Title: Biofuel-Related Price Transmission Using Renewable Identification Number Prices to Signal Mandate Regime

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1. Introduction

Rising biofuel use in the United States has raised questions about the interactions between energy and agricultural commodity prices. This expansion of use has been attributed, in part, to tax credits and the Renewable Fuel Standard (RFS). These interventions can lead to questions about whether public policy has helped generate links between energy markets and agricultural markets, with the potential consequence that volatility in one market can be communicated to the other. In this study, we derive theoretical relationships among petroleum, biofuel, and agricultural commodity prices in the context of biofuel mandates, then apply time series methods to estimate the strength of these links.

Studies that use historical data often represent market conditions when there were only very small shares of biofuel in liquid fuels and very small shares of feedstocks devoted to biofuel production. In the case of ethanol and corn, for example, the current shares are on the order of ten times their levels in the early 1980s (Figure 1). A key question, then, is whether rising biofuel use has created strong links between petroleum product prices and biofuel feedstock prices. If so, then this finding might lead decision makers to consider the potential for biofuel policies to achieve objectives relating to energy security and greenhouse gas emissions while putting greater weight on impacts of such policies on agricultural commodity price levels and volatility. If biofuels do not create a strong link between petroleum and agricultural crop markets, then the possible impacts on producers and other consumers of agricultural commodities might not be a serious consideration.

Figure 1. The shares of corn used for ethanol and co-products in total corn demand and ethanol in total motor vehicle fuel (by volume) in the United States.

Sources: USDA, EIA.

The United States RFS was created by the Energy Policy Act of 2005, then revised and expanded by the Energy Independence and Security Act (EISA) of 2007. This latter Act created four nested renewable fuel use mandates: (1) overall renewable fuels, which includes conventional ethanol made from corn, that meet certain criteria including at least a 20% reduction in greenhouse gas (GHG) emissions relative to the competing petroleum product in the base period; (2) advanced biofuels that reduce GHG emissions by no less than 50% and are not made from corn starch; (3) biomass-based diesel with at least 50% GHG reduction; and (4) renewable fuels made from cellulosic and agricultural wastes that reduce GHG emissions by at least 60%. Basic economic theory suggests that the presence of a mandate can affect prices in the market (Thompson et al., 2009b).

Renewable Identification Numbers (RINs) are the mechanism by which obligated parties demonstrate their compliance with the RFS requirements. There is a type of RIN associated with each category of the mandate. They are generated when biofuels are produced domestically or imported, and they are retired to meet the mandate or to offset other uses (namely exports). RINs are tradable, and data services that report energy prices also report RIN prices (Figure 2). Large RIN prices could imply a large price wedge and binding mandate, and small RIN prices could imply a small price wedge and potentially non-binding mandate. Thus, RINs are a useful, available gauge of whether or not mandates are binding. Thompson et al. (2010) outline complications, such as the interaction of RIN prices given that the mandates are not independent

of one another, the responsibility of the EPA to waive mandates if conditions warrant, and the limited potential for carryover given the rules

Figure 2. Renewable Identification Number (RIN) prices.

review provided by Serra and Zilberman (2013). Reviewed studies identify that fuel and energy costs of agricultural production might have driven the inter-market links historically, before biofuel use expanded. Serra and Zilberman acknowledge the role of structural models in studying price levels over time, while advocating time series estimation to study the short- and long-term price relationships in terms of level and volatility, although this method's limits are also acknowledged. They conclude from their review that energy prices determine agricultural commodity prices over time, and that volatility in energy markets is transferred to agricultural commodity markets.

We identify a few germane studies that are not included in this review. Gardebroek and Hernandez (2013) test the transmission of volatility among petroleum, ethanol, and corn prices from 1997 to 2011, finding greater transmission from corn price to ethanol price beginning in 2006, not vice versa, which they attribute at least in part to MTBE replacement. They did not, however, find evidence of links between petroleum and corn prices. The role of MTBE replacement in ethanol markets has also been discussed in the context of general market assessment, and identified as a key driving force behind the increasing ethanol price in 2006 (Westhoff et al., 2007). Relevant to the question of wholesale-retail price links, Venditti (2013) estimates nonlinear impulse response functions using weekly prices of petroleum, gasoline, and ethanol-gasoline to find asymmetric adjustment in retail prices in the US, but mixed evidence of asymmetric adjustment in selected euro area countries. Tong et al. (2013) also estimate

asymmetric links between petroleum and petroleum product markets, but use a copula model. Other studies investigate the links between petroleum price and other factors, such as equity markets (Souček et al., 2013), global economic activity as proxied by shipping costs (Kolodziej and Kaufmann, 2014), or exchange rate (Beckmann and Czudaj, 2013). Merkusheva and Rapsomanikis (2014) estimate a non-linear long-run relationship between monthly crude oil, ethanol, maize, wheat, and rice prices from January 1980 to April 2012, but this is subject to prices drifting apart in shorter time periods.

Many empirical studies have estimated price transmission between petroleum and agricultural markets, but none of them take advantage of key information about the biofuel mandates that can affect these relationships. Serra and Zilberman's review and the individual studies listed above attempt to align results indicating faster or slower price adjustment in recent years to market conditions and the mandate, but make no reference to the RIN price as a means of measuring the degree to which the mandate is binding. The one exception that uses time series RIN price data for assessing mandate regime is an analysis that focuses on RIN prices themselves, testing whether RIN price behavior is consistent with theoretical expectations, and appends tests of ethanol-corn-gasoline price links that divide the sample according to mandate regime as signaled by the conventional RIN price (Whistance and Thompson, 2014). The fact that mandates are present and matter is hardly new, even to the point of identifying the potential for regime switching (Thompson et al., 2009a) However, that research employs simulation output from a forward-looking structural economic model rather than historical time series price data. Their finding relies on how the market structure and behavior are modeled initially and is not a result of estimated relationships that are validated over observed data.

To the best of our knowledge, no research exploits RIN price data thoroughly to support assessment of crop, biofuel, and petroleum market price links. In particular, we are aware of no efforts to develop a broad theoretical framework that relates RIN prices to price links that might be caused by the recent sharp increase in ethanol and biodiesel volumes and apply it to spot and futures prices.

Our method takes into account the fact that a binding mandate can affect energy and agricultural commodity price relationships, uses RIN prices to determine whether or not a mandate is binding, and then applies this information to tests of interaction in futures and spot price levels. We sidestep complications regarding RIN markets and mandates because we do not focus on either per se. Instead, we rely on the power of RIN prices to signal whether markets operate in a binding mandate regime or a non-binding mandate regime. Applying this framework to observed levels of futures and spot prices of petroleum, petroleum products, biofuels, and agricultural commodities, we test for different relationships in the binding and non-binding regimes separately.

