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## **Estimating the Influence of Ethanol Policy on Plant Investment Decisions: A Real Options Analysis with Two Stochastic Variables**

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# Estimating the Influence of Ethanol Policy on Plant Investment Decisions: A Real Options Analysis with Two Stochastic Variables

T.M. Schmit, Luo J., and J.M. Conrad<sup>1</sup>

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## Abstract

Ethanol policies have contributed to changes in the levels and the volatilities of revenues and costs facing ethanol firms. The implications of these policies for optimal investment behavior are investigated through an extension of the real options framework that allows for the consideration of volatility in both revenue and cost components, as well as the correlation between them. The effects of policy affecting plant revenues dominate the effects of those policies affecting production costs. In the absence of these policies, much of the recent expansionary periods would have not existed and market conditions in the late-1990s would have led to some plant closures. We also show that, regardless of plant size, national ethanol policy has narrowed the distance between the optimal entry and exit curves, implying a more narrow range of inactivity and a more volatile evolution for the industry than would have existed otherwise.

## Introduction

Since 2005, the U.S. has witnessed a substantial increase in fuel ethanol production. This sizable growth has been due, at least in part, to the revision and/or creation of numerous federal, state, and local policies targeting both revenue enhancement and cost savings for ethanol producers (e.g., biofuels mandates, construction subsidies, tax credits, grants, loan guarantees).<sup>2</sup> Over the same time period, these policies, coupled with other market effects that increased the demand for corn (e.g., favorable exchange rates, increasing incomes in importing countries) and reduced expected supplies (e.g., weather-induced yield shocks), have contributed to record-high and more volatile market prices for agricultural and energy commodities.

More recently, continual changes in market conditions have tempered the expansion of corn-ethanol production. Large increases in the price of corn, coupled with falling crude oil prices in 2008 and the current economic downturn, have narrowed profit margins to corn-ethanol producers. In addition, the federal volumetric ethanol excise tax credit (VEETC or blender's credit) was reduced from 51 to 45 cents per gallon in the 2008 Farm Bill, and production and construction subsidies for corn-based ethanol facilities via the USDA Bioenergy Program have been reduced or eliminated.<sup>3</sup> These factors have led to a number of either temporary or permanent ethanol plant closures, stalled construction intentions, or plant sales at reduced valuations. For

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<sup>2</sup> While a primary objective of these policies is to increase production of renewable liquid fuels, the policies have also been justified by their contributions to global climate change, domestic energy security, farm income support, and rural development (de Gorter and Just 2010; Tyner and Taheripour 2008; Rajagopal and Zilberman 2007).

<sup>3</sup> The original USDA Bioenergy Program was terminated in 2006 and replaced with a new Bioenergy Program for Advanced Biofuels where firms who produce biofuels from corn kernel starch are not eligible for funding (USDAa 2010).

example, VeraSun Energy, the largest U.S. ethanol producer at the time, filed for bankruptcy in October 2008, halting construction plans on several sites and selling active plants to other ethanol producers or oil refiners (Energy Business Daily 2009). Overall, the rate of expansion in ethanol production capacity averaged less than 1% (0.6%) per month in 2009, compared with 4.6% growth between 2005 and the end of 2008 (O'Brien and Woolverton 2009).

Given the importance of U.S. biofuel production and the substantial risk on both the revenue and cost sides of ethanol production, the purpose of this article is to develop a better understanding of the effect of changing economic conditions and policy on investment decisions in ethanol production. In so doing, we make several important contributions to the literature. To begin, we extend the real options (RO) framework to better understand the investment behavior of firms. To date, the application of RO to agricultural and other risky investments of this type have been generally limited to models with a single random component, most often some measure of net return or profitability.<sup>4</sup> However, these models ignore the stochastic details of the individual components that are particularly important for policy analysis.

Our approach addresses this limitation directly. In particular, we extend the traditional RO approach to accommodate two stochastic variables, derive analytical solutions to the value functions, and then solve for the optimal entry and exit triggers. While the framework increases the computational burden relative to the traditional approach, we are now able to model revenue and cost separately and investigate the influence of individual variance and covariance effects on optimal switching conditions.

Numerical approximation procedures are necessary to solve optimal switching problems when analytical solutions cannot be determined (e.g., Miranda and Fackler 2002; Fackler 2004; Nostbakken 2006). However, our derivation of analytical solutions to the value functions contributes to their empirical precision and avoids the use of these methods that are mostly ad hoc to approximate these functions (Dixit and Pindyck 1994, p. 209). Solutions to the final entry and exit trigger conditions still have no closed-form solution (as in the traditional approach) so a numerical approach is required at this stage of the solution, but now limited to solving a system of equations based on known value functions. To investigate the significance of our extensions to the standard RO model, we compare the new results to those from a traditional single-variable model specification.

To facilitate policy analysis, we explicitly separate the effects of those financial incentives that affect revenue from those that affect cost. While considerable recent literature has evaluated more aggregate market or industry effects of ethanol policy, along with consequences for social welfare (see de Gorter and Just (2010) for a useful summary), less attention has been focused on the influence of policies on firm-level investment decisions.

To conduct the policy analysis, we first adapt the procedures from de Gorter and Just (2008b) to estimate historical prices for ethanol, corn, and distillers dried grains with solubles (DDGS), a byproduct of ethanol production, that would have existed in the absence of ethanol policy. These alternative price series are then substituted into the two-variable RO model. The results from these

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<sup>4</sup> A useful summary of RO applications of investments in agriculture is found in Luo (2009). In particular to ethanol investment applications, Pederson and Zou (2009) use a net cash flow measure when considering plant expansion, and Schmit, Luo, and Tauer (2009) use an ethanol gross margin in identifying triggers for entry and exit.

solutions are compared with those based on actual prices in order to identify the incidence of ethanol policy on optimal behavior and the entry and exits of firms. By using this two-variable model specification, we are also able to isolate the effects of policies that primarily affect cost from those that primarily affect revenue for ethanol producers. While our present empirical application focuses on ethanol production from corn, such a framework may well facilitate a similar understanding of the factors that will influence investments in cellulosic ethanol, once that technology is proven.

We begin the remainder of the article by developing the conceptual model of optimal entry and exit for the case of two stochastic, potentially correlated, variables. This is followed by a discussion of the historical price series developed for ethanol and corn under alternative policy and no-policy scenarios, and the estimation of stochastic-process parameters. The empirical results follow, comparing optimal entry-exit curves under alternative RO models (i.e., one- and two-variable cases) and policy scenarios (i.e., with and without policy). We close with conclusions, considerations for policy development, and directions for future research.

### Conceptual Framework

Following Dixit (1989), consider a fixed, linear, production technology transforming corn grain into ethanol, and a discount rate of  $\delta > 0$ . An idle project can be activated with an initial sunk investment cost  $k$ , expressed in dollars per gallon of plant production capacity. For operating plants, there is an exit (or shut-down) cost per unit of output,  $l$ , to close it. While in operation, the plant produces a fixed outflow of product each year and, for ease of exposition, it is normalized to unity. The operating plant receives unit revenues of  $y$  and incurs unit operating costs of  $x$  per gallon of ethanol produced. In this application,  $y$  consists of sales of ethanol ( $y_e$ ) and byproducts ( $y_{bp}$ ), such that  $y = y_e + y_{bp}$ . Operating costs include corn feedstock costs ( $x_c$ ) and other operating costs ( $x_{oc}$ ) (e.g., labor, utilities), such that  $x = x_c + x_{oc}$ . Finally, define the firm's net returns as  $p = y - x$ .

The stochastic variables are assumed to evolve according to Geometric Brownian motion (GBM). For ease of exposition, we refer the reader to Schmit, Luo, and Tauer (2009) for the one-variable ( $p$ ) model solution applied to corn-ethanol investment. Our focus below considers the extension to the two-variable case.<sup>5</sup> Accordingly, the cost and revenue components are modeled as individual, potentially correlated, GBMs, or:

$$(1) \quad dx = \mu_x x dt + \sigma_x x dz_x$$

$$(2) \quad dy = \mu_y y dt + \sigma_y y dz_y,$$

where  $\mu_x$  ( $\mu_y$ ) is the drift rate of  $x$  ( $y$ ),  $\sigma_x$  ( $\sigma_y$ ) is the standard deviation rate of  $x$  ( $y$ ), and  $dz_x$  ( $dz_y$ ) is the increment of a Wiener process with  $dz_x = \epsilon_{tx} \sqrt{dt}$  ( $dz_y = \epsilon_{ty} \sqrt{dt}$ ) and  $\epsilon_{tx}$  and  $\epsilon_{ty}$  drawn from the standard normal distribution  $N(0,1)$ . Further,  $x$  and  $y$  are potentially correlated with correlation coefficient  $\rho_{xy}$ , where

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<sup>5</sup> Dixit and Pindyck (1994, pp 207-211) provide a similar framework with both price and cost uncertainty. However, they consider investment cost, rather than operating cost, as stochastic. This special case can be solved by reducing the problem to a one-state variable problem since once the investment is made, further uncertainty in the evolution of investment costs is irrelevant. This approach can be seen as a restrictive form of the more general framework we propose that, to the authors' knowledge, has not been previously developed within this setting.

$$\rho_{xy} = \text{cov}(dz_x, dz_y) / \sqrt{\text{var}(dz_x) \text{var}(dz_y)} = E(\epsilon_{tx}, \epsilon_{ty}).$$

### Bellman Equations

A dynamic programming approach is used to determine the value of the project (active or idle). With an infinite time horizon and all parameters fixed (i.e.,  $k, l, \delta, \mu_x, \mu_y, \sigma_x, \sigma_y,$  and  $\rho_{xy}$ ), the value of the project will only depend on the values of  $x$  and  $y$ . An idle project does not generate any revenue or incur any cost. However, it could, under favorable future prices, become active and generate revenue. As a result, an idle project does have value.

Following the framework of the one-variable case (Dixit 1989), denote the value function of an idle project as  $V_0(x,y)$ , or simply  $V_0$ . An active plant receives (stochastic) net returns  $y - x$  in each period and has the option of shutting down; its value function is represented as  $V_1(x,y)$ , or simply  $V_1$ . Given the time increment  $dt$ , and the ranges of  $(x, y)$  where it is optimal for a project to stay in its previous states (either idle or active), the changes in value functions (i.e.,  $dV_0$  and  $dV_1$ ) must satisfy the following Bellman Equations for equilibrium in the asset market:

$$(3) \quad \delta V_0 dt = E[dV_0]$$

$$(4) \quad \delta V_1 dt = E[dV_1] + (y - x)dt,$$

where  $E$  is the expectation operator at time  $t$ . In the case of the idle state (3), the left-hand-side represents the return if the option to invest is sold, while the right-hand-side represents the expected capital gain from holding the option to invest. In the case of the active state (4), the left-hand-side is the return if the plant was sold and the proceeds invested at  $\delta$ , while the right-hand-side is the expected capital gain of the active project plus instantaneous net revenue.

