Spatial Price Dynamics: Implications for Investment Decisions and Energy Policy in Canada

by

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ABSTRACT

SPATIAL PRICE DYNAMICS: IMPLICATIONS FOR INVESTMENT DECISIONS AND ENERGY POLICY IN CANADA

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This thesis, entitled Spatial Price Dynamics: Implications for Investment Decisions and Energy Policy in Canada, studies the long-run relationship between crude oil prices in different geographical areas and evaluates the impact spatial price differences have on the value of oil sands investments in Alberta. The impassioned debate surrounding the approval of new crude oil export pipelines has been the primary motivation for this research. Beginning in 2011 a larger than normal spread emerged between crude oil prices in Alberta and the rest of the world as constrained transportation capacity has meant excess supply could not be transported from production regions in Northern Alberta to those markets that would yield the highest return. This has led many participants in Canada's energy sector to advocate for expanding Canada's pipeline transportation system, meanwhile, opponents argue the benefits do not justify the direct and indirect economic and social costs of new pipeline capacity.

In the first chapter a two-factor real options model is developed to examine the impact spatial price differences have on the value of an oil sands project and the incentive to invest. Spatial arbitrage theory shows that large, volatile price differences between locations can emerge when demand to ship exceeds capacity limits. This may have a significant impact on production, investment, and policy in exporting regions. I assume the price difference between two locations follows a stationary process implying prices in different locations move together. The investment decision is formulated as a linear complementarity problem that is solved numerically using a fully implicit finite difference method. Parameters for the stochastic processes are estimated from monthly spot price data for West Texas Intermediate (WTI) and Western Canadian Select (WCS). Production parameters for the oil sands project

were selected to represent a typical steam-assisted gravity drainage project. Results show the value of an oil sands project and the incentive to invest in a new project will increase when price differences decrease. Surprisingly, the standard deviation of the price difference has very little impact on project value or the incentive to invest.

The second chapter studies the co-movement of weekly crude oil spot prices from different geographic regions for the period from May 2008 to February 2016 using a cointegration approach that allows for endogenously determined structural breaks. The emergence of large, persistent price differences between land-locked North American crude oil prices and international benchmarks has cast doubt on the 'one great pool' hypothesis which holds that crude oil prices in different geographical regions move together. Results indicate crude oil prices, for similar and different quality crude oils, are cointegrated with a structural break suggesting oil markets are still integrated. Estimated break dates range from the July 30, 2010 to December 16, 2014, with break dates for price pairs including a land-locked North American crude oil and an international benchmarks occurring in December 2010 and January 2011. These break dates correspond to the beginning of the unconventional crude oil production boom in North America.

The results of the second chapter suggest that crude oil markets are integrated but indicate that capacity constraints may have a significant impact on the relationship between crude oil prices. The third chapter builds on the second by considering the impact constrained transportation capacity has on the WTI-WCS spread. The WTI-WCS spread is modeled as a two regime Markov-switching model where one regime corresponds to normal times when there is sufficient transportation capacity and the other regime corresponds to times when there is insufficient transportation capacity. The results of this chapter confirm predictions in the spatial arbitrage literature. When there is sufficient transportation capacity the spread reflects transport costs and quality differences between WTI and WCS. During periods of tight capacity the spread becomes more volatile and on average exceeds transport costs and quality difference.

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Chapter 1

The Impact of Spatial Price Differences on Oil Sands Investments

1.1 Introduction

The feasibility of natural resource investments depends critically on access to markets. The decision of whether to build additional pipeline capacity to export crude bitumen and its derivatives from Alberta has been a contentious policy issue. Proponents argue the large price difference between Western Canadian Select (WCS) and international benchmarks is mostly attributed to inadequate pipeline infrastructure[1] and claim that both firms and governments would benefit from expanding pipeline capacity. Firms would gain access to international markets, higher world prices, and lower transportation costs while governments would receive more tax revenue through higher royalties. These claims are supported, theoretically, by spatial arbitrage models which show that significant variation in price differences can emerge as a result of capacity constraints (Coleman (2009)).

Figure 1.1 plots monthly spot price data for West Texas Intermediate (WTI),

[1]WCS a heavy crude oil located in Hardisty, Alberta. It is a blend of heavy crude oil, crude bitumen and diluents with an API gravity of 20.5°.

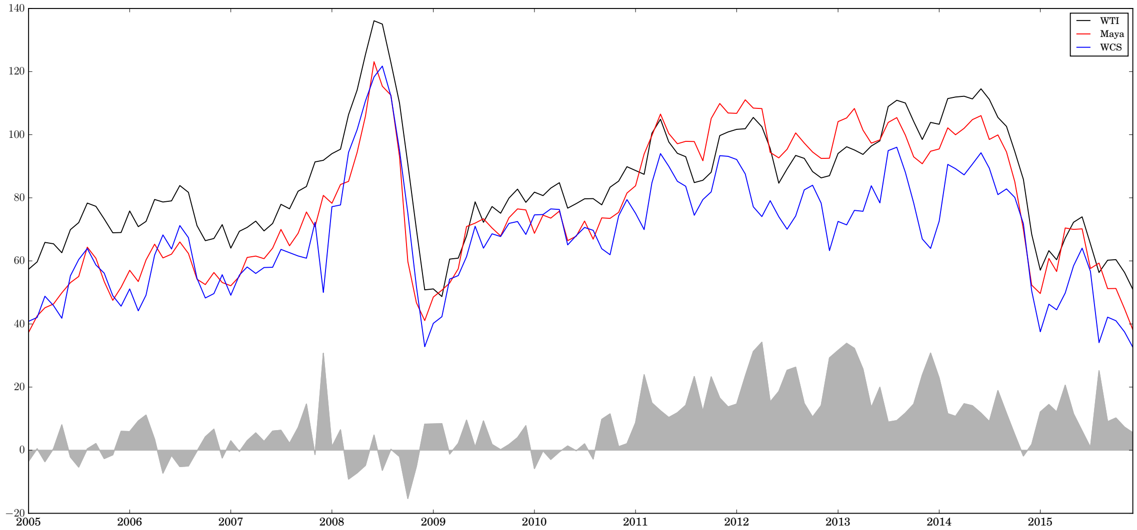
WCS, and Mexican Maya as well as the price difference between Mexican Maya and WCS from January 2005 to December 2015. Mexican Maya is a heavy crude oil similar in quality to WCS located in the Gulf Coast. Prior to 2011, Mexican Maya received a small location premium over WCS and large price differences were short lived. Beginning in 2011 Mexican Maya and WCS diverged. The persistence of the large price difference suggests there are substantial costs required to move heavy crude oil from Northern Alberta to the Gulf Coast, if not, there is a opportunity to arbitrage between the two markets.[2]

In this paper we incorporate transportation costs into a real options model to study the impact spatial price differences have on the value of an oil sands project and the incentive to invest in new oil sands projects. The value of an oil sands project is contingent upon uncertain output prices and transportation costs. We assume the output price follows a geometric Brownian motion (GBM) and transportation costs follow a Ornstein-Uhlenbeck (OU) mean-reverting process. This assumption implies the world oil market is 'one great pool' (Adelman (1984)) as crude oil prices in different markets move together in the long-run. The decisions of when to invest in a new project and when to abandon a project for scrap value are evaluated under different scenarios. Optimal stopping is used identify the threshold prices when it is optimal to invest in a new project and abandon an operating project. The optimal stopping problems result in free boundary problems that do not have known analytical solutions. Following Wilmott et al. (1993) and Insley and Rollins (2005), the free boundary problems are redefined as linear complementarity problems and we approximate the solutions numerically using the fully implicit finite difference method (IFDM). The model parameters are chosen to approximate a typical *in situ* oil sands project in Northern Alberta.

To preview the results, we find that a decrease in transportation costs increases the value of the oil sands project, investments in new projects happen earlier, and operating projects are abandoned later. These results are consistent with the claims

[2]The spatial equilibrium model of Samuelson (1952) and Takayama and Judge (1971) show the price of a good in one market is equal to the price of the good in another market minus the cost of transporting it between the two markets.

Figure 1.1: Monthly crude oil spot prices



made by supporters of the policy to expand pipeline capacity. Surprisingly, we also find that an increase in transportation cost uncertainty has little effect on the value of the oil sands project or on the decision of when to invest and when to abandon. Typically, the value of an option increases as uncertainty increases as upside potential increases while the option limits downside loses.

1.2 Literature Review

Evaluating natural resource investments using real options analysis is a standard approach in the literature. Brennan and Schwartz (1985) apply option pricing theory to the problem of valuing uncertain investments. They determine the combined value of the options to shut down and restart a copper mine when spot prices are uncertain and the convenience yield is constant. Paddock et al. (1988) combine option-pricing techniques with a model of equilibrium in the market for the underlying asset to value offshore petroleum leases. Bjerksund and Ekern (1990) value a Norwegian oil field with options to defer and abandon. Clarke and Reed (1990) consider the option to abandon a currently producing oil-well when oil prices and extraction rates are uncertain. Conrad and Kotani (2005) determine the trigger prices to initiate investment in the Arctic National Wildlife Refuge under different assumptions about the evolution of crude oil prices. Morck et al. (1989) value forestry resources under stochastic inventories and prices. Insley (2002) and Insley and Rollins (2005) consider the optimal tree harvest problem when tree harvesting can be delayed and output prices follow known stochastic processes. Conrad (2000) determines the order and timing of wilderness preservation, resource extraction, and development when amenity value, the value of the resource, and return from development all follow geometric Brownian motions.

Recently, a number of papers have analyzed the management of oil sands projects and the rate of oil sands development using real options analysis. Almansour and Insley (2016) extend the Brennan and Schwartz (1985) model to include cost uncertainty and study the optimal management of an oil sands project. *In situ* oil sands projects face high levels of cost uncertainty from fluctuations in natural gas prices, natural gas is an important input in the extraction process. Commodity prices follow a non-stationary stochastic process made up of three factors: a long-run factor (non-stationary process), a short-run factor (stationary process), and a deterministic function that represents seasonality in the prices.[3] They find the value of the project is significantly negatively affected by stochastic costs and the value of the project decreases as cost volatility increases.

Kobari et al. (2014) evaluate the rate of oil sands expansion under different environmental cost scenarios in a dynamic, game-theoretic model. Their model considers a multi-plant/multi-agent setting with price and cost uncertainty. Like Almansour and Insley (2016), cost uncertainty is driven by uncertainty in natural gas prices. The price of oil follows a mean-reverting process with an increasing long-run average price. The cost of natural gas depends on a deterministic seasonality component and a mean-reverting stochastic component. They consider two environmental cost scenarios: an increasing environmental cost scenario and a decreasing environmental cost scenario. Their results show that decreasing environmental costs cause new investments to be delayed compared to increasing environmental costs but decreasing

[3] Almansour and Insley (2016) extend the Schwartz and Smith (2000) two factor commodity price model by incorporating a deterministic seasonality component.

environmental costs have little effect on projects that have already been constructed.