To test those relationships in the context of this framework, we rely on standard cointegration testing methods. Individual data series, discussed in detail below, are first tested for stationarity. We use the Augmented Dickey-Fuller (ADF) method as our primary stationarity test and, as a robustness check, the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) method. To test for cointegration among pairs of nonstationary variables, we perform the ADF test on estimated

residuals. As a further check for cointegrating relationships, we also perform the Johansen Trace test on those pairs¹.

3. Theory and calculation

In this section, we introduce a representation of long-term price relationships in a competitive market, identify how RIN prices signal mandate regimes, discuss the practical obstacles that separate the derived equations and feasible empirical tests, then list the tests of spot and futures prices that we conduct.

3.1. The role of RINs in price relationships

Economic theory suggests that a binding mandate can affect the relationship between prices producers receive and consumers pay for the good. In the context of biofuels, the producer price, consumer price, and applicable RIN price relationship are assumed to take the following form for a given biofuel in a competitive market:

$$(1) P^{\text{producer}} = (P^{\text{consumer}} - M) + P^{\text{RIN}} + C.$$

P^{producer} is the price paid to the biofuel processor or importer. P^{consumer} is the price that the biofuel consumer pays. The consumer price is adjusted by M , the marketing margin, including fuel taxes, to derive a wholesale equivalent. Any tax credit, C , available for blending the biofuel in question must also be taken into account.² Prolonged deviations from the price relationship of equation 1 over time could imply sustained long-run economic profits or losses in this representation.

The RIN price, P^{RIN} , is a key variable in this equation. If there was no tax credit and the mandate was not binding, then the zero-profit condition of a competitive market over time would suggest that the producer and consumer prices are equal, after taking account of marketing margins. In the presence of a binding mandate, then the zero-profit condition of a competitive market could require that the effects of a market shock are bid into prices such that the difference between producer and consumer prices (evaluated at wholesale level) continues to equal the RIN price. Considering shifts in market supply and demand in the presence of a binding mandate, a positive RIN price can signal a disconnect between biofuel producer and consumer prices. For example, weakening biofuel demand in the presence of a binding mandate would lead to a falling consumer price and rising RIN price, but no change in producer price. A shock that reduces biofuel supply would lead to a rising producer and RIN price, but no change in consumer price if the use mandate determines the quantity consumed.

The long-run relationship between a biofuel feedstock price and the producer price of that biofuel in a competitive market can also be represented in a single equation, namely

$$(2) P^{\text{producer}} = \alpha P^{\text{feedstock}} + O - S.$$

¹ For further details of our testing method, please refer to the supplementary information document.

² The blenders tax credit for ethanol expired during the sample period, at the end of December 2011. The biodiesel blenders tax credit expired at the end of 2009, was reinstated in late 2010 and applied retroactively, expired at the end of 2013, and was reinstated retroactively at the end of 2014 before being allowed to expire again.

The producer price of the biofuel is the same as before. The feedstock price, $P^{\text{feedstock}}$, is multiplied with a fixed conversion rate, α , to calculate total feedstock cost per unit of biofuel produced. Other costs, O , are included as well. In principle, subsidies, S , could play a role during the sample period for cellulosic biofuel.³ Setting aside state-level support to biofuel plant production or refineries, S is zero for other biofuels at the federal level.

The price relationship between the biofuel and related petroleum product price is assumed to be
 (3) $P^{\text{consumer}} = f(P^{\text{petroprod}}, Z)$.

The consumer price for the biofuel is expressed as an inverse demand that depends on the price of the associated petroleum product, $P^{\text{petroprod}}$, and other factors, Z . It might be appropriate for many applications simply to assume that the two goods are necessarily substitutes, perhaps at energy equivalence.

The market structure and mandate operation during our sample period lead to another possibility: a complementary relationship between at least one biofuel and corresponding petroleum product. Recent data suggest that E10, a blend of 10% ethanol and 90% gasoline, use is ubiquitous in the US, and market commentary indicates that petroleum derivatives used as inputs into liquid fuel production are designed to be mixed with ethanol in order to achieve the appropriate octane level at that blend rate. Thus, MTBE replacement with ethanol as the primary oxygenate could suggest that ethanol and gasoline are complements, not substitutes. The mandate is applied as a minimum share of biofuel use in total domestic fuel use within any given year, also suggesting the possibility of a complementary relationship (EPA, 2009). While the view that these fuels are substitutes in the long run or looking ahead to potential high-blend fuel use might be more relevant for certain decision makers, the short-run interaction might be characterized by complementarity.

Potential complementarity will be relevant in the discussion of results. *A priori*, we expect the prices of complementary goods need not move alike in response to all shocks. For example, a negative supply shock to either good will tend to increase the price of that good but decrease the price of the complement, all else equal. In contrast, motor fuel demand shocks might tend to cause the prices of the goods to rise or fall together. As a consequence, we take evidence of no cointegrating relationship between two prices in our empirical results as an indication that the goods are not strong substitutes, but this result does not rule out the possibility of a complementary relationship.

In the extreme case of perfect substitution, then the price relationship in a competitive market takes the form

$$(3a) \quad P^{\text{consumer}} = \sigma P^{\text{petroprod}},$$

where a coefficient, σ , might be thought of as an adjustment based on physical properties that affect substitutability, like energy content. More generally, prices of substitutes are expected to tend to move alike, rising and falling together, depending on degree and speed of substitution.

³ The present paper focuses on historical data and the policies and technologies present in that period. Other policies that target cellulosic biofuel might be relevant in other contexts. To give two examples, there was a tax credit associated with cellulosic biofuel production and the Biomass Crop Assistance Program to facilitate cellulosic feedstock development during the sample period. These policies are not relevant to our empirical exercises.

A goal of the present exercise is to test this relationship empirically, if possible. Similar price movements could be driven by factors other than substitution but would also be consistent with a substituting relationship between the biofuel and petroleum product. On the other hand, prices failing to move alike might argue against a substituting relationship but does not prove that there is no relationship at all, as noted above.

We assume that the petroleum price, P^{petro} , and petroleum product price, $P^{petroprod}$, are also related through the refinery activities as

$$(4) P^{petroprod} = \beta P^{petro}.$$

This representation omits many important considerations, chief of which might be the fact that gasoline and diesel are co-products from the refining process. It is useful for the purposes of this exercise to simplify the representation to a linear relationship and maintain the focus on a single biofuel, and more particularly on the role of the corresponding RIN price. A more elaborate representation could take into account the cracking margin and consequently develop the relationships between the key biofuels, ethanol and biodiesel, and their associated petroleum-based products, gasoline and diesel, at the same time.

