we see that that gasoline prices largely track crude prices (the crude coefficient is not statistically different than one) and that there is volatility clustering (alpha is positive and different than zero). We also see that ethanol lowers gasoline prices and gasoline volatility.

Section V: Policy analyses

Binding mandate

If the mandate is binding, the ethanol price is set by the price necessary to induce mandated production, which is above the blendstock price. This means that even if oil prices increase, ethanol prices (and thus production) will not increase unless blendstock prices increase all the way to the ethanol price. If blendstock prices cannot spike that high, the mandate is tightly binding and the ethanol supply equation becomes

$$P^E = f^{-1}(\underline{E})$$

And the price equilibrium becomes

$$P^G = \alpha\, P^E + (1-\alpha\,)P^B$$

The variance of the price of gasoline is then

$$Var(P^G) = \alpha^2 Var(P^E) + (1-\alpha)^2 Var(P^B) + 2\alpha(1-\alpha)Cov(P^E, P^B)$$

I can solve for these terms separately.

Solving algebraically, the ethanol price is

$$P^E = \frac{\frac{\underline{E}}{K} - \frac{v_0}{K} - v_2 P^N - v_3 P^C - v_4}{v_1}$$

While the petroleum blendstock price is[8]

$$P^B = \frac{\phi_0 + \phi_1 P^O + \phi_2 \underline{E} + Y\varphi + \eta Z - \lambda Z \alpha f^{-1}(\underline{E})}{(1-\alpha)\lambda Z - \phi_2}$$

The blendstock supply and finished gasoline demand equations remain the same, however the price equilibrium becomes

$$P^G = \alpha\,\left(\frac{\frac{\underline{E}}{K} - \frac{v_0}{K} - v_2 P^N - v_3 P^C - v_4}{v_1}\right) + (1-\alpha\,)\left(\frac{\phi_0 + \phi_1 P^O \phi_2 + Y\varphi + \underline{E} - \eta Z - \lambda Z \alpha f^{-1}(\underline{E})}{(1-\alpha)\lambda Z - \phi_2}\right)$$

And thus under a tightly binding mandate, the variance of gasoline prices becomes

---

[8] Note that I assume that the elasticity of demand is small. This is well supported in the empirical literature and makes the functional forms much more tractable.

$$
\begin{aligned}
Var(P^G) = {} & (2\alpha-\alpha^2)+(\frac{\nu_2^2}{\nu_1^2}Var(P^N)+\frac{\nu_3^2}{\nu_1^2}Var(P^C)+\frac{\nu_2\nu_3}{\nu_1^2}Cov(P^N,P^C))+ \\
& \frac{(1-\alpha)^2}{((1-\alpha)\lambda Z-\phi_2)^2}(\phi_1^2 Var(P^O)+\ \varphi^2 Var(Y)-(\lambda Z)^2\alpha^2(\frac{\nu_2^2}{\nu_1^2 K}Var(P^N)+\frac{\nu_3^2}{\nu_1^2 K}Var(P^C)+ \\
& \frac{\nu_2\nu_3}{\nu_1^2 K}Cov(P^N,P^C))+2\phi_1\lambda Z\alpha\frac{\nu_2}{\nu_1}Cov(P^O,P^N)+2\phi_1\lambda Z\alpha\frac{\nu_3}{\nu_1}Cov(P^O,P^C))+ \\
& (2\alpha-\alpha^2)(\phi_1\frac{\nu_2}{\nu_1}Cov(P^O,P^N)+\phi_1\frac{\nu_3}{\nu_1}Cov(P^O,P^C))
\end{aligned}
$$

I graph the impact of increasing the ethanol blend percent (assuming production at the nameplate capacity level) for both binding (blue) and non-binding (red) mandates in Figure 10. While the benefits under a non-binding mandate are modest (less than 1% at current levels), a binding mandate can lower volatility by up to approximately 10%. However, is only because it decouples ethanol prices from crude prices. If the mandate is binding, an increase in crude oil prices does not increase the price of ethanol because the price of ethanol is (higher) price necessary to induce production at the mandated level.

Full RFS2 coverage

I also consider the price impacts if conventional ethanol were used to meet the full 36 billion mandate of the RFS2. If ethanol were used to meet the entire 36 billion gallon per year mandate, PADDs' shares remained constant, nameplate capacity were 36 billion gallons per year and the mandate was not tightly binding, ethanol would lower variance by 1.2 percent

However, a mandate at this level would likely bind production decisions in addition to infrastructure decisions. With this market structure, the variance would decrease by 14%. However, a binding mandate equivalent to current blend rates would lower volatility by an equivalent amount, and a binding mandate of 25 billion gallons would lower variance by 16%. Increasing the mandate beyond 25 billion gallons causes variance to rise because the high variance of corn prices becomes more important than the volumetric effect.

Optimal Fuel Portfolio

To this point, the model of ethanol policy has focused on the short run. In the short term, the existence of ethanol production capacity lowers consumer gasoline price levels and can lower volatility. Figure 10 shows this effect. The red dotted line shows the variance in gasoline prices per gallon for different blend rates, including those observed (below 10%) and extrapolated (above 10%). At current blend rates, ethanol lowers gasoline price volatility by approximately 0.54%.

The blue line shows the variance with a binding mandate. This can be thought as an equal cap and floor such that the exact quantity of ethanol is fixed. Note that this is a modeling simulation based on our estimated supply curve, but is not directly observed. If the mandate were binding, at current blend rates it would lower volatility by approximately 12%. This is because the volumetric effect (oil price shocks do not raise prices on ethanol) is greater than the ability of ethanol production to increase in response to shocks. At blend rates above 17%, the variance increases again as the higher variance of corn prices becomes more important than the volumetric effect. This means that the optimal blend rate is less than 17%.