Almansour and Insley (2016) and Kobari et al. (2014) both assume that the price of crude oil and natural gas in Northern Alberta follows the same dynamics as international crude oil and natural gas benchmarks.[4] These assumptions ignore the crude oil price differential and factors that affect the differential such as the availability of pipeline capacity, weather and the cost of diluent.[5] Carney et al. (2013) expect Canadian crude oil prices to remain depressed and more volatile than international crude oil benchmarks until sufficient capacity is in place. They believe this is an important issue facing Canada's energy sector and a major factor restraining business investment. This paper hopes to contribute to this literature by focusing on the effect transportation costs have on a firm's investment decision. Due to the cost of investing in new pipeline projects, understanding how oil sands producers will respond to a decrease in transportation costs is important for oil transportation firms proposing new pipeline projects and for policymakers weighing the cost and benefit of these new pipeline projects.

The rest of the paper is organized as follows. Section 1.3 presents the general valuation model when price and cost are uncertain. Section 1.4 presents the results for each transportation cost scenario. Section 1.5 summarizes the results and concludes the paper.

1.3 General Model

This section presents a model for the valuation of a nonrenewable resource asset with nested real options subject to uncertain prices and transportation costs. Here, an oil sands project has two stages: the development stage where a firm holds an option to develop an oil sands project and the operating stage where a firm operates an oil

[4]Almansour and Insley (2016) use weekly WTI futures and Henry Hub (HH) natural gas futures data from January 1995 to August 2010 to calibrate their model and Kobari et al. (2014) use daily WTI futures and HH natural gas futures data from February 2, 2009 to May 10, 2012 to calibrate their model.

[5]Diluent is any lighter hydrocarbon added to heavy crude oil or bitumen in order to facilitate its transportation in crude oil pipelines, National Energy Board (2013, p. 80).

sands project and has an option to abandon for scrap value. Similar to Paddock et al. (1988), the value of the oil sands project in the development stage is contingent on the value of the oil sands project in the operating stage and is therefore a compound option, i.e. option on an option.

The motivation for this model is a Canadian oil sands project located in Northern Alberta that must transport its output from remote production areas to consuming markets thousands of kilometers away,[6] but we believe it can be applied to any nonrenewable resource project that faces price and transportation cost uncertainty.

1.3.1 Option to Develop an Oil Sands Project

Consider a firm that holds a lease to a previously undeveloped parcel of land that contains a known quantity of crude oil.[7] We assume all expenditures relating to exploration have been made. The lease gives the firm the proprietary right to extract and sell the crude oil for a specified period of time. If, by the end of the lease, production has not begun the lease expires and the land is returned to the leasee.[8] If production has begun the lease is extended indefinitely, meaning the lease is extended until reserves are exhausted or the project is abandoned.

The lease is viewed as an option to develop an oil sands project. The underlying asset is an operating oil sands project whose value is contingent on the price of the crude oil, the cost of transporting crude oil to market, and the amount of reserves in place. The exercise price is the cost of building the required production facilities and transportation infrastructure. The firm's problem is to determine the value of the option to develop and decide at what point in time they will exercise the option to develop given price and transportation cost follow known stochastic processes.

Assume price, $S(t)$, follows a GBM and transportation cost, $C(t)$, follows an OU

[6] The distance between Hardisty, Alberta and Cushing, Oklahoma, two major transportation hubs, is over 2500 kilometers.

[7] The standard term of a primary lease is 15 years.

[8] Generally, the leasee refers to the provincial Crown as it own 97 percent of oil sands mineral rights.

mean-reverting process.

$$dS = \mu S dt + \sigma_S S dW_S, \tag{1.1}$$

$$dC = \kappa(\bar{C} - C)dt + \sigma_C dW_C. \tag{1.2}$$

Where μ is the drift and σ_S is the standard deviation in price, κ is the speed of reversion, $\bar{C}$ is the long-run average transportation cost, and σ_C is the standard deviation in transportation cost. dW_S and dW_C are increments of a correlated Brownian motion with correlation coefficient of $\rho_{S,C}$.

Assuming GBM in commodity prices is a standard assumption in the real options literature (Brennan and Schwartz (1985) for copper prices, Paddock et al. (1988) for the value of developed reserves, Clarke and Reed (1990) and Conrad and Kotani (2005) for crude oil prices). Schwartz and Smith (2000) consider a two-factor model for commodity prices that incorporates short-term deviations from the equilibrium price and long-term random fluctuations in the equilibrium price. They show that for long-term investments, short-term deviations from the equilibrium price have little effect on the value of the investment. Therefore, they argue, to simplify analysis a single-factor model that considers uncertainty in the equilibrium price can be used to value long-term investments.

Assuming transportation costs follow the OU mean-reverting process is consistent with the literature on crude oil price differentials. A number of authors have examined the co-movement of crude oil prices (Gülen (1997 and 1999), Hammoudeh et al. (2008), and Fattouh (2010)) and have found that crude oil prices are cointegrated; meaning crude oil price differences are stationary. Recently, Wilmot (2013) found that secondary crude oil blends of similar and differing qualities are cointegrated with a structural break.

Let $G(S, C, \tau)$ be the value of the option to develop an oil sands project at the current price, S, current transportation cost, C, and with τ time remaining on the lease. Where $\tau = \bar{T} - t$, t is the current date, and $\bar{T}$ is the expiration date of the lease. If $F(S, C, \bar{Q})$ is the value of an operating oil sands project with initial reserves

$\bar{Q}$ and IC is the required investment cost then the firm's payoff from exercising the option to develop is $F(S, C, \bar{Q})-\mathrm{IC}$. If the firm decides not to exercise the option, they receive a payoff of $\mathrm{M}(t)$ per unit of time from the undeveloped parcel of land,[9] and the option to develop an oil sands project in the next period.

The firm's problem of valuing the option to develop an oil sands project and determining the optimal development threshold can be formulated as an optimal stopping problem

$$G(S, C, \tau) = \max\left\{ F(S, C, \bar{Q}) - \mathrm{IC},\ \mathrm{M}dt + \frac{\mathrm{E}_t[G(S + dS, C + dC, \tau + d\tau)]}{1 + \delta_G dt} \right\}. \quad (1.3)$$

Where E_t is the conditional expectations operator and δ_G is the risk-adjusted constant discount rate.

The optimal development threshold defines a surface that divides the (S, C, τ)-space into two regions: the continuation region and the development region. Let $\hat{S}(C, \tau)$ be the optimal development threshold. The optimal development threshold specifies the output price at which the payoff from exercising the option to develop is equal to the payoff from waiting for a given amount of time remaining, τ, and transportation cost, C. The continuation region lies below the optimal development threshold, $S < \hat{S}(C, \tau)$. In this area it is optimal to delay development of the oil sands project as the value of delaying exceeds the payoff from development. The development region lies above the optimal development threshold, $S > \hat{S}(C, \tau)$. In this area it is optimal to exercise the option to develop immediately. When $S = \hat{S}(C, \tau)$, the continuation payoff equals the exercise payoff.

In the continuation region, $S \leq \hat{S}$, the value of the option to develop an oil sands project satisfies the following Bellman equation

$$\delta_G G = \mathrm{M} + (1/dt)\mathrm{E}_t[dG]. \quad (1.4)$$

The Bellman equation requires the firm's payoff from waiting to exercise the option

[9] The payoff from the undeveloped parcel of land can be either positive or negative.

to develop, the right hand side of (1.4), to equal the required return from holding the option to develop.

Apply Ito's Lemma to $G(S, C, \tau)$ and substitute equations (1.1) and (1.2) and rearrange to get

$$\begin{aligned} dG =& (\mu G_S + \kappa(\bar{C} - C)G_C - G_\tau + \frac{1}{2}(\sigma_S^2 S^2 G_{SS} + \sigma_C^2 G_{CC} + 2\sigma_S\sigma_C\rho_{S,C} S G_{SC}))dt \\ &+ \sigma_S S G_S dW_S + \sigma_{TC} G_C dW_{TC}. \end{aligned} \tag{1.5}$$

Equation (1.5) is the stochastic differential equation for the option to develop an oil sands project. Substitute (1.5) into the Bellman equation (1.4) and pass it through the expectations operator to obtain the partial differential equation for the value of the option to develop an oil sands project in the continuation region,

$$\delta_G G = \mathrm{M} + \mu S G_S + \kappa(\bar{C} - C)G_C - G_\tau + \frac{1}{2}(\sigma_S^2 S^2 G_{SS} + \sigma_C^2 G_{CC} + 2\sigma_S\sigma_C\rho_{S,C} S G_{SC}). \tag{1.6}$$

This partial differential equation is subject to the following boundary condition,

$$G(S, C, 0) = \max\{F(S, C, Q) - \mathrm{IC}, 0\}. \tag{1.7}$$

If the lease reaches the expiration date and the oil sands project has not yet been developed, the option to develop an oil sands project is exercised if the value of the operating oil sands project exceeds the investment cost otherwise the option to develop expires unused.

The optimal development threshold is determined by the following value-matching condition

$$G(\hat{S}(C, \tau), C, \tau) = F(\hat{S}(C, \tau), C, Q) - \mathrm{IC}, \tag{1.8}$$

and smooth-pasting conditions

$$G_S(\hat{S}(C, \tau), C, \tau) = F_S(\hat{S}(C, \tau), C, Q), \tag{1.9.1}$$

$$G_C(\hat{S}(C, \tau), C, \tau) = F_C(\hat{S}(C, \tau), C, Q). \tag{1.9.2}$$

The value-matching condition matches the value of the option to develop to the value of the operating oil sands project minus the investment cost on the optimal stopping boundary. The smooth-pasting conditions are required to jointly solve for the unknown function G and the unknown development threshold $\hat{S}$. On the boundary the functions, G and F, must meet tangentially for $\hat{S}$ to be the optimal stopping boundary.[10]

Option to Develop as a Linear Complementarity Problem

Equation (1.6) and conditions (1.7), (1.8), and (1.9) define a free boundary problem, the solution to the problem determines the value of the option to develop an oil sands project as well as the optimal development threshold. We follow Wilmott et al. (1993) and Insley and Rollins (2005) and redefine the free boundary problem as a linear complementarity problem (LCP).[11] A solution to the LCP is a solution of the free-boundary problem and *vice versa*.[12] A benefit of redefining the free boundary problem as a LCP is that the complications caused by the free-boundary are eliminated and the free boundary can be recovered after the LCP has been solved.

The free boundary problem for the option to develop can be redefined as the

[10]See Dixit and Pindyck (1994) for a detailed discussion on value-matching and smooth-pasting conditions.

[11]A LCP has the following form

$$\begin{aligned} x, F(x) &\geq 0, \\ x^T F(x) &= 0. \end{aligned} \tag{1.10}$$

Where x is a vector and $F(x)$ is a linear vector valued function.