We combine the equations above and rearrange terms to sketch out additional relationships between these prices in a competitive market. The set of price relationships culminates in a link between the key indicator prices of petroleum and the agricultural commodity feedstock:

$$(5) P^{producer} = f(P^{petroprod}, Z) + P^{RIN} + (C - M);$$

$$(6) P^{producer} = f(\beta P^{petro}, Z) + P^{RIN} + (C - M);$$

$$(7) P^{consumer} + P^{RIN} + (C - O + S - M) = \alpha P^{feedstock};$$

$$(8) f(P^{petroprod}, Z) + P^{RIN} + (C - O + S - M) = \alpha P^{feedstock}; \text{ and}$$

$$(9) f(\beta P^{petro}, Z) + P^{RIN} + (C - O + S - M) = \alpha P^{feedstock}.$$

More direct relationships are possible if a biofuel and the corresponding petroleum product are perfect substitutes. In this special case, the consumer price of the biofuel can be linked to the petroleum product price using a single coefficient. Equations above can be simplified to

$$(5a) P^{producer} = \sigma P^{petroprod} + P^{RIN} + (C - M);$$

$$(6a) P^{producer} = \sigma \beta P^{petro} + P^{RIN} + (C - M);$$

$$(8a) \sigma P^{petroprod} + P^{RIN} + (C - O + S - M) = \alpha P^{feedstock}; \text{ and}$$

$$(9a) \sigma \beta P^{petro} + P^{RIN} + (C - O + S - M) = \alpha P^{feedstock}.$$

These equations imply testable long-run relationships among these prices. There are any number of complications, as discussed later. However, this representation highlights the role of the RIN price in these relationships, as well as in signaling mandate regime change.

Take the case of a non-binding mandate. In this case, the RIN price is zero in the approach above. All the price relationships above should be unaffected by the mandate. If the biofuel and corresponding petroleum product are substitutes, then we expect from the relationships outlined above to see co-movements in the prices of the biofuel, petroleum product, petroleum, and feedstock to be manifested in the data over time. Failure to detect such a link could indicate there is no relationship or, as noted earlier, that the products are complements.

If the use mandate is binding and the RIN price is greater than zero, then the binding mandate regime can sever these price relationships. As stated in the context of equation 1, a binding mandate means that changes in the biofuel producer and consumer prices might be transmitted to

changes in the RIN price. The link between these two prices is severed by the binding use mandate. As a consequence, the links of equations 5-9 are also severed. The feedstock price and the biofuel producer price are unrelated because a shock that affects either price would be absorbed by a change in the RIN price. Similarly, the link between feedstock price and the prices of petroleum and the related petroleum product would no longer be present in the presence of a binding biofuel use mandate because shocks to one price would affect RIN prices, not the other fuel prices.

3.2. Reality is inconvenient

There are practical obstacles to applying this theory. We discuss three that are particularly germane. In addition, there are any number of complications to empirical examination of these prices. Some are noted above, such as the fact that gasoline and diesel are co-products from petroleum, and the role of fuel and energy prices in agricultural commodity production costs. Similarly, marketing margins and other biofuel processing costs in the equations above likely are related, at least somewhat, to fuel prices. In addition, price relationships might be attenuated or more difficult to test if the length of adjustment time is long or in the presence of non-competitive behavior.

One challenge is that biofuels are blended with petroleum products, not sold as explicit, separate goods. As noted above, ethanol in the United States can be sold in blends with 10% ethanol, called E10, and this form of fuel comprises nearly the entire motor fuel pool used in the country at the time of writing. E85 contains more ethanol, but can only be used in flex fuel vehicles. In addition, regulatory approval for E15 has not translated into any significant amount of E15 sales. A key challenge associated with the mandates is reconciling the rising biofuel use mandates that could lead to a rising need for ethanol use and the difficulty of expanding ethanol use beyond the levels of the now-saturated E10 market (called the blend wall). In 2013, the challenge was manifested in the run-up in conventional RIN prices and proposals to use the waiver to reduce the mandates to lower amounts. Biodiesel does not face the same blend wall problem at present, but it is also blended with a petroleum product, diesel, for retail sales.

A consequence of blending is that there is no measured retail price of these biofuels in the United States. Data representing clear gasoline (i.e. 0% ethanol) price at retail have also become scarce, and perhaps are no longer representative. Instead, retail fuel prices for E10, E85, B2, and diesel can be observed. No tests are conducted here using blended fuel retail prices because the meaning of results for price transmission among markets would be unclear. Equation 1 cannot be tested.

Equation 1 provides a proxy value for the fuel value of biofuel. Rewriting, this equation becomes (1a) $(P^{\text{consumer}} - M) = P^{\text{producer}} - P^{\text{RIN}} - C$.

For example, ethanol fuel value at the wholesale level equals the conventional ethanol wholesale price minus conventional RIN price minus any tax credit. Similarly, biodiesel fuel value equals the biodiesel wholesale price minus biodiesel RIN price minus any tax credit. However, this approach ignores marketing margins and fuel taxes, so the proxy is a wholesale equivalent of the implied retail value of the fuel.

Another challenge is that RIN rules are complicated. Our focus in this study, however, is on the relationship among key petroleum, petroleum product, biofuel, and agricultural commodity spot and future prices, not RINs. We use RIN prices to signal mandate regimes, but we have no interest in deducing how RIN prices might be taken explicitly into account in some sense, much less subject to direct testing. Such an investigation would require an elaboration of the implications of mandate law and implementing regulations. For example, how do interlocking mandates affect RIN prices? How do rules about RIN rollover from one year to a next, implying that they expire, affect pricing? Such questions presumably must be considered if RIN prices are to be assessed.⁴

All RIN pricing complications cannot be completely ignored, however, even for our purposes. One key decision is to determine how low the RIN price must be to indicate a non-binding mandate, and for how long. There are always transaction costs built into RIN prices, as some parties must buy RINs to meet their requirement, so RIN prices are never actually zero (see Figure 2) even if total biofuel use vastly exceeds the mandated volume. There is also the potential for a speculative component. If the mandate is not binding in the current year, but has at least a remote chance to become binding the next year, then there will be some demand to carry extra RINs. This speculative demand could lead to a RIN price running a bit above zero, yet might not affect the links among commodity prices very much, if at all.