However, this does not consider the costs of building the ethanol capacity. Figure 11 shows gasoline price volatility versus the cost of building out ethanol production capacity. This is one way to think about the existing ethanol mandate – a de facto mandate to build capacity.

We can invert the short-term ethanol supply function to show that the short-term marginal cost of producing E units of ethanol is $f^{-1}(E,K,X)$. If ethanol capacity can be built for a constant marginal price P^K, then the total and average costs of producing E units of ethanol are

$$TC(E,K)=\int_0^E f^{-1}(e,K,X)de+P^K*K$$

$$AC(E,K)=\frac{1}{E}\int_0^E f^{-1}(e,K,X)de+P^K*\frac{K}{E}$$

Changing ethanol capacity and production also changes blendstock production. This makes the change in total production cost relative to having no ethanol capacity equal to

$$TC(K)=P^K*K+\int_0^{E(P^G(K),K,X)} f^{-1}(e,K,X)de+\int_{B(P^G(0),P^O)}^{B(P^G(K),P^O)} g^{-1}(b,P^O)db \tag{1.22}$$

where g() is the blendstock supply curve from equation (1.14). Note that the second integral –the change in blendstock production cost - will be a negative number because ethanol production will displace blendstock production.

How much of an oil shock does ethanol prevent?

We can also ask how much of an oil shock is prevented by having an ethanol industry by calculating how much gasoline prices go up when world oil prices go up and how this depends on K. Differentiating P^G from equation (1.16) with respect to P^O, we find that

$$\frac{dP_{it}^G}{dP_{it}^O} = \frac{\phi_1}{(\lambda Z_{it} - K_t \nu_1 - \phi_2)}$$

Without ethanol, we find that a one unit in oil prices causes a 1.05 unit increase in finished gasoline prices. At current ethanol capacity, the one unit increase in oil prices causes a 1.01 unit increase in finished gasoline prices. Equivalently, the current ethanol industry mitigates 4.2% of an oil price shock. Instead of causing prices to ride by $1 in the absence of an ethanol industry, an oil price shock would now only lead to a 95.8 cent price increase. Figure 12 shows the proportion of an oil shock that ethanol prevents for a range of blend rates. At a 9% blend rate, ethanol would mitigate approximately 0.038 dollars of every dollar of oil price increase. This amount, while seemingly small, could prevent some of the macroeconomic effects of oil shocks. We can think of avoided GDP losses as benefits and calculate them in the next section.

Expected benefits

To calculate the expected benefits from avoiding GDP losses, we need to understand both the likelihood of an oil shock and the GDP impacts of oil shocks (Brown and Huntington 2010). Beccue and Huntington (2005) conducted an expect elicitation study of a range of events that could lead to oil shocks and their probabilities and magnitudes. Table 13 lists their results as annualized in Brown and Huntington (2010).

Brown and Huntington (2010) also calculate that the elasticity of world oil prices with respect to oil supply quantity interruption is approximately -0.136. Estimates of the elasticity of U.S. GDP with respect to world oil shocks vary substantially, from approximately -0.01 to -0.12 (Jones, Leiby and Paik 2004). Recent research finds somewhat lower elasticities and argue that previous papers overstated the impact of oil shocks on the economy (Blanchard and Gali 2007). Due to this strong uncertainty, we use a range of estimates.

As noted above, a number of causal pathways have been proposed to explain the impact of oil shocks on GDP. Some attributed disproportionate impact to consumer gasoline prices, either because consumers purchase fewer new automobiles when gasoline prices are high and that the decrease in automobile sales reverberates through the economy, or who attribute GDP impacts to consumer wealth effects (Hamilton 2009). Ethanol only directly mitigates shocks to gasoline, which accounts for approximately 45% of refined oil products (EIA). Indirect spillover effects into other oil product markets and their impacts are unclear, so we consider GDP impacts ranging from 45% to 100% of literature estimates.

At current levels of ethanol use, ethanol has expected benefits of 114 to 254 million dollars per year from mitigating oil shocks. Figure 13 shows the expected annual benefits for a range of blend rates for both the base nonbinding case (solid line) and a binding mandate (dashed line) assuming 100% of literature estimates.

Section VI: Conclusions

Ethanol has been suggested as a solution to a number of policy problems, including explicitly energy security and implicitly gasoline price volatility. I show that the presence of ethanol production capacity can theoretically reduce gasoline price volatility by increasing in response to oil price shocks. I then show that ethanol production does increase in response to oil price shocks and does lower the variance of gasoline prices. However, even with generous assumptions such as holding the correlation between corn and oil prices constant, ethanol's ability to dampen volatility is very small whether measured as the variance of gasoline price as a function of ethanol capacity or by ethanol production's ability to prevent oil price spikes from reaching consumers. Current ethanol policy does have an expected energy security net benefit of over a hundred million dollars annually. While a full cost-benefit analysis is beyond the scope of this study, this benefit is less than annualized capacity costs and thus does not suggest that the ethanol mandate clearly has positive net benefits.

This suggests that ethanol is unlikely to be able to substantially lower the exposure of US energy consumers to volatility in international oil markets and thus unlikely to substantially contribute to a major aspect of energy security.

