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A Ban on One is a Boon for the Other: Strict Gasoline Content Rules and Implicit Ethanol Blending Mandates

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A Ban on One Is a Boon for the Other: Strict Gasoline Content Rules and Implicit Ethanol Blending Mandates*

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Abstract

Ethanol and methyl-tertiary butyl ether (MTBE) were close substitutes in the gasoline additives market until MTBE was banned due to concerns about groundwater contamination, leading to a sudden and dramatic substitution toward ethanol as an alternative oxygenate and octane-booster. We use variation in the timing of MTBE bans across states to identify their effects on gasoline prices. We find that state bans increased reformulated gasoline prices by 6 cents in non-Midwestern states for which the bans were binding, with larger impacts during times of high ethanol prices relative to MTBE and crude oil. We find qualitatively similar, yet smaller effects for conventional gasoline. We argue on the basis of a simple conceptual model and supporting empirical evidence that these bans functioned as implicit state-level ethanol blending mandates in areas that were previously using MTBE to comply with strict environmental constraints. Overall, our results are consistent with the theoretical prediction that mandating a minimum market share for a more costly alternative fuel—either directly, or implicitly through a ban on the preferred conventional fuel—will inevitably increase fuel prices in a competitive market.

JEL classification numbers: Q4
Key words: ethanol; gasoline; MTBE; gasoline content regulations

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1 Introduction

Gasoline refiners have faced a series of increasingly stringent environmental constraints in recent decades, which have significantly narrowed their options for maintaining high levels of fuel octane.[1] By the late 1990s, suppliers in many cities came to rely heavily on a chemical fuel additive known as MTBE (methyl-tertiary butyl ether) to boost octane in the presence of environmental constraints, while suppliers in a handful of other cities used ethanol instead. Like ethanol, MTBE was valued for its energy content, high oxygen content, high octane rating, and clean-burning properties—but was found to leak from underground storage tanks, contaminating groundwater supplies. Thus, a total of 19 states banned MTBE in gasoline from 2000–2006 before it was phased out nationwide in mid-2006, leading to a sudden and dramatic substitution toward ethanol as an alternative oxygenate and octane booster. We use a combination of applied theory, econometric estimation, and institutional background to shed light on this era of gasoline content regulation, which came after a flurry of regulatory activity flowing out of the Clean Air Act Amendments in the early 1990s, and which served as prelude to the implementation of the federal Renewable Fuel Standard in the late 2000s.

We show theoretically that MTBE bans function as implicit ethanol blending mandates in the presence of strict environmental constraints that compel refiners to blend either MTBE or ethanol. We confirm this interpretation empirically by examining ethanol and MTBE blend shares before and after the enforcement of state MTBE bans, finding that they had large, discrete, and immediate effects on ethanol blending shares, consistent with direct substitution. We then use variation in the timing of MTBE bans across states to identify their effects on gasoline prices. We distinguish the heterogeneous effects of these bans by (1) conventional gasoline versus reformulated gasoline, which faced more stringent environmental constraints that led to highly inelastic demand for ethanol as a substitute blending

[1] High-octane fuels are more resistant to "knocking," which occurs when the pressurized fuel-air mixture in the engine ignites prior to the spark plug firing, reducing engine efficiency. Thus, octane is a critical measure of gasoline quality, and the need for high-octane fuel has risen over time with improvements in engine performance.

component, (2) geography, to account for whether the bans were binding or not, and (3) time, based on shifts in the wholesale prices for ethanol, MTBE, and crude oil—the key commodity inputs into oxygenate-blended gasoline.

We find that state MTBE bans increased reformulated gasoline prices by 6 cents in non-Midwestern states, for which the bans were binding, with little effect in the Midwest, which was already using ethanol. In contrast, we find minimal effect on average prices for conventional gasoline, which faced less stringent blending requirements, regardless of location. As expected, price impacts were larger when ethanol prices were high relative to MTBE and crude oil, and again, these effects were more pronounced for reformulated gasoline than for conventional gasoline. In addition, we find that MTBE bans increased the monthly pass-through rate of wholesale ethanol prices into retail gasoline prices, while decreasing the pass-through rates of wholesale MTBE and crude oil prices. Importantly, we find that state MTBE bans that took effect after the unexpected nationwide ban have virtually no effect on gasoline prices, which eases potential concerns about differential price trends in states with MTBE bans. Overall, our results are consistent with the theoretical prediction that a ban on a less costly conventional fuel, which in extreme cases operates as a de-facto mandate for the more costly alternative fuel, will inevitably increase fuel prices in a competitive market.

This paper is closely related to a recent empirical literature that exploits variation in gasoline content regulations across locations and over time to identify their effects on gasoline prices, mainly using reduced-form empirical methods. In general, this literature finds that gasoline content regulations increase average prices (Muehlegger 2006; Chouinard and Perloff 2007; Brown, Hastings, Mansur and Villas-Boas 2008; Chakravorty, Nauges and Thomas 2008), while seasonally and geographically differentiated regulations segment markets in ways that limit arbitrage over time and across space, exacerbating local price spikes following refinery outages (Muehlegger 2006; Brown et al. 2008) and increasing opportunities for refiners to exercise market power (Brown et al. 2008; Chakravorty et al. 2008). Overall, however, environmental regulations explain a relatively small fraction of the variation in gasoline prices, which is largely driven by crude oil and state, local, and federal taxes (Chouinard and Perloff 2007).[2]

Our paper contributes to this literature in three ways. First, while previous papers focus on the gasoline content regulations flowing directly from the Clean Air Act Amendments of the early 1990s, we focus on state MTBE bans, which occurred later, which apply to gasoline sold everywhere in a state, and which likely had different impacts on prices. Thus, our paper helps document an important era in gasoline content regulation that led to a significant increase in ethanol consumption, well before the implementation of the federal Renewable Fuel Standard (RFS) in the late 2000s. In particular, these bans are important pre-existing regulations that must be considered when assessing the marginal impacts of the federal RFS on gasoline markets.

Second, like previous studies, we allow gasoline content regulations to have heterogeneous effects on gasoline prices according to location and the level of regulatory stringency. In particular, we allow the effects of MTBE bans to differ for Midwestern states, which were closer to ethanol supply, as well as for conventional gasoline, which faced much less stringent environmental regulations. Unlike previous studies, however, we allow the effects of gasoline content regulations to vary over time according to the prices of key gasoline inputs, since

[2]Brown et al. (2008) estimate the effects of federal Reid Vapor Pressure (RVP) and reformulated gasoline (RFG) regulations on weekly wholesale prices in affected cities, controlling for wholesale prices in nearby cities that lacked such regulations. They find prices in treated cities increased following the onset of the regulations, while the number of wholesalers decreased, suggesting that market power played a role in the price increase. They also find that gasoline price volatility increased in treated cities, arguing that geographically fragmented regulations limit opportunities to arbitrage prices across locations. Chakravorty et al. (2008) use a state-panel design to estimate the effect of reformulated gasoline and winter oxygenated fuel regulations (measured by the fraction of a state's population subject to such regulations) on state-average annual gasoline prices, also finding that such regulations led to higher fuel prices, both by increasing refining and distribution costs and by segmenting gasoline markets in a way that increased market power of refineries. Muehlegger (2006) estimates the impact of gasoline content regulations on prices using a structural model of refinery behavior, which he estimates using data on monthly average prices and quantities by state. He finds that content regulations led to higher average prices through higher refining and distribution costs and that geographically uniform regulations could substantially mitigate the severity of local price spikes. Finally, Chouinard and Perloff (2007) use a state-panel design to estimate the effects of crude oil prices, taxes, refiner market power, vertical integration, and environmental regulations on gasoline prices, finding that environmental regulations explain a relatively small fraction of the overall costs.

the bans dramatically shift the demand for these inputs. Thus, our estimates may have greater external validity in the face of changing market conditions. Importantly, modeling heterogeneity based on input prices also addresses potential concerns about spillovers of state-level policies to gasoline prices in other states via national wholesale markets for gasoline and fuel additives—something that is ignored in previous studies.

Third, we argue on the basis of a simple conceptual model and supporting empirical evidence that state MTBE bans approximated direct state-level ethanol blending mandates in areas that were previously using MTBE to comply with strict oxygenation requirements or to maintain fuel octane levels in the presence of other environmental constraints. Theory implies that a fractional ethanol blending mandate acts like a tax on gasoline and a subsidy for ethanol, increasing average fuel prices when the ethanol supply curve is more steeply sloped than that of gasoline, and calibrated simulation models bear this prediction out (Holland, Knittel and Hughes 2008). Yet controversy regarding the effects of ethanol blending mandates on gasoline prices continues to fester, due in large part, we suspect, to the conflation of higher ethanol *production* in general with specific ethanol *policies* that lead to higher production—along with the difficulty of distinguishing statistically the effects of the national mandate from other trends affecting gasoline prices (see Knittel and Smith 2012). Thus, our results are relevant not just for understanding the impacts of the MTBE bans during this era, but also for inferring the potential impacts of ethanol mandates on gasoline prices, thereby helping to inform an important current policy debate. In this case, our results suggest that direct, state-level ethanol blending mandates would have increased fuel prices. Our approach may prove useful in other contexts, when the reduced-form impact of a new or future policy cannot be estimated, but can be inferred from a surrogate policy sharing a similar economic structure.[3]

[3]Other policies that share a similar economic structure include the U.S. federal Renewable Fuel Standard (RFS) and California's Low-Carbon Fuel Standard (LCFS). While the federal RFS is legislated as a minimum quantity, it is implemented by EPA as a minimum market share requirement. Likewise, in the case of a conventional high-carbon fuel (gasoline) and a single low-carbon fuel (say ethanol), the LCFS is equivalent to a minimum market share for the low-carbon fuel.