A relationship embedded in RIN prices can be used to infer a price of advanced ethanol. Wholesale conventional, or corn starch, ethanol prices are available, but domestic prices of advanced ethanol are not so easily observed. Most advanced ethanol is imported sugarcane ethanol, but the available Brazilian ethanol prices are set at a distant location relative to the US market and might not relate to US prices directly at times when no trade is taking place. There are at least three alternative relationships that can be used to calculate an advanced ethanol price:

(10a) $P^{\text{advanced ethanol}} = f(P^{\text{Brazilian ethanol}})$, if US imports ethanol;

(10b) $P^{\text{advanced ethanol}} = P^{\text{advanced RIN}} + (P^{\text{conventional ethanol}} - P^{\text{conventional RIN}})$, under all conditions; and

(10c) $P^{\text{advanced ethanol}} = f(P^{\text{conventional ethanol}})$, if US exports conventional ethanol to Brazil.

Advanced ethanol price relationships can be tested using the Brazilian price as a proxy for the domestic advanced ethanol price, as in equation 10a. Alternatively RIN prices and the known conventional ethanol price at wholesale can be used to derive an implicit advanced ethanol price as in equation 10b: advanced ethanol price equals conventional ethanol price minus conventional RIN price plus advanced RIN price. The intuition is that the conventional ethanol price less conventional RIN price estimates the value of ethanol at wholesale, independent of RINs and the mandates. At that point, there is no distinction between ethanol derived from corn starch or sugarcane. Adding the advanced RIN price to the implied ethanol value at wholesale estimates the price of advanced ethanol as the sum of the (a) value of ethanol as a fuel and (b) the value of this fuel towards complying with the mandate. We test this calculated advanced ethanol value by comparing it statistically to the Brazilian ethanol price in section 4.

⁴ As noted earlier, the only example of which we are aware focuses mostly on RIN prices themselves, and only extends to some of the considerations regarding corn and conventional ethanol (see Whistance and Thompson, 2014).

A complicating factor during the sample period regarding the interaction of Brazilian and US ethanol prices is that the US, at times, exported conventional (corn starch) ethanol at one price while importing advanced (sugarcane) ethanol at a higher price, sometimes concurrently. In part to test the potential that the link between Brazilian and US advanced prices might be driven through US conventional ethanol exports to Brazil rather than by US advanced ethanol imports from Brazil, we test the relationship of ethanol prices between these countries using the conventional ethanol price, as described in equation 10c, in section 4.

Finally, we also test cointegration between key indicator prices. It is possible that the interaction between biofuels, petroleum products, and biofuel feedstocks might cause relationships such as the following to hold over time:

$$(11a) P^{\text{producer}} \leftrightarrow P^{\text{petroprod}};$$

$$(11b) P^{\text{feedstock}} \leftrightarrow P^{\text{producer}};$$

$$(11c) P^{\text{feedstock}} \leftrightarrow P^{\text{petroprod}}; \text{ and}$$

$$(11d) P^{\text{feedstock}} \leftrightarrow P^{\text{petro}}.$$

These relationships might be sensitive to whether or not the mandate is binding. Their inclusion without incorporating RIN price information about mandate conditions might be questioned given the text above. That said, these more direct tests that are not informed by RIN price information are apt to be most comparable with previous findings. Moreover, the final test represented in equation 11d is perhaps the one that might correspond with one argument of the food-versus-fuel debate, namely that energy prices could dictate agricultural prices through their influence on biofuel markets and feedstock demand. Even this interaction falls short of measuring food and fuel prices by ignoring the fact that prices of biofuel feedstocks, such as corn and soybean oil, might be separated from food prices consumers pay by any amount of refining or processing, packaging, distribution, and other activities.

3.3. Data

Tests are conducted using mostly daily data, much of it beginning in January 2009 and ending at the close of March 2015, with some exceptions (Table 1). In this period, changes to the mandates caused by the EISA of 2007 were mostly implemented, so RIN prices can be assessed in a consistent manner. In contrast, earlier RIN price data might have to be interpreted at least somewhat differently because their meanings changed when the mandates changed.

More recent data are presumably more relevant to decision-makers, who look ahead. Changes in the ethanol markets jeopardize the relevance of older data that predate the current ubiquity of E10. Some price data extend further back in time, but the relevance of those data to current markets seems limited given the small quantities of biofuels used, the market changes wrought by MTBE replacement and other factors (Figure 1). For example, relationships through agricultural production costs associated with fuel and electricity might have been the dominant link between energy and agricultural prices, whereas modest volumes of biofuel use might have been irrelevant. As discussed earlier, there are other studies of historical price relationships. Our contribution focuses on recent events and the role of the mandate, not a review of historical relationships that predate current market structure and policy.

1 We do not test links between spot and futures prices. While such tests are certainly important
2 (e.g. Chen et al., 2014), they are not relevant to the questions addressed here, namely RIN price
3 signal of mandate regime change in cross-good price relationships. The potential that RIN prices
4 could signal mandate regime change in the inter-temporal links of one good's spot and future
5 prices is not addressed here.
6

1 Table 1. Data used for analysis.

	Units	Description/Source	Dates
Futures prices			
Gasoline	\$/gal	Front-month RBOB futures, NYMEX	01/02/2009 to 03/31/2015
Corn	\$/bu	Front-month Corn futures, CBOT	01/02/2009 to 03/31/2015
Ethanol	\$/gal	Front-month Ethanol futures, CBOT	01/02/2009 to 03/31/2015
Crude oil	\$/bbl	Front-month WTI futures, NYMEX	01/02/2009 to 03/31/2015
Sugar	\$/cwt	Front-month Sugar futures, ICE	01/02/2009 to 03/31/2015
Diesel	\$/gal	Front-month ULSD futures, NYMEX	01/02/2009 to 03/31/2015
Soybean oil	\$/cwt	Front-month Soybean oil futures, CBOT	01/02/2009 to 03/31/2015
Spot prices			
Retail gasoline	\$/gal	National average for regular unleaded, AAA	01/02/2009 to 03/31/2015
Implied retail ethanol	\$/gal	Implied value of ethanol at retail level, Calculated	02/09/2012 to 03/31/2015
Corn	\$/bu	North Central IL No.2 Yellow, USDA	01/02/2009 to 03/31/2015
Conventional ethanol	\$/gal	Chicago spot price, OPIS	02/09/2012 to 03/31/2015
Advanced ethanol	\$/gal	Implied value of advanced ethanol, calculated	02/09/2012 to 12/31/2013
Brazilian ethanol ^a	\$/gal	Sao Paulo anhydrous, UNICA	01/02/2009 to 03/31/2015
Gasoline	\$/gal	Kankakee, IL reformulated 87 unleaded, DTN Energy	01/02/2009 to 03/31/2015
Crude oil	\$/bbl	WTI spot, Bloomberg	01/02/2009 to 03/31/2015
Sugar	\$/50 kg	Brazil crystal sugar, CEPEA	01/02/2009 to 03/31/2015
Retail diesel	\$/gal	National average for No.2 ULSD, AAA	01/02/2009 to 03/31/2015
Retail Biodiesel	\$/gal	Implied value of biodiesel at retail level, Calculated	02/09/2012 to 03/31/2015
Biodiesel	\$/gal	Chicago SME spot, OPIS	02/09/2012 to 03/31/2015
Diesel	\$/gal	Argo, IL No. 2 ULSD spot, DTN Energy	01/02/2009 to 03/31/2015
Soybean oil	\$/cwt	North Central IL Crude Soybean Oil, USDA	01/02/2009 to 03/31/2015
RIN prices			
Overall (D6)	\$/RIN	Daily average, OPIS	02/09/2012 to 03/31/2015
Advanced (D5)	\$/RIN	Daily average, OPIS	02/09/2012 to 03/31/2015
Biodiesel (D4)	\$/RIN	Daily average, OPIS	02/09/2012 to 03/31/2015