Appendix 1. Costly finished gasoline retail

Let us instead model finished gasoline prices as a markup c from input prices:

$$P^G = \alpha P^E + (1-\alpha)P^B + c = P^B + c \tag{2.1}$$

Recall my blendstock supply equation:

$$B = \phi_0 + \phi_1 P_{it}^O + \phi_2 P_{it}^B + Y_{it}\varphi + \delta_{it}$$

Substituting in P^G-c for P^B, we see that

$$B = \phi_0 + \phi_1 P_{it}^O + \phi_2 (P_{it}^G - c) + Y_{it}\varphi + \delta_{it}$$

$$B = \phi_0 - \phi_2 c + \phi_1 P_{it}^O + \phi_2 P_{it}^G + Y_{it}\varphi + \delta_{it}$$

Thus if finished gasoline retail is not costless, the cost will be reflected in the constant term which does not show up in volatility calculations. An analogous calculation holds for the ethanol model

$$E = \nu_0 + \nu_1 P^N K + \nu_2 (P^G - c)K + \nu_3 P^C K_t + \nu_4 K$$

$$E = \nu_0 + \nu_1 P^N K + \nu_2 P^B K + \nu_3 P^C K_t + (\nu_4 + \nu_2 c)K$$

In this case, the finished gasoline retail cost will bias the average capacity utilization coefficient. Again, this term drops out when I take the variance. Thus assuming costless retail does not affect my volatility calculations.

Appendix 2. Ethanol tax credit

If I add a constant ethanol blending tax subsidy to my model, the price equilibrium becomes

$$P^E = P^B + \tau$$

Substituting that into the ethanol supply function and rearranging, we see that

$$E = \nu_0 + \nu_1 P^N K + \nu_2 (P^B + \tau) K + \nu_3 P^C K_t + \nu_4 K$$

If τ is constant, this becomes

$$E = \nu_0 + \nu_1 P^N K + \nu_2 P^B K + \nu_3 P^C K_t + (\nu_4 + \tau) K$$

Omitting the tax subsidy may bias the baseline utilization rate, but without variation we cannot estimate this effect. Further, because capacity is exogenous and constant at a time, this drops out from volatility calculations.

Appendix 3: Fuel price equilibrium

In this appendix I show that the price equilibrium in my theory model does seem to hold when appropriate constants and energy equivalence are considered. I show in other appendices that the model can accommodate the constant terms, and the energy equivalence is a matter of units.

I obtained daily national average ethanol wholesale prices, spot petroleum blendstock prices (NYMEX RBOB) and daily average retail gasoline price from January 1, 2007 through Dec 31 2010. These are shown in Figure 1. Visually it certainly appears that gasoline prices and RBOB prices track move together with a constant offset. While the correlation is somewhat weaker, ethanol prices also seem to track RBOB prices. Ethanol prices did depart somewhat from RBOB prices in the summer of 2010 due to an unusually and unexpectedly large U.S. corn harvest. We can also test this a bit more formally.

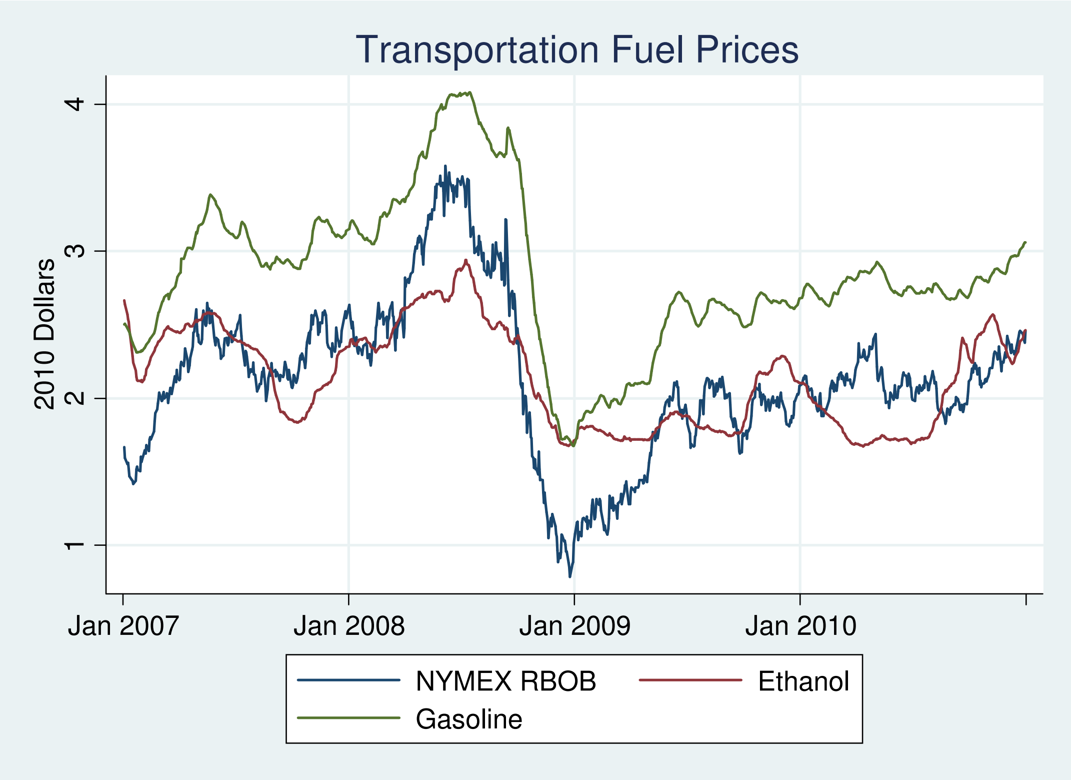


Figure 1: Transportation Fuel Prices

To test this formally, I look for a cointegrating relationship between gasoline, ethanol, and RBOB prices. Standard trace statistics suggest the presence of potentially two cointegrating relationships. I estimate them and show the results in Figure 2. All cointegrating coefficients are significant at the 1% level and are marked with "***".