In addition, our paper contributes to a more general applied theory and empirical economic literature on overlapping environmental policies and rent-seeking behavior in environmental regulation. Gasoline refiners now face a host of overlapping constraints on gasoline content. Our paper illustrates how a ban on a gasoline input (MTBE) can—in the presence of other environmental policy constraints—lead to dramatic substitution toward one particular close substitute (ethanol). In the extreme, when other options have been eliminated through regulation, a ban on one input operates as a de-facto mandate for its alternative. Excessive regulation also comes with a hidden political cost: eliminating substitute technologies through regulation inflates incentives for rent-seeking behavior among the industries whose technologies remain viable. Indeed, ethanol producers were among the most ardent supporters of MTBE bans, with virtually all corn-growing Midwestern states banning MTBE, despite the fact that few of these states had problems with MTBE contamination.

The rest of this paper proceeds is as follows. Section 2 discusses important background on the economics of ethanol and MTBE blending in the United States before presenting our conceptual model. Section 3 presents descriptive evidence on MTBE bans and their effects on ethanol usage. Section 4 describes our estimation strategy and presents our regression results for the effects of MTBE bans on retail gasoline prices. Section 5 summarizes and concludes.

2 Industry background and conceptual model

Historically, ethanol and MTBE have been used for several reasons, including to boost fuel octane levels, to comply with minimum fuel oxygenation requirements, and to extend fuel supplies during times of relatively high crude oil prices. In this section, we briefly review the history of environmental regulation that led gasoline suppliers to blend either ethanol or MTBE for these reasons, as well as the slate of bans that eliminated MTBE from gasoline during the 2000s. We discuss the economics of ethanol versus MTBE blending, and we outline a simple conceptual model that clarifies the predicted effects of MTBE bans—as well as the conditions under which such bans approximate direct ethanol blending mandates. Our goal is to motivate our empirical analyses below, which are based on comparing gasoline markets across states before and after the MTBE bans took effect.

2.1 Maintaining octane under strict environmental constraints

A major theme in the gasoline refining industry over the past four decades has been the industry's struggle to maintain fuel octane levels in the face of increasingly stringent environmental constraints. With each new environmental regulation, refiners have responded with new, cost-minimizing approaches to maintain octane, leading to new, often unanticipated environmental side-effects, leading in turn to further environmental regulations. Over time, this pattern of regulation, industry response, and further regulation has significantly narrowed the set of octane-enhancing options available to refiners. Thus, by the late 1990s, suppliers in many cities had few cost-effective alternatives outside of blending ethanol or MTBE. In such contexts—that is, when gasoline suppliers are compelled to blend either ethanol or MTBE to maintain octane or to comply with explicit fuel oxygenation requirements—bans on MTBE act as de-facto ethanol mandates. This is the key insight of our paper.[4]

Initially, gasoline refiners blended an octane-rich, lead-based compound into gasoline, but the widespread use of leaded gasoline was found to generate significant public health and environmental impacts. Thus, the EPA began regulating leaded gasoline in the 1970s, leading to its eventual ban in the 1980s. Industry responded by altering the refining process to boost the production of high-octane aromatic hydrocarbons, such as benzene and toluene, as well as butane, which is a high-octane byproduct of this altered refining process. However, benzene was a suspected carcinogen, while the increased use of aromatics and butane led to a significant rise in emissions of evaporative volatile organic compound (VOCs)—precursors to the formation of ground-level ozone. Meanwhile, some cities were experiencing elevated

[4]The discussion of gasoline production and environmental regulation in this section relies heavily on Stikkers (2002) and Brown et al. (2008).

levels of carbon monoxide emissions due to incomplete combustion of fuel during cold winter months. Thus, in the 1990s, the EPA placed caps on Reid Vapor Pressure (RVP) in select cities to limit evaporative emissions of VOCs, began requiring oxygenate blending in select cities during winter months to reduce emissions of carbon monoxide, and required so-called reformulated gasoline (RFG) in select cities with particularly poor air quality. These changes were authorized by Congress in a series of amendments to the Clean Air Act. Fuel sold under the RFG program was subject to a suite of environmental constraints, including caps on Reid Vapor Pressure (RVP), caps on aromatic hydrocarbon content, and caps on benzene and other toxic substances, as well as mandated year-round blending of oxygenates—almost always provided by ethanol or MTBE.[5,6,7]

Thus, by the late 1990s, gasoline suppliers faced a multitude of restrictions on gasoline content that generated strong incentives to blend either ethanol or MTBE into gasoline, with the strength of these incentives varying geographically according to the stringency of the local environmental regulations. At one extreme, producers selling gasoline under the RFG program were required to blend either ethanol or MTBE into gasoline to comply with explicit oxygenation mandates—and faced additional caps on aromatics and toxics that likely would have led them to blend ethanol or MTBE regardless, simply to maintain octane levels. In somewhat less extreme cases, producers selling conventional gasoline under the winter oxygenation program were required to blend either ethanol or MTBE, but only during

[5]Limits on RVP were phased-in gradually during the early 1990s. A fuel's RVP measures its propensity to evaporate and therefore generate emissions of VOCs, which react with nitrogen oxides (NOx) in the presence of sunlight to form ground-level ozone, causing respiratory illness. Auffhammer and Kellogg (2011) show that limits on RVP were ineffective outside of California, since refiners responded by reducing butane, which is not particularly potent for smog formation. In contrast, California's unique regulations targeted the most potent VOCs directly, leading to significant improvements in air quality.

[6]Winter oxygenation requirements took effect in 39 cities in the early 1990s, mandating a minimum of 2.7% oxygen by weight in most areas, which translated to 7.4% ethanol or 15.0% MTBE by volume; most remaining areas required 3.1% oxygen by weight. While oxygenates other than ethanol and MTBE were available, virtually all demand was met with these two oxygenates. Oxygenates help gasoline burn more completely in older engines that lack carburetors, reducing carbon monoxide emissions. Most cities have since exited the program due to improved air quality.

[7]The RFG program was mandated for nine large cities with the worst smog, and a number of other cities opted to join the program voluntarily. The program began in 1995, superseding existing RVP and winter oxygenation programs in some cities. The program required 2.1% oxygen by weight in most areas, which translated to 5.8% ethanol or 11.7% MTBE by volume.

winter months. Lastly, even producers selling conventional gasoline in locations without such requirements sometimes opted to blend ethanol or MTBE to boost octane or to extend fuel supplies when prices for these additives were sufficiently low. These myriad restrictions set the stage for the MTBE bans that were to come and the resulting dramatic shift to ethanol.

By the late 1990s, some cities began to notice that MTBE, a suspected carcinogen, was contaminating their drinking water. Because this problem was most pronounced in areas with RFG, it soon became clear that the contamination was coming from leaking underground gasoline storage tanks. Thus, starting around 2000, a number of states begin to ban MTBE in gasoline, and pressure built for a nationwide ban.[8] Meanwhile, the fuel industry sought liability protection against lawsuits stemming from MTBE contamination, arguing that they should not be penalized for blending MTBE when they were compelled to do so by federal environmental regulation. Finally, in late 2005, the Energy Policy Act of 2005 failed to grant the liability protection that MTBE blenders were seeking. Given the large number of state MTBE bans and rising concerns about liability risk, the industry treated this failed legislative remedy as an implicit ban on MTBE and opted to phase-out the use of the chemical almost entirely by the summer of 2006. Given the myriad restrictions on gasoline content that were already in place, these explicit and implicit MTBE bans acted as de-facto ethanol mandates in RFG cities, as well as in cities subject to minimum oxygenation requirements during winter months, and led to increased demand for ethanol in other areas and at other times to boost octane or to extend fuel supplies.[9]

[8]Political economy motivations were also clearly at play. State and federal MTBE bans were strongly supported by the Midwest-based ethanol industry. Indeed, most Midwestern states had MTBE bans, despite the fact that relatively few Midwestern cities required RFG and that most Midwestern suppliers would have chosen ethanol over MTBE anyway, given ethanol's proximity.

[9]Besides failing to grant liability protection for the use of MTBE, the 2005 legislation eliminated the explicit oxygenation requirement in RFG, which made the threat of legal liability even more salient. Rather than cease oxygenate blending altogether, however, refiners switched to ethanol, as we show below, despite the removal of the oxygenation requirement. Why? There are two probable reasons. First, given other constraints on aromatics and toxics, continuing to blend ethanol may in fact have been the cheapest way to maintain fuel octane. Second, the same legislation that removed the oxygenation requirement for RFG also imposed the federal Renewable Fuel Standard (RFS), which mandated a minimum quantity of ethanol blending in the overall fuel supply, equal to roughly 5% of gasoline consumption in 2012. Thus, making costly changes to the refining process in an effort to boost octane in other ways would have been unwise, given that the looming RFS would soon lead to increased octane anyway via mandated ethanol blending.

2.2 Ethanol versus MTBE blending economics

While ethanol and MTBE are close substitutes in the gasoline additives market, their production, distribution, and integration into the gasoline supply chain differ in several important ways. Unlike ethanol, MTBE is typically produced and mixed with gasoline directly at petroleum refineries.[10] After the blending is complete, the finished gasoline can be shipped through refined product pipelines virtually anywhere in the country at low cost (Trench 2001). Alternatively, the MTBE itself can be shipped independently via pipeline to wholesale distribution terminals, blended immediately with an MTBE-ready gasoline blendstock, and then stored as finished gasoline in common storage tanks.