^a denotes weekly price series

4. Results and discussion

Our empirical tests show how the theoretical outline above can be implemented in statistical experiments. The results presented reflect one application over one choice of time period, frequency, and source data. The experiments are organized in this section as follows:

- 1) Preliminary tests for stationarity among variables
- 2) Experiments without using information in RIN prices test relationships among prices in the broadest terms;
- 3) RIN price data are used to generate an estimate of the advanced ethanol price in the US, and this price is tested against theoretical expectations of its relationship with other observed prices that should be related to US advanced ethanol price; and

- 4) RIN price data are exploited to generate estimated prices and also to define binding and non-binding mandate regimes for empirical tests of the theoretical relationships presented earlier.

This last element of the empirical tests raises the question of what level of RIN price indicates that a mandate is binding or not. We do not see this as a yes-or-no cutoff. Instead, we define a band of RIN price levels that are indeterminate. We exclude strings of observations associated with those ranges, with sets of observations associated with RIN prices below that range judged to be in the non-binding regime and observations associated with RIN prices above that range judged to be in the binding regime. The reasons for this treatment are discussed later, after the first two sets of experiments that do not divide the sample period according to mandate regime.

4.1. Preliminary tests for stationarity

We first tested the individual variables for stationarity using the Augmented Dickey-Fuller (ADF) test (Table 2). Autoregressive lags for the ADF tests were chosen by minimizing the Schwarz-Bayesian Criterion (SBC) while assuming the moving-average lag is zero. For the ADF test, this study used the τ critical values (given by SAS). The appropriate estimate for each test was determined by the number of AR lags and whether or not the variables exhibited a zero mean, a non-zero mean, or an apparent trend.

As a robustness check, we also tested the variables for stationarity using the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test (Table 2). The null hypothesis of the KPSS test is opposite that of the ADF test. In every case, the KPSS and ADF tests reach the same conclusion at the 10% significance level. As a further check, there was only one discrepancy at the 5% significance level.

Table 2. Results of stationarity tests applied to individual variables (S=stationary, NS=nonstationary)

	Full Sample		Regime 1 (02/2012 to 09/2012)		Regime 2 (01/2013 to 04/2015)	
	ADF test	KPSS test	ADF test	KPSS test	ADF test	KPSS test
Futures prices						
Gasoline	NS	NS	NS	NS	NS	NS
Corn	NS	NS	NS	NS	NS	NS
Ethanol	NS	NS	NS	NS	NS	NS
Crude oil	NS	NS	NS	NS	NS	NS
Sugar	NS	NS	NS	NS	NS	NS
Diesel	NS	NS	NS	NS	NS	NS
Soybean oil	NS	NS	NS	NS	NS	NS
Spot prices						
Retail gasoline	NS	NS				
Retail ethanol	NS	NS				
Corn	NS	NS	S	S	NS	NS
Conventional ethanol	NS	NS	NS	NS	NS	NS
Advanced ethanol ^a	NS	NS				
Brazilian ethanol ^a	NS	NS				
Gasoline	NS	NS	NS	NS	NS	NS
Crude oil	NS	NS	NS	NS	NS	NS

Sugar	NS	NS						
Retail diesel	NS	NS						
Retail biodiesel ^b	NS	NS						
Biodiesel	NS	NS						
Diesel	NS	NS						
Soybean oil ^{a,b}	NS	NS						
^a : KPSS test results were sensitive to whether or not a trend was present								
^b : ADF test results were sensitive to whether or not a trend was present								
Note: Significance level in each case is 10%								

4.1. Experiments without using information in RIN prices

Statistical tests to detect cointegration in daily commodity price data are conducted over the full sample period. Results of the tests start with the broadest measures (Table 3). These are the tests that are most aligned with the basic premise of the general food-versus-fuel theme that price changes in energy markets can be transmitted to agricultural commodity prices through biofuel markets. These experiments are narrowly defined relative to that broad theme: we test short-run cointegration over daily data and only during a specific interval of time. The purpose of these experiments is to set the stage for later tests that exploit information contained in RIN prices.

These initial tests do not incorporate RIN price data in any way. However, based on the discussion above, it should be clear that expectations of cointegrating relationships in this table might implicitly assume something about RIN prices. Consider the first test, which relates the spot prices of conventional ethanol and gasoline. This experiment tests the direct relationship outlined in equation 11a. If this experiment is based on the earlier equations that delineate price relationships with greater detail, then the conventional ethanol and gasoline prices should be related if the RIN price is constant – and presumably zero – in equation 5. As the first relationship speaks to how movements in gasoline price relate to movements in the conventional ethanol price, the corresponding conventional RIN must not be changing to absorb price changes on one side or the other. If RIN price fluctuations absorb market shocks, then the outcome of shocks in ethanol demand or biofuel supply is a more or less binding mandate (higher or lower RIN price), not a transmission of the shock between biofuel supply and demand. If this is the case, then the prospect of a cointegrating relationship is diminished if the RIN price is not constant.

In the table of results, we state the equation tested. We also state the assumption about the RIN price that corresponds to the expectation that the two prices are correlated. Thus, while these tests do not use RIN prices, they bear implicit assumptions about what the RIN price could be. This is not the only assumption implied by assertions of price links. For example, the goods are likely deemed to be substitutes, and this is why prices could tend to move together and are cointegrated. In fact, as noted earlier, the biofuel and petroleum product could be complements, particularly in this time period over daily data. Prices of complementary goods can be related, but might not tend to move alike, depending on whether demand- or supply-side shocks are more prevalent (as discussed earlier).