[12]See Elliot and Ockendon (1982), Friedman (1988), and Kinderlehrer and Stampacchia (1980) for proofs of the existence and uniqueness of the solutions.

following LCP

$$
\begin{aligned}
&\delta_G G - \mathrm{M} - \mu S G_S - \kappa(\bar{C} - C)G_C + G_\tau \\
&\qquad - \frac{1}{2}(\sigma_S^2 S^2 G_{SS} + \sigma_C^2 G_{CC} + 2\sigma_S\sigma_C\rho_{S,C} S G_{SC}) \geq 0, && (1.11.1)\\
&G - F + \mathrm{IC} \geq 0, && (1.11.2)\\
&\big(\delta_G G - \mathrm{M} - \mu S G_S - \kappa(\bar{C} - C)G_C + G_\tau \\
&\qquad - \frac{1}{2}(\sigma_S^2 S^2 G_{SS} + \sigma_C^2 G_{CC} + 2\sigma_S\sigma_C\rho_{S,C} S G_{SC})\big) \times \big(G - F + \mathrm{IC}\big) = 0. && (1.11.3)
\end{aligned}
$$

The option to develop, like all American-type options, defined as LCPs has the intuitive interpretation of a rational individual's strategy with regard to holding versus killing the option. For the option to develop, equation (1.11.1) holds with an equality when it is optimal to hold the option to develop and equation (1.11.2) is a weak inequality. Equation (1.11.1) holds with a weak inequality and equation (1.11.2) holds with an equality when it optimal to exercise the option to develop. Equation (1.11.1) can be interpreted as the difference between the required return for holding the option to develop and the actual return from holding the option. When the required return equals the actual return it is optimal to hold the option to develop. When the required return exceeds the actual return it is optimal to exercise the option to develop. Equation (1.11.1) is nonnegative as realized returns cannot be consistently greater than required returns in equilibrium. Equation (1.11.2) is nonnegative, if negative it is optimal to exercise the option.

1.3.2 Operating Oil Sands Project

In subsection (1.3.1) we derived the free boundary problem for the value of the option to develop an oil sands project and the optimal development threshold for a given value function for the operating oil sands project, $F(S, C, \bar{Q})$. Now we turn to the problem of valuing an operating oil sands project with the option to abandon for scrap value.

After exercising the option to develop, the firm receives an operating oil sands project with the option to abandon for scrap value. While it is operating, crude oil is extracted, transported, and then sold in a perfectly competitive market. The after-tax cash flows from operations, $\pi(q; S, C, Q, z)$, are affected by the amount of output sold, q, the current price and transportation cost, the amount of reserves remaining, and other factors that include taxes, z. The payoff to the firm from the operating oil sands project is the cash flows from operations and the future value of the operating oil sands project. If the firm decides to exercise the option to abandon the firm gets the scrap value of the oil sands project, $\Omega(S, C, Q)$. Here, scrap value represents all the costs associated with abandoning the project and restoring the land to its previous state and is likely to be negative.[13]

The firm's problem of valuing the operating oil sands project with the option to abandon for scrap value can be represented by the following optimal stopping problem

$$F(S, C, Q) = \max \Bigg\{ \Omega(S, C, Q), \\ \max_{q \in [\underline{q}, \bar{q}]} \pi(q; S, C, Q, z)dt + \frac{\mathrm{E}_t[F(S + dS, C + dC, Q + dQ)]}{1 + \delta_F dt} \Bigg\}. \tag{1.12}$$

The value of an operating oil sands project is the larger of either exercising the option to abandon immediately or continuing to operate the project. Where δ_F is the risk-adjusted constant discount rate for the operating oil sands project. The firm chooses the flow of output over time to maximize the expected discounted value of the operating oil sands project. Due to technological and capacity constraints management cannot produce output below $\underline{q}$ or above $\bar{q}$.

The optimal abandonment threshold defines a surface that divides the (S, C, Q)-space into two regions: the continuation region and the abandonment region. Let $S^*(C, Q)$ be the optimal abandonment threshold. The threshold specifies an output price for a given amount of reserves, Q, and transportation costs, C, where the payoff from abandonment equals the payoff from continuing to operate. The continuation

[13]Scrap Value may be positive if the option to abandon is exercised before reserves are exhausted and the restored land has some value to other oil producers or another purposes.

region lies above the surface, $S > S^*(C,Q)$. In this area it is optimal to continue operating the project. The abandonment region lies below the surface, $S < S^*(C,Q)$. In this area it is optimal to abandon the project for scrap value. When $S = S^*(C,Q)$, the continuation payoff is equal to the abandonment payoff.

In the continuation region the value of an operating oil sands project satisfies the following Bellman equation

$$\delta_F F = \max_{q \in [\underline{q}, \bar{q}]} \pi(q) + (1/dt)\mathrm{E}_t[dF]. \tag{1.13}$$

Similar to equation (1.4), the Bellman equation here requires the firm's payoff from operations to be equal to the required return from operations.

Let $q(t)$ represent the quantity of reserves extracted at a particular point in time so that changes is reserves are

$$dQ = -qdt. \tag{1.14}$$

Apply Ito's Lemma to $F(S,C,Q)$ and make the appropriate substitutions to get

$$\begin{aligned} dF =& (\mu S F_S + \kappa(\bar{C} - C)F_C - qF_Q + \frac{1}{2}(\sigma_S^2 S^2 F_{SS} + \sigma_C^2 F_{CC} + 2\sigma_S\sigma_C\rho_{S,C} S F_{SC}))dt \\ & + \sigma_S S F_S dW_S + \sigma_C F_C dW_C. \end{aligned} \tag{1.15}$$

Equation (1.15) is the stochastic differential equation for the operating oil sands project. Substitute (1.15) in to the Bellman equation (1.13) and pass through the expectations operator to obtain the following partial differential equation for the value of an operating oil sands project with the option to abandon in the continuation region,

$$\delta_F F = \max_{q \in [\underline{q}, \bar{q}]} \pi + \mu S F_S + \kappa(\bar{C} - C)F_C - qF_Q + \frac{1}{2}(\sigma_S^2 S^2 F_{SS} + \sigma_C^2 F_{CC} + 2\sigma_S\sigma_C\rho_{S,C} S F_{SC}) \tag{1.16}$$

The optimal flow of output is determined by differentiating the right hand side of equation (1.16) with respect to q. The firm will produce at an interior solution if the marginal cash flow from selling an extra unit of output, π_q is equal to the shadow price of producing an extra unit of output, F_Q. The firm will produce at the lower boundary if the shadow price exceeds the marginal cash flow at $\underline{q}$, the firm will produce at the upper boundary if the marginal cash flow exceeds the shadow price at $\bar{q}$.

$$q^* = \begin{cases} \underline{q} & \text{if } \pi_q(\underline{q}) < F_Q \\ q^* & \text{if } \pi_q(q^*) = F_Q \\ \bar{q} & \text{if } \pi_q(\bar{q}) > F_Q \end{cases}$$

At the optimal flow of output the partial differential equation becomes

$$\delta_F F = \pi(q^*) + \mu S F_S + \kappa(\bar{C} - C)F_C - q^* F_Q + \frac{1}{2}(\sigma_S^2 S^2 F_{SS} + \sigma_C^2 F_{CC} + 2\sigma_S \sigma_C \rho_{S,C} S F_{SC}) \tag{1.17}$$

The partial differential equation is subject to the following boundary condition,

$$F(S, C, 0) = \Omega(S, C, 0). \tag{1.18}$$

When reserves are exhausted the value of an operating oil sands project is equal to the remaining scrap value of the project.

The optimal abandonment threshold is determined by the value-matching

$$F(S^*(C, Q), C, Q) = \Omega(S^*(C, Q), C, Q), \tag{1.19}$$

and smooth-pasting conditions

$$F_S(S^*(C, Q), C, Q) = \Omega_S(S^*(C, Q), C, Q), \tag{1.20.1}$$

$$F_C(S^*(C, Q), C, Q) = \Omega_C(S^*(C, Q), C, Q). \tag{1.20.2}$$

Operating Oil Sands Project as a Linear Complementarity Problem

Equation (1.17) and conditions (1.18), (1.19), and (1.20) define a free boundary problem that determines the value of an operating oil sands project and the optimal abandonment threshold. The free boundary problem for the operating oil sands project can be redefined as the following LCP

$$\delta_F F - \pi(q^*) - \mu S F_S - \kappa(\bar{C} - C)F_C + q^* F_Q$$
$$- \frac{1}{2}(\sigma_S^2 S^2 F_{SS} + \sigma_C^2 F_{CC} + 2\sigma_S \sigma_C \rho_{S,C} S F_{SC}) \geq 0, \tag{1.21.1}$$
$$F - \Omega \geq 0, \tag{1.21.2}$$
$$\big(\delta_F F - \pi(q^*) - \mu S F_S - \kappa(\bar{C} - C)F_C + q^* F_Q$$
$$- \frac{1}{2}(\sigma_S^2 S^2 F_{SS} + \sigma_C^2 F_{CC} + 2\sigma_S \sigma_C \rho_{S,C} S F_{SC})\big) \times \big(F - \Omega\big) = 0. \tag{1.21.3}$$

Equation (1.21) has the same intuitive interpretation as equation (1.11).

1.4 Results

In this section we use the fully implicit finite difference method (IFDM) to approximate the value of an typical *in situ* oil sands project in Northern Alberta and determine the optimal development and abandonment thresholds. A detailed explanation of the IFDM can be found in appendix 1.6.1. There are two main methods for recovering crude bitumen from the oil sands mixture, the choice of extraction method depends on the depth of the oil sands deposits. Open-pit mining is used to recover crude bitumen from shallow deposits while *in situ* methods are used to extract it from deep deposits.[14] We focus on a project that uses *in situ* methods in this paper for two reasons. First, production from *in situ* projects has exceed the production from mining projects since 2014 (CAPP, 2015). Second, approximately 80 percent of oil sands deposits are too deep to be recovered from open-pit mining and must be extracted using *in situ* methods.

Table 1.1 summarizes the assumptions we make about a typical *in situ* oil sands project. The investment cost, initial reserves, and annual production are from Millington et al. (2014) who estimate the supply costs for various oil sand projects based

[14] *In situ* methods involves drilling several wells into deep oil sands deposits then injecting steam to heat the bitumen so that it flows and can be pumped to the surface. The primary *in situ* methods used today are the thermal techniques of Cyclic Steam Stimulation (CSS) and Steam Assisted Gravity Drainage (SAGD).