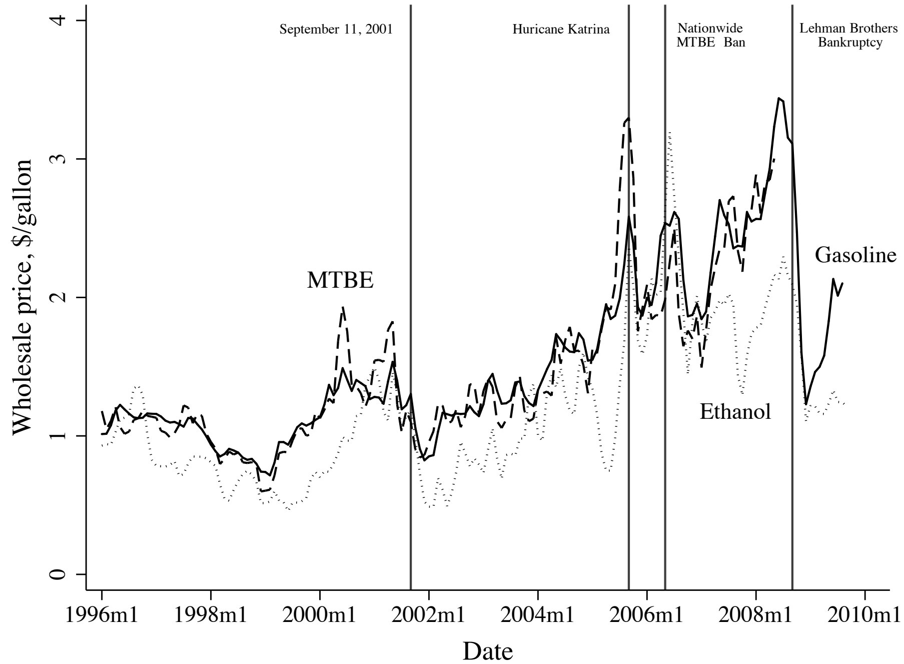
Ethanol, by contrast, is produced in geographically isolated refineries in the Midwest, far away from most petroleum refineries and large cities, and unlike MTBE, it cannot be shipped through existing refined product pipelines.[11] Instead, ethanol must be transported at relatively high cost via rail, barge, or tanker truck to wholesale fuel blending and distribution terminals. The cost of transporting ethanol by rail from the Midwest to the coasts, for example, is about 15 cents per gallon (Hughes 2011). Upon arrival at the terminals, ethanol is stored separately from gasoline in dedicated tanks and then, in the final step, splash blended with an ethanol-ready gasoline blendstock in the tank of a delivery truck for transmission to an individual retail outlet.

These differences between ethanol and MTBE supply and distribution have two key consequences. First, high transportation costs, limited fungibility in refined product pipelines, and (until recently) the lack of blending infrastructure outside of the Midwest seriously con-

[10]MTBE is a petroleum-based chemical fuel additive. It is produced by reacting methanol with isobutylene in dedicated MTBE production facilities or by using byproduct streams of isobutylene at petroleum refineries or petrochemical ethylene plants (Lidderdale 2001).

[11]Existing pipelines are not suitable for two reasons. First, existing pipelines are configured to transport high volumes of gasoline from large oil refineries to cities, whereas ethanol refineries are smaller, located in rural agricultural areas, and are widely dispersed. Second, water tends to accumulate at low points in refined product pipelines. Unlike petroleum, ethanol mixes with water, and so pure ethanol cannot be shipped via existing pipelines, lest it become contaminated. Likewise, if ethanol-blended gasoline comes into contact with water, the ethanol will separate from the gasoline and combine with the water. Thus, ethanol must be shipped separately and only blended in the last step.

Figure 1: Fuel price trends



Note: This figure shows monthly wholesale rack prices for gasoline (U.S. average), MTBE (Gulf Coast), and ethanol (in Omaha, Nebraska). Ethanol prices are net of the federal ethanol blending incentive. Prices are in real 2010 dollars. See text for details.

strained opportunities for ethanol price arbitrage across locations in response to high prices for gasoline or for competing oxygenates and octane enhancers. Thus, while MTBE prices track gasoline prices very closely over time, ethanol prices do not. See Figure 1. Wholesale MTBE prices track wholesale gasoline prices closely, rarely falling below the price of gasoline and sometimes spiking above it. This behavior is consistent with MTBE being a close substitute for gasoline, except for in rare cases when MTBE supply falls short relative to inelastic oxygenate demand.

Second, ethanol's high transportation costs lead to significant geographic variation in ethanol usage. Thus, prior to the bans, suppliers of RFG on the coasts, facing relatively high ethanol transportation costs, tended to choose MTBE, while suppliers of RFG in the Midwest, facing relatively low transportation costs, and in some cases encouraged by attractive ethanol blending subsidies, chose ethanol.

Other cost considerations were also relevant. First, ethanol has higher RVP than MTBE, which in turn has higher RVP than gasoline. Thus, for suppliers subject to RVP constraints, choosing ethanol would have required reducing the RVP of the underlying gasoline blendstock, which is costly. As a result, suppliers of RFG that chose ethanol rarely blended the full 10% of ethanol allowed by EPA regulations, just the minimum needed to meet the oxygenation mandate. Second, suppliers subject to winter oxygenation requirements also tended to choose ethanol, regardless of location, due to ethanol's higher oxygen content per volume and the lack of RVP limits in such locations. Finally, ethanol blending was supported by a federal subsidy of roughly $0.50 per gallon during this time period, which only recently expired. All told, ex-ante estimates were that the MTBE bans would increase RFG prices by 3.6 cents per gallon on average, with larger increases in coastal states (U.S. Energy Information Administration 2003).

2.3 Direct and indirect ethanol blending mandates

Figure 2(a) presents stylized model of a perfectly competitive state fuel market in the presence of a percent ethanol blending mandate. The demanders in this market are fuel blenders, implicitly buying ethanol and gasoline on behalf of retail consumers. For simplicity, these retail consumers are assumed to have perfectly inelastic overall demand for fuel, which is given by the width of the horizontal axis, while treating ethanol and gasoline as perfect substitutes.[12] Thus, fuel blenders inherit these preferences, as well, attempting to minimize the overall cost of fuel, subject to their inelastic demand, while also meeting their fuel blending

[12]These assumptions are consistent with vast empirical evidence showing that overall demand for fuel is inelastic, perhaps declining to less than 0.1 in magnitude in recent years (Small and Dender 2007; Hughes, Knittel and Sperling 2008), as well as more recent empirical evidence showing that consumers in the United States and Brazil treat high-concentration ethanol blends and gasoline as very close, albeit not perfect, substitutes (Anderson 2012; Salvo and Huse 2012). Given our focus here on low-concentration ethanol blends, for which ethanol concentrations are rarely transparent to consumers, and for which impacts on driving range and performance are negligible, the assumption of perfect substitutes is an even better approximation. In addition, for simplicity, we abstract away from differences in energy content, which are minor when blending small fractions of ethanol.

obligations. The suppliers in this market are fuel refiners and distributors that produce fuel and deliver it to market. Gasoline supply is represented as a horizontal marginal cost curve, while ethanol supply is represented as an upward-sloping marginal cost curve.[13] Before the ethanol mandate takes effect, blenders of ethanol are only willing to pay up to the marginal cost of gasoline. Thus, ethanol's market price and quantity are given by point A, at which the marginal cost of ethanol equals the marginal cost of gasoline, with a small amount of ethanol competing directly as a gasoline substitute.[14] Thus, small shifts in gasoline supply pass through fully to fuel prices, while small shifts in the ethanol supply pass through not at all.

After the ethanol mandate takes effect, fuel blenders are forced to increase their ethanol demand to point B, at which ethanol's marginal cost exceeds that of gasoline. At the standard, the marginal cost to blenders of acquiring one more gallon of fuel while remaining in compliance with the standard—and therefore, the fuel price that retail consumers will pay—is the quantity-weighted average of ethanol's and gasoline's marginal costs.[15] Thus, the impact of the mandate on fuel prices is higher when either ethanol supply shifts up or when gasoline supply shifts down. Small shifts in gasoline supply now pass through only partially to fuel prices, and similarly for ethanol supply, according to their respective shares in the overall fuel supply, given by the ethanol mandate.

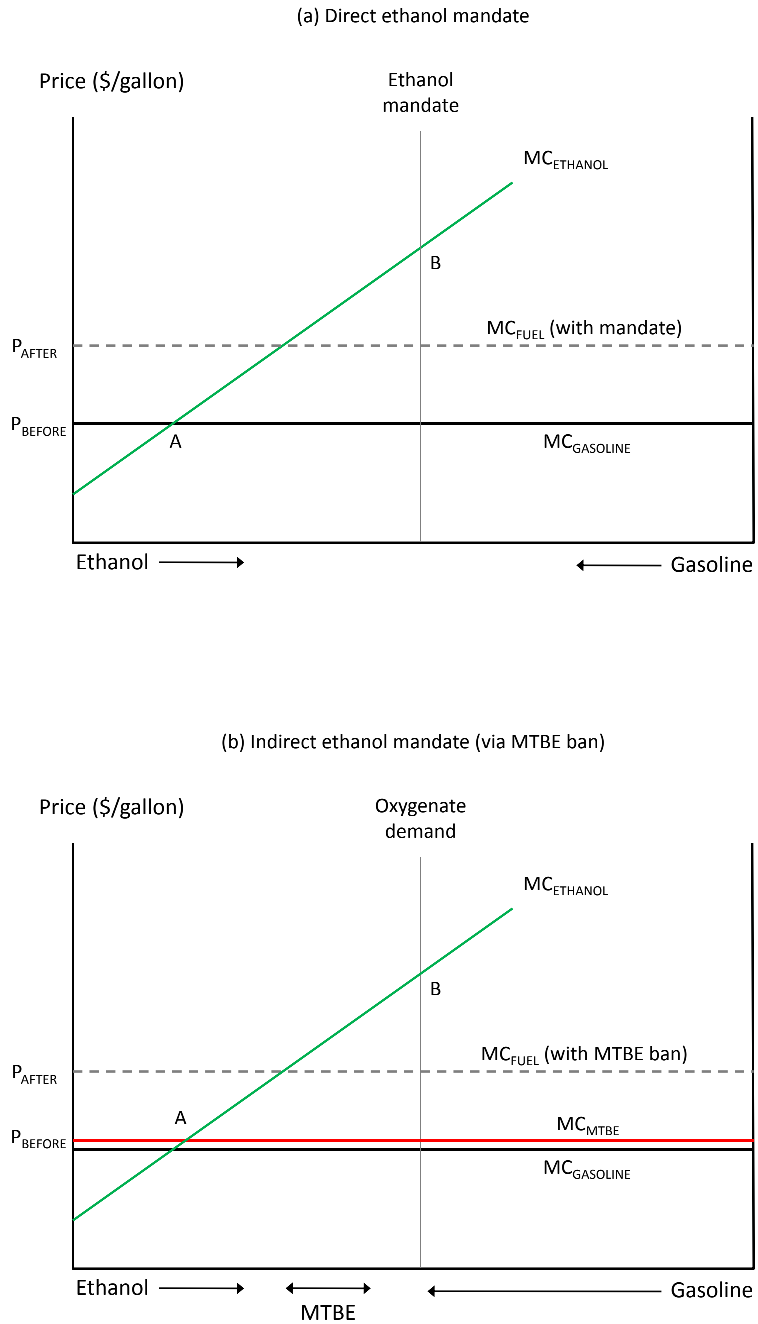
Figure 2(b) presents a similar figure for a competitive state fuel market in the presence of inelastic demand for oxygenates (to satisfy a minimum oxygenation requirement or to