From Itô's lemma, we know for a function  $F = F(x_1, \dots, x_m, t)$ , twice differentiable in potentially correlated Itô processes  $x_1, \dots, x_m$ , and once in time  $t$ , that the total differential of  $F$  is given by:

$$(5) \quad dF = \frac{\partial F}{\partial t} dt + \sum_i \frac{\partial F}{\partial x_i} dx_i + \frac{1}{2} \sum_i \sum_j \frac{\partial^2 F}{\partial x_i \partial x_j} dx_i dx_j.$$

Applying (5) to  $V_0$  and  $V_1$ , substituting in (1) and (2), and noting that  $(dz)^2 = dt$ ,  $dz_x dz_y = \rho_{xy} dt$ , and the higher order terms  $dt dz_x$ ,  $dt dz_y$ , or  $dt^2$  vanish in the limit as  $dt \rightarrow 0$ , results in:

$$(6) \quad dV_0 = \left[ V_{0,t} + \mu_x x V_{0,x} + \mu_y y V_{0,y} + \frac{1}{2} \sigma_x^2 x^2 V_{0,xx} + \frac{1}{2} \sigma_y^2 y^2 V_{0,yy} + \sigma_x \sigma_y \rho_{xy} xy V_{0,xy} \right] dt + \sigma_x x V_{0,x} dz_x + \sigma_y y V_{0,y} dz_y$$

$$(7) \quad dV_1 = \left[ V_{1,t} + \mu_x x V_{1,x} + \mu_y y V_{1,y} + \frac{1}{2} \sigma_x^2 x^2 V_{1,xx} + \frac{1}{2} \sigma_y^2 y^2 V_{1,yy} + \sigma_x \sigma_y \rho_{xy} xy V_{1,xy} \right] dt + \sigma_x x V_{1,x} dz_x + \sigma_y y V_{1,y} dz_y$$

where  $V_{i,t} = \frac{dV_i}{dt}$ ,  $V_{i,x} = \frac{\partial V_i}{\partial x}$ ,  $V_{i,y} = \frac{\partial V_i}{\partial y}$ ,  $V_{i,xx} = \frac{\partial^2 V_i}{\partial x^2}$ ,  $V_{i,yy} = \frac{\partial^2 V_i}{\partial y^2}$ , and  $V_{i,xy} = \frac{\partial^2 V_i}{\partial x \partial y}$  ( $i = 0,1$ ).

Finally, substituting (6) and (7) into (3) and (4), and noting that  $E[dz_x] = E[dz_y] = 0$ , the asset equilibrium conditions can be expressed as:

$$(8) \quad \frac{1}{2} \sigma_x^2 x^2 V_{0,xx} + \sigma_x \sigma_y \rho_{xy} xy V_{0,xy} + \frac{1}{2} \sigma_y^2 y^2 V_{0,yy} + \mu_x x V_{0,x} + \mu_y y V_{0,y} - \delta V_0 = 0$$

$$(9) \quad \frac{1}{2} \sigma_x^2 x^2 V_{1,xx} + \sigma_x \sigma_y \rho_{xy} xy V_{1,xy} + \frac{1}{2} \sigma_y^2 y^2 V_{1,yy} + \mu_x x V_{1,x} + \mu_y y V_{1,y} - \delta V_1 = x - y.$$

### General Solution

Equations (8) and (9) represent second-order partial differential equations (PDE) that, in present form, have no well-known solution. However, using methods defined in O'Neil (2008) and Hanna and Rowland (1990), one can apply a change of variables to transform (8) and (9) into standard linear constant-coefficient second-order PDEs, with known analytical solutions. Specifically, consider the transformation  $V(x, y) = u(t(x), s(y))$  where  $t = \ln x$  and  $s = \ln y$ . The partial derivatives of  $V$  are:  $V_x = \frac{1}{x} u_t$ ,  $V_y = \frac{1}{y} u_s$ ,  $V_{xx} = \frac{1}{x^2} (u_{tt} - u_t)$ ,  $V_{yy} = \frac{1}{y^2} (u_{ss} - u_s)$ , and  $V_{xy} = \frac{1}{xy} u_{ts}$ . Substituting these expressions into (8) and simplifying implies:

$$(10) \quad \sigma_x^2 u_{tt} + 2\rho_{xy} \sigma_x \sigma_y u_{ts} + \sigma_y^2 u_{ss} + (2\mu_x - \sigma_x^2) u_t + (2\mu_y - \sigma_y^2) u_s - 2\delta u = 0,$$

where (10) is the desired constant-coefficient PDE. Now, let a proposed solution to (10) be:

$$(11) \quad u = e^{\alpha t + \beta s},$$

where  $\alpha$  and  $\beta$  are constant real numbers to be determined. Substituting the partial derivatives of (11) with respect to  $t$  and  $s$  and rearranging yields:

$$(12) \quad \sigma_y^2 \beta^2 + (2\mu_y - \sigma_y^2 + 2\rho_{xy} \sigma_x \sigma_y \alpha) \beta + (\sigma_x^2 \alpha^2 + (2\mu_x - \sigma_x^2) \alpha - 2\delta) = 0.$$

Solving (12) for  $\beta$  provides two solutions (roots):

$$(13) \quad \beta_1 = \frac{-(2\mu_y - \sigma_y^2 + 2\rho_{xy} \sigma_x \sigma_y \alpha) + \sqrt{(2\mu_y - \sigma_y^2 + 2\rho_{xy} \sigma_x \sigma_y \alpha)^2 - 4\sigma_y^2 (\alpha^2 \sigma_x^2 + \alpha(2\mu_x - \sigma_x^2) - 2\delta)}}{2\sigma_y^2}$$

$$\beta_2 = \frac{-(2\mu_y - \sigma_y^2 + 2\rho_{xy} \sigma_x \sigma_y \alpha) - \sqrt{(2\mu_y - \sigma_y^2 + 2\rho_{xy} \sigma_x \sigma_y \alpha)^2 - 4\sigma_y^2 (\alpha^2 \sigma_x^2 + \alpha(2\mu_x - \sigma_x^2) - 2\delta)}}{2\sigma_y^2}$$

Given that  $\beta_1 > 0$  and  $\beta_2 < 0$  are functions of  $\alpha$ , the general solution to (10) can be expressed as:

$$(14) \quad u = A_1 e^{\alpha t + \beta_1(\alpha) s} + A_2 e^{\alpha t + \beta_2(\alpha) s}$$

where  $A_1$  and  $A_2$  are unknown constants to be determined. Finally, substituting the expressions for  $x$  and  $y$  into (14) we have:

$$(15) \quad V_0(x, y) = A_1 x^{\alpha} y^{\beta_1(\alpha)} + A_2 x^{\alpha} y^{\beta_2(\alpha)}.$$

An idle plant does not generate any income, so  $V_0$  consists only of the value to enter, i.e., a real call option, which is nonnegative. It follows then that  $A_1$  and  $A_2$  must both be nonnegative. Given that  $V_0$  is decreasing in  $x$  ( $V_{0,x} \leq 0$ ), we need  $\alpha < 0$ , which is to be determined. Also, since  $V_0$  is increasing in  $y$  ( $V_{0,y} \geq 0$ ) and  $\beta_2 < 0$ ,  $A_2 = 0$  for the solution to hold on the whole domain. Letting  $A \equiv A_1$  and  $\alpha_1 \equiv \alpha$ , the general solution to (8) becomes:

$$(16) \quad V_0(x, y) = Ax^{\alpha_1} y^{\beta_1(\alpha_1)},$$

where  $A$  and  $\alpha_1$  are parameters to be determined.

The same change of variables procedure is applied to (9) yielding:

$$(17) \quad \sigma_x^2 u_{tt} + 2\rho_{xy} \sigma_x \sigma_y u_{ts} + \sigma_y^2 u_{ss} + (2\mu_x - \sigma_x^2)u_t + (2\mu_y - \sigma_y^2)u_s - 2\delta u = 2e^t - 2e^s$$

Noting that the homogeneous part of (17) is the same as (10), they share a common general solution given by (14). To determine the general solution of (17), one must define a particular solution that satisfies (17) and then combine it with the homogenous solution. Let a particular solution to (17) be:

$$(18) \quad u = ae^t + be^s,$$

where  $a$  and  $b$  are parameters to be determined. For (18) to satisfy (17), substitute the partial derivatives of (18) with respect to  $t$  and  $s$  (i.e.,  $u_t = u_{tt} = ae^t$ ,  $u_s = u_{ss} = be^s$ , and  $u_{ts} = 0$ ) into (17) and solve for  $a$  and  $b$ . After simplifying, the result becomes:

$$(19) \quad (\mu_x - \delta)ae^t + (\mu_y - \delta)be^s = e^t - e^s,$$

which holds for  $a = -\frac{1}{\delta - \mu_x}$  and  $b = \frac{1}{\delta - \mu_y}$ . Combining the homogenous and particular solutions defines the general solution to (17) as:

$$(20) \quad u = B_1 e^{\alpha't + \beta'_1(\alpha')s} + B_2 e^{\alpha't + \beta'_2(\alpha')s} - \frac{e^t}{\delta - \mu_x} + \frac{e^s}{\delta - \mu_y},$$

where  $\alpha'$ ,  $B_1$ ,  $B_2$  are parameters to be determined. Finally, substituting the expressions for  $x$  and  $y$  back into (20) we have:

$$(21) \quad V_1(x, y) = B_1 x^{\alpha'} y^{\beta'_1(\alpha')} + B_2 x^{\alpha'} y^{\beta'_2(\alpha')} + \frac{y}{\delta - \mu_y} - \frac{x}{\delta - \mu_x}.$$

In (21),  $\frac{y}{\delta - \mu_y} - \frac{x}{\delta - \mu_x}$  is the expected net present value of the net returns from operating the plant forever, and  $B_1 x^{\alpha'} y^{\beta'_1(\alpha')} + B_2 x^{\alpha'} y^{\beta'_2(\alpha')}$  is the value of the option to exit. It follows that  $B_1$  and  $B_2$  must both be nonnegative. Given the value of the option to exit is increasing in  $x$ , we need  $\alpha' > 0$ , which is to be determined. Also, since the value of the option to exit is decreasing in  $y$  and  $\beta'_1 > 0$ , this implies  $B_1 = 0$  for the solution to hold on the whole domain. Letting  $B \equiv B_2$  and

$\alpha_2 \equiv \alpha'$ , the general solution to (9) becomes:

$$(22) \quad V_1(x, y) = Bx^{\alpha_2}y^{\beta_2(\alpha_2)} + \frac{y}{\delta - \mu_y} - \frac{x}{\delta - \mu_x},$$

where  $B$  and  $\alpha_2$  are parameters to be determined.