1 We conduct these tests on spot and futures prices. Augmented Dickey-Fuller (ADF) and
2 Johansen Trace (Johansen) tests confirm that there is a link between petroleum and petroleum
3 product prices, indicating that equation 4 holds in this period, as expected. The conventional
4 ethanol and gasoline prices are also cointegrated in tests of equation 11a, if tested over the entire
5 period and hence ignoring the fact that the RIN price changed substantially in this interval. With
6 the exception of the sugar-crude oil relationship and the corn-conventional ethanol futures
7 relationship, all tests involving feedstock prices (i.e. equations 11b and 11d) give mixed or no
8 evidence of cointegration. With regard to equation 11c, the corn and gasoline futures prices
9 appear to be cointegrated over the entire period but soybean oil and diesel futures have mixed
10 results. Again, these tests use the entire period and implicitly assume that RIN prices are zero. In
11 reality, the conventional RIN was near zero at times during this period, but also rose to
12 unprecedented peaks, as discussed earlier, and the advanced and biodiesel RIN prices were
13 always well above zero in this period.
14

1 Table 3. Tests of price relationships without RIN price information.

Tested price relationship	Any RIN price expectation implied if cointegrated		Cointegrated (C) or not cointegrated (NC)	
			ADF	Johansen
<i>Spot prices</i>				
Equation 4: $p^{\text{petroprod}} = \beta p^{\text{petro}}$				
Gasoline - crude oil	None		C*	C*
Diesel - crude oil	None		C*	C*
Equation 11a: $p^{\text{producer}} \leftrightarrow p^{\text{petroprod}}$				
Conv ethanol - gasoline	Conv RIN=0		C*	C*
Biodiesel - diesel	BD RIN=0		C	NC
Equation 11b: $p^{\text{feedstock}} \leftrightarrow p^{\text{producer}}$				
Corn - conv ethanol	None		C*	NC
Soybean oil - biodiesel	None		C*	NC
Equation 11d: $p^{\text{feedstock}} \leftrightarrow p^{\text{petro}}$				
Corn - crude oil	Conv RIN=0		NC	NC
Sugar - crude oil	Adv RIN=0		C*	C
Soybean oil - crude oil	BD RIN=0		NC	NC
<i>Futures prices</i>				
Equation 4: $p^{\text{petroprod}} = \beta p^{\text{petro}}$				
Gasoline - crude oil	None		C*	C*
Diesel - crude oil	None		C*	C
Equation 11a: $p^{\text{producer}} \leftrightarrow p^{\text{petroprod}}$				
Conv ethanol - gasoline	Conv RIN=0		C*	C*
Equation 11b: $p^{\text{feedstock}} \leftrightarrow p^{\text{producer}}$				
Corn - conv ethanol	None		C*	C*
Equation 11c: $p^{\text{feedstock}} \leftrightarrow p^{\text{petroprod}}$				
Corn - gasoline	Conv RIN=0		C*	C*
Soybean oil - diesel	BD RIN=0		C	NC
Equation 11d: $p^{\text{feedstock}} \leftrightarrow p^{\text{petro}}$				
Corn - crude oil	Conv RIN=0		C	NC
Sugar - crude oil	Adv RIN=0		C*	C
Soybean oil - crude oil	BD RIN=0		C	NC

2 Notes: C* indicates cointegrated at 5% significance and C indicates cointegration at 10% level;
3 and conv is conventional, adv is advanced, and BD is biodiesel.

4.2. Exploit RIN price data: constructing an advanced ethanol price

7 The advanced ethanol price is not readily available in our data, as discussed above. We derive
8 the advanced ethanol price from RIN price data, as shown in equation 10b. This identity is
9 attractive because it would result in the exact value of advanced ethanol in the US market, if it
10 holds. In contrast, the other relationships that we hypothesize to hold are based on substitution
11 between ethanol produced in the US, Brazil, or elsewhere, and suggests a potential for
12 cointegration among prices rather than exact values (equations 10a and 10c). We test for a
13 relationship between the advanced ethanol price, calculated from conventional ethanol price less
14 conventional RIN price plus advanced RIN price, and Brazilian price of equation 10a, and we
15 test the Brazilian and conventional ethanol prices of equation 10c (Table 4).

In principle, these tests should only be conducted when trade is present. Cointegrating relationships are most likely to be present if trade is active, as compared to the no-trade case where natural or policy barriers prevent substitution of goods. Import data from EIA over the sample period suggest wide variations, with weekly data revealing extended periods at zero for 2014-15 but always some level of imports on a monthly basis. Export data from EIA are monthly, and also show no zero values at this level of aggregation. In this period, there was no prolonged period without trade, so the no-trade regime is not germane in this sample period and cointegrating relationships should normally be expected if the goods are substitutes and if the calculated advanced ethanol price is accurate.

We find evidence of cointegration, particularly between conventional ethanol and Brazilian ethanol. This finding suggests that equation 10c holds, and that US exports of ethanol compete with Brazilian ethanol. We also find evidence of cointegration between the calculated advanced ethanol price and the Brazilian price. This result could suggest that the calculated advanced ethanol price is perhaps representative of the market price, and equations 10a and 10b have some support as well. While the calculated advanced ethanol price will be used in a few of the later experiments, there is still a caveat drawn from this experiment that the calculated price might not be the most accurate measure of the actual advanced ethanol price in daily data.

Table 4. Tests of relationships between spot prices relating to the advanced ethanol price.

Tested price relationship	Theoretical basis	Regime: trade or no-trade		Cointegrated (C) or not cointegrated (NC)	
		Indicator	Regime	ADF	Johansen
Adv ethanol - Brazil ethanol	Eqs. 10a and 10b	US ethanol imports	Trade regime	C*	C*
Conv ethanol - Brazil ethanol	Eq. 10c	US Ethanol exports	Trade regime	C*	C*

Notes: C* indicates cointegrated at 5% significance and C indicates cointegration at 10% level; and adv is advanced.

4.3. Exploit RIN price data: binding and non-binding mandate regimes

RIN price data signal whether or not mandates are binding. As emphasized before, if the mandate is binding then RIN prices will be high, and RIN prices might absorb supply- or demand-shocks, preventing price transmission at some stages.

We exploit RIN price data to define when mandates are binding. Contrary to the theoretical model presented in equations 1-10 and the implied RINs of Table 3, however, RIN prices are not expected actually to equal zero. Even if the biofuel use exceeds the mandate in aggregate, there will be some trading as people with a surplus sell to people with a deficit relative to their individual obligations, so some price will be charged to cover transaction costs, at least. Moreover, because there is some potential for RIN storage, speculative demand for RINs might tend to keep the price above zero, as well, even if RIN volumes exceed the mandate. In practice, we define a cutoff value in the ratio of RIN prices to the competing petroleum product price at the retail level (e.g. Conventional RIN price/Wholesale gasoline price). Ratios below 1% are taken as a signal of a mostly non-binding mandate and higher ratios indicate a binding mandate. (Figure 3.) We exclude a range of values around the transition from one regime to the other in

order to heighten the potential difference in price relationships in statistical tests, and also because it is difficult to argue that there is a clear and constant single cutoff that marks so sharply this transition.