Table 1.1: *In situ* Oil Sands Project Design Parameters

Option to Develop	
Length of Lease, years (T)	15
Investment Costs, millions of dollars (IC)	\$1050
Benefits(Costs) from lease (M)	0
Discount Rate (δ_G)	10%
Operating Project	
Production life, years	30
Initial Reserves, millions of barrels ($\bar{Q}$)	328.5
Annual Production, millions of barrels (q)	10.95
Average cost, per barrel (AC)	\$35.00
Scrap Value, (Ω)	0
Royalty Rate (λ_R)	30%
Income Tax Rate (λ_I)	40%
Property Tax Rate (λ_P)	10%
Discount Rate (δ_F)	10%

on their type. We assume the deflated average cost of producing a barrel of oil is constant and equal to \$35. We feel this is a fair assumption as a number of firms operating *in situ* projects in Alberta reported average production costs ranging from \$25-\$49 in 2014 and Millington et al. (2014) estimate supply costs of \$50.89 (excluding transportation and blending costs). They define supply cost as the constant dollar price needed to recover all capital expenditures, operating costs, royalties, and taxes and earn a specified return on investment. In Alberta, the royalty rates applied to gross revenue and net revenue depend on the price of WTI and range from 25 to 40 percent. To simplify the analysis we assume a constant royalty rate of 30% applied to net revenue, $S - C$. Income tax rate includes both provincial and federal taxes.[15] We assume that the discount rate for the option to develop and the operating project are both 10 per cent. We assume an after-tax cash flows are given by

$$\begin{aligned}\pi(q^*; S, C, Q, z) =& \big((1-\lambda_R)(S-C) - AC\big)q^* + \max\{\lambda_I[\big((1-\lambda_R)(S-C) - AC\big)q^*], 0\} \\ & - \lambda_P F(S, C, Q).\end{aligned} \tag{1.22}$$

To estimate the parameters in equations (1.1) and (1.2) we collect monthly spot

[15] The general federal tax rate is 28 percent and the Alberta provincial corporate tax rate is 10 percent.

price data for WTI and WCS for the period January 2005 to December 2015. WTI data was collected from the EIA and WCS data was collected from Natural Resources Canada. The WTI price series were converted to Canadian dollars using Canada/U.S. exchange rates from the U.S. Federal Reserve and both price series were deflated using the Consumer Price Index from Statistics Canada. Transportation costs estimates were generated by subtracting WCS from WTI.

Table 1.2: Summary Statistics

	WTI	WCS	TC
Mean	71.94	58.52	13.42
St Dev.	14.32	14.65	5.64
Min	40.44	25.88	3.55
Max	117.03	104.32	37.28
Obs	132	132	132

Crude oil prices are assumed to be log-normally distributed with a mean of $\mu - \sigma_S^2/2$ and a variance of σ_S^2. Following Wilmott et al. (1993), the mean and variance are estimated with the following equations

$$\hat{m} = \frac{1}{ndt} \sum_{t=1}^{n} \log(\text{WTI}_t/\text{WTI}_{t-1}),$$

$$\hat{\sigma}_S^2 = \frac{1}{(n-1)dt} \sum_{t=1}^{n} (\log(\text{WTI}_t/\text{WTI}_{t-1}) - \hat{m})^2.$$

The drift, $\hat{\mu}$, is recovered by adding $\hat{\sigma}_S^2/2$ to $\hat{m}$. For the selected data period, the average growth rate in WTI is 1 percent with a standard deviation of 28 percent. The parameters for equation (1.2) are estimated by running the regression

$$TC_t - TC_{t-1} = a + bTC_{t-1} + \epsilon_t$$

and then calculating

$$\hat{\kappa} = \frac{-\hat{a}}{\hat{b}},$$

$$\bar{C} = -\log(1 + \hat{b}),$$

$$\hat{\sigma}_C = \sigma_\epsilon \sqrt{\frac{\log(1 + \hat{b})}{(1 + \hat{b})^2 - 1}},$$

where $\hat{\sigma}_\epsilon$ is the standard error of the regression. Over this period the long run average transportation cost, $\bar{C}$, is \$13.38, the speed of reversion to the long run average, $\hat{\kappa}$, is 0.39, and the standard deviation, $\hat{\sigma}_C$, is \$3.53. The estimated correlation between oil prices and transportation costs, $\hat{\rho}_{S,C}$, is 0.14.

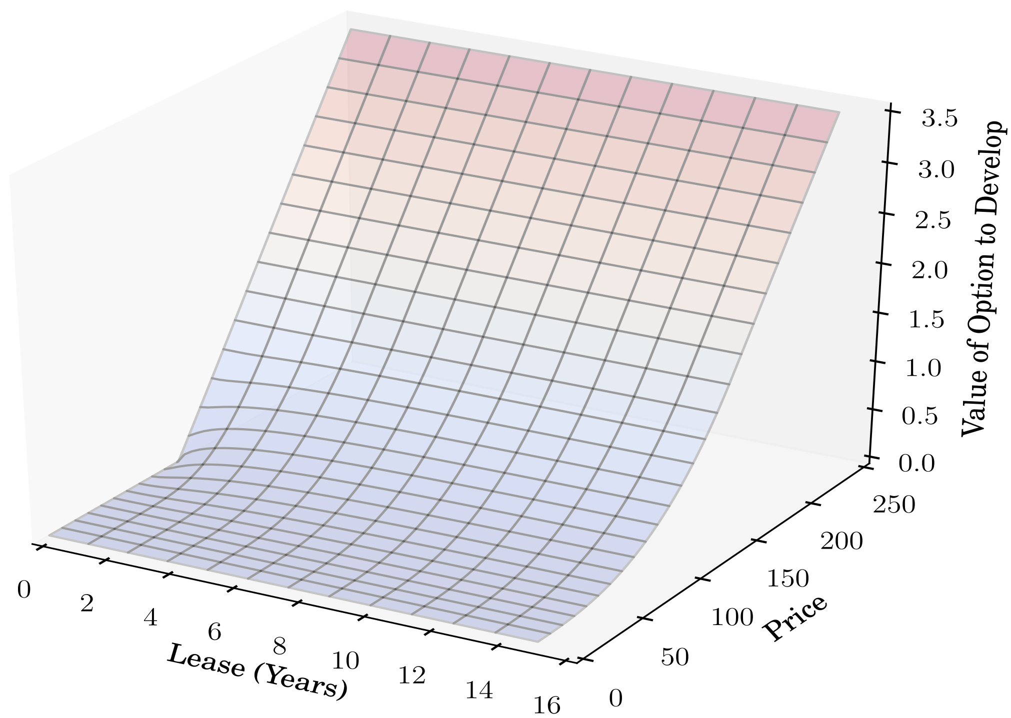
To understand the effect changes in transportation costs have on the value of an oil sands project and the incentive to invest we consider changes in the mean and variance of transportation costs. To focus on the first-order effects of a change in mean we set transportation cost variance equal to zero then solve the model for different mean values. To focus on the second-order effects of transportation cost uncertainty we set the current transportation cost equal to its mean value then solve the model for different standard deviation values.

Figure 1.2 plots the value of an oil sands project that faces fixed transportation costs of \$13.38 per barrel. In the development stage, the value of the option to develop (Figure 1.2a) is increasing in both price and lease. When the lease expires if the price of oil is above \$101.50 the option is exercised and the project is developed, if not, the lease expires unused and the value of the project is zero. The optimal development threshold is shown in Figure 1.3. It exceeds the supply costs estimated by Millington et al. (2014) but is comparable to some of the results found by Kobari et al. (2014). Millington et al. (2014) estimate supply costs of US\$84.99 per barrel when adjusting for blending and transportation for a steam-assisted gravity drainage project.[16] In their increasing environmental cost scenario, Kobari et al. (2014) find critical thresholds ranging from \$50 to \$150 per barrel. In their decreasing environmental cost scenario, they find critical thresholds ranging from \$150 to \$300 per barrel.

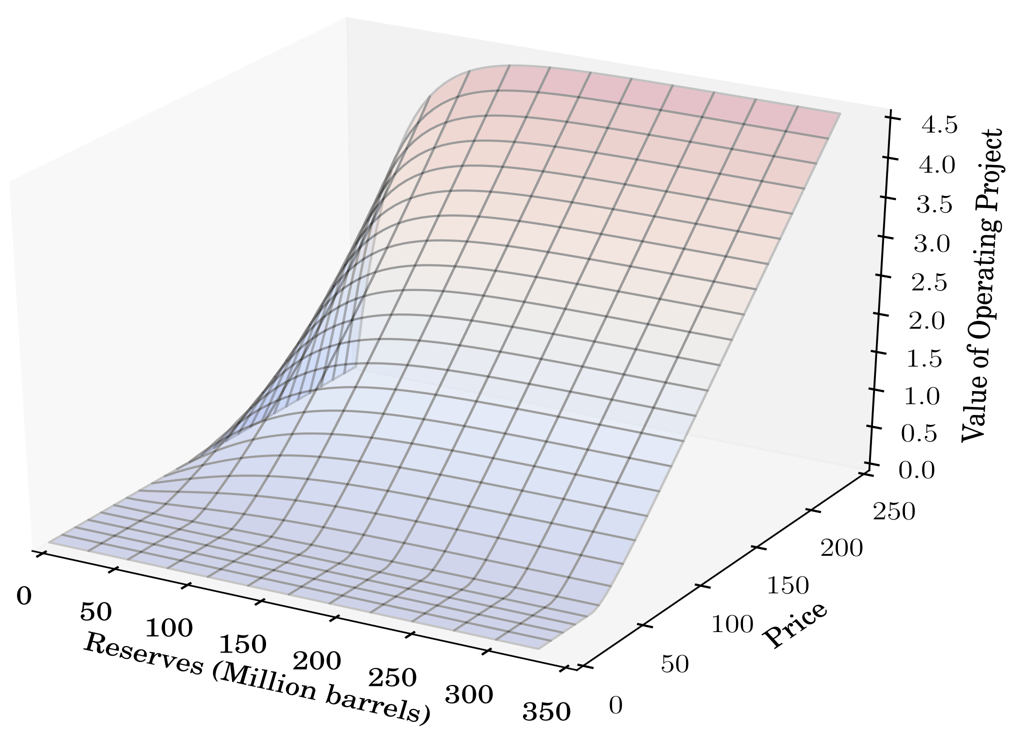
In the operating stage, the value of the operating project (Figure 1.2b) is increasing in both price and reserves. When reserves are exhausted the value of the project equals the project's scrap value, in this case zero. The optimal abandonment threshold is shown in Figure 1.4. Cash flows from operations range from -\$5 to -\$16 on the optimal abandonment threshold. In this example the project will have a negative net present value before it is abandoned because of the positive value of managerial flexibility. The

[16] They assume a fixed exchange rate of US\$0.98.