[13] An approximately horizontal state gasoline supply curve is consistent with a large national market and low transportation costs via refined product pipelines. In contrast, an upward-sloping ethanol supply curve is consistent with a smaller national market, geographic dispersion of ethanol refineries, relatively high transportation costs, limited infrastructure for ethanol blending at terminals, and relatively few retail storage tanks that can handle ethanol-blended fuel.

[14] We have drawn the initial equilibrium as an interior solution. In general, corner solutions at zero or at the 10% upper limit for ethanol blending are also possible. In the former case, our conclusions are unchanged. In the latter case, the ethanol mandate is not binding. The so-called "blend wall" of 10% ethanol is determined by EPA regulation (only recently increased to 15%) and by manufacturer warranties for most cars.

[15] While we have arbitrarily drawn in the ethanol standard at a 50% blend share, so that the marginal cost of fuel is shown as the simple average of ethanol's and gasoline's marginal costs, this obviously need not be the case. For example, at a 10% blend share, the marginal cost of fuel would be 10% of ethanol's marginal cost plus 90% of gasoline's marginal cost.

Figure 2: Illustration of conceptual model



Note: Figure (a) illustrates the effects of a direct percent ethanol blending mandate. Figure (b) illustrates the effects of an MTBE ban in the presence of inelastic percent oxygenate demand satisfied using ethanol and/or MTBE. The ethanol mandate in (a) and the MTBE ban in (b) have virtually identical effects when MTBE supply hugs gasoline supply. See text for details.

enhance octane) and potential ban on MTBE; the same qualitative results would hold with more elastic oxygenate demand. Again, gasoline supply is horizontal, while ethanol supply is upward-sloping. The supply of MTBE is represented as a horizontal supply curve at or just above the marginal cost of gasoline.[16] In the absence of a ban on MTBE, ethanol's marginal cost and quantity supplied are given by point A, at which a small amount of ethanol competes with MTBE in the market for oxygenates. At this point, the marginal cost of fuel is set by the quantity-weighted average of gasoline and oxygenates, the latter of which is set by the constant marginal cost of MTBE. Thus, small shifts in MTBE and gasoline supply pass through partially to fuel prices according to the share of total oxygenates and gasoline in the fuel supply, respectively, while small shifts in ethanol supply pass through not at all. When the MTBE ban takes effect, ethanol's marginal cost and quantity supplied are given by point B, at which ethanol is the sole oxygenate. At this point, the price of fuel is set by the average marginal cost of fuel, that is, the quantity-weighted average of ethanol's and gasoline's marginal costs. Thus, the impact of the MTBE ban on fuel prices is higher when either ethanol supply shifts up or MTBE supply shifts down. Small shifts in ethanol supply now pass through partially to fuel prices, according to ethanol's fixed share in the overall fuel supply, while shifts in MTBE supply pass through not at all.[17]

Comparing these two figures, we therefore see that an MTBE ban in the presence of inelastic demand for oxygenates closely approximates the economic structure of an ethanol mandate. In both cases, the policy leads to an increase in fuel prices that is more pronounced either when the supply of ethanol shifts up or when the supply of the conventional fuel (gasoline, in the first case, MTBE in the second) shifts down. Pass-through rates increase

[16]Historically, MTBE prices track conventional gasoline prices very closely over time, with relatively few exceptions (see Figure 1). In addition, the wholesale premium for RFG over conventional gasoline tracks MTBE prices very closely (Lidderdale 2001). Both facts are consistent with our choice to model MTBE as having a horizontal supply curve at or just above that of gasoline.

[17]While we have drawn inelastic demand for oxygenates as implying the same level of ethanol and MTBE by volume, the relevant choice for suppliers of RFG was typically between 6% ethanol and 11% MTBE. Thus, after the MTBE ban, the impact of the ban should increase with gasoline prices, while the pass-through rate for gasoline should also increase. In practice, this distinction will usually not matter, since MTBE prices track gasoline prices closely.

for ethanol and decrease for the conventional fuel according their shares in the overall fuel supply before and after the policy change. Thus, had the states that imposed MTBE bans during the 2000s imposed ethanol mandates instead, we argue that the economic effects in many cases would have been qualitatively similar, particularly in areas that were subject to minimum oxygenation requirements or that faced other environmental constraints that compelled refiners to blend either ethanol or MTBE with gasoline.

3 State MTBE bans and their effects on blending

3.1 State MTBE bans

Table 1 lists states with MTBE bans based on Weaver, Exum and Prieto (2010), U.S. Energy Information Administration (2003), and U.S. Enviornmental Protection Agency (2007). The second and third columns list the dates that these bans were enacted and became effective, while the fourth column lists their precise limits on MTBE content. Finally, the fifth and sixth columns present average market shares for RFG and for winter oxygenated fuel by state during the sample period, thereby indicating which states will be included in our regression for RFG prices, as well as the share of conventional fuel subject to minimum oxygenation requirements in affected states. States whose bans took effect prior to the nationwide phase-out in May 2006 are listed first, ordered by the effective dates of their bans, while states whose bans took effect after the nationwide phase-out are listed below, ordered alphabetically.

This table highlights several salient facts. First, roughly two-thirds of states with RFG eventually banned MTBE, although several bans took effect after the nationwide phase-out. Second, for the 12 states that banned MTBE but did not have any RFG, most were in the Midwest. The only exceptions were Colorado and Washington, which had large shares of oxygenated fuel, and North Carolina and Vermont. Lastly, every state in the Midwest banned MTBE, regardless of whether it had RFG, winter oxygenated fuel, both, or neither. In short, it was primarily states that were at risk of groundwater contamination from MTBE

Table 1: State MTBE bans and regulated fuel shares

State	Enactment date	Effective date	MTBE cap (%)	RFG size (%)	Oxy-fuel size (%)
South Dakota	2000-02	2000-07	2.00		
Minnesota	2000-04	2000-07	0.33		70
Nebraska	2000-04	2000-07	1.00		
Iowa	2000-07	2001-01	0.50		
Colorado	2000-09	2002-05	0.00		22
Michigan	2000-06	2003-06	0.00		
California	2003-03	2004-01	0.60	63	
Connecticut	2003-06	2004-01	0.50	100	
New York	2000-05	2004-01	0.00	55	
Washington	2001-05	2004-01	0.60		10
Kansas	2001-07	2004-07	0.50		
Illinois	2001-07	2004-07	0.50	60	
Indiana	2002-07	2004-07	0.50	14	
Wisconsin	2003-08	2004-08	0.50	27	
Arizona	2004-05	2005-01	0.30	42	7
Missouri	2002-09	2005-07	0.50	20	
Ohio	2002-09	2005-07	0.50		
North Dakota	2005-04	2005-08	0.50		
Kentucky	2002-07	2006-01	0.50	24	
Nationwide ban		2006-05		33	3
Alaska					5
Delaware				94	
Dist. of Columbia				100	
Maine	2005-08	2007-01	0.50	14	
Maryland				76	
Massachusetts				97	
Montana					1
Nevada				7	14
New Hampshire	2004-06	2007-01	0.50	67	
New Jersey	2005-08	2009-01	0.50	85	
New Mexico					5
North Carolina	2005-06	2008-01	0.50		
Oregon					9
Pennsylvania				26	
Rhode Island	2005-07	2007-06	0.50	97	
Texas				29	
Utah					1
Vermont	2005-06	2007-01	0.50		
Virginia				57	

Note: Table reports states whose MTBE bans took effect prior to the nationwide phase-out in May 2006 (ordered by enforcement date), as well as states whose bans took effect afterwards (ordered alphabetically), along with RFG and oxygenated fuel consumption in all states with such regulations. Most bans took effect on the first day of the indicated month. Bans in California, Colorado, and Iowa took effect on the last day of the month prior to the indicated month. Bans in Illinois, Indiana, and Nebraska took effect during the middle of the indicated month. MTBE cap is the maximum allowable percent MTBE content by volume or weight (in Minnesota). RFG size and oxy-fuel size are the fractions of total fuel statewide sold under the federal RFG and winter oxygenated fuel programs during 1996–2010, based on EIA data available here: `http://www.eia.gov/dnav/pet/pet_cons_prim_a_EPM0_P00_Mgalpd_m.htm`. See Weaver et al. (2010) and the text for details.

and states that had a specific interest in promoting corn-based ethanol that banned MTBE in their fuel supplies.