Figure 3. D6 RIN/Wholesale gasoline price ratio.

Sources: OPIS, DTN Energy

The ratio of conventional RIN price to ethanol price is below the 1% cutoff at the start of the period and then rises above the cutoff, so there is a non-binding regime and a binding regime. Cointegration tests are conducted separately over these periods. Ratios using the advanced and biodiesel RIN prices are above the cutoff at all times, so RIN price evidence suggests that all observed data in this period are outcomes of a binding regime.

Cointegration tests relating to equations 5-9 as they relate to conventional RINs and conventional ethanol – and, hence, the overall mandate and the type of ethanol that accounts for the majority of US domestic ethanol production – are reported (Table 5). Daily futures prices give only mixed or weak evidence of cointegration in most cases, although there was evidence of cointegration between conventional ethanol and gasoline prices in both mandate regimes. There is limited evidence of cointegration between corn and crude oil prices in the non-binding regime and no evidence of cointegration between them in the binding regime. There is not a sharp distinction between binding and non-binding regimes, but there are some differences. Overall, these data and tests give limited evidence of co-movement in these daily futures price data over this period of time.

1 The cointegration tests that are defined to be under the binding regime based on the advanced
2 and biodiesel RIN prices are actually identical to the earlier tests (Table 3). The advanced and
3 biodiesel RIN prices indicate that these mandates were binding throughout the sample period.
4 The results are reproduced here, but are tied to the theoretical equation that details relationships
5 with reference to RIN prices, rather than the general relationship (Table 5). As before, these tests
6 show mixed evidence of cointegration between daily future prices of petroleum and petroleum
7 products and biofuel feedstocks, except for the sugar-gasoline and sugar-petroleum cases where
8 there is evidence using both tests.
9

Table 5. Tests of relationships among future prices, exploiting RIN price information to define binding or non-binding mandate regimes.

Tested price relationship	Regime: binding (B) or non-binding (NB)		Cointegrated (C) or not cointegrated (NC)	
	Indicator	Dates	ADF	Johansen
Equation 5: $P^{\text{producer}} = f(P^{\text{petroprod}}, Z) + P^{\text{RIN}} + (C - M)$				
Conv ethanol –gasoline	Conv RIN	NB: 2/12-6/12 B: 9/12-12/13	NB: C B: C*	NB: C B: C*
Equation 6: $P^{\text{producer}} = f(\beta P^{\text{petro}}, Z) + P^{\text{RIN}} + (C - M)$				
Conv ethanol - crude oil	Conv RIN	NB: 2/12-6/12 B: 9/12-12/13	NB: C* B: C*	NB: NC B: NC
Equation 8: $f(P^{\text{petroprod}}, Z) + P^{\text{RIN}} + (C - O + S - M) = \alpha P^{\text{feedstock}}$				
Gasoline - Corn	Conv RIN	NB: 2/12-6/12 B: 9/12-12/13	NB: C* B: C	NB: NC B: NC
Gasoline - sugar	Adv RIN	Always binding	B: C	B: C*
Diesel - soybean oil	BD RIN	Always binding	B: C	B: NC
Equation 9: $f(\beta P^{\text{petro}}, Z) + P^{\text{RIN}} + (C - O + S - M) = \alpha P^{\text{feedstock}}$				
Crude oil - corn	Conv RIN	NB: 2/12-6/12 B: 9/12-12/13	NB: C* B: NC	NB: NC B: NC
Crude oil - sugar	Adv RIN	Always binding	B: C*	B: C
Crude oil - soybean oil	BD RIN	Always binding	B: C	B: NC

Notes: C* indicates cointegrated at 5% significance and C indicates cointegration at 10% level; and conv ethanol is conventional ethanol, adv ethanol is advanced ethanol, and BD is biodiesel.

We conduct similar experiments on spot prices, as well as additional experiments based on values or prices implied by combining RIN and other price data (Table 6). Where the tests overlap most, covering the same commodity prices, the spot prices give approximately the same limited evidence of cointegration among these prices.

RIN price and spot market price data can be combined to derive the value of biofuels as fuels, net of RIN values (equation 1a) and the advanced ethanol price (equation 10b and Table 4). We test the relationships between these derived values or prices of biofuels and corresponding petroleum products (Table 6). The advanced RIN price indicates that this binding mandate regime is present in all observations of this sample period. The experiments give some evidence of cointegration between advanced ethanol and crude oil prices and evidence of cointegration between advanced ethanol and sugar prices. This last result matches well with the evidence of cointegration between the derived advanced ethanol price and the Brazilian ethanol price (Table 4), indicating that price transmission in this period might have occurred along the processing sequence between sugar, Brazilian ethanol, and US advanced ethanol.

The implied fuel values are stripped of any effect of the RFS, in principle, so they should represent the implied price of these goods as liquid fuels. Tests of relationships using implied fuel values examine most directly the relationships of these goods in demand (equation 3). If users substituted readily between the biofuel and petroleum product during this period, then this activity would tend to force prices to move alike with, in the extreme case, an exact relationship based on some well-defined physical differentiation in the case of perfect substitutes (equation 3a). Cointegration test results indicate that this might have been the case during this period; there

is some evidence of cointegration between the retail gasoline price and the implied ethanol fuel value and between retail diesel price and implied biodiesel fuel value in this sample (Table 6).

Table 6. Tests of relationships among spot prices, exploiting RIN price information to define mandate regime and to calculate implied prices.

Tested price relationship	Regime: binding (B) or non-binding (NB)		Cointegrated (C) or not cointegrated (NC)	
	Indicator	Dates	ADF	Johansen
Equation 2: $P^{\text{producer}} = \alpha P^{\text{feedstock}} + O - S$				
Adv ethanol (10b) – sugar	N.A.	All	B: C*	B: C*
Equation 3: $P^{\text{consumer}} = f(P^{\text{petroprod}}, Z)$				
Retail gasoline – fuel value of ethanol (1a)	N.A.	All	C*	C
Retail diesel – fuel value of biodiesel (1a)	N.A.	All	C*	NC
Equation 5: $P^{\text{producer}} = f(P^{\text{petroprod}}, Z) + P^{\text{RIN}} + (C - M)$				
Conv ethanol –gasoline	Conv RIN	NB: 2/12-6/12 B: 9/12-12/13	NB: C* B: C*	NB: NC B: C*
Biodiesel - diesel	BD RIN	Always binding	B: C	B: NC
Equation 6: $P^{\text{producer}} = f(\beta P^{\text{petro}}, Z) + P^{\text{RIN}} + (C - M)$				
Adv ethanol (10b) – crude oil	Adv RIN	Always binding	B: C*	B: NC
Equation 9: $f(\beta P^{\text{petro}}, Z) + P^{\text{RIN}} + (C - O + S - M) = \alpha P^{\text{feedstock}}$				
Crude oil – corn ^a	Conv RIN	NB: 2/12-6/12 B: 9/12-12/13	NB: N/A B: NC	NB: N/A B: NC
Crude oil - sugar	Adv RIN	Always binding	B: C*	B: C
Crude oil - soybean oil	BD RIN	Always binding	B: NC	B: NC

Notes:

^a Table 2 indicates corn spot prices were stationary during the non-binding regime, so a cointegration test is between corn and crude oil prices during that regime is unnecessary. C* indicates cointegrated at 5% significance and C indicates cointegration at 10% level; and conv ethanol is conventional ethanol, adv ethanol is advanced ethanol, and BD is biodiesel.