Figure 1.2: Value of an oil sands project that faces fixed transportation costs of $13.38



(a) Option to Develop an Oil sands Project



(b) Operating Oil sands Project with the Option to Abandon for Scrap Value

Figure 1.3: Optimal Development Threshold

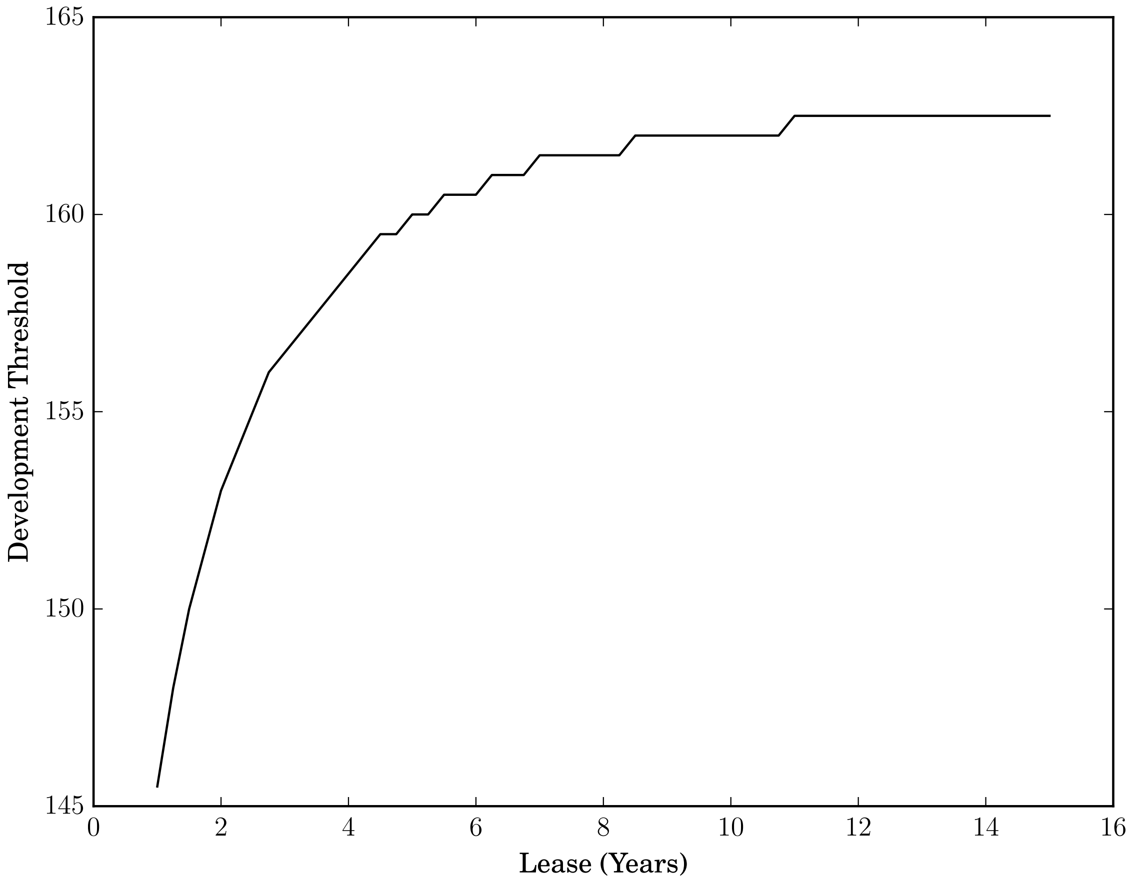
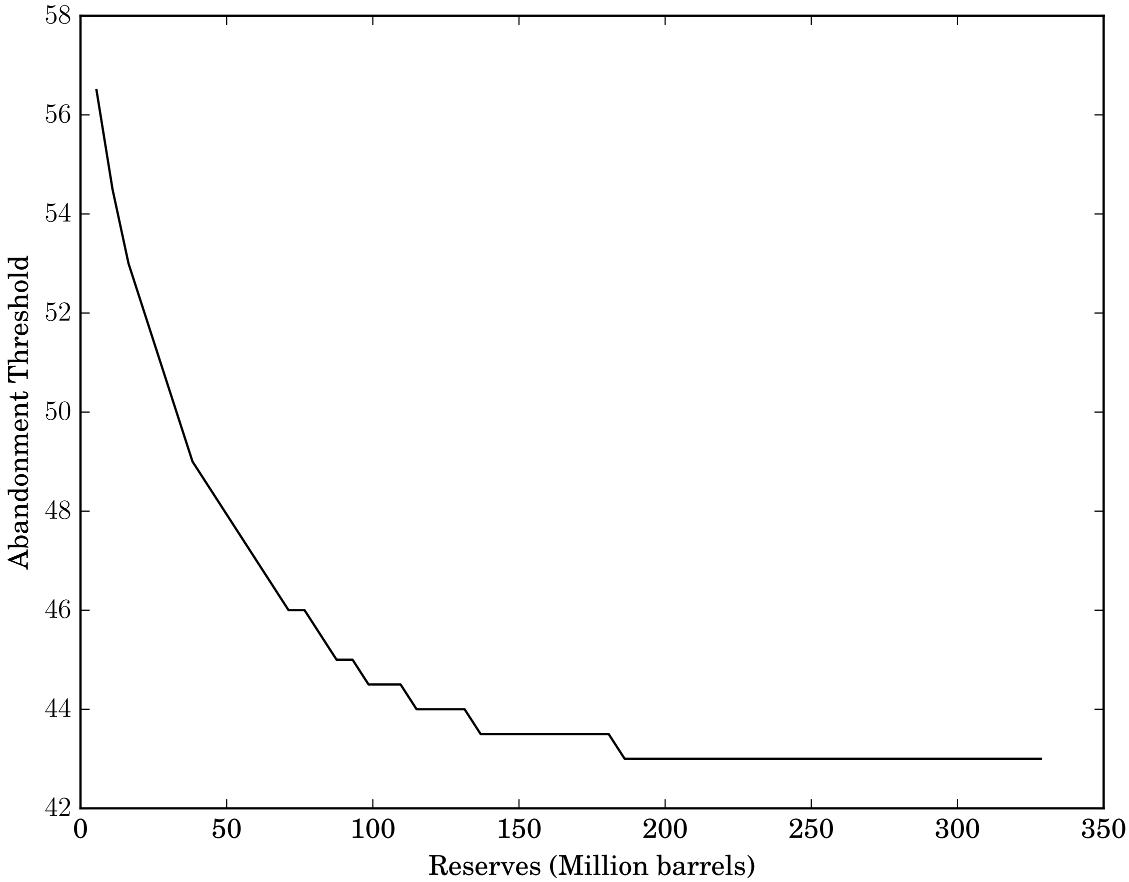


Figure 1.4: Optimal Abandonment Threshold



abandonment threshold found in this example is similar to abandonment threshold found by Almansour and Insley (2016). In their paper, an oil sands project is closed when the price of bitumen is between US$20 and US$35 per barrel and a project is abandoned when the price of bitumen is between US$10 and US$20 per barrel. They assume the difference between crude oil prices and crude bitumen prices is about US$30 per barrel. Adding the US$30 to their closure and abandonment results and they look similar to the abandonment threshold found here.

1.4.1 Effect of a Change in Transportation Cost Mean

Consider a change in transportation costs caused by a change in pipeline capacity. A decrease in transportation costs, resulting from an increase in pipeline capacity, will lead to an increase in the value of an oil sands project. The value of an operating project will increase as the expected present value of cash flows increase for all price levels. The value of the option to develop an oil sands project increases because the value of the operating project increases. Oil sands projects will be developed earlier (Figure 1.5) because the value of the underlying asset has increased and the benefits from the undeveloped lease have remained the same. Operating projects will be abandoned later following an increase in pipeline capacity (Figure 1.6) as cash flows increase and the scrap value of the project remains unchanged.

1.4.2 Effect of a Change in Transportation Cost Volatility

So far we have estimated the value of an oil sands project and the optimal development and abandonment thresholds when transportation costs are fixed and evaluated how these values change when transportation costs increase or decrease. We have seen that a decrease in transportation costs increases the value of an oil sands project and increases the incentive to invest in new projects. Now we turn our attention to the effect of transportation cost uncertainty on the value of a project. We solve the model for different transportation cost standard deviation levels while holding current transportation cost equal to its long-run average.