### *Switching Conditions*

To identify the conditions for  $x$  and  $y$  where it is optimal to switch states (idle or active) we must define the value-matching conditions and smooth-pasting conditions for the value functions above. Consider the cost-revenue combinations  $(x_H, y_H)$  and  $(x_L, y_L)$  that trigger entry and exit, respectively. In the two-variable model, the level of  $y_H$  ( $y_L$ ) that triggers entry (exit) is dependent on the existing level of  $x$ , defined as  $x_H$  ( $x_L$ ). As such, in determining the solution to the two-variable problem, we interpret  $y_H$  and  $y_L$  as functions of  $x_H$  and  $x_L$ , respectively.<sup>6</sup> Unlike the one-variable case where the switching conditions are defined at single threshold prices ( $p_H$  and  $p_L$ ), the two-variable model defines switching conditions in the nonnegative quadrant of the  $x$ - $y$  plane, which are now referred to as trigger curves. When the cost-revenue combination  $(x, y)$  hits the entry trigger  $(x_H, y_H)$ , an idle project should be activated, whereas when the cost-revenue combination  $(x, y)$  hits the exit trigger  $(x_L, y_L)$ , an active project should be terminated.

Given this, the value-matching conditions follow similarly to the one-variable case, but now must be satisfied at the coordinate pairs of trigger conditions  $(x_H, y_H)$  and  $(x_L, y_L)$ . When  $(x, y) = (x_H, y_H)$ , the project commits sunk cost  $k$  to switch from idle to active (value-matching equation 23). When  $(x, y) = (x_L, y_L)$ , the project commits sunk cost  $l$  to switch from active to idle (value matching equation 24). Similarly, the tangency requirements of the value functions  $V_0$  and  $V_1$  under the smooth-pasting conditions must be satisfied with respect to both  $x$  and  $y$  at the entry and exit trigger pairs (equations 25 through 28). Collectively, these conditions may be written as:

$$(23) \quad V_0(x_H, y_H) + k = V_1(x_H, y_H),$$

$$(24) \quad V_0(x_L, y_L) = V_1(x_L, y_L) + l,$$

$$(25) \quad V_{0,x}(x_H, y_H) = V_{1,x}(x_H, y_H),$$

$$(26) \quad V_{0,x}(x_L, y_L) = V_{1,x}(x_L, y_L),$$

$$(27) \quad V_{0,y}(x_H, y_H) = V_{1,y}(x_H, y_H),$$

$$(28) \quad V_{0,y}(x_L, y_L) = V_{1,y}(x_L, y_L),$$

To obtain the optimal trigger curves, a series of values for  $x_H$  and  $x_L$  must be given and the six-equation system (23-28) is solved over these values for the six unknowns ( $A$ ,  $B$ ,  $\alpha_1$ ,  $\alpha_2$ ,  $y_H$ , and  $y_L$ ). Once  $y_H$ , and  $y_L$  are determined, the optimal trigger pairs  $(x_H, y_H)$  and  $(x_L, y_L)$  can be plotted to illustrate the estimated trigger curves.

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<sup>6</sup> The argument can be equivalently stated where  $x_H$  and  $x_L$  are functions of  $y_H$  and  $y_L$ , respectively.

To better understand the shapes of the trigger curves, substitute (16) and (22) into either (23) or (24) and totally differentiate with respect to  $x$  and  $y$ . After rearranging, the slope of the trigger curves can be expressed as:

$$(29) \quad \frac{dy}{dx} = \frac{A\alpha_1 x^{\alpha_1-1} y^{\beta_1} - B\alpha_2 x^{\alpha_2-1} y^{\beta_2} + (\delta - \mu_x)^{-1}}{B\beta_2 x^{\alpha_2} y^{\beta_2-1} - A\beta_1 x^{\alpha_1} y^{\beta_1-1} + (\delta - \mu_y)^{-1}}.$$

From (29), the slopes of the nonlinear trigger curves are functions of the levels of  $x$  and  $y$ ; i.e.,  $(x_H, y_H)$  or  $(x_L, y_L)$ , and the parameters  $(\mu_x, \mu_y, \sigma_x, \sigma_y, \text{ and } \rho_{xy})$  via the nonlinear expressions in (13). While the individual component effects cannot be disentangled, we describe some of the general movements of the trigger curves in the empirical application below. In contrast, for the one variable case where  $p = y - x$ , the slopes of the trigger curves in  $(x, y)$  space are necessarily restricted to unity (i.e., from  $y - x = p$ ,  $dy - dx = 0$ , or  $dy/dx=1$ ).

## Data

For the empirical application, we must provide estimates of the entry ( $k$ ) and exit ( $l$ ) costs and the parameters  $\mu_x, \mu_y, \sigma_x, \sigma_y$ , and  $\rho_{xy}$ . The parameters, in turn, depend on the historical time series data on unit revenues ( $y_e$  and  $y_{bp}$ ) and feedstock and other operating costs ( $x_c$  and  $x_{oc}$ ). Furthermore, to evaluate investment behavior in the absence of ethanol policy ( $np$ ), alternative price series are needed for unit revenues ( $y_e^{np}$  and  $y_{bp}^{np}$ ) and feedstock costs ( $x_c^{np}$ ).

### *Plant Investment and Operating Costs*

Average investment and operating costs for dry-grind corn-based ethanol plants are taken from Schmit, Luo and Tauer (2009), where data were collected from existing literature (Table 1). The data are grouped by plant size to assess differences in investment decisions when accounting for changes in costs. Plant sizes were categorized as either small, medium, or large, with average plant sizes by category reported in Table 1. While numerous small- and medium-sized plants are still in operation, more recent industry entrants have been primarily large plants with nameplate capacities of 100 mgpy or higher.

Capital investment costs ( $k$ ) include construction costs (e.g., equipment, engineering, installation) and non-construction costs (e.g., land, start-up inventories, working capital). As expected, average capital costs decrease from \$1.95/gal to \$1.22/gal for small and large plants, respectively (Table 1). Exit costs depend on the liquidation value of assets. If residual asset value upon exit exists, overall exit costs can be less than zero; however, these estimates are not available in the literature. Given that land holds its value and production facilities might be retrofitted for alternative uses, we follow Schmit, Luo, and Tauer (2009) and assume a conservative 10% liquidation value (i.e.,  $l = -0.1k$ ).

Non-corn operating costs ( $x_{oc}$ ) include chemicals, energy and utilities, depreciation, labor and other miscellaneous costs.<sup>7</sup> Average operating costs are \$0.74, \$0.69, and \$0.70 per gallon for the small, medium, and large plant classes, respectively (Table 1). Economies of size in production are expected; however, the limited number of observations used in each category (see Schmit, Luo, and Tauer 2009) may not fully represent these costs. For the application that follows, we assume that other operating costs are \$0.70/gal for all firm sizes. Since these costs are included in total unit

<sup>7</sup> We assume that depreciated capital is replaced to maintain the initial capital stock.

costs (i.e.,  $x = x_c + x_{oc}$ ) from which stochastic parameters are estimated ( $\mu_x, \sigma_x, \rho_{xy}$ ), other operating costs were converted to current month-year equivalents by the Petroleum and Coal Products Producer Price Index (USDL 2010). Finally, an annual discount rate ( $\delta$ ) of 8% is assumed.

#### *Price, Tax, and Production Data*

Monthly prices were collected for the time period January 1997 through March 2010. Corn ( $x_c$ ) and DDGS ( $y_{bp}$ ) prices were obtained from the Feed Grains Database (USDA 2010), representing market prices for No. 2 yellow corn (Chicago, IL) and wholesale DDGS prices (Lawrenceburg, IN), respectively. Ethanol prices were obtained from the Nebraska Energy Office (NEO 2010), representing average rack (wholesale) prices (FOB Omaha, NE). In contrast to daily or weekly prices, monthly prices were used to eliminate short-term fluctuations in prices more pertinent to short-term holdings rather than long-term investments.

Following Bothast and Schlicher (2005), conversion rates of 2.80 gal of ethanol and 17 lb of DDGS produced per bushel of corn were used to convert all prices to dollars per gallon, and unit revenues ( $y = y_e + y_{bp}$ ), unit costs ( $x = x_c + x_{oc}$ ), and net returns ( $p = y - x$ ) were computed. Corn feedstock costs have represented the majority of total operating costs (around 70%); however, volatility in other costs, particularly energy and utility costs, remain important. Similarly, ethanol sales have represented the largest portion of total plant sales (around 80%); but the growing use of DDGS in livestock production should also be considered given the inherent price linkages to corn prices and other agricultural commodities. As shown in Figure 1, positive trends in unit revenues and costs are apparent; albeit dampened considerably beginning in 2009.

To estimate the influence of ethanol policy on ethanol, corn, and DDGS prices, additional data are required, including gasoline prices, fuel taxes, ethanol tax credits, federal commodity loan rates, and estimates of corn production and disposition. Average monthly unleaded wholesale (rack) gasoline prices (FOB Omaha, NE) were obtained from NEO (2010). *Feed Yearbook* tables available in USDA (2010) were used to obtain market-year loan rates for corn and estimates of U.S. corn production and corn sold for domestic nonethanol consumption, nonethanol exports, and domestic ethanol production.<sup>8</sup> Finally, annual federal and state-average fuel tax rates were obtained from the Federal Highway Administration (USDOT 2010), and federal tax credits for ethanol (excluding individual state estimates) were obtained from USDE (2010).

#### *Effects of Ethanol Policy on Prices*

At the beginning of the sample period (1997), a federal motor fuels excise tax credit for blending ethanol with gasoline existed, as did an ethanol import tariff (both equivalent to \$0.54/gal of ethanol). An additional \$0.10/gal tax credit (up to 15 mgal) existed for small ethanol producers (less than 30 mgal/yr). The tax credits provide an incentive for refiners and blenders to bid up the price of ethanol above that of gasoline by the amount of the tax credit (de Gorter and Just 2008a, 2008b, 2009a). The Transportation Efficiency Act in 1998 extended the subsidies through 2007, but mandated the excise tax credit to be reduced to \$0.51/gal by 2005.

Beginning in 2000, the U.S. Environmental Protection Agency recommended a nation-wide ban

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<sup>8</sup> Due to lack of available data, all US corn exports reported (around 13% of total supply in 2008/09) were assumed for nonethanol use.

on the use of methyl tert-butyl ether (MTBE) as an oxygenator in gasoline. As such, numerous states began adopting this ban (notably California in 2003/2004), which increased the demand for ethanol (a substitute for MTBE). Ethanol price premiums can be equally affected by these types of environmental regulations and ethanol's additive value as an oxygenator or octane enhancer, acting as de facto mandates that can push ethanol premiums above the level of the tax credit (de Gorter and Just 2008b, 2010).

Following the initial Renewable Fuels Standard (RFS1), established by the Energy Policy Act of 2005, ethanol prices rose more than proportionally to input costs, with net returns reaching \$2.25/gal by mid-2006 (Figure 1). In addition, the threshold for which small ethanol producers qualified for additional tax credits of \$0.10/gal (up to 15 mgal) was increased to 60 mgal/year. While the incidence of the tax credit is such that ethanol producers derive most of the benefit, when a mandate (real or de facto) is binding, the price of ethanol will be determined by the point on the ethanol supply curve that satisfies the required level of production and a higher premium may be realized (de Gorter and Just 2008b).