3.2 MTBE bans had discrete effects upon enforcement

Our empirical approach compares fuel prices in states with and without MTBE bans, exploiting the staggered timing of the MTBE bans across states. Thus, our approach depends on the MTBE bans having fairly immediate and discrete impacts on fuel composition. Figure 3 shows monthly ethanol and MTBE blending quantities at the national level and in each of the five Petroleum in Administration of Defense (PAD) Districts, or PADDs, which correspond to the East Coast, Midwest, Gulf Coast, Rocky Mountain, and West Coast regions of the country, all expressed as a volumetric percentage of total gasoline consumption in those regions.[18] The vertical lines correspond to the dates of major MTBE bans affecting these regions. Figure 4 shows aggregate production of reformulated and conventional gasoline blended with ethanol and MTBE.[19] Table 2 shows ethanol's share of total oxygenate blending in RFG based on EPA surveys of gasoline content in RFG cities during the summer months (U.S. Environmental Protection Agency 2006).[20] These data all show that the MTBE bans had large, discrete effects that coincided with the timing of their enforcement.

Figure 3(b) shows a precipitous decline in MTBE consumption on the East Coast in 2004 that coincided with the New York and Connecticut bans that year, another sharp decline in MTBE consumption at the time of the nationwide phase-out in 2006, and a corresponding surge in ethanol consumption in 2006.[21] Similarly, Figure 3(d) shows a drop

[18]We divide ethanol and MTBE blending quantities by total production by region to get regional blending shares. Data from EIA on blending quantities are available here: `http://www.eia.gov/dnav/pet/pet_pnp_inpt_dc_nus_mbbl_m.htm`. Data from EIA on total production are available here: `http://www.eia.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_m.htm`.

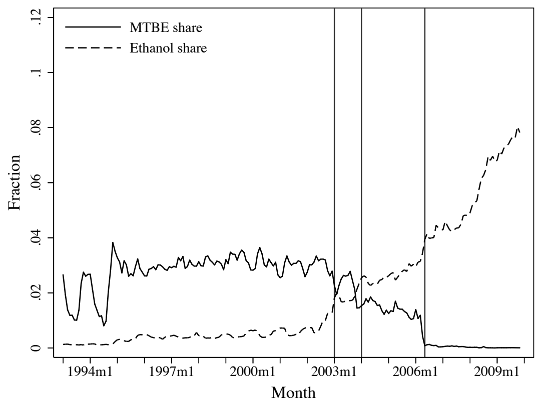
[19]Data from EIA available here: `http://www.eia.gov/dnav/pet/pet_pnp_wprodrb_dcu_nus_w.htm`.

[20]Data from EPA here: `http://www.epa.gov/oms/fuels/rfgsurvey.htm`

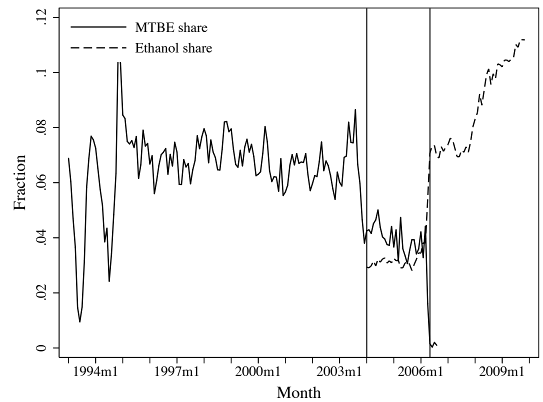
[21]EIA hides ethanol consumption quantities in earlier years to maintain confidentiality; ethanol consumption presumably spiked in 2004 when the New York and Connecticut bans took effect.

Figure 3: Ethanol and MTBE blending quantities by region

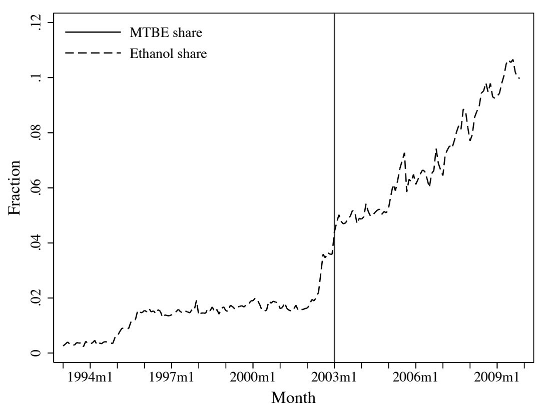
(a) United States



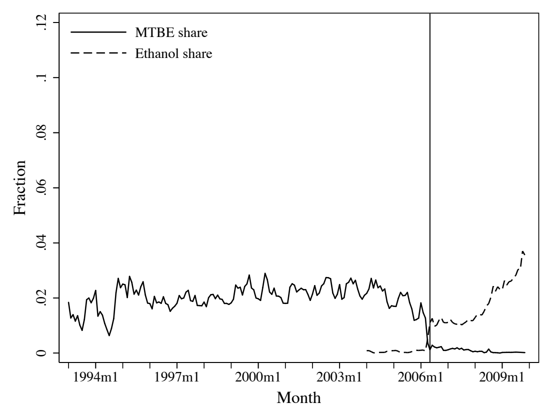
(b) East Coast (PADD 1)



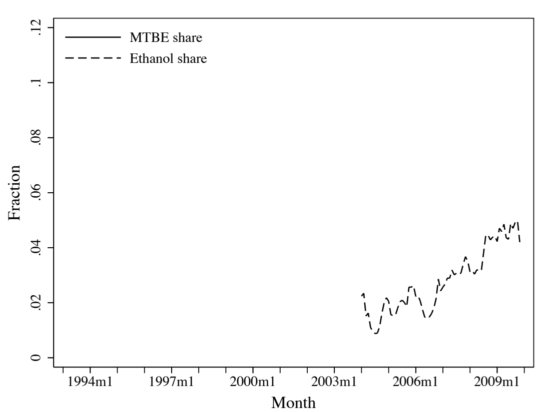
(c) Midwest (PADD 2)



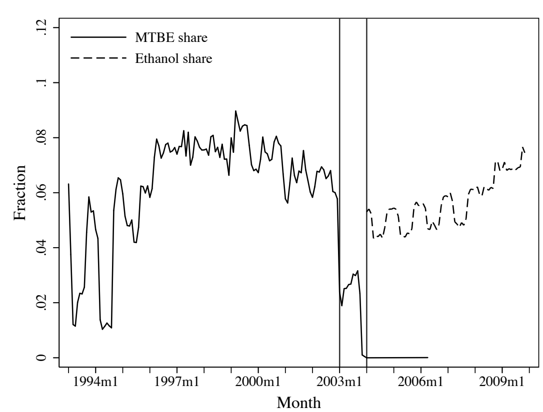
(d) South (PADD 3)



(e) Rocky Mountain (PADD 4)



(f) West Coast (PADD 5)



Note: These figures show monthly ethanol and MTBE volumetric blending shares by U.S. Petroleum Administration for Defense District (PADD). Vertical lines correspond to California's initial MTBE ban and Kentucky's phase-out (January 2003), bans in California, Connecticut, New York, and Washington (January 2004), and the nationwide ban (May 2006) for the regions in which these policy changes were active. See text for details.

Table 2: Ethanol market shares in Reformulated Gasoline, Summers 1999–2006

Area	1998	1999	2000	2001	2002	2003	2004	2005	2006
MIDWEST									
Chicago, IL-Gary, IN	96	100	100	100	100	100	100	100	100
Milwaukee-Racine, WI	97	100	100	100	100	100	100	100	100
St. Louis, MO		20	13	15	98	97	99	100	100
Louisville, KY	30	24	21	26	19	100	100	100	100
Covington, KY	46	75	67	66	67	100	100	100	100
EAST COAST									
Knox-Lincoln Co, ME									
Lewiston-Auburn, ME	0								
Portland, ME	0								
Manchester, NH	0	0	0	0	0	0	0	0	100
Portsmouth-Dover, NH	0	0	0	0	0	0	0	0	100
Springfield, MA	0	0	0	0	0	0	3	24	100
Boston-Worcester, MA	0	0	0	0	0	0	0	3	100
Poughkeepsie, NY	0	0	0	0	0	0	98	100	100
NYC-Long Island, NY-NJ-CT	0	0	0	0	0	0	54	56	100
Hartford, CT	0	0	0	0	0	0	99	100	100
Connecticut	0				0	0	99	100	100
Warren Co, NJ	0	0				0	0	0	100
Atlantic City, NJ		0	0	0	0	0	0	0	100
Rhode Island	0	0	0	0	0	0	0	3	100
Sussex Co, DE		0	0	0	0	0	0	0	99
Philadelphia, PA	0	0	0	0	0	0	0	0	100
Baltimore, MD	0	0	0	0	0	0	0	0	96
Queen Anne-Kent Co, MD				0	0		0	0	93
Washington, DC	0	0	0	0	0	0	0	0	100
Norfolk-Virginia Beach, VA	0	0	0	0	0	0	0	0	99
Richmond, VA	0	0	0	0	0	0	0	0	100
GULF COAST									
Dallas-Forth Worth, TX	0	0	0	0	0	0	0	0	99
Houston-Galveston, TX	0	0	0	0	0	0	0	0	100
WEST COAST									
Phoenix, AZ									
Los Angeles, CA	0	0	0	7	9	93	100	100	
Sacramento, CA	0	0	0	6	7	41	100	100	
San Diego, CA	0	0	0	4	5	65	100	100	
San Joaquin, CA						32	100	100	

Note: This table reports ethanol's summer market share in RFG by year and region, expressed as a percentage of average oxygenate content (ethanol plus MTBE, by weight) that comes from ethanol. Market shares are also available for winter months, but it is unclear whether the winter samples were collected prior to the summer or afterwards, since winter collection dates vary but are not reported. Thus, for consistency, and to ensure proper ordering in time, we only show summer ethanol market shares. The boxes denote location and timing of samples affected by new MTBE bans. All bans are state bans, with the exception of Chicago's city ban in 2001. Note that California's ban initially was to begin in January 2003. See text for details.

in MTBE consumption in the South and corresponding increase in ethanol consumption in 2006. Figure 3(f) shows a precipitous decline in MTBE consumption on the West Coast that coincided with the California ban in 2003–2004.[22] Table 2 confirms these patterns of ethanol and MTBE consumption in RFG for the East Coast, the South (namely, Texas), and the West Coast.