Figure 1.5: Optimal Development Threshold

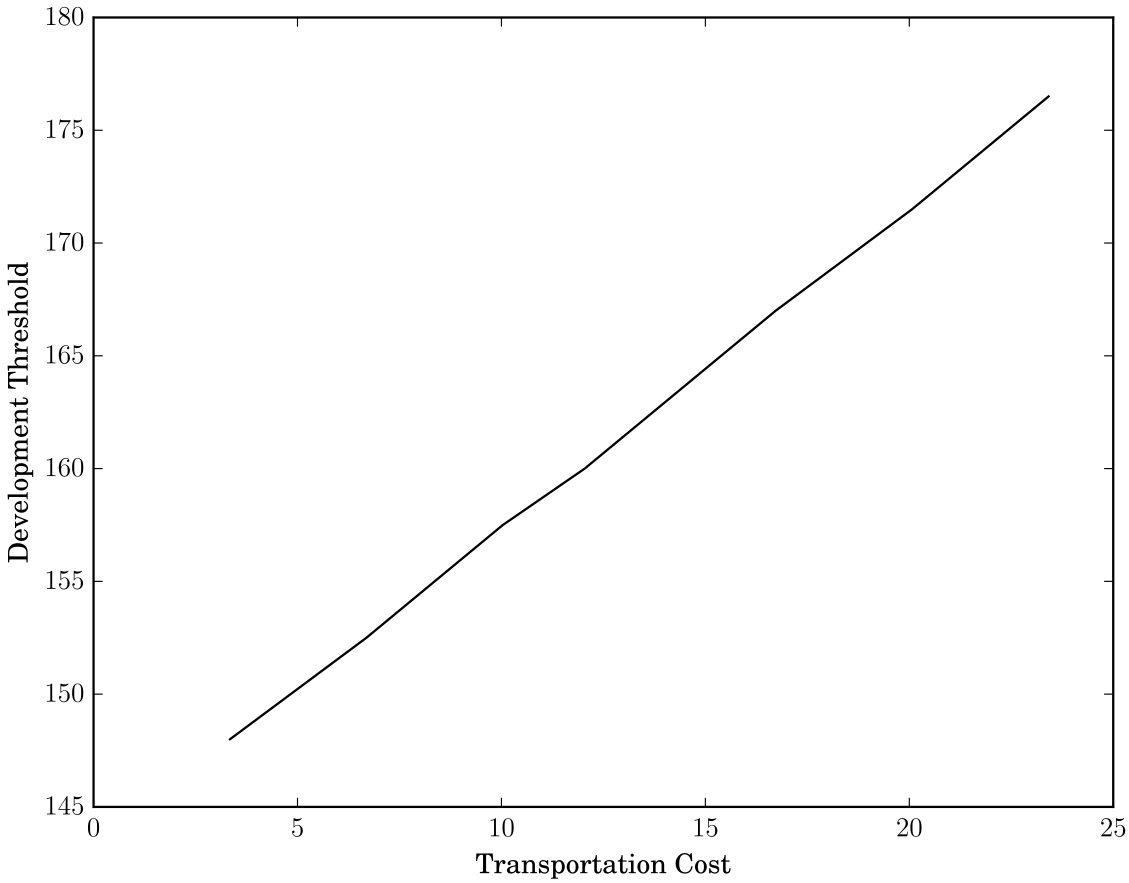


Figure 1.6: Optimal Abandonment Threshold

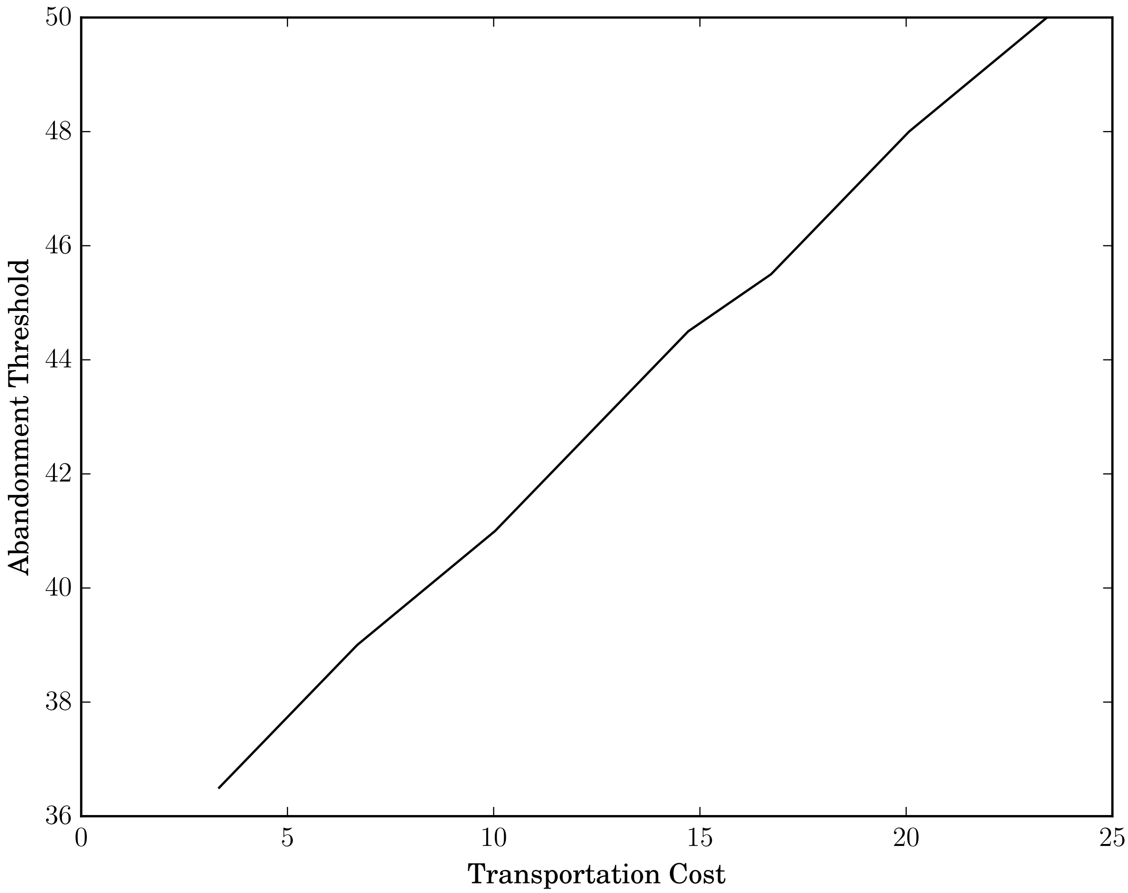


Table 1.3 presents results from solving the model with different transportation cost standard deviation levels. We can see that transportation cost uncertainty has a small positive impact on the value of the option to develop an oil sands project, a 10 percent increase in transportation cost standard deviation increases the value of the option to develop by 2 percent. The positive relationship between volatility and option value is consistent with option-pricing literature, an increase in volatility increases the upside potential of an option. The effect of transportation cost uncertainty on the value of the operating project is more complicated. Increasing the standard deviation from 0 to 3.53 reduces the value of the operating project but an increase in the standard deviation, when it is already positive, increases the value of the operating project. Although transportation cost uncertainty has a small effect on the value of an oil sands project, surprisingly, it has virtually no effect on the optimal development and abandonment thresholds. Increasing transportation cost standard deviation from zero to a positive value decreases the development boundary by $0.50 but large deviations from the estimated standard deviation has no effect on either of the optimal thresholds.

Table 1.3: Changes in Transportation Cost Volatility

	Transportation Cost Volatility, σ_C					
	0	2.65	3.18	3.53	3.88	4.41
Option to Develop	-0.07	-0.04	-0.02	0	0.02	0.04
Development threshold	162	161.50	161.50	161.50	161.50	161.50
Operating Project	0.003	-0.004	-0.002	0	0.002	0.005
Abandonment threshold	43	43	43	43	43	43

Option to Develop and Operating Project shows the average percent difference from the value of an oil sands project with transportation cost standard deviation of 3.53. Lease is fixed at $\tau = 10$ and reserves are fixed at $Q = 219000000$.

The results presented here are similar to those from Schwartz and Smith (2000). The risks of short-term deviations in transportation costs has very little effect on the value of a oil sands project that has a operating life of 30 years. What matters here is the expected transportation cost over the life of a project. A reduction in expected transportation costs, resulting from an expansion in pipeline capacity, will increase the incentive to invest in new oil sands projects.

1.5 Conclusion

This paper examines the impact transportation costs have on the value of an oil sands project and the incentive to invest in new projects. A real options model for the valuation of an oil sands project located in Northern Alberta is developed that incorporates price and transportation cost uncertainty. The free-boundary problems that determines the value of the oil sands and the investment thresholds are defined as linear complementarity problems and numerically solved using the fully implicit finite difference method.

Results for the typical *in situ* oil sands project show that average transportation costs are an important factor in the decision whether to start a new project or not while transportation cost uncertainty has virtually no impact on the investment decision. Results indicate that the price differential faced by oil sands producers is an important factor restraining new investments. New pipeline projects that would reduce the price differential would increase the value of existing oil sands projects and would increase the incentive to invest in new projects.

We have seen that transportation cost uncertainty has very little impact on the value of an oil sands project and the incentive to invest. What matters here is the average transportation cost over the life of the oil sands project. In this paper we considered changes in the average transportation cost but ignored uncertainty in average transportation costs. Future research could incorporate this uncertainty into the value of an oil sands project by modeling average transportation costs as a Poisson process. At some future date transportation costs might jump up or down as a result of an decrease or increase in pipeline capacity.

1.6 Appendices

1.6.1 Numerical Methods

Fully Implicit Finite Difference Method

The fully implicit finite difference method (IFDM) is an established technique for numerically solving option pricing problems (Wilmott et al. (1993) and Zhu et al. (2004)) that involves discretizing the domain and replacing partial derivatives with backward difference and symmetric central difference approximations. A benefit of the IFDM is that it does not require step lengths in one direction on the domain to be proportionate to step lengths in another direction for stability or convergence. In this appendix we numerically approximate the value of an oil sands project using the IFDM. The following linear complementarity problems determine the value of the oil sands project. The option to develop an oil sands project is the solution equation (1.11) and the value of an operating oil sands project with the option to abandon is the solution to equation (1.21).

The value functions $G(S, C, \tau)$ and $F(S, C, Q)$ depend on three state variables. To simplify the numerical scheme and reduce the dimensionality of the domain, let $P = S - C$ so that $g(P, \tau) = G(S, C, \tau)$, and $f(P, Q) = F(S, C, Q)$. The partial derivatives in equation (1.11) can be replaced with,

$$\begin{aligned} G_S &= g_P, & G_{SS} &= g_{PP}, \\ G_C &= -g_P, & G_{CC} &= g_{PP}, \\ G_\tau &= g_\tau, & G_{SC} &= -g_{PP}. \end{aligned}$$

Similarly for equation (1.21)

$$\begin{aligned} F_S &= f_P, & F_{SS} &= f_{PP}, \\ F_C &= -f_P, & F_{CC} &= f_{PP}, \\ F_Q &= f_Q, & F_{SC} &= -f_{PP}. \end{aligned}$$

Substitution and rearrange to get simplified LCPs for the option to develop

$$\begin{aligned}
&\delta_G g - \mathrm{M} - (\mu(P+C) - \kappa(\bar{C}-C))g_P + g_\tau \\
&\qquad - \frac{1}{2}(\sigma_S^2(P+C)^2 + \sigma_C^2 - 2\sigma_S\sigma_C\rho_{S,C}(P+C)g_{PP} \geq 0, && (1.23.1)\\
&g - f + \mathrm{IC} \geq 0, && (1.23.2)\\
&\big(\delta_G g - \mathrm{M} - (\mu(P+C) - \kappa(\bar{C}-C))g_P + g_\tau \\
&\qquad - \frac{1}{2}(\sigma_S^2(P+C)^2 + \sigma_C^2 - 2\sigma_S\sigma_C\rho_{S,C}S)g_{PP}\big) \times \big(g - f + \mathrm{IC}\big) = 0. && (1.23.3)
\end{aligned}$$

and the simplified LCP for the operating project

$$\begin{aligned}
&\delta_F f - \pi(q^*) - (\mu(P+C) - \kappa(\bar{C}-C))f_P + q^* f_Q \\
&\qquad - \frac{1}{2}(\sigma_S^2(P+C)^2 + \sigma_C^2 - 2\sigma_S\sigma_C\rho_{S,C}(P+C))f_{PP} \geq 0, && (1.24.1)\\
&f - \Omega \geq 0, && (1.24.2)\\
&\big(\delta_F f - \pi(q^*) - (\mu S - \kappa(\bar{C}-C))f_P + q^* f_Q \\
&\qquad - \frac{1}{2}(\sigma_S^2(P+C)^2 + \sigma_C^2 - 2\sigma_S\sigma_C\rho_{S,C}(P+C))f_{PP}\big) \times \big(f - \Omega\big) = 0. && (1.24.3)
\end{aligned}$$

Define on the axes for S, τ, and Q by

$$\begin{aligned}
\{0, S_1, \ldots, S_i, \ldots, S_M\},\\
\{0, \tau_1, \ldots, \tau_n, \ldots, \tau_N\},\\
\{0, Q_1, \ldots, Q_j, \ldots, Q_K\}.
\end{aligned} \qquad (1.25)$$

For a given value of C, a typical grid point $(S_i - C, \tau_n)$ on the discretized $(S-C)\times\tau$ mesh, the value of the option to develop is $g(S_i - C, \tau_n) = g_i^n$. For a typical grid point $(S_i - C, Q_j)$ on the discretized $(S-C)\times Q$ mesh, the value of the operating project is $f(S_i - C, Q_j) = f_i^j$.

The IFDM involves using backward difference approximation for g_τ and f_Q and symmetric central difference approximation for the terms g_P, g_{PP}, f_P and f_{PP}. The backward difference and symmetric central difference equations can be written

$$
\begin{aligned}
g_\tau &= \tfrac{g_i^{n+1}-g_i^n}{\Delta\tau} + O(\Delta\tau) & f_Q &= \tfrac{f_i^{j+1}-f_i^j}{\Delta Q} + O(\Delta Q) \\
g_P &= \tfrac{g_{i+1}^{n+1}-g_{i-1}^{n+1}}{2\Delta P} + O(\Delta P^2) & f_P &= \tfrac{f_{i+1}^{j+1}-f_{i-1}^{j+1}}{2\Delta P} + O(\Delta P^2) \\
g_{PP} &= \tfrac{g_{i+1}^{n+1}-2g_i^{n+1}+g_{i-1}^{n+1}}{\Delta P^2} + O(\Delta P^2) & f_{SS} &= \tfrac{f_{i+1}^{j+1}-2f_i^{j+1}+f_{i-1}^{j+1}}{\Delta P^2} + O(\Delta P^2)
\end{aligned}
\tag{1.26}
$$

where ΔP is the constant step length in the P direction,[17] $\Delta\tau$ is the constant step length in the τ direction, and ΔQ is the constant step length in the Q direction.