Combined with other market adjustments increasing the demand for corn (e.g., growing export demand), strong growth in corn prices in late-2006 and 2007 resulted in large reductions in net returns for ethanol producers. Net returns stabilized somewhat in early 2007, notably at a time coincident with the implementation of a higher Renewable Fuel Standard (RFS2) by the Energy Independence and Security Act of 2007, although the mandate for corn-based ethanol was more limited relative to advanced biofuels.<sup>9</sup> In 2008, the blenders credit was reduced to \$0.45/gal via the 2008 U.S. Farm Bill, and since then estimated net returns have generally been below \$0.50/gal, and for some months negative (Figure 1).

It is difficult to determine a priori whether the ethanol tax credit or mandates (explicit or de facto) are more influential on ethanol price premiums; however, the market effects of a tax credit have been shown to be negligible if a mandate is binding (de Gorter and Just 2009b). In addition, while corn prices can be highly sensitive to changes to ethanol policy, the tax credit (or ethanol price premium due to the mandate) can only impact corn prices to the extent that it exceeds the level of "water" in the tax credit; i.e., the amount the intercept of the supply curve for ethanol is above the price of oil. The relative uncompetitiveness of the U.S. ethanol industry in the absence of government policy indicates that positive levels of "water" have historically been the case (de Gorter and Just 2008b). It is not our intention here to estimate the relative impacts of the various ethanol policies, but, instead, how the combined influence of existing ethanol policies has affected firm-level investment behavior over time. To better understand this, we use actual (policy) and estimated (no policy) price data to conduct "what if" analyses under alternative ethanol premium assumptions.

Our approach is adapted from de Gorter and Just (2008b) to estimate prices for ethanol, corn, and DDGS in the absence of policy. In addition, estimated policy premiums are based on alternative assumptions regarding the form of consumer response to fuel prices. In the first case (called the Mix model), consumers do not adjust fuel purchases to take into account the share of ethanol and the reduced mileage impacts of ethanol relative to gasoline due to its lower energy value (i.e., around 70%). This is arguably the case for U.S. consumers in the past. In this case, the premium to

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<sup>9</sup> Advanced biofuels are those derived from renewable biomass, other than corn kernel starch (e.g., cellulose, lignin, sugar, and crop residues)

ethanol prices ( $Prem_e^{Mix}$ ) can be computed by simply subtracting the gasoline price ( $y_g$ ) from the ethanol price ( $y_e$ ), or:

$$(30) \quad Prem_e^{Mix} = y_e - y_g .$$

If the difference is equal to the tax credit, then the tax credit determines the market price of ethanol and the mandate is dormant, if the difference is greater than the value of the tax credit then the mandate is binding, and if the difference is less than the tax credit then the market is in disequilibrium (de Gorter and Just 2008b).

Alternatively, in what is referred to as the Flex model, consumers purchase ethanol on the basis of contribution to mileage (as has been the case in Brazil). Here, the price premium is more complicated since mileage differences must be considered as well as the penalty on ethanol due to the fuel tax ( $t$ ) being levied on a volume basis (de Gorter and Just 2008b). Letting  $\varphi = 0.70$  be the differential mileage rate, the premium to ethanol prices ( $Prem_e^{Flex}$ ) can be expressed as:

$$(31) \quad Prem_e^{Flex} = y_e - \varphi y_g + (1 - \varphi)t.$$

Ethanol premiums were computed under each assumption to derive ethanol price estimates in the absence of historical policy; i.e.,  $y_e^{Mix} = y_g$  and  $y_e^{Flex} = \varphi y_g - (1 - \varphi)t$ .

To investigate the cost-side consequences of ethanol policy, we consider what corn prices would have been if there was no ethanol production ( $x_c^{NE}$ ). According to de Gorter and Just (2008b, p. 406),  $x_c^{NE}$  depends on current prices, the disposition of corn to alternative uses (ethanol or nonethanol) and locations (domestic or export), and elasticities of supply and demand. They characterize this relationship in the following way:

$$(32) \quad \frac{Q_c}{\max(x_c, L)^{\epsilon_c^S}} (x_c^{NE})^{\epsilon_c^S} = \frac{Q_{NE}^D + \varepsilon x_{byp} Q_E}{(x_c)^{\epsilon_{NE}^D}} (x_c^{NE})^{\epsilon_{NE}^D} + \frac{Q_{NE}^X + (1 - \varepsilon) x_{byp} Q_E}{(x_c)^{\epsilon_{NE}^X}} (x_c^{NE})^{\epsilon_{NE}^X}$$

where  $L$  is the loan rate,  $Q_c$  is U.S. corn production,  $Q_{NE}^D$  is the quantity of corn sold for domestic nonethanol consumption,  $Q_{NE}^X$  is the quantity of corn sold for nonethanol export,  $\varepsilon = \frac{Q_{NE}^D}{Q_{NE}^D + Q_{NE}^X}$  is the proportion of nonethanol corn consumed domestically, and  $Q_E$  is the amount of corn sold for ethanol production. Assuming, as they do, that  $\epsilon_c^S = 0.4$ ,  $\epsilon_{NE}^D = -0.2$ , and  $\epsilon_{NE}^X = -1.0$  are the price elasticities for corn supply, domestic demand for nonethanol, and export demand for nonethanol, respectively, we solve (32) numerically for  $x_c^{NE}$ . The policy premium to corn prices ( $Prem_c$ ) can then be expressed as:

$$(33) \quad Prem_c = x_c - x_c^{NE} .$$

Since  $Prem_c$  must be computed on a market year basis, the corn price premium is assumed to be the same for all months during each market year. The adjusted unit revenue from byproduct sales in the case of no policy ( $x_{byp}^{NP}$ ) is computed by multiplying the estimated corn price  $x_c^{NE}$  by the ratio of actual byproduct and corn prices, or:

$$(34) \quad y_{bp}^{NP} = \frac{y_{bp}}{x_c} x_c^{NE}.$$

Finally, the estimated price series for unit revenues,  $y^{Mix} = y_e^{Mix} + y_{bp}^{NP}$  and  $y^{Flex} = y_e^{Flex} + y_{bp}^{NP}$ , and unit costs,  $x^{NP} = x_e^{NE} + x_{oc}$ , were computed. The price series are shown in Figures 2 and 3 and summarized in columns one through three of Table 2. The estimated policy premiums per gallon on unit revenues were, on average, \$0.38 and \$0.87 for the Mix and Flex models, respectively, over the entire 1997-2009 time period (Table 2). However, premiums reached as high as \$1.36 and \$2.14, respectively, in 2006 (Figure 2). The average price premium in the Mix model is below the average tax credit over the same time period (approximately \$0.51) and is due to some observations where the estimated premium was negative and indicative of a temporary market disequilibrium (de Gorter and Just 2008b). However, if consumers had adjusted demand based on mileage performance factors (the Flex model), ethanol prices (and unit revenues) would have been consistently below actual historical conditions (Figure 2).

As expected, the policy premiums to corn prices show lower differential effects for much of the sample, and result in an average premium of approximately \$0.13/gal, or \$0.38/bu. The average is higher than de Gorter and Just's estimate of \$0.13/bu (2008b), and Elobeid and Tokdoz's estimate of \$0.05 (2008), however these studies do not include more recent data (i.e., since 2007), where the estimated premiums have exceeded \$1 per bushel. In addition, the average premium represents about 14% of corn prices over this time period, an estimate consistent with McPhail and Babcock (2008) who estimate a 14.5% corn price premium due to the mandate, tax credit, and import tariff. Much of the relatively small premium effects were prior to 2004 when RFS mandates were not yet in effect and few states had implemented MTBE bans. Consistent with de Gorter and Just (2010), only when oil prices increased sharply more recently did the ethanol premiums due to policy have a measurable impact on corn prices.

### Stochastic Parameters

In this section, we estimate the stochastic parameters. From above, GBM is assumed for the stochastic variables; however, GBM cannot be used in the presence of negative values. This is not an issue in the two-variable case since by definition  $x$  and  $y$  are strictly nonnegative. However, as shown in Figure 1, net returns have been negative for some months. To minimize the problems associated with this, we utilize an alternative gross margin measure ( $p^* = y - x_c$ ) for the one-variable model where  $x_{oc}$  is assumed fixed and accounted for separately. This does not completely eliminate the problem, however, as  $p^*$  is still less than zero some months in scenarios when policy premiums have been removed. To account for this, we subsequently vertically shift  $p^*$  by \$0.50 for all scenarios and all  $t$ .<sup>10</sup>

For ease of exposition, we use  $x$  in describing the estimation procedure; however, the approach is identical for the other stochastic variables. To begin, if  $x$  follows a GBM, then  $\ln x$  follows Brownian motion with parameters  $\mu_x - \frac{1}{2}\sigma_x^2$  and  $\sigma_x^2$ , or:

$$(35) \quad d\ln x = \theta_x dt + \sigma_x dz_x,$$

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<sup>10</sup> Shifting the data is a common approach to remedy this issue; however, this is necessarily ad hoc and the estimation results are not invariant to the level of the shift. We argue that this provides more reason to support the two-stochastic-variable approach for these types of analysis.

where  $\theta_x = \mu_x - \frac{1}{2}\sigma_x^2$ .

GBM requires  $\ln x$  to have a unit root. While price theory suggests agricultural commodity prices should be stationary, the literature has frequently implied the opposite empirically (Wang and Tomek 2007). In addition, crude oil prices have been shown to reasonably follow GMB and are strongly correlated with ethanol prices (Postali and Pichcetti 2006).

While not shown (available in online appendix), augmented Dickey-Fuller (ADF) tests were conducted to test for unit roots, with the results demonstrating only weak arguments against the presence of unit roots (once differenced, the time series  $\Delta \ln x$ ,  $\Delta \ln y$ , and  $\Delta \ln p$  all show stationarity).<sup>11</sup> Accordingly, the stochastic parameters were estimated by regressing  $\Delta \ln x_t$  on a constant term and lagged values  $\Delta \ln x_{t-i}$  using ordinary least squares (OLS), or:

$$(36) \quad \Delta \ln x_t = c + \sum_{i=1}^{n-1} \psi_i \Delta \ln x_{t-i} + \varepsilon_{x_t}$$

where sufficient lag terms ( $n-1$ ) added until  $\varepsilon_{x_t}$  becomes white noise; and

$E(\Delta \ln x_t) = \frac{c}{1 - \sum_{i=1}^{n-1} \psi_i} = \mu_x - \frac{1}{2}\sigma_x^2$ . The deviation rate,  $\sigma_x$ , is read directly from the root mean square error (RMSE) estimation results. Finally, the correlation parameter,  $\rho_{xy}$ , is determined by the correlation coefficient of the residuals from the  $d \ln x$  and  $d \ln y$  fitted equations.<sup>12</sup> Given we are considering annual production, the estimated monthly parameters were converted to annual equivalents based on the fact that the drift rate and variance of the increments of a Brownian motion are both linear in time. The complete set of estimation and test results are available in a supplementary appendix online for the interested reader.