Figure 3(c) shows a surprising increase in ethanol consumption in the Midwest in 2002–2003, since no bans affecting RFG areas took effect that year.[23] Table 2 shows that RFG suppliers in Kentucky and Missouri (both located in the Midwest PADD) switched from MTBE to ethanol in 2002–2003. While MTBE bans in these states took effect in 2005 and 2006, the bans were enacted in the summer of 2002.[24] In addition, Michigan's MTBE ban in 2003 also likely played a role. Michigan had no RFG, but ethanol and MTBE are also valued as octane boosters. In any case, most Midwestern states were already using ethanol prior to when their MTBE bans took effect. Thus, it will be important in our empirical analysis to distinguish the Midwest from the rest of the country where the MTBE bans were actually binding.

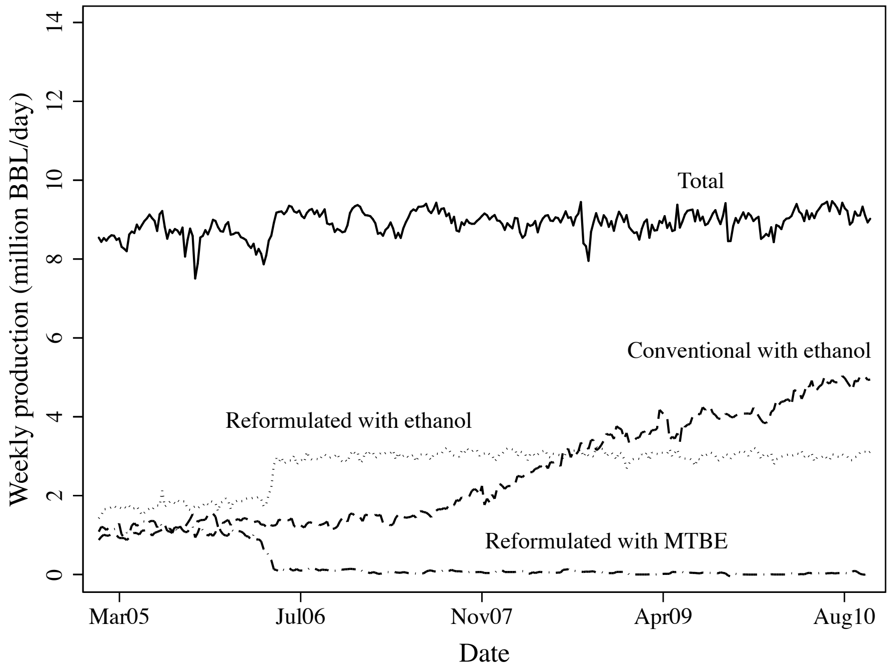
Figures 3 and 4 show a marked rise in ethanol blending beyond 2007, even though the industry had had all but eliminated MTBE from gasoline by this time. The likely reason is that the federal RFS had begun to bind, creating incentives to blend ethanol beyond what earlier regulations required. Beyond 2007, it is clear that ethanol consumption is rising above the level necessary to replace the banned MTBE. A binding federal RFS will tend to increase national gasoline prices, while diminishing the shadow cost of an individual state's MTBE

[22] California's ban was originally scheduled to take effect in 2003, with several gasoline suppliers committing to eliminate MTBE that year. The ban was then delayed until 2004 and some suppliers waited (Executive Department State of California 2002). Table 2 shows that the Los Angeles area nearly eliminated MTBE in 2003, while other areas cut their MTBE consumption roughly in half, and that all areas in California had switched to ethanol by 2004.

[23] While Minnesota increased its explicit ethanol blending requirement from 2.7% to 10% in 2003, the state was already subject to a year-round oxygenation requirement and MTBE ban. Thus, as far as we can tell, Minnesota's policy change in 2003 should have had little effect on ethanol blending.

[24] Besides the MTBE bans, low ethanol prices around this time would have created fairly strong incentives to boost volumes using ethanol as a direct gasoline substitute in regular gasoline, and the Midwest was in a position to do so, given that it already had ethanol distribution and blending infrastructure.

Figure 4: Gasoline production



Note: This figure shows weekly U.S. production of gasoline, conventional gasoline blended with ethanol, reformulated gasoline blended with ethanol, and reformulated gasoline blended with MTBE. See text for details.

ban or ethanol mandate relative to gasoline prices in other states. Thus, we suspect that a binding RFS pushes the estimated impacts of state-level MTBE bans toward zero.

4 Econometric models and estimation results

In this section we present our econometric analyses for retail gasoline prices. We begin by estimating the impact of MTBE bans on average gasoline price levels by state. We then estimate the impact of the bans on the monthly pass-through rates for key commodity inputs, including crude oil, ethanol, and MTBE.

4.1 Data sources

We obtain monthly, state-level data on pre-tax retail gasoline prices from the U.S. Energy Information Administration (EIA). These data report average prices for reformulated and conventional gasoline.[25] We express these and all other prices in January 2009 dollars using the Consumer Price Index (all goods, urban consumers) from the Bureau of Labor Statistics. In our econometric analysis below, we focus on the years 1996–2009—a period that covers all state MTBE bans and during which other major fuel regulations that affected oxygenate blending remained largely unchanged.

We obtain monthly crude oil prices from the EIA. These data measure national average prices paid by domestic refiners for imported crude oil.[26] We obtain monthly ethanol prices from the State of Nebraska Energy Office, which measure monthly wholesale rack prices in Omaha, Nebraska.[27] We obtain weekly data on wholesale MTBE prices from Platt's, which measure wholesale rack prices on the U.S. Gulf Coast. We used these data to calculate monthly average prices.

Table 3 presents summary statistics for these price variables.

4.2 Gasoline price levels

We estimate the effects of MTBE bans on average pre-tax retail gasoline price levels using the following econometric equation:

$$price_{jst} = \alpha_{jt} \cdot ban_{jst} + \delta_{js} + \theta_t + \epsilon_{jst}, \tag{1}$$

[25] Available here: `http://www.eia.gov/dnav/pet/pet_pri_allmg_a_EPM0_PTA_dpgal_m.htm`. Conventional gasoline includes winter oxygenated gasoline in cities and time periods subject to such regulation. While price data for winter oxygenated gasoline areas are also reported separately, these data include many missing observations. In addition, the specific cities and time periods subject to winter oxygenation change over time, conflating changes in gasoline content regulations with changes in seasonality and geography.

[26] Available here: `http://tonto.eia.doe.gov/dnav/pet/pet_pri_rac2_dcu_nus_m.htm`.

[27] Available here: `http://www.neo.ne.gov/statshtml/66.html`. We also obtained weekly data on wholesale rack prices for several-dozen individual U.S. cities for 1996–2008. Monthly average prices based on this sample of cities closely align with the Nebraska series, which is publicly available for the entire sample period.

Table 3: Summary statistics

Variable	Mean	Std.Dev.	Observations
$price_{conventional}$	1.56	0.62	7225
$price_{rfg}$	1.58	0.61	2971
$price_{wholesale}$	1.54	0.61	8364
$price_{oil}$	0.97	0.53	8415
$price_{ethanol}$	1.19	0.53	8415
$price_{mtbe}$	1.46	0.59	7599

Note: This table reports summary statistics for the retail gasoline and wholesale input prices used in the estimation. All prices are in real 2010 dollars per gallon. See text for details.

where $price_{jst}$ is the average price of gasoline sold in state j in season s at time t. The policy variable of interest is ban_{jst}, which is a dummy variable indicating whether a given state is subject to an MTBE ban in a given month, including both state bans as well as the implicit nationwide ban for all states starting in May 2006 and onwards. The coefficient of interest is α_{jt}, which measures the effect of the MTBE ban on average gasoline prices. The variable δ_{js} is a state-season (e.g., Michigan-July) effect that controls for persistent differences in average prices across states and seasons, including seasonality in local gasoline content regulations. The variable θ_t is a time effect that controls for time trends that are constant across states. Lastly, ϵ_{jst} is an error term that we assume is uncorrelated with the MTBE bans.