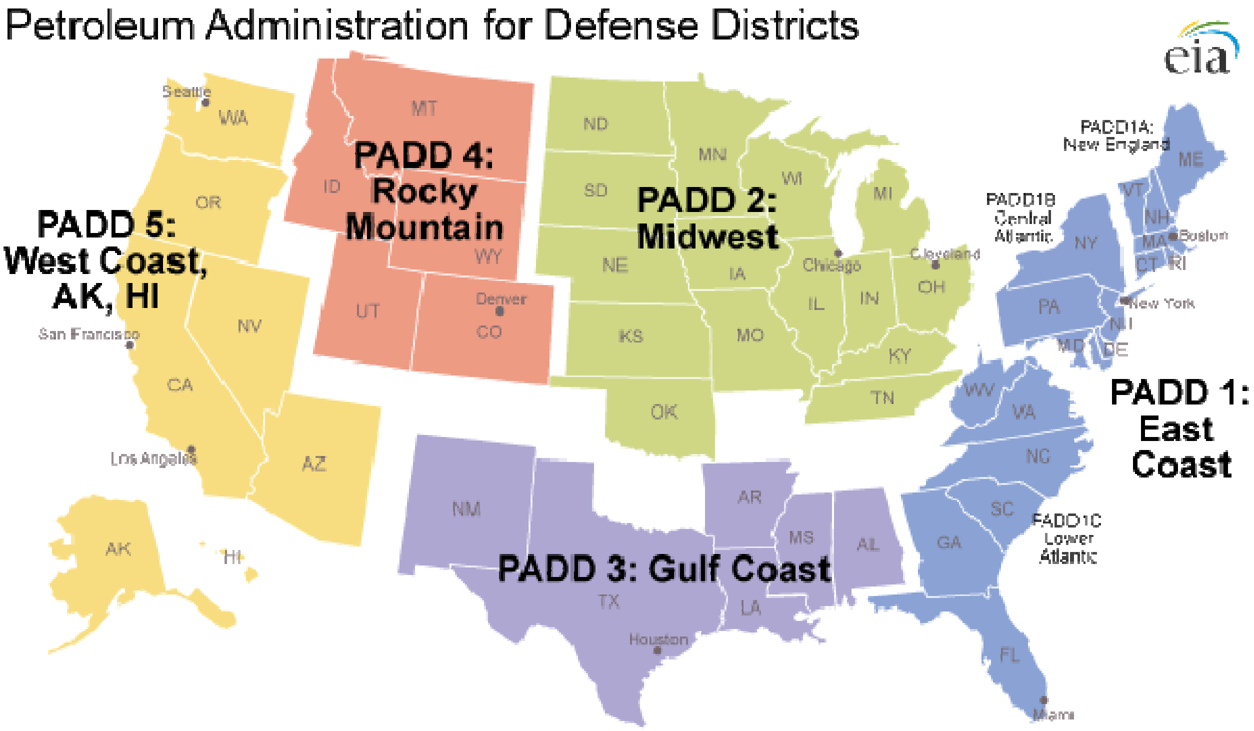
	Cointegrating equation 1	Cointegration equation 2
Gasoline	1(fixed)	
RBOB	-0.984***	-0.729***
Ethanol		1
Constant	-0.744	-0.464

Figure 2: Transportation fuel price cointegration

The first cointegration equation describes the price equilibrium between the RBOB and gasoline markets and means that an increase of $1 in the gasoline price is associated with a decrease of 0.984 dollars in the RBOB price. This estimate is not significantly different than exactly 1. The second cointegrating equation describes the RBOB and ethanol substitution markets. It means that an increase of $1 in the RBOB price is associated with a decrease of 0.729 dollars in the ethanol price. This is not significantly different than the ratio of the energy in a gallon of ethanol to the energy in a gallon of petroleum-based fuel and suggests that substitution is on an energy-equivalent basis.

Note that there is a constant offset of approximately 74 cents per gallon of gasoline between the gasoline and RBOB prices. As shown in Appendix 1, this may bias coefficient estimates but will not affect my volatility calculations. Similarly, the ethanol blending tax credit is reflected in constant of $0.464. As shown in Appendix 2, this may also bias a coefficient estimate but will not affect my volatility calculations.

Appendix 5: Map of PADDS



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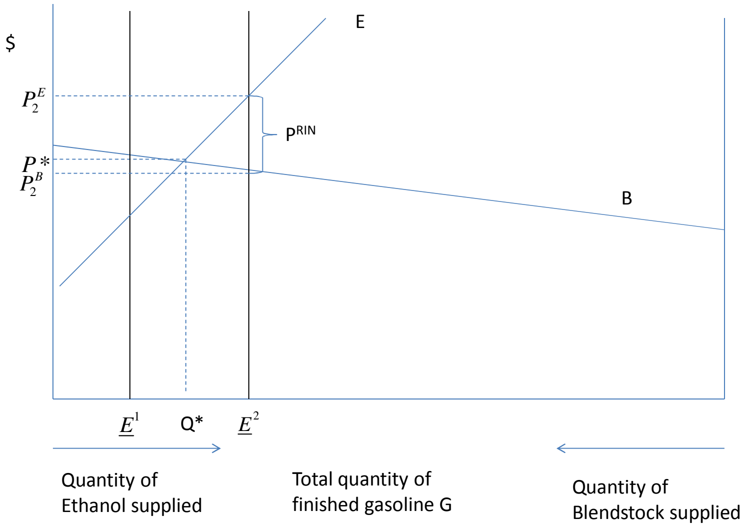