Due to lack of statistical significance, all drift rate parameters ( $\mu_x$ ,  $\mu_y$ ,  $\mu_p$ ) were set to zero; the estimated deviation rate parameters and correlation estimates for the actual (policy) and derived (no policy) price series are shown in Table 2, columns (4), (5), (6), and (7). As indicated, both the deviation rates of  $x$  and  $y$ , as well as the correlation between them, increase in the absence of policy. A reduction in the correlation is reasonable, since ethanol policy has no (or a limited) effect on oil prices, while oil prices are increasingly linked to changes in ethanol and corn prices. When policy perturbs ethanol prices (and to a lesser extent corn prices), the ethanol-oil correlation is reduced implying a reduction in the ethanol-corn correlation as well. The smaller change exhibited in the deviation rate for  $x$  is consistent with the derived data that showed relatively less policy effects (Figure 3). The implications of these results will be presented next when considering the alternative policy scenarios on plant investment behavior.

## Empirical Results

To generate empirical results from the applications of this two-variable RO model, we chose a

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<sup>11</sup> Only for  $\ln p$  were specification tests for a unit root consistently rejected; thus, providing further support for the two-variable model application. The empirical results for  $\ln x$  and  $\ln y$  that could not reject unit roots are important to the application of the two-variable model, since otherwise other forms of stochastic behavior would be necessary (e.g., mean-reverting, jump-diffusion processes) that do not have analytical solutions to the value functions and require numerical methods to approximate (see for example Fackler and Livingston 2002; Kim and Brorsen 2008; Hillard and Reis 1999; and Martzoukos and Trigeorgis 2002).

<sup>12</sup> The regression and correlation estimates were determined using the PROC REG and PROC CORR procedures, respectively, in SAS, v. 9.2.

series of values of  $x_H$  and  $x_L$  to cover a wide interval  $x$  may take over time; i.e.,  $x_H \in [0.50, 0.60, \dots, 4.50, 4.60]$  and  $x_L \in [0.40, 0.50, \dots, 4.40, 4.50]$ . They are paired in such a way that  $\Delta = x_H - x_L = 10$ , where  $\Delta > 0$  is necessary to solve (25) through (30).<sup>13</sup> The values of  $x_H$  and  $x_L$  are input into the system, along with the entry and exit costs from Table 1; unless otherwise indicated, the results that follow assume investment and exit costs for the medium-size plant.

As discussed below, the stochastic parameters for the base case differ from those for the several policy scenarios (Table 2). For each policy scenario, the appropriate set of parameters are used to solve for the  $y$ -coordinate pairs,  $y_H$  and  $y_L$ , along with the other parameters ( $A$ ,  $B$ ,  $\alpha_1$ ,  $\alpha_2$ ).<sup>14</sup> The empirical results are discussed in three distinct sections below. The first section contains a discussion of the baseline results -- the solution to the two-variable RO model based on actual prices. The second section contains a comparison of the baseline results with the results from the one-variable RO model, also based on actual prices. This section highlights the additional information obtained through the modeling of revenue and costs separately.

The third section contains the policy analysis. The impacts of policy on firm investment decisions are measured relative to the results of the base case. To conduct the policy analysis we begin by removing policy effects on both unit costs and revenues (scenario II), followed by simulations removing the policy effects on revenues (scenario III) and costs (scenario IV) in isolation. When revenue effects are considered, we also analyze two sub-cases where the alternative forms of consumer response are modeled (i.e., Mix or Flex). Finally, we consider the effects of alternative levels of investment costs in the two-variable setting, juxtaposed with the policy effects on revenues and costs.

### *Baseline Results*

The estimated trigger curves for the baseline (scenario I) are presented in Figure 4.<sup>15</sup> The figure provides an intuitive way to identify for a given unit cost ( $x$ ), what level of unit revenue ( $y$ ) is required for an idle firm to become active and for an active firm to exit. Ignoring the one-variable trigger lines for now, quadrant one of the  $(x, y)$  plane is divided into three parts by the two-variable trigger curves. If  $(x, y)$  is in the upper left portion above the  $y_H$  trigger curve, idle projects should enter. Alternatively, if  $(x, y)$  is in the lower right portion below the  $y_L$  trigger curve, currently active plants should exit. If neither is the case, idle projects should stay idle and active plants should stay active. For example, for  $x = \$2.00/\text{gal}$ , idle projects would enter when total expected revenues exceed  $\$2.92/\text{gal}$ , while existing firms would exit when expected revenues drop below  $\$1.45/\text{gal}$ .

One way to judge the performance of this model is to determine how the actual monthly data points on revenue and cost  $(x, y)$  are positioned relative to the trigger curves. In Figure 4, the data points that lie above the two-variable entry trigger curve ( $y_H$ ) generally represent months during the years of 2001, 2005, and 2006. Thus, the two-variable model does predict plant entry activity during the three highest levels of annual plant expansion over the time period evaluated.<sup>16</sup>

<sup>13</sup> The results are robust to the choice of  $\Delta$ , where in testing  $\Delta$  from 0.01 to 30, the trigger curves are virtually identical.

<sup>14</sup> The system of equations was programmed in Matlab (ver 7.10) and solved using the `fsolve` function.

<sup>15</sup> Full sets of the estimated parameters for each scenario, including  $A$ ,  $B$ ,  $\alpha_1$ , and  $\alpha_2$ , are available in a supplementary online appendix.

<sup>16</sup> Given the large number of data points included in the figures, individual points were not labeled by date. For the interested reader, the complete data series for the policy and no-policy scenarios are available in a supplementary

Specifically, the annual percentage changes in plant numbers (either in operation or under construction) immediately subsequent to these periods were 21.3%, 29.9%, and 47.6%, respectively (RFA 2010). The next highest annual increase in plant numbers was in 2005, with an 11.5% increase from 2004 (indeed, a more limited number of 2004 observations are also above the two-variable entry trigger curve).

On the exit side, no actual data points were located in the exit region delineated by the two-variable model results. Total annual plant numbers did drop in 2009 by small amount (6 or -3.0%) from 2008 (RFA 2010), but this was largely the result of a loss of plants under construction (a drop of 37 plants), some of which may not have yet invested fully in the project and left, while the balance completed construction and moved on to active status.

Some firms, not necessarily plants, have exited since 2008, but this has been commonly associated with devaluations of assets and plant sales often through bankruptcy proceedings to other firms at reduced plant values, and implying lower investment costs per gallon of output. For example, a \$200 million investment in a 114 mg/y plant in Volney, NY by Northeast Biofuels, LLC began construction in 2006 (a \$1.75/gal investment cost). Limited-scale production was initiated in 2008, but design problems prevented the plant from ever reaching full capacity. Under a bankruptcy filing in 2009, the plant was sold to Sunoco at a sales price of \$8.5 million (Little 2009). Even with expected repair costs of \$11 million, the per unit investment cost by Sunoco was only \$0.17/gal. The model presented here generally assumes decisions made by “first owners”, and the estimated trigger curves assume a constant investment cost (here, \$1.39/gal). However, as will be discussed later, lower capital investment costs do shift the entry trigger curve down.

#### *Comparison of Baseline with One-Variable Model*

The solution to the model assigning only one random variable (net returns) is also plotted in Figure 4, where the trigger lines are derived by transforming the one-variable solution (i.e.,  $p_H = \$1.40$  and  $p_L = \$0.44$  in this case) into equivalent  $(x, y)$  pairs via the equation  $y_i^{One} = (p_i^* - x_{oc}) + x_c$  for  $i = H, L$ . The one-variable model, by definition, is more restrictive since it defines a range of inactivity (i.e., the distance between the entry and exit trigger lines) that is constant. The two-variable model relaxes this restriction by considering individual component variability and the correlation between components, resulting in a range of inactivity that changes with  $x$  (i.e.,  $\frac{\partial y_H}{\partial x} > 1$  and  $\frac{\partial y_L}{\partial x} < 1$ ).

The underlying reason for this fundamental difference in the two models is in the nature of the stochastic processes. Since  $x$  follows GBM, the deviation in  $x$  is proportional to its current level (i.e.,  $\sigma_x x$ ). A higher level of  $x$  is simply riskier for investors, so it makes sense to be more cautious.<sup>17</sup> The same logic applies to  $y$ . While the deviation in  $p$  is also proportional to its current level (i.e.,  $\sigma_p p$ ), when defined in  $(x, y)$  space, net returns are measured linearly.

In either case, higher deviation rates expand the range of inactivity; the  $y_H$  trigger curve shifts up

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online appendix.

<sup>17</sup> For example, suppose  $x_{t=0}$  increases by 20% to  $x_{t=1}$  and then decreases by 20% to  $x_{t=2}$ , then  $x_{t=2} = 0.96x_{t=0}$ . Since  $\epsilon_x$  in  $dz_x$  is drawn from the standard normal without serial correlation, the two events have the same probability, regardless of the level of  $x$ . Suppose  $x_{t=0} = \$1/\text{gal}$ , when  $x$  evolves to  $x_{t=2}$ , net returns decrease by 4¢; if  $x_{t=0} = \$2/\text{gal}$ , however, net returns decrease by 8¢, a larger drop in absolute terms at higher prices of  $x$ .

and the  $y_L$  trigger curve shifts down. Higher volatility in prices causes firms to wait longer before entering and, once active, will wait longer before exiting. However, if a concurrent increase in the correlation between unit revenues and costs occurs (indistinguishable in the one-variable model), the range of inactivity will shrink and offset some, all, or more of the increasing variance effects, depending on the relative magnitudes of the individual components. This makes sense; i.e., for a given level of  $x$  and a higher correlation with  $y$ , firms will enter (exit) sooner in the face of increasing (decreasing) unit revenues since the proportional changes in  $y$  are expected to be higher.

The one-variable model reveals similar entry results at lower cost levels when compared with the actual data. However, several observations in 2007 are also above the one-variable entry trigger; in a region where the two-variable entry trigger curve is increasingly above the one-variable result. In this case, the one-variable result is likely indicative of a larger expansion in plant numbers than that represented by the actual change in plant numbers showing only a modest increase of 7.5%, including a decrease of 15 plants under construction (RFA 2010). On the exit side, the results between the two models are more similar. In fact, only in June 2008, when costs reached a record high of \$3.61/gal, did the one-variable model indicate it was optimal to exit.

The empirical results indicate that the two-variable model better predicts past expansionary behavior, particularly at higher levels of prices. This would seem particularly important given policy interests towards industry expansion. The exit side is arguably more difficult to accommodate given the multitude of other factors likely influencing firm decisions (e.g., lender relations, equity capital interests, etc.). In addition, the two-variable model is necessary to evaluate the incidence of policy effects relative to revenues and costs; an area we turn to next.