We have reason to believe that the effect of an MTBE ban will vary over time t and across locations j. For example, MTBE bans will likely have milder effects on gasoline prices in the Midwest, while MTBE bans could raise average prices dramatically when ethanol prices are high. Thus, we allow α_{jt} to vary for Midwestern and non-Midwestern states and with input prices for crude oil, ethanol, and MTBE. In our most general and favored model, the impact of an MTBE ban on gasoline prices takes the form:

$$\alpha_{jt} = \beta_0 + \beta_1 \cdot Midwest_j + \sum_{input} (\beta_{input} + \gamma_{input} \cdot Midwest_j) \cdot price_{input,t}, \quad (2)$$

where $Midwest_j$ is a dummy variable indicating whether a state is in the Midwest PADD and $price_{input}$ is the wholesale price of a particular gasoline input—crude oil, ethanol, or MTBE—less its sample mean (reported in Table 3). Thus, we can interpret α_0 as the effect of an MTBE ban on gasoline prices outside of the Midwest when crude oil, ethanol, and MTBE prices equal their sample-mean values, while $\beta_0 + \beta_1$ is the corresponding effect in the Midwest. The summation term then allows these effects to vary as input prices deviate from their sample-mean values.[28]

We estimate equation (1) separately for conventional gasoline (which includes winter oxygenated fuel in affected areas) and RFG using OLS. The key identification assumption is that the timing of the MTBE bans is uncorrelated with state trends in state gasoline prices. This is a reasonable assumption given that bans were driven primarily by concerns about groundwater contamination and support for the ethanol industry, rather than in response to fuel prices, and were enacted months or years before they became effective. We estimate Newey-West standard errors, which are robust to both heteroskedasticity and serial correlation.[29]

Table 4 presents the results. Focusing on column (4), the coefficients on *ban* and on $ban \times midwest$ indicate that the MTBE bans had virtually no effect on gasoline prices for conventional gasoline, either in the Midwest or elsewhere, when evaluated sample mean oil, ethanol, and MTBE input prices. All else equal, however, a $1 increase in ethanol input prices increases the impact of the MTBE ban by about 3.4 cents per gallon outside of the Midwest, as indicated by the coefficient on $ban \times price_{ethanol}$. All else equal, a $1 increase in MTBE input prices decreases the impact of the MTBE ban by about 5.7 cents per gallon outside of the Midwest, as indicated by the coefficient on $ban \times price_{mtbe}$. The negative

[28]Since an MTBE ban in one state could potentially affect gasoline prices in a different state indirectly via national wholesale markets for fuel inputs, these interactions are also important for identifying all-else-equal effects in the presence of general-equilibrium spillovers.

[29]We regressed the OLS residuals on their lagged values after one month, two months, and so on. We found these autocorrelations to be significant for lag lengths as long as seven months. Thus, we use a seven-month lag when calculating our Newey-West standard errors. To test the robustness of our standard error estimates, we also varied the lag length from 3 to 11 months. While estimated standard errors tended to increase with longer lag lengths, the increase was so slight that it did not meaningfully affect precision relative to the magnitude of our point estimates.

Table 4: Main estimation results: gasoline price levels (dollars)

Coefficient	Conventional gasoline				Reformulated gasoline			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ban	0.014**	0.017**	0.006	0.007	0.013	0.017	0.044***	0.059***
	(0.007)	(0.008)	(0.006)	(0.011)	(0.010)	(0.011)	(0.014)	(0.015)
$ban \times price_{oil}$			-0.084**	-0.041			-0.041	-0.003
			(0.034)	(0.040)			(0.058)	(0.060)
$ban \times price_{ethanol}$			0.020	0.034**			-0.012	0.003
			(0.013)	(0.017)			(0.019)	(0.020)
$ban \times price_{mtbe}$			0.003	-0.057**			-0.037**	-0.078***
			(0.015)	(0.025)			(0.018)	(0.023)
$ban \times midwest$		-0.005		0.002		-0.012		-0.048***
		(0.007)		(0.011)		(0.009)		(0.017)
$ban \times midwest \times price_{oil}$				-0.051**				0.013
				(0.025)				(0.031)
$ban \times midwest \times price_{ethanol}$				-0.021**				-0.044***
				(0.010)				(0.015)
$ban \times midwest \times price_{mtbe}$				0.077***				0.072***
				(0.021)				(0.025)
Observations	7225	7225	6527	6527	2971	2971	2684	2684

Note: This table reports main estimation results. Dependent variable is the average real price of gasoline (either conventional or reformulated) in a given state and month in real 2010 dollars. All regressions control for month effects (e.g., November 2004) and state-season (e.g., Massachusetts-March) effects. Standard errors in parentheses are robust to serial correlation and heteroskedasticity (Newey-West standard errors with a seven-month lag).

coefficients on $ban \times midwest \times price_{ethanol}$ and $ban \times midwest \times price_{mtbe}$ indicate that these impacts are considerably smaller in the Midwest, which makes sense, given that the Midwest would not have been consuming much MTBE prior to the bans anyway. Higher crude oil prices have a statistically insignificant effect on the ban's impact.

Moving now to column (8), which reports results for RFG, we should expect to see a similar pattern of coefficients. The magnitudes should be larger, however, reflecting the fact that all producers of RFG were required to blend either ethanol or MTBE prior to 2006 and had little flexibility to do otherwise, even after the oxygenation requirement for RFG was removed, given other constraints. The coefficient on *ban* indicates that the MTBE bans increased prices for RFG by 5.9 cents outside of the Midwest, assuming sample-mean input prices.[30] The impact on prices in the Midwest is not statistically different from zero. It

[30] These results are consistent with Brown et al. (2008) who find that RFG regulations increased wholesale gasoline prices in select Midwestern cities by 4–9 cents *more* than on the coasts, mainly reflecting higher refining costs for the ethanol-ready RFG blendstock used in the Midwest. Our higher estimates for retail gasoline in coastal states reflect both these higher refining costs, as well as the add-on costs for ethanol transportation and blending.

is not surprising that these impacts are bigger for RFG than for conventional fuel, since RFG requires oxygenate blending, either directly or indirectly—as the lowest-cost approach to meeting other RFG performance standards—and because blending ethanol with RFG requires that refiners significantly reduce the RVP of the underlying gasoline blendstock.

Again, these impacts depend on input prices. Strangely, higher ethanol prices do not increase the impact of the ban, although higher ethanol prices decrease the impact of the ban in the Midwest relative to other states, as expected. Higher MTBE prices strongly reduce the impact of the MTBE ban outside of the Midwest, however, while having little effect on the impact of a ban in the Midwest. These impacts are all higher for RFG than for conventional fuel, which is not surprising, given the greater flexibility of conventional fuel producers. The impact of a ban on RFG prices does not appear to be sensitive to crude oil prices, controlling for other inputs.

In addition to these preferred models, the table also presents results for models that restrict the impacts of MTBE bans to be the same for all states and time periods (columns 1 and 5), different across states but the same across time periods (columns 2 and 6), and different across time periods but the same across states (columns 3 and 7). Two patterns emerge. First, the estimated impact of an MTBE ban is smaller when imposing a constant effect across all locations, which implies that it is important to differentiate the Midwest from states for whom the MTBE bans were binding. Second, the estimated impact of an MTBE ban declines in magnitude when not controlling for nationwide input prices. Apparently, either the timing of the MTBE bans is correlated with wholesale input prices, or local retail markets are connected via national input markets in ways that bias the coefficient estimates toward zero.

4.3 Monthly pass-through rates for wholesale inputs

We now estimate how MTBE bans alter monthly pass-through rates for wholesale input costs using the following econometric equation:

$$\Delta price_{jst} = \sum_{input} (\beta_{input} + \gamma_{input} \cdot Midwest_j) \cdot ban_{jst} \cdot \Delta price_{input,t} + \delta_{js} + \theta_t + \Delta\epsilon_{jst}, \quad (3)$$

where $\Delta price_{jst}$ is the monthly change in gasoline prices in state j in season s at time t. The variables of interest are interactions between the state MTBE bans and monthly changes in the various input prices, given by $ban_{jst} \cdot \Delta price_{input,t}$. Thus, the corresponding coefficients given by $\beta_{input} + \gamma_{input} \cdot Midwest_j$ measure *changes* in input pass-through rates when a state imposes an MTBE ban. As before, these effects are allowed to differ regionally through an additional interaction with $Midwest_j$. Of the remaining terms, δ_{js} is a state-season effect that allows retail prices to follow different time trends by state and season in this first-differenced model, θ_t is a month effect, and $\Delta\epsilon_{jst}$ is an error term. Note that the month effects prevent us from estimating pass-through rates directly, given that our input price data do not vary across states; we are only able to estimate *changes* in pass-through rates. Also note that we have omitted the direct effects of the bans, since the changeovers from MTBE to ethanol in response to state bans, while rapid, typically occurred over the span of several months leading up to the enforcement dates, with the exact timing varying from state to state. Thus, the direct effect on prices would be unlikely to show up in monthly first-differenced data.

As above, we estimate equation (3) separately for conventional gasoline and RFG using OLS. Here, the key identification assumption is that the monthly change in gasoline prices in a state is uncorrelated with the timing of its MTBE ban after controlling for linear state-season trends, which is a weaker assumption than before.

Table 5 presents our results. Focusing on column (2), the coefficient on $ban \times price_{ethanol}$ indicates that an MTBE ban increases the monthly pass-through rate for ethanol prices by

Table 5: Main estimation results: gasoline price first differences (dollars)

Coefficient	Conventional gasoline		Reformulated gasoline	
	(1)	(2)	(3)	(4)
$ban \times \Delta price_{oil}$	0.098**	0.010	-0.035	-0.072
	(0.042)	(0.045)	(0.088)	(0.084)
$ban \times \Delta price_{ethanol}$	-0.011	0.046***	-0.051*	0.008
	(0.015)	(0.018)	(0.029)	(0.027)
$ban \times \Delta price_{mtbe}$	0.029*	-0.086***	-0.056**	-0.121***
	(0.016)	(0.018)	(0.025)	(0.024)
$ban \times midwest \times \Delta price_{oil}$		0.133***		0.079
		(0.031)		(0.053)
$ban \times midwest \times \Delta price_{ethanol}$		-0.080***		-0.152***
		(0.014)		(0.021)
$ban \times midwest \times \Delta price_{mtbe}$		0.151***		0.157***
		(0.014)		(0.024)
Observations	6454	6454	2657	2657

Note: This table reports main estimation results. Dependent variable is the monthly change in the average real price of gasoline (either conventional or reformulated) in a given state and month in real 2010 dollars. All regressions control for month effects (e.g., November 2004) and state-season (e.g., Massachusetts-March) effects. Standard errors in parentheses are robust to serial correlation and heteroskedasticity (Newey-West standard errors with a six-month lag).