Figure 3: Ethanol supply with a mandate

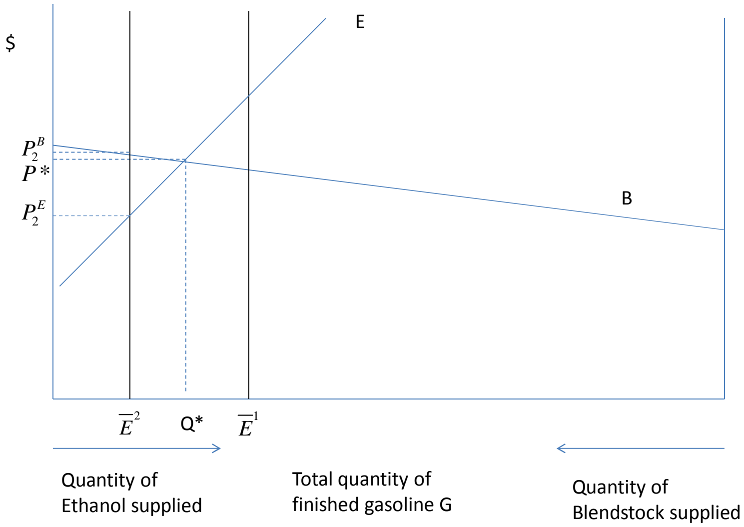

Figure 4: Ethanol supply with a blend wall

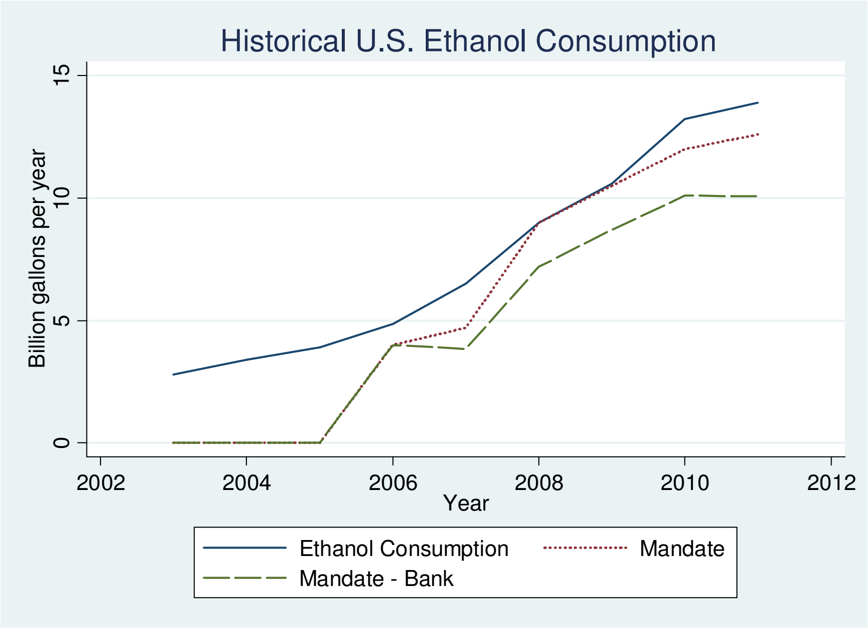

Figure 5: Mandated and actual ethanol consumption. Data from the Renewable Fuels Association.