### *Policy Analysis*

The plant entry and exit environment changes considerably when policy effects are removed. To understand this, one must consider both the revised data series (to reflect changes in the levels of prices) and the revised trigger curves (to reflect changes in the variance and covariance components).

### Combined Effects of Policies Affecting Revenues and Costs

Initially, we consider Scenario II where policy effects are removed from both the revenue and cost price series (Figure 5). In the Mix model case (i.e., where consumers do not adjust fuel purchases to account for differential impacts on mileage between ethanol and gasoline), the number of time periods supporting new plant investment is severely curtailed when policy-induced revenue and cost effects are removed, relative to the baseline, and limited to only a few months in late-2005 and early-2006 (Figure 5, panel II-Mix). In particular, none of the historical 2001 expansion would have been optimal in the absence of policy. Furthermore, some plant exits would be supported in late-1998.

If, alternatively, consumers responded according to the Flex model case (i.e., consumers purchase ethanol on the basis of mileage factors), no optimal expansionary periods are indicated at all (Figure 5, panel II-Flex). Furthermore, market conditions in much of the late-1990s (1997-1999) would have signaled considerable plant exits.

### Separate Effects of Policies Affecting Revenues and Costs

Figure 6 and Figure 7 show the ‘what if’ scenarios when only policy-induced revenue or cost

effects are included in the simulations, respectively. By comparing the two figures, it is clear that most of the effect of ethanol policy on plant decisions has been due to revenue-side influences. Indeed, under the Mix model, the no-policy effects are relatively similar between Figure 5 (II-Mix) and Figure 6 (III-Mix). However, when revenue effects are removed under the Flex model in the presence of higher (policy-induced) unit costs, even more monthly periods would signal plant exits (Figure 6, III-Flex). In particular, much of mid- to late-1998, 2001, 2002, and early-2009 would exhibit conditions supporting plant exit.

As expected, removing the policy effects on unit costs (i.e., lower corn prices), while retaining higher policy-induced revenues would favor more expansionary periods with no cases for plant exit throughout the time period evaluated (Figure 7). In particular, additional entry support is evident in more of 2004 and some months of 2007.

### Effects of Investment Costs

As discussed above, the range of inactivity in the two-variable RO model is increasing in prices. The level of this range is computed by subtracting  $y_L$  from  $y_H$  at each level of  $x$ . The results considering large and small plant entry and exit costs (Table 1), and under the policy (I) and no policy (II-Mix, II-Flex) scenarios are shown in Figure 8. Since higher unit investment costs increase entry triggers and lower exit, it was expected to see higher levels of inactivity for the smaller plant size. However, plants associated with higher ranges of inactivity can also be thought of as more stable market participants. From the perspective of the current ethanol situation, further entry by smaller plants will be inhibited by their higher costs, but those already in operation will stay in longer than larger-sized plants through periods of low returns.

Importantly, this downward shift in the inactivity curves between the small and large plants can also be viewed in the context of ethanol policies aimed at decreasing investment costs for firms through various direct subsidies such as grants, low interest loans, and loan guarantees. As such, investment cost subsidies cause firms to enter sooner (at lower unit revenues) than would otherwise be the case. However, under these conditions, a lower range of inactivity also implies a more volatile entry/exit environment for those firms, and contributing to more industry volatility. Indeed, many of the plants sold recently via bankruptcy proceedings (under construction or operational) have been larger, more recent entrants (Energy Business Daily 2009).

Another important implication from Figure 8 is with respect to the differences in ranges of inactivity between the policy and no policy cases. Regardless of plant size, ethanol policy has lowered the ranges of inactivity implying the development of a more volatile industry regarding firm investment decisions. For our particular application, this is due to the fact that under policy, changes in the variance effects (i.e., lower  $\sigma_x$  and  $\sigma_y$ ) dominate the change in the correlation (i.e., lower  $\rho_{xy}$ )

### **Conclusions**

Existing ethanol policies have clearly affected market conditions, prices, and expansion of the industry. Policies such as blending mandates and tax credits have fostered stronger linkages between agricultural and energy commodity markets resulting in price effects on both cost and revenue dimensions for ethanol producers. An extended RO framework is developed that allows for the consideration of volatility in both revenue and cost components, as well as the correlation between them.

Analytical solutions for the two-variable value functions are derived and used to estimate the influence of ethanol policy on firm-level investment decisions. Through the empirical application we derive entry-exit trigger curves signaling the conditions (in revenue-cost space) when it is optimal to change states. The empirical results based on prices resulting from actual policies are consistent with historical expansionary behavior and increases in new plant investment, with improved performance of the two-variable model relative to the traditional one-variable framework. Importantly, by examining the influence of policy on revenues and costs separately, we show that most expansion was induced by the revenue-enhancing effects of policy. A result indistinguishable in the one-variable net return approach.

When the estimated effects of policy on revenues and costs are removed, and consumers do not take into account the differential mileage rates of ethanol and gasoline, the optimal entry/exit environment changes considerably. Not only would much of the actual expansion have never taken place, but additional plant exits would have been optimal in the late-1990s.

The case is even worse if consumers would have responded to fuel prices based on the changes in mileage (like they have done in Brazil for some time). Indeed, no optimal expansionary periods are indicated at all since 1997, and market conditions in much of late-1990s (1997-1999) would have signaled considerable plant exits. If the utilization of ethanol within the domestic fuel industry continues to expand (with corn or other advanced feedstocks), it can be expected that U.S. consumers will increasingly react to appropriate market signals in making fuel purchase decisions. If so, these results would indicate an increasing need for alternative policy designs or other incentives relative to historical experience to prevent increased consolidation in the US ethanol industry and large reductions in industry output (if that, indeed, is the intention). In other words, the size of policy contributions would need to grow over time.

Regardless of plant size, we show that ethanol policy has narrowed the distance between the optimal entry and exit curves, implying a more narrow range of inaction and supporting more volatile industry development. This has occurred for two reasons. First, for our particular application, lower ranges of inaction occur since the reduction in variance effects under policy dominate the lower covariance effect. Second, lower unit investment costs due either to firm investment incentives or economies of scale in production contribute to a narrowing of the range of inaction.

As policy incentives are increasingly promoting the development and expansion of advanced biofuels production (i.e., fuel derived from renewable biomass other than corn kernel starch), adaptations of the two-variable model presented in this article will be useful for future policy analysis. In particular, given the development and expanded production of cellulosic feedstocks for bioenergy production (e.g., switchgrass, miscanthus), the predicted price levels and volatilities of these feedstocks is relatively uncertain. Sensitivity analyses on a range of feedstock volatilities and investment costs will be important to consider in the development of this industry. In addition, the ability of current corn-based ethanol facilities to retrofit their operations to accommodate alternative feedstocks may have particular relevance to changes in optimal industry entry and exit for firms. We leave these considerations to future research.

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**Table 1. Average Capital and Operating costs (excluding corn feedstock) for Dry-Grind Corn-Ethanol Plants**

Category	Average Size <sup>a</sup>	Capital Cost	Operating Costs				Total
			Chemical	Energy & Utilities	Depreciation	Labor & Other	
Small	18.7	1.95	0.13	0.27	0.17	0.17	0.74
Medium	40.0	1.39	0.13	0.31	0.12	0.12	0.68
Large	100.0	1.22	0.11	0.29	0.12	0.17	0.69

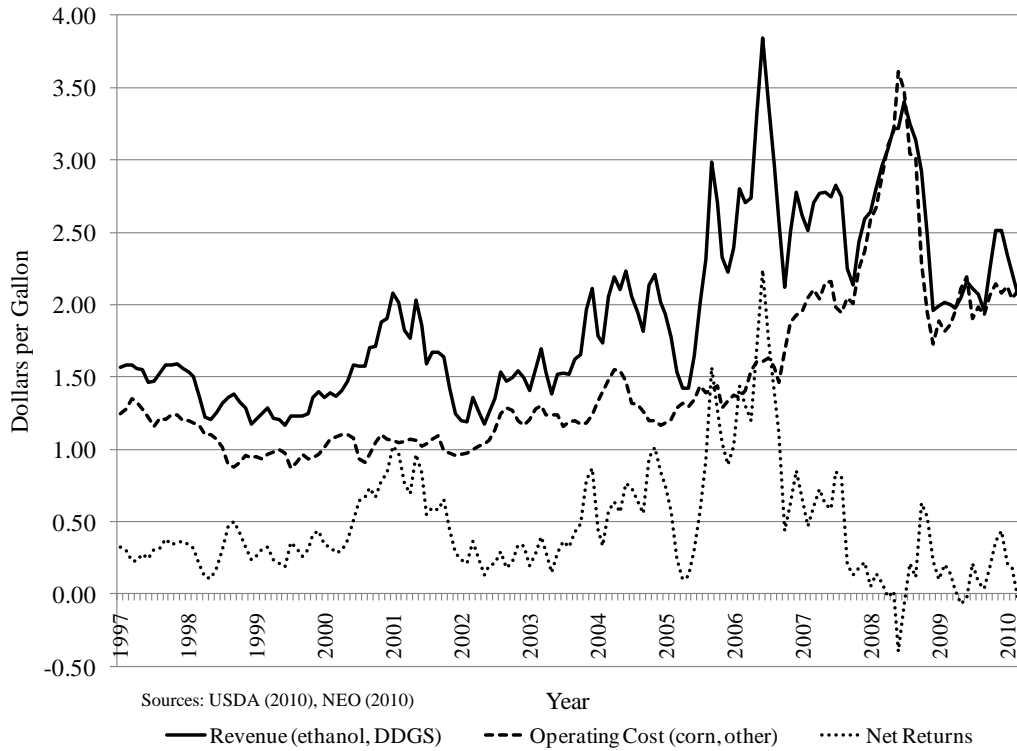
Note: Adapted from Schmit, Luo, and Tauer (2009). All costs are in 2006 U.S. dollars per gallon.

<sup>a</sup> Size is reported in million gallons per year, generally defined as nameplate capacity.