0.046 outside of the Midwest, while decreasing the pass-through rate for MTBE prices by 0.086. In the Midwest, an MTBE ban does little to change the pass-through rate for ethanol prices, as expected. Surprisingly, an MTBE ban in the Midwest increases the pass-through rate for MTBE prices by $-0.086 + 0.151 = 0.065$ and increases the monthly pass-through for crude oil prices by $0.010 + 0.133 \approx 0.143$.

Now focusing on column (4), the coefficient on $ban \times price_{ethanol}$ indicates that the MTBE ban unexpectedly does little to change the monthly pass-through of wholesale ethanol prices to retail RFG prices outside of the Midwest, while the coefficient on $ban \times price_{mtbe}$ indicates that the ban decreases the pass-through of wholesale MTBE prices by 0.121, which is what we would have expected. In the Midwest, the MTBE ban unexpectedly decreases the pass-through of ethanol prices while having little effect on the pass-through of MTBE or crude oil prices, as expected. Overall, however, the results are consistent with our conceptual model above. The MTBE bans generally increase the monthly pass-through of ethanol prices and decrease the monthly pass-through of MTBE prices outside of the Midwest, while having little effect on the pass-through of crude oil prices. In the Midwest, the ban's effects either tend to zero or have the opposite sign as in other regions.

In addition to these preferred models, the table also presents results for models that restsrict the effects to be identical across states (columns 1 and 3). As expected, imposing coefficients that are equivalent across states tends to reduce their magnitudes, which again implies that it is important to differentiate between the Midwest and the rest of the country.

4.4 Late enforcement of MTBE bans

A total of six states enacted MTBE bans that took effect subsequent to the nationwide phase-out in the spring of 2006. In principle, these bans should have had no effect on gasoline price levels or input price pass-through rates, given the nationwide phase-out. This is a testable hypothesis. Thus, we create a second policy variable, called $lateban_{jst}$, which equals one for states whose bans took effect after May 2006, in the months these "late" bans were in effect, and zero otherwise. We then repeat each of our previous regressions, including both $lateban_{jst}$ and its interactions with wholesale input prices as additional controls. There is no need to differentiate this policy variable by location, however, since every state with a late MTBE ban was located outside of the Midwest.

Table 6 presents the results for gasoline price levels. We find that the individual coefficients on the late ban variables are generally small and statistically insignificant. Along the bottom of the table, we present the P-values for Wald tests of the joint significance of the *lateban* variables. In our preferred models in columns (4) and (8), the late MTBE bans are only borderline significant at the 8% and 16% levels. Overall, these results are consistent with our identification assumption above that the state MTBE bans were not timed in a way that correlated with gasoline prices, conditional on controls.

Table 7 presents the corresponding results for the impact of MTBE bans on pass-through rates for wholesale input prices. Here, the results are somewhat less rosy. While most coefficients are again statistically insignificant, the interactions with ethanol prices are large and significant, and the P-values for the joint tests are quite small. One possible explanation is that since the nationwide phase-out was not a literal ban, MTBE is in fact used in some rare circumstances when other options are quite costly. In any case, these late bans only occur in four RFG locations, including Maine, New Hampshire, New Jersey, and Rhode Island.

5 Conclusion

We estimate the impacts of MTBE bans on gasoline prices. While interesting in their own right, these bans approximate direct ethanol blending mandates in areas that require oxygenate blending. Thus, these bans help us learn about the potential effects of renewable fuel blending mandates on gasoline prices. We find that MTBE bans increased RFG prices by 6 cents per gallon in areas where the bans were binding. The impacts of a ban would have been bigger had ethanol prices been higher or had MTBE prices been lower. These results represent the first rigorous empirical confirmation of the theoretical result that a percent ethanol blending mandate will inevitably increase fuel prices in a competitive market when the ethanol supply curve is more steeply sloped than that of gasoline—with the obvious qualification that this inference is based on a surrogate policy with similar economic structure.

There are several important caveats to our results and their interpretation. First, we have identified the effects of the MTBE bans on consumers through retail prices. A more complete welfare analysis would obviously require information on producer costs, as well as information on the potential health benefits to those not exposed to environmental contamination. Second, we only present reduced-form impacts on retail prices during the era of the MTBE bans. While we partially decompose these effects according to prices for wholesale inputs, the effects could look different in the long run, as new ethanol blending infrastructure is added, or under substantially different market conditions. Third, while we have shown qualitatively that a state MTBE ban can approximate a state ethanol mandate under certain conditions, the two policies are not identical. Moreover, the shapes of the ethanol and gasoline supply curves to a particular state could look quite different from the shapes of national supply. Thus, while a state ethanol mandate might have qualitatively similar effects to a national RFS, the precise magnitudes would likely differ considerably.

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Table 6: Late bans: gasoline price levels (dollars)

Coefficient	Conventional gasoline				Reformulated gasoline			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ban	0.013**	0.015*	0.006	0.007	0.013	0.018*	0.044***	0.059***
	(0.007)	(0.009)	(0.006)	(0.017)	(0.010)	(0.011)	(0.014)	(0.015)
$ban \times price_{oil}$			-0.084**	-0.044			-0.041	-0.002
			(0.034)	(0.041)			(0.058)	(0.060)
$ban \times price_{ethanol}$			0.020	0.035**			-0.012	0.003
			(0.013)	(0.017)			(0.019)	(0.020)
$ban \times price_{mtbe}$			0.003	-0.057**			-0.037**	-0.078***
			(0.015)	(0.026)			(0.018)	(0.023)
$ban \times midwest$		-0.003		0.002		-0.013		-0.050***
		(0.007)		(0.011)		(0.010)		(0.017)
$ban \times midwest \times price_{oil}$				-0.047*				0.015
				(0.026)				(0.032)
$ban \times midwest \times price_{ethanol}$				-0.023**				-0.044***
				(0.010)				(0.015)
$ban \times midwest \times price_{mtbe}$				0.077***				0.072***
				(0.022)				(0.025)
lateban	0.024***	0.023**	-0.006	-0.006	-0.007	-0.010	-0.044	-0.057**
	(0.009)	(0.010)	(0.022)	(0.023)	(0.009)	(0.009)	(0.028)	(0.028)
$lateban \times price_{oil}$			0.041	0.024			0.019	0.023
			(0.029)	(0.031)			(0.037)	(0.038)
$lateban \times price_{ethanol}$			0.014	0.005			-0.001	-0.016
			(0.032)	(0.032)			(0.035)	(0.034)
$lateban \times price_{mtbe}$			-0.021	0.008			0.015	0.038
			(0.038)	(0.039)			(0.046)	(0.044)
Observations	7225	7225	6527	6527	2971	2971	2684	2684
P-value	0.006	0.016	0.117	0.080	0.435	0.251	0.439	0.157

Note: This table reports results for the "late" state MTBE bans that took effect subsequent to the nationwide ban in May 2006. Dependent variable is the average real price of gasoline (either conventional or reformulated) in a given state and month in real 2010 dollars. All regressions control for month effects (e.g., November 2004) and state-season (e.g., Massachusetts-March) effects. Standard errors in parentheses are robust to serial correlation and heteroskedasticity (Newey-West standard errors with a seven-month lag). P-value in the bottom row is the Wald test P-value for the null hypothesis that the coefficients on all *lateban* variables are jointly zero.

Table 7: Late bans: gasoline price first differences (dollars)

Coefficient	Conventional gasoline		Reformulated gasoline	
	(1)	(2)	(3)	(4)
$ban \times \Delta price_{oil}$	0.098**	0.006	-0.035	-0.074
	(0.042)	(0.045)	(0.088)	(0.084)
$ban \times \Delta price_{ethanol}$	-0.011	0.045**	-0.050*	0.008
	(0.015)	(0.018)	(0.029)	(0.027)
$ban \times \Delta price_{mtbe}$	0.029*	-0.088***	-0.056**	-0.122***
	(0.016)	(0.018)	(0.025)	(0.024)
$ban \times midwest \times \Delta price_{oil}$		0.138***		0.081
		(0.031)		(0.054)
$ban \times midwest \times \Delta price_{ethanol}$		-0.079***		-0.151***
		(0.014)		(0.021)
$ban \times midwest \times \Delta price_{mtbe}$		0.153***		0.159***
		(0.014)		(0.024)
$lateban$	0.006	0.006	0.008	0.009
	(0.006)	(0.006)	(0.005)	(0.005)
$lateban \times \Delta price_{oil}$	-0.025	0.025	-0.040	-0.017
	(0.071)	(0.073)	(0.053)	(0.055)
$lateban \times \Delta price_{ethanol}$	0.102***	0.071*	0.102***	0.057
	(0.039)	(0.038)	(0.037)	(0.035)
$lateban \times \Delta price_{mtbe}$	-0.020	0.037	-0.026	0.023
	(0.031)	(0.030)	(0.032)	(0.030)
Observations	6454	6454	2657	2657
Placebo test P-value	0.046	0.000	0.013	0.016

Note: This table reports results for the "late" state MTBE bans that took effect subsequent to the nationwide ban in May 2006. Dependent variable is the monthly change in the average real price of gasoline (either conventional or reformulated) in a given state and month in real 2010 dollars. All regressions control for month effects (e.g., November 2004) and state-season (e.g., Massachusetts-March) effects. Standard errors in parentheses are robust to serial correlation and heteroskedasticity (Newey-West standard errors with a six-month lag). P-value in the bottom row is the Wald test P-value for the null hypothesis that the coefficients on all *lateban* variables are jointly zero.