Assume the flow of benefits (costs) from an undeveloped oil sands lease is

$$
\mathrm{M} - \lambda_P g(P, \tau) \tag{1.27}
$$

and the cash flow from operations are

$$
\begin{aligned}
\pi(q^*; S-C, Q) =& \big((1-\lambda_R)(S-C) - AC\big)q^* + \max\{\lambda_I[\big((1-\lambda_R)(S-C) - AC\big)q^*], 0\} \\
& - \lambda_P f((S-C), Q).
\end{aligned}
\tag{1.28}
$$

Regardless of whether the project has been developed on not, property tax rates, λ_P, are applied to the value of the oil sands project. When the project has been developed, royalty rates, λ_R, are applied to net revenue and income tax rates, λ_I, are applied to profits net royalty payments. The output flow, q^* and the average cost of producing a barrel of oil, AC, are assumed to be constant over the life of the project.

Using the finite difference equations defined in (1.26) and equation (1.27), the discretized LCP for the option to develop at an interior node is

$$
-\Delta\tau a_i g_{i-1}^{n+1} + (1 + \Delta\tau(\delta_G + \lambda_P + a_i + b_i))g_i^{n+1} - \Delta\tau b_i g_{i+1}^{n+1} - g_i^n - \Delta\tau \mathrm{M} \geq 0 \tag{1.29.1}
$$

$$
g_i^{n+1} - f_i^N + \mathrm{IC} \geq 0 \tag{1.29.2}
$$

$$
\begin{aligned}
&\big(-\Delta\tau a_i g_{i-1}^{n+1} + (1 + \Delta\tau(\delta_G + \lambda_P + a_i + b_i))g_i^{n+1} - \Delta\tau b_i g_{i+1}^{n+1} - g_i^n - \Delta\tau \mathrm{M}\big) \\
&\quad \times (g_i^{n+1} - f_i^N + \mathrm{IC}) = 0.
\end{aligned}
\tag{1.29.3}
$$

[17] Here the step length $\Delta P = \Delta S$ because $P = S - C$.

With equation (1.22), the discretized LCP for the operating project at an interior node is

$$
\begin{aligned}
&-\Delta Q a_i f_{i-1}^{j+1} + (q + \Delta Q(\delta_F + \lambda_P + a_i + b_i)) f_i^{j+1} - \Delta Q b_i f_{i+1}^{j+1} - q f_i^j \\
&\qquad - \Delta Q(((1-\lambda_R)P_i - AC)q - \max\{\lambda_I[((1-\lambda_R)P_i - AC)q], 0\}) \geq 0 && (1.30.1) \\
&f_i^{j+1} - \Omega \geq 0 && (1.30.2) \\
&\big(-\Delta Q a_i f_{i-1}^{j+1} + (q + \Delta Q(\delta_F + \lambda_P + a_i + b_i)) f_i^{j+1} - \Delta Q b_i f_{i+1}^{j+1} - q f_i^j \\
&\qquad - \Delta Q(((1-\lambda_R)P_i - AC)q - \max\{\lambda_I[((1-\lambda_R)P_i - AC)q], 0\})\big) \\
&\qquad \times \left(f_i^{j+1} - \Omega\right) = 0 && (1.30.3)
\end{aligned}
$$

Where

$$
\begin{aligned}
a_i &= \frac{\sigma_S^2 S_i^2 + \sigma_C^2 - 2\sigma_S\sigma_C\rho_{S,C}S_i}{2\Delta P^2} - \frac{\mu S_i - \kappa(\bar{C} - C)}{2\Delta P}, && (1.31.1) \\
b_i &= \frac{\sigma_S^2 S_i^2 + \sigma_C^2 - 2\sigma_S\sigma_C\rho_{S,C}S_i}{2\Delta P^2} + \frac{\mu S_i - \kappa(\bar{C} - C)}{2\Delta P}. && (1.31.2)
\end{aligned}
$$

To implement the IFDM we need to impose the following boundary conditions on the value of the option to develop an oil sands project,

$$
\begin{aligned}
g(-C,\tau) &= \mathrm{M}\Delta t + \frac{\mathrm{E}_t[g(-C,\tau + d\tau)]}{1 + \delta_G dt} && (1.32.1) \\
\lim_{S\to\infty} g(S - C,\tau) &= \lim_{S\to\infty} f(S - C, Q) - \mathrm{IC}, && (1.32.2)
\end{aligned}
$$

When price goes to zero, the likelihood of development gets very small and the value of the option to develop approaches the present discounted value of benefits (costs) from the undeveloped land. When the price gets very large, the option to develop will be exercised immediately as the benefits from immediate development outweigh the costs. From these assumptions we get the following boundary conditions for the discrete LCP

$$g_0^n = \frac{(1+\delta_G)(1+\lambda_P) - [(1+\delta_G)(1+\lambda_P)]^{n-1}}{(1+\delta_G)(1+\lambda_P) - 1} \frac{\mathrm{M}}{1+\lambda_P} + \frac{g_0^0}{[(1+\lambda_P)(1+\delta_G)]^n}, \tag{1.33.1}$$

$$g_M^n = f_M^K - \mathrm{IC}. \tag{1.33.2}$$

The boundary conditions for the operating oil sands project are

$$f(-C, Q) = \Omega \tag{1.34.1}$$

$$\lim_{S\to\infty} f(S-C, Q) = \lim_{S\to\infty} \pi(\bar{q}; S-C, Q)dt + \frac{\mathrm{E}_t[F(S-C, Q+dQ)]}{1+\delta_F \Delta t}. \tag{1.34.2}$$

When the prices goes to zero, the option to abandon will be exercised immediately. When the price gets very large, the value of an operating project approaches the present discounted value of cash flows from operation and the value of the option to abandon goes to zero. This happens because the likelihood of exercising the abandonment option is very small when the price is very large. From these assumptions we get the following boundary conditions for the discrete LCP

$$f_0^j = \Omega \tag{1.35.1}$$

$$\begin{aligned} f_M^j =& \frac{(1+\lambda_P)(1+\delta_F) - [(1+\lambda_P)(1+\delta_F)]^{n-1}}{(1+\lambda_P)(1+\delta_F) - 1} \frac{\big((1-\lambda_I)(1-\lambda_R)(S_M - C) - AC\big)q}{1+\lambda_P} \\ &+ \frac{f_M^0}{[(1+\lambda_P)(1+\delta_F)]^n}. \end{aligned} \tag{1.35.2}$$

For a given value of τ_n, equation (1.23) can be arranged from S_1 to S_{M-1} to form the following system of equations

$$Ag^{n+1} - g^n - \Delta\tau \mathrm{M}^n \geq 0 \tag{1.36.1}$$

$$g^{n+1} - (f^K - \mathrm{IC}) \geq 0 \tag{1.36.2}$$

$$\langle Ag^{n+1} - g^n - \Delta\tau \mathrm{M}^n, g^{n+1} - (f^K - \mathrm{IC})\rangle = 0 \tag{1.36.3}$$

Where A is a $M-1 \times M-1$ tridiagonal positive semi-definite matrix,[18] with diagonal terms $A_{i,i} = 1 + \Delta\tau(\delta_G + \lambda_P + a_i + b_i)$ and off diagonal terms $A_{i,i-1} = -\Delta\tau a_i$ and $A_{i,i+1} = -\Delta\tau b_i$. g^{n+1} is an $M-1$ vector of unknown values, g^n and M^n are $M-1$ vectors of known values.

$$g^{n+1} = \begin{pmatrix} g_1^{n+1} \\ \vdots \\ g_{M-1}^{n+1} \end{pmatrix}, \quad g^n = \begin{pmatrix} g_1^n \\ \vdots \\ g_{M-1}^n \end{pmatrix}, \quad \mathrm{M}^{n+1} = \begin{pmatrix} (1+a_1)\mathrm{M} + a_1 \frac{1-\lambda_P-\lambda_P\delta_G}{1+\delta_G} g_0^n \\ \mathrm{M} \\ \vdots \\ \mathrm{M} + b_{M-1}(f_M^K - IC) \end{pmatrix}.$$

The terminal condition specifies the value of the option to delay development of an oil sands project when the lease has expired. Using this and the information given by equations (1.32.1) and (1.32.2) the value of the option to develop an oil sands project can be approximated at all other nodes in the domain. The optimal stopping boundary $\hat{S}_i(C, \tau_n)$ is recovered using equation (1.36.2). For a given τ_n, the smallest indexed price S_i where $g_i^n = f_i^K - \mathrm{IC}$ is the price where it is optimal to exercise the option to develop.

For a given value of Q_j, equation (1.24) can be arranged to form the following system of equations

$$Bf^{j+1} - f^j - \Delta Q \Pi^j \geq 0 \tag{1.37.1}$$

$$f^{j+1} - \Omega \geq 0 \tag{1.37.2}$$

$$\langle Bf^{j+1} - f^j - \Delta Q \Pi^j, f^{j+1} - \Omega) \rangle = 0 \tag{1.37.3}$$

B is a $M-1 \times M-1$ tridiagonal positive semi-definite matrix, with diagonal elements $B_{i,i} = q + \Delta Q(\delta_F + \lambda_P + a_i + b_i)$ and off diagonal elements $B_{i,i-1} = -\Delta Q a_i$ and $B_{i,i+1} = -\Delta Q b_i$. f^{j+1} is a $M-1$ vector of unknown values, f^j and Π^j are $M-1$

[18] A is a strictly diagonally dominant matrix.

vectors of known values. With

$$f^{j+1} = \begin{pmatrix} f_1^{j+1} \\ \vdots \\ f_{M-1}^{j+1} \end{pmatrix}, \quad f^j = \begin{pmatrix} f_1^j \\ \vdots \\ f_{M-1}^j \end{pmatrix},$$

$$\Pi^j = \begin{pmatrix} ((1-\lambda_R)((S_1 - C) - AC)q + a_1\Omega \\ ((1-\lambda_R)(S_2 - C) - AC)q - \max\{\lambda_I[(1-\lambda_R)(S_2 - C) - AC]q, 0\} \\ \vdots \\ (1-\lambda_I)((1-\lambda_R)(S_{M-1} - C) - AC)q + b_{M-1}f_M^{j+1} \end{pmatrix},$$

and

$$f_M^{j+1} = \frac{(1-\lambda_I)((1-\lambda_R)(S_M - C) - AC)q}{1+\lambda_P} + \frac{f_M^j}{(1+\delta_F)(1+\lambda_P)}.$$

The terminal condition specifies the value of the operating oil sands project when reserves are exhausted. Using this condition and the conditions given by equations (1.34.1) and (1.34.2) the value of the of an operating oil sands project with an option to abandon can be approximated on all nodes in the domain. The optimal stopping boundary $S_i^*(C, Q_j)$ is recovered using equation (1.37.2). For any Q_j, the highest indexed price S_i where $f_i^j = \Omega$ is the price where it is optimal to exercise the option to abandon for scrap value.

Pseudo Code

We use the python package OpenOpt to numerically solve equations (1.36) and (1.37). OpenOpt is a package designed to numerically solve complementarity problems. To employ OpenOpt, LCPs must be written in the following form

$$w = Mz + q,$$
$$w \geq 0, z \geq 0, \text{ and } w^T z = 0,$$
$$\text{with } M \text{ and } q \text{ given.}$$

For the option to develop, let $w_g \equiv Ag^{n+1} - g^n - \Delta\tau M^n$ and $z_g \equiv g^{n+1} - f^K + \mathrm{IC}$.