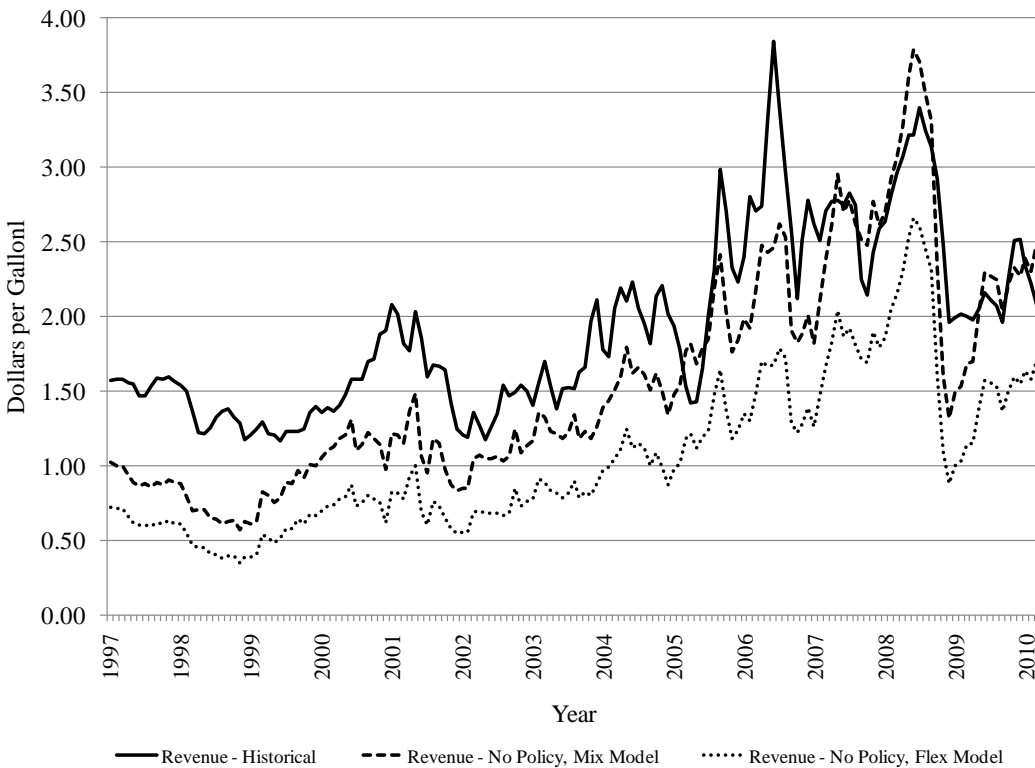
**Table 2. Average Prices and Estimated Stochastic Parameters by Scenario, Consumer Response, and Real Options Model**

Scenarios	Case Description	Average Prices			One-Var. Model	Two-Variable Model		
		1997 - 2010			Deviation Rate	Deviation Rate		Corr.
		$p^*$	$x$	$y$	$p^*$	$x$	$y$	$x,y$
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
I	Base case: actual prices reflecting ethanol policy.	0.94	1.45	1.92	0.371	0.189	0.275	0.220
II	Remove policy price effects on both $y$ and $x$ :							
	Mix model	0.70	1.32	1.54	0.437	0.221	0.348	0.455
	Flex model	0.20	1.32	1.05	0.642	0.221	0.375	0.441
III	Remove policy price effects on $y$ only:							
	Mix model	0.56	1.45	1.54	0.505	0.189	0.348	0.426
	Flex model	0.06	1.45	1.05	0.875	0.189	0.375	0.406
IV	Remove policy price effects on $x$ only:							
	Mix or Flex model	0.38	1.32	1.92	0.333	0.221	0.275	0.296

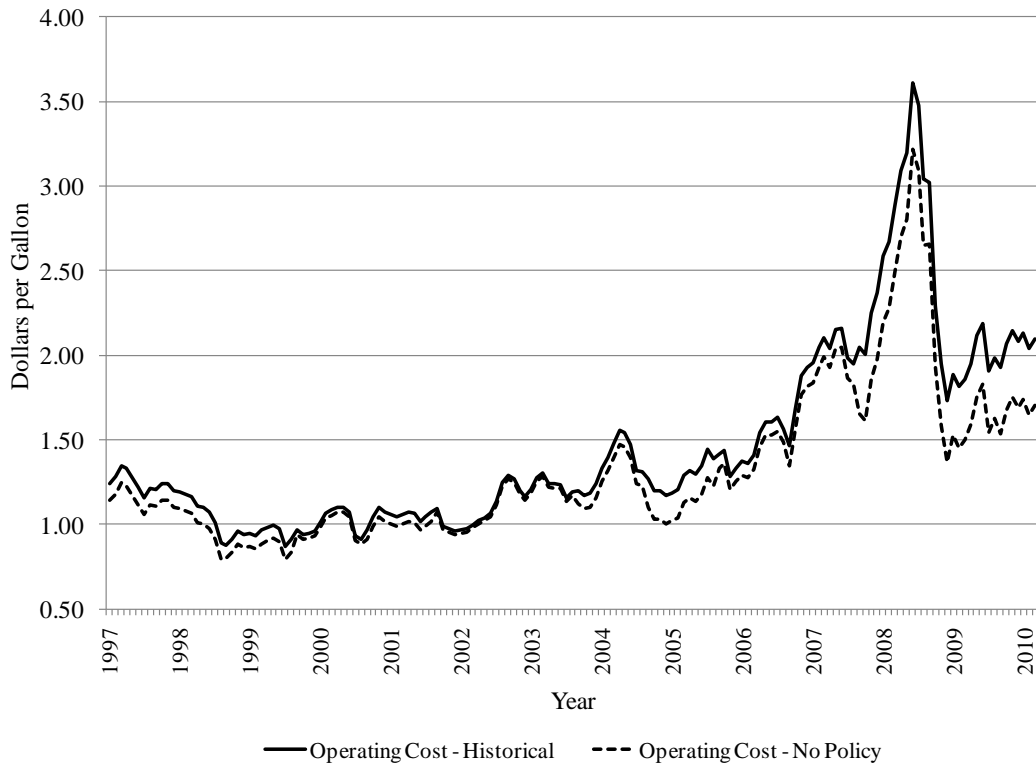
Note: All prices are measured in dollars per gallon of ethanol;  $y$  = unit revenue, including ethanol and byproduct sales;  $x$  = unit cost, including corn and other operating costs;  $p^*$  = unit revenue less corn feedstock cost, other operating costs assumed fixed and accounted for separately. All  $p^*$  data series are scaled up by \$0.50/gal to avoid negative values in the no-policy scenarios. In the Mix model consumers do not distinguish ethanol and gasoline mileage performance, while in the Flex model consumers distinguish mileage and tax consequences between ethanol and gasoline. All drift rate parameters are assumed equal to zero (not statistically different from zero at 95% significance level).



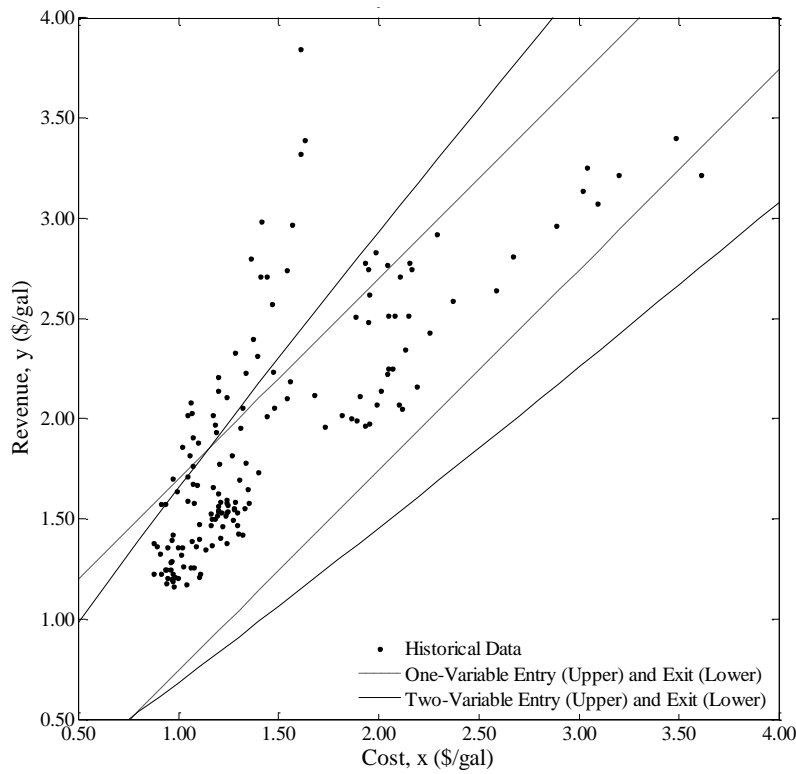
**Figure 1. Historical corn-ethanol unit revenues, costs, and net returns, 1997-2010**



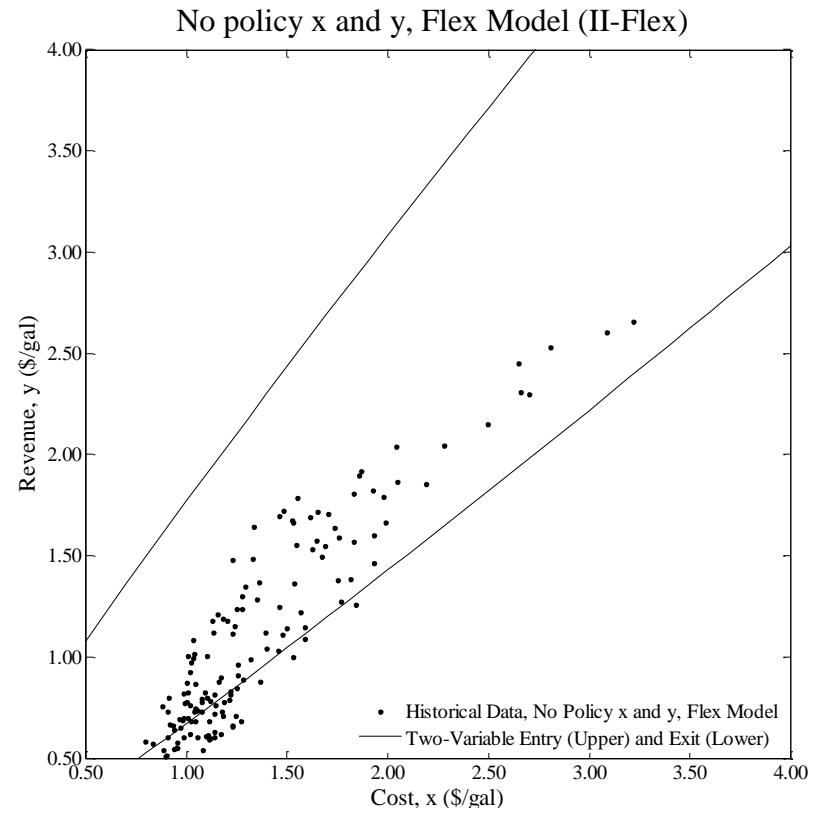
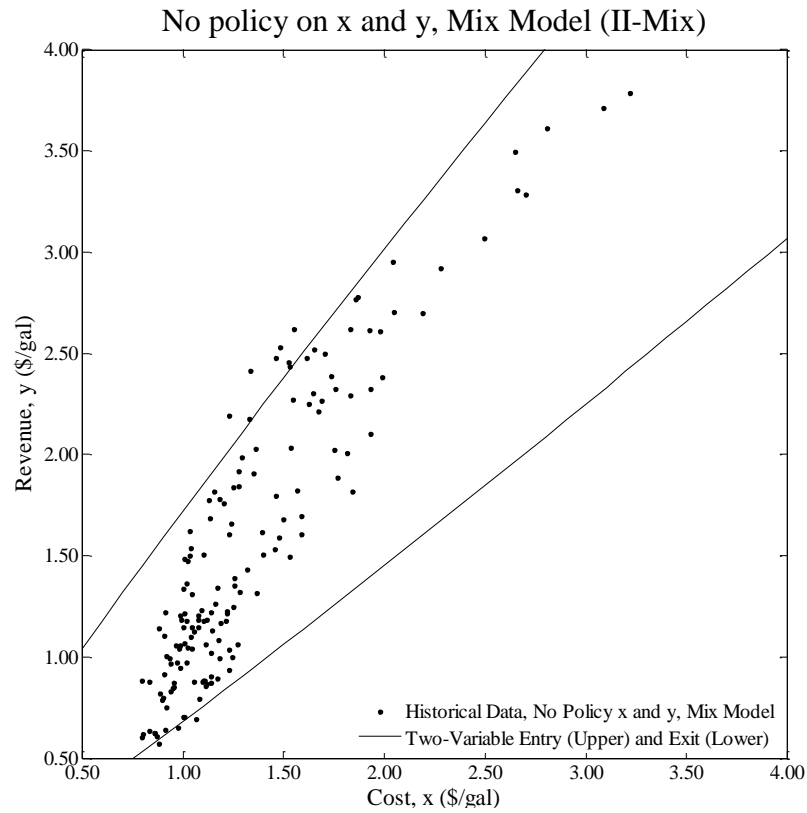
**Figure 2. Actual and derived (no policy) ethanol plant revenues, with mix model and flex model consumer assumptions.**