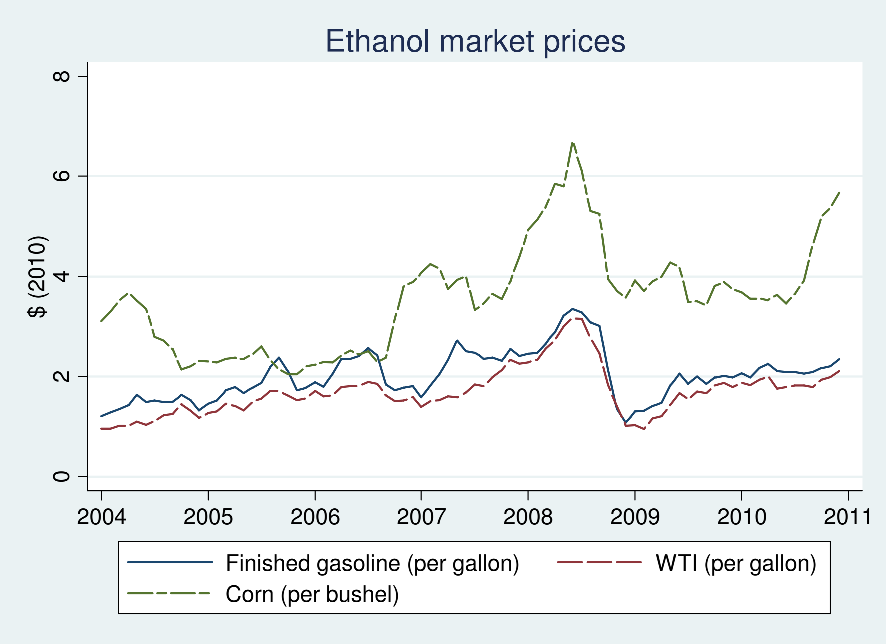

Figure 6: Ethanol blending market prices

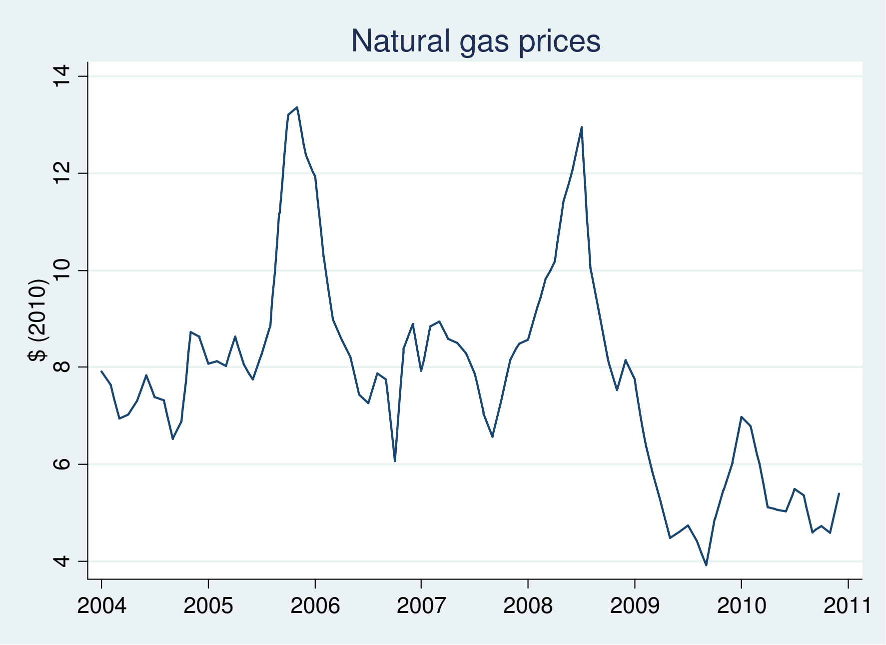

Figure 7: Natural gas prices

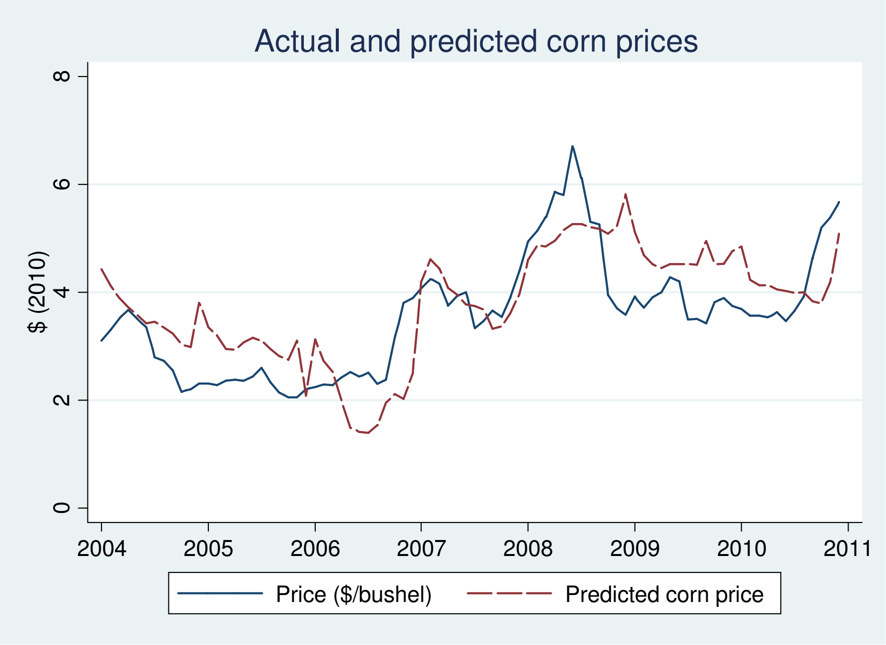

Figure 8: Actual and instrumented corn prices

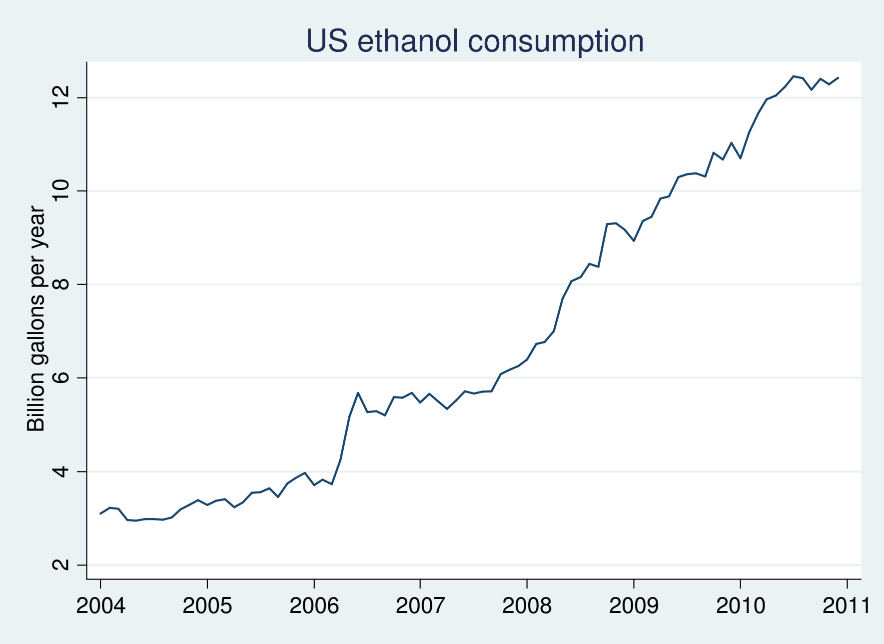

Figure 9: US ethanol consumption

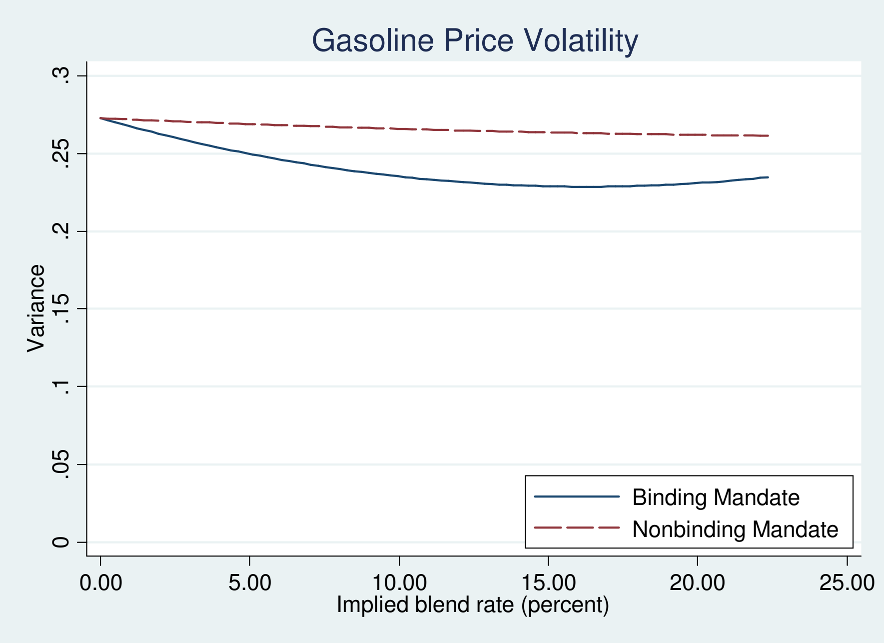

Figure 10: Volatility impact of ethanol blending versus blend rate

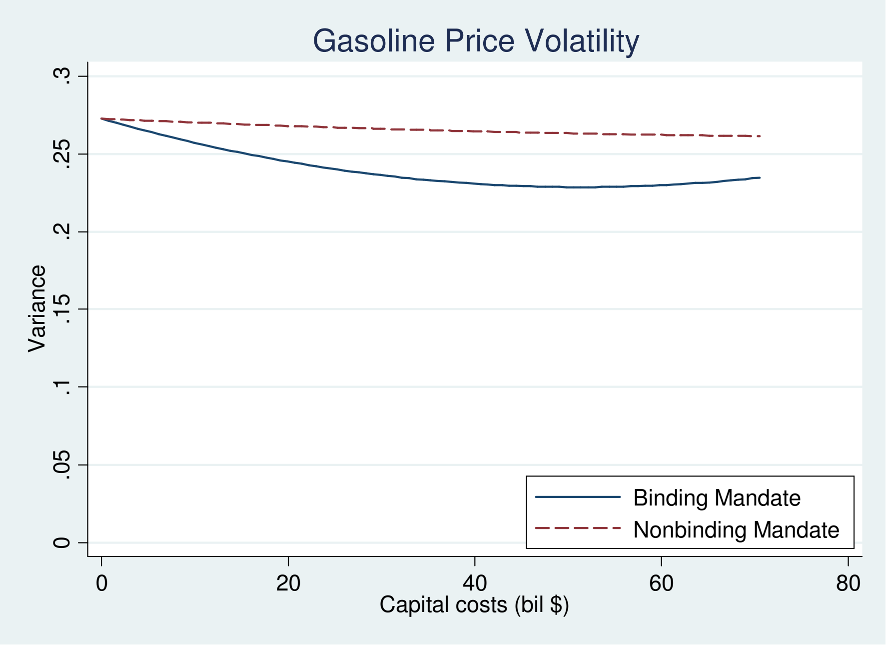

Figure 11: Volatility impact of ethanol blending versus ethanol capacity cost

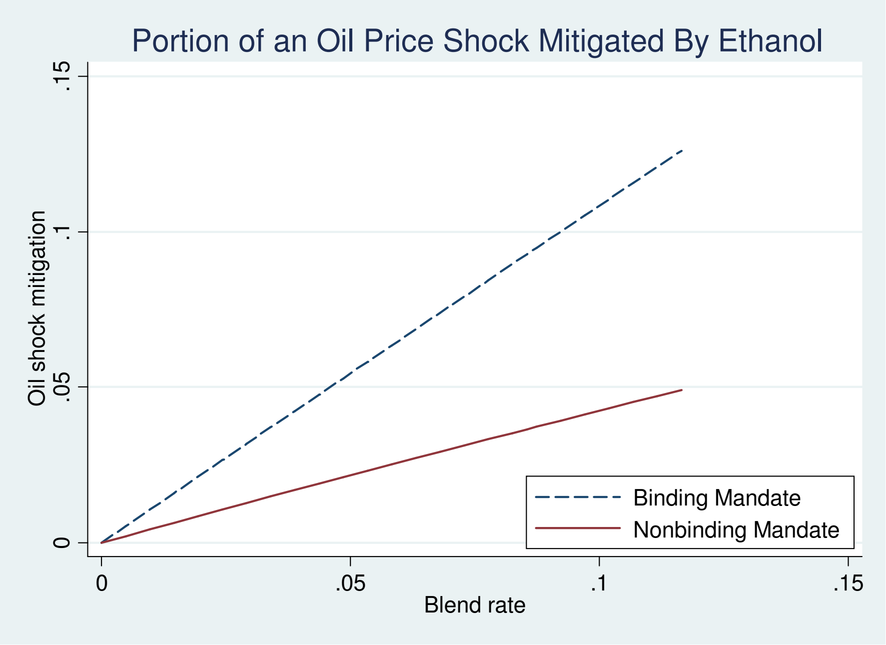

Figure 12: Portion of an oil price spike that is mitigated by ethanol

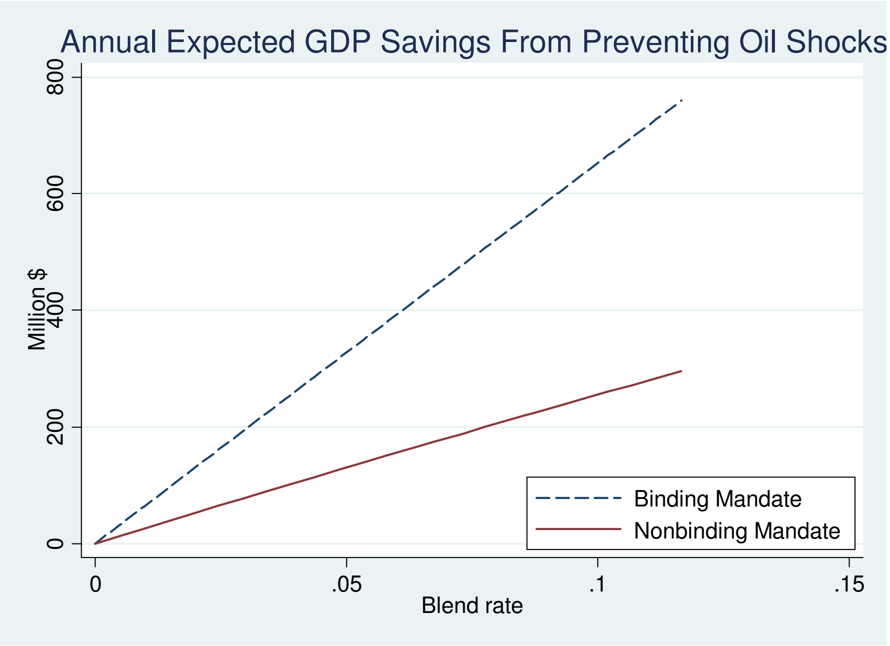

Figure 13: Annual expected GDP savings from ethanol preventing oil shocks

	Crude oil	Corn	Instrumented corn	Natural gas
Crude oil	1			
Corn	0.66	1		
Instrumented corn	0.29	0.72	1	
Natural gas	0.23	-0.061	-0.16	1

Table 1: Correlations among basic fuel inputs

Variable name	Description
E	Quantity of ethanol blended into gasoline, thousand barrels per day
P^G	Retail price of gasoline, dollars per gallon
K	National ethanol production capacity, thousand barrels per day
P^O	Average refiner acquisition costs of crude oil per gallon
P^C	CME spot price of corn per quantity to make one gallon of ethanol
P^N	Spot price of natural gas to industrial customers per MCF in PADD 2

Table 2: Variable descriptions