A troubling possibility is that noise in the data undermines the reliability of these tests if the sample is dissected. To consider this possibility, we test the conventional ethanol and corn price relationship for the periods of binding and non-binding mandate even though the RIN price should not affect this relationship (see equation 2). For spot prices, the results were quite similar, with no evidence of cointegration in three of the tests. The exception was a mild indication of cointegration under the ADF test for the binding regime (at 10% significance). The test of this relationship based on futures prices deviated from the original test more substantially. Whereas the original test over the whole sample indicated that these futures prices were cointegrated in the period, the Johansen Trace test provided no evidence in binding or non-binding regime, and the ADF test results were weakened in the non-binding regime. Daily and weekly data are messy, and by dividing the four-year sample into two parts, plus omitting a middle period, these tests might place substantial demands on those data. Moreover, one lesson from an examination of relationships among RIN prices is that while those data seem mostly to comply with expectations based on the regulations that define RIN markets and arbitrage, there are some occasional inconsistencies based on perhaps anomalies, noisy data, or possibly imperfect

1 information in markets (Whistance and Thompson, 2014). In the end, although these results are
2 indicative of possible relationships during the sample period, we do not argue that they are
3 conclusive.

4 5 **5. Conclusions**

6
7 The innovation of this paper is to exploit RIN price information to improve applied research
8 related to the links between petroleum, biofuel, and agricultural commodity markets. RINs are
9 the instrument for obligated parties to show they comply with the biofuel mandate and RINs are
10 actively traded, so RIN price data can be used to distinguish between binding and non-binding
11 mandates. Moreover, prices of RINs and biofuels can be combined to derive fuel values that are
12 not observed in market data. Ignoring the information provided by RIN prices in applied time
13 series research can result in the treatment of data collected over binding and non-binding
14 mandate regimes as though they are generated in the same context, despite evidence showing
15 otherwise that should be exploited to heighten test power and accuracy.

16
17 A chief concern in this regard is statistical methods that represent US mandates as a mere
18 dummy or regime change that starts in 2005, 2006, or 2007. These experiments omit important
19 information provided by the RIN prices and consequently can mislead authors and readers. For
20 example, a study of this type might attribute some effects to the mandate, but the actual driving
21 force might be MTBE replacement or any of the long list of factors that led to the rise in
22 commodity prices in general, including agricultural prices (Abbott et al., 2008, 2009; Dewbre et
23 al., 2008; FAO, 2008; IFPRI, 2007; OECD-FAO, 2008, 2010; Westhoff, 2010; World Bank,
24 2008). Assuming a mandate regime change based on the date of legislation ignores information
25 about the degree to which mandates are binding, if at all, that is available in RIN price data.
26 Using the market's assessment of whether or not the mandates are binding and have direct
27 impacts, as observed in RIN price data, allows for more accurate timing of the transition from a
28 binding to a non-binding regime and consequently more accurate tests of the impacts of the
29 mandate.

30
31 RIN price data also provide information that can be used to distinguish between the part of a
32 biofuel producer price that is associated with its value as a fuel and the part that is associated
33 with its value towards meeting the mandate, thereby introducing the possibility to test for
34 relationships among fuels as such, with price data scrubbed of the mandate component. Thus, in
35 contrast to the vast majority of previous studies, our innovation allows researchers to test the
36 demand relationship of biofuels and petroleum products directly.

37
38 Our application of this method is based on daily spot and future price data from the beginning of
39 2009 through March 2015, the full period available under the latest manifestation of the US
40 mandate. We test relationships associated with ethanol and biodiesel, and exploit information in
41 conventional, advanced, and biodiesel RIN prices. This empirical exercise uses more information
42 from RIN prices than any other study of which we are aware. Results suggest cointegrating
43 relationships between prices of feedstocks and final products, including both agricultural
44 feedstocks and biofuel outputs and also petroleum and petroleum products.

1 The results suggest that there was generally limited cointegration among the prices of
2 agricultural commodities and the prices of petroleum and petroleum products over daily data
3 during this period. Evidence of links between biofuel and petroleum markets appear to be mixed,
4 if judged by our results. Perhaps because of the mandate implementation, the conditions in the
5 market – that might not be safely extrapolated to other times –, or because of the high frequency
6 of data, there is limited evidence of a demand substitution between biofuel and petroleum
7 products in this data sample. One possible explanation is that petroleum products and biofuels
8 are complements in daily and weekly decision-making in this sample period. If complements,
9 then the prices might move alike or differently depending on the sources of market shocks in this
10 period of time. Using other data sources, different data frequency, and estimating over a shorter
11 sample period, Whistance and Thompson (2014) find evidence of a link between ethanol and
12 gasoline fuel values. (Those authors do not test biodiesel and diesel relationships.) This
13 comparison of results argues for cautious conclusions about data frequency and historical periods
14 rather than wholehearted extrapolations of findings of any single test to other time periods,
15 including future periods that are relevant to decision makers. While the present study provides an
16 innovation regarding how RIN prices can be used and the empirical application goes well beyond
17 any other of which we are aware, there is scope to refine this approach.

18
19 Further research could improve on this work by extending it to consider price volatility, combine
20 these data with older data to consider if historical relationships are relevant to present markets,
21 use a different data frequency, or test different definitions of regimes. The blend wall debate,
22 regarding the point at which the motor fuel market is comprised entirely of E10 and further
23 ethanol use expansion must be in high blend fuels, might be relevant. Lessons about how
24 wholesale and retail fuel prices relate to one another now that the market appears to have run into
25 the blend wall might produce different functional representations or even different research
26 questions to test. Empirical estimates can always be improved, but our innovation of using RIN
27 prices as a source of information about mandate regimes and fuel prices should inform future
28 efforts to measure cross-market price linkages, with implications for future assessments that
29 speak to the food-versus-fuel debate.

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