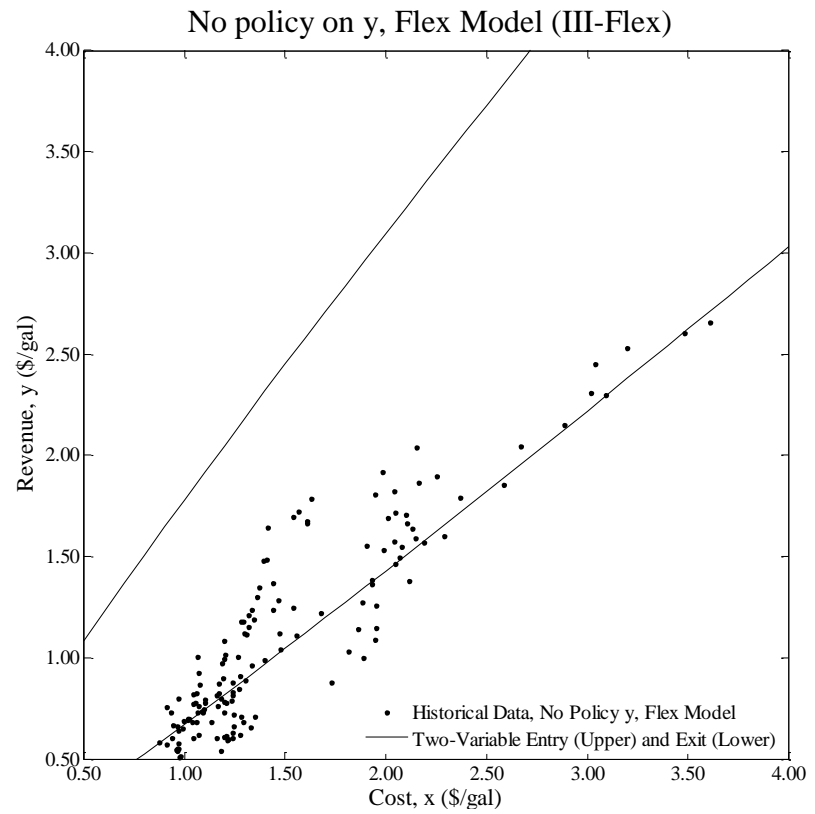
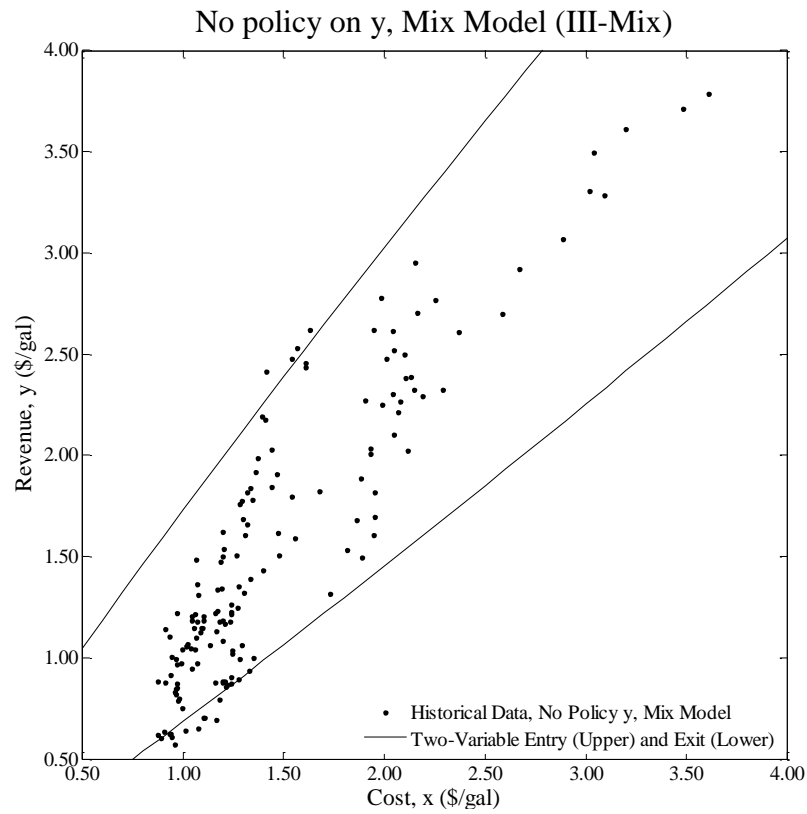
**Figure 3. Actual and derived (no policy) ethanol plant costs.**



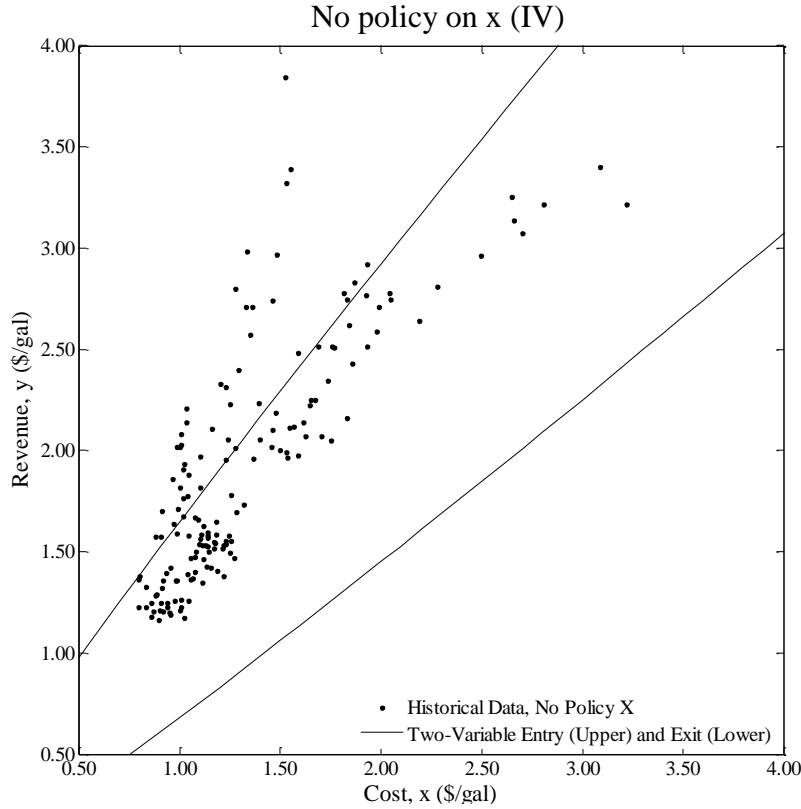
**Figure 4. Estimated investment trigger curves under actual policy (scenario I), medium-size plant investment costs.**



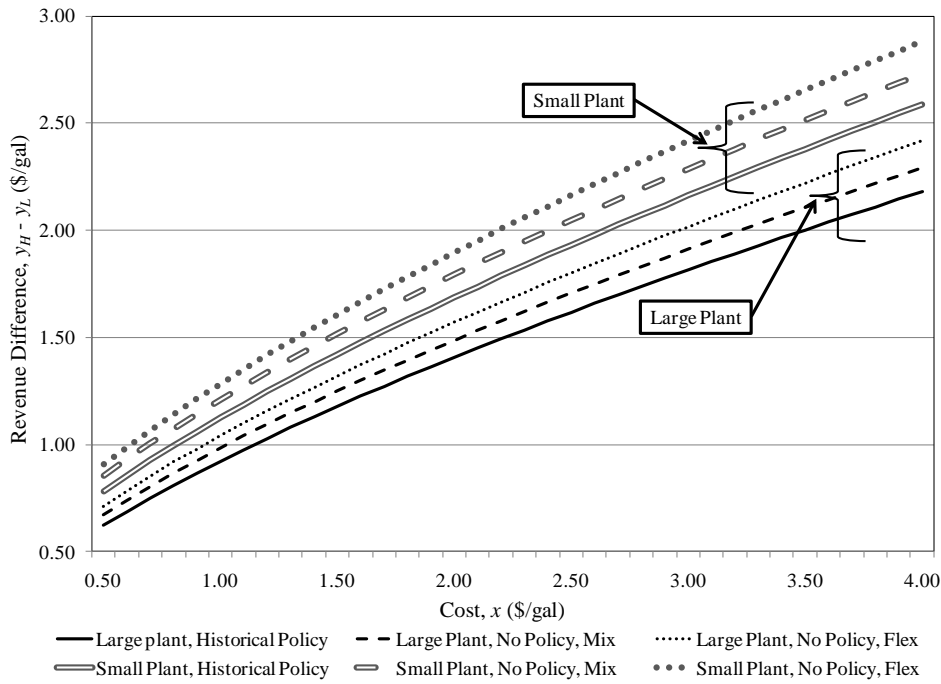
**Figure 5. Estimated investment trigger curves with no policy effects on cost and revenue (scenario II), by consumer response type, medium-size plant investment costs.**



**Figure 6. Estimated investment trigger curves with no policy effects on revenue (scenario III), by consumer type, medium-size plant investment costs.**



**Figure 7. Estimated investment trigger curves with no policy effects on cost (scenario IV), medium-size plant investment costs.**



**Figure 8. Levels of the range of inactivity, by policy level and plant size.**

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