WTI	Average West Texas Intermediate
Brent	Average Brent crude benchmark
HDD, CDD	Heating, cooling degree days

Table 3: Instrumental variable descriptions

Variable	Mean	Std Dev	N
E (per PADD)	88.2	76.9	420
K (nationwide)	438.	211.	420
P^G	2.05	0.493	420
P^O	1.59	0.473	420
P^C	3.56	1.07	420
P^N	7.75	2.12	420

Table 4: Summary statistics

Results in Levels

Blendstock	1	2	3	Logs
Gasoline price	621***	417***	174***	0.235***
Crude price	-626***	-403***	-240***	-0.235***
Trend		-1.30***		
Constant	1453.***	1636.	1744***	7.12***

Table 5: Regression results for gasoline prices in levels, *10%, **5%, ***1% confidence levels.

Ethanol	1	2	Logs
Ethanol capacity	0.198***	0.182***	1.30***
Gasoline price	0.0143*	0.00851***	0.202***
Corn price	-0.0883*	-0.00351*	-0.109***
Natural gas price	-0.000106	-0.00152**	0.00241
Constant	1.63	8.18***	-3.89***

Table 6: Regression results for ethanol production in levels, *10%,5%,***1% confidence levels.**

Gasoline Consumption	
Population	0.0360***
Income	-0.000291***
Pop * price	0.00368***
Income * price	-0.0000659**
Price	-27.4**
Constant	207***

Table 7: Regression results for gasoline consumption in levels, *10%,5%,***1% confidence levels.**

Results in Differences

Blendstock	1
Crude price	402
Gasoline price	-416
Constant	-1.38

Table 8: Regression results for gasoline prices in first differences, *10%, **5%, ***1% confidence levels

Ethanol	1
Ethanol capacity	0.143*
Gasoline price	0.00588
Natural gas price	-0.000156
Corn price	-0.00466
Constant	0.521

Table 9: Regression results for ethanol production in first differences, *10%, **5%, ***1% confidence levels

Gasoline Consumption	
Population	-0.110***
Income	-0.000279
Pop * price	-0.0035
Income * price	0.00013
Price	-47
Constant	4.24

Table 10: Regression results for gasoline consumption in first differences, *10%, **5%, ***1% confidence levels

	Crude	Gasoline	Gas	Corn
Crude	0.257			
Gasoline	0.245	0.277		
Gas	-0.00285	0.0518	4.80	
Corn	0.526	0.493	-1.01	2.00

Table 11: Variance of inputs

Equation	Variable	1	2	3
Price	Constant	0.308***	0.334***	0.324***
	Crude	1.06***	1.02***	1.04***
	Ethanol	-6.12e-6**	-3.33e-6	-5.04e-6**
Variance	ARCH	0.544***	0.625***	0.517***
	GARCH	-0.220	-0.0315	-0.120*
	Constant	-4.85***	-5.78***	-5.54***
	Ethanol	-1.42e-4***	1.31e-4***	-1.29e-4***
	Crude	1.54***	1.88***	1.89***
Ethanol measure		K	E	E-hat

Table 12: Reduced form estimation results

Disruption size (mmbd)	Probability	Oil price change
0	0.8439	0.00
1	0.0309	0.20
2	0.0325	0.39
3	0.0453	0.59
4	0.00216	0.79
5	0.00776	0.98
6	0.0103	1.18
7	0.0109	1.38
8	0.00764	1.57
9	0.00108	1.77
10	0.00156	1.97
11	0.00118	2.16
12	0.00173	2.36
13	0.000831	2.55
14	0.0005111	2.75
15	0.000986	2.95
16	0.000119	3.14

Table 13: Probability of oil supply shock. Based on Brown and Huntington (2010).