Then equation (1.23.3) can be written

$$w_g = Az_g + A(f^K - IC) - (g^n + \Delta\tau \mathrm{M}^{n+1}),$$

with the conditions $w_g \geq 0$, $z_g \geq 0$, and $w_g^T z_g = 0$ where A and $A(f^K - IC) - (g^n + \Delta\tau \mathrm{M}^{n+1})$ are given. Similarly for the operating project we get

$$w_f = Bz_f + B\Omega - (f^j + \Delta Q \Pi^{j+1})$$

with $w_f \geq 0$, $z_f \geq 0$, and $w_f^T z_f = 0$ where B and $B\Omega - (f^j + \Delta Q \Pi^{j+1})$ are given.

When an element of w_{gi} is equal to zero the option to develop is in the continuation region and it is optimal to continue to hold the option and delay development. The value of the option to develop is

$$g_i^{n+1} = [A^{-1}(g^n + \Delta\tau \mathrm{M}^{n+1})]_i.$$

When an element of z_{gi} is equal to zero the option to develop is in the development region and it is optimal to exercise the option to develop. The value of the option to develop is

$$g_i^{n+1} = f_i^K - \mathrm{IC}.$$

Similarly for the operating project, if w_{fi} is equal to zero the value of the project is

$$f_i^{j+1} = [B^{-1}(f^j + \Delta Q \Pi^{j+1})]_i.$$

When z_{fi} is equal to zero the value of the project is

$$f_i^{j+1} = \Omega.$$

The option to develop depends on the value of the operating project. We start by solving for the value of the operating project with the option to abandon for scrap value. Iterating over reserves from reserve exhaustion, $j = 0$, to initial reserves,

$j = K-1$. Then we solve the option to develop an oil sands project using the solution to the value of the operating project at initial reserves. Iterate over time remaining on lease from expiration, $\tau = 0$, to initial day of lease, $\tau = N - 1$.

Chapter 2

Are Crude Oil Markets Integrated? Testing the Co-movement of Weekly Crude Oil Spot Prices

2.1 Introduction

The integration of oil markets has received much attention in the literature (Gülen (1997 and 1999), Bachmeier and Griffin (2006), Hammoudeh et al. (2008), Fattouh (2010), Wilmot (2013), and Ji and Fan (2016)). Most observers consider the world oil market to be 'one great pool' (Adelman (1984)), implying the price of crude oils with similar qualities in different locations move together. This hypothesis is supported, theoretically, by the law of one price and spatial arbitrage. Others argue, that due to long-term contracts, regulatory or technological constraints, the world oil market is divided into a number of submarkets; so that, crude oil prices do not move together as they are affected by local supply and demand factors that do not register in other submarkets. The degree of market integration has important implications for energy policies, extraction and investment decisions, and hedging strategies.

The accumulation of evidence suggests oil markets are integrated. Gülen (1999) and Wilmot (2013) use cointegration analysis to show crude oil spot prices, for similar and different quality crude oils, move together. Maslyuk and Smyth (2009) find a long-run relationship between spot and future prices. Using a copula approach, Reboredo (2011) finds symmetric tail dependence between crude oil prices suggesting crude oil prices are linked. However, the recent divergence between West Texas Intermediate (WTI) and Brent blend (Brent), as seen in Figure 2.1a, has called into question the continued integration of these markets. Alquist and Guénette (2013) argue the rapid increase in unconventional crude oil production has segmented North American crude oil markets from world markets as the lack of optimized transportation infrastructure and US export restrictions limits producers ability to move excess supply out of the US Midwest to other regions to take advantage of large price differences between markets. Alternatively, spatial arbitrage theory[1] suggests markets may still be integrated during periods of large price differences as constrained transportation capacity between markets causes transportation costs to increase, shippers increase prices to take advantage of high demand and producers choose high cost alternatives to avoid bottlenecks.[2]

The purpose of this article is to analyze the long-run relationship between North American crude oil prices (WTI, Western Canadian Select (WCS), Louisiana Light Sweet (LLS), and Edmonton Syncrude Sweet (ESS)) and international benchmarks (Brent, Dubai Fateh (Dubai), and Mexican Maya (Maya)) for the period from May 2, 2008 to February 26, 2016 using a cointegration approach that allows for endogenously determined structural breaks to understand the impact unconventional crude oil production has had on North American crude oil markets. The Engle and Granger (1987) and Gregory and Hansen (1996) residual-based cointegration tests are used to test for a long-run relationship between crude oil price pairs. The sup-Wald test proposed by Kejriwal and Perron (2010) is used to test for parameter stability in the

[1]In a spatial arbitrage model with transportation capacity constraints, Coleman (2009) finds transportation costs and spatial price differentials exceed those found in standard spatial arbitrage models so long as transportation capacity is fully utilized and there is a shortage in the importing center.

[2]In Canada producers are transporting more crude oil by rail to avoid congested pipelines. From 2010 to 2015, the average number of rail cars per month used to transport fuel oils and crude petroleum in Canada increased from 5359 to 13127 (Statistics Canada, Table 404-0002).

cointegrating relation. Failing to reject the null hypothesis of both cointegration tests might suggest crude oil prices are no longer cointegrated. Rejecting the null hypothesis of the sup-Wald test indicates crude oil prices are cointegrated with a structural change. Crude oil prices may have a stable long-run relationship if we fail to reject the null hypothesis of the sup-Wald test. The parameters of the structural change model, including the break date, are estimated following Kejriwal and Perron (2008).

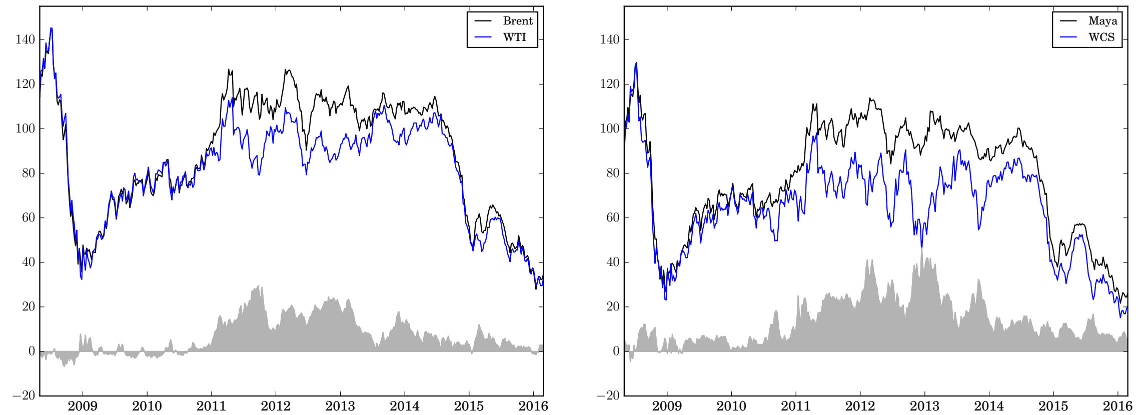
The divergence between land-locked North American crude oil prices and international benchmarks has had a significant impact on production and investment decisions and energy policy in Canada. From 2008 to 2010, WCS, the benchmark for heavy crude oil in Canada, averaged $13 less than international benchmarks. From 2011 to 2016, the discount increased to $28. The Premier of Alberta has said that getting Alberta oil to tidewater is critical for both economic and environmental reasons (Starr (2016)). Many believe that the large price differential between WCS and international benchmarks is mostly attributed to inadequate pipeline infrastructure; as a result, there has been a push to add additional pipeline capacity to the west coast. With 75 percent of Alberta crude oil exports directed to the US Midwest the assumption is that a lack of pipeline access to tidewater is forcing WCS to be sold at discounted rates, so, with access to tidewater and international markets will come higher prices and more investment. Recently, the National Energy Board (2016) estimated constrained capacity could reduce output by 8 percent compared to their reference scenario which assumes sufficient transportation capacity.

In a recent article, Wilmot (2013) examined the cointegration of regional oil prices with a structural break. He applies the Gregory-Hansen cointegration test to monthly spot price data for the period of 1991 to the middle of 2012; his results indicate that crude oils of similar and different qualities are cointegrated with a structural break.[3] He finds events with a direct and indirect impact on crude oil markets are linked to structural breaks.[4] Unconventional crude oil production represents an event that

[3] The estimated structural break dates range from December 2007 to March 2009 (the last possible break date).

[4] An event with a direct impact on crude oil markets is a changes in OPEC production. An event with an indirect impact on crude oil markets is the Great Recession which affected crude oil prices through a decrease in demand.

Figure 2.1: Weekly spot price and differential



(a) Light sweet crude oil: Brent blend and West Texas Intermediate

(b) Heavy sour crude oil: Mexican Maya and Western Canadian Select

has had a large direct impact on North American crude oil markets as nearly half of North American crude oil production now comes from unconventional reserves. Previous studies that analyze the co-movement of crude oil prices do not cover this period of rising crude oil production in North American. Wilmot's study has a last possible break point on March 2009; that date is too early to allow the unconventional crude oil boom to affect the cointegration results.

To preview the results, we find price pairs including land-locked North American crude oils and international benchmarks (WTI - Brent, WTI - Dubai, Brent - ESS, and WCS - Maya) are cointegrated with a structural break. Break dates range from December 31, 2010 to May 27, 2011. Land-locked North American crude oils WTI, WCS, and ESS are cointegrated. WTI and ESS are cointegrated without a structural break. While WTI and WCS are cointegrated with a break occurring on July 30, 2010. International benchmarks Brent, Dubai, and Maya are cointegrated. Maya and Brent have a stable long-run relationship. Maya - Dubai and Brent - Dubai are cointegrated with a structural break. Surprisingly, WTI is not cointegrated with crude oils located in the Gulf Coast (LLS and Maya).

The rest of the article is organized as follows. Section 2.2 reviews the relevant cointegration analysis literature. Section 2.3 introduces the methodology used to test for a long-run relationship between crude oil prices. Section 2.4 describes the data used in this study. Section 2.5 presents the results and provides discussion. Section 2.6 concludes.

2.2 Literature Review

The co-movement of crude oil prices has received significant attention in the literature. In an early empirical analysis, Weiner (1991) applied correlation analysis and a switching-regression system to monthly spot price data to measure the degree of regionalization in world oil markets. He argues regionalization is at the heart of some important economic and policy debates; if the world oil market is 'one great pool', policies aimed at supplier diversification would not yield any benefits. His results indicate that oil prices in different regions do not move together and oil price pairs are often in different markets implying a high degree of regionalization in world crude oil markets. Using regression analysis, Milonas and Henker (2001) identify variables that affect the price differential and convenience yield for Brent and WTI. Their results suggest the two markets are not completely integrated as temporary deviations in the price differential cannot be ruled out.

Gülen (1997 and 1999) investigates Weiner's regionalization hypothesis using bivariate and multivariate cointegration tests with implications for market efficiency. If the world oil market is regionalized, there will be arbitrage opportunities for crude oil traders which would render the market inefficient. Applying the Engle and Granger (1987) and Johansen (1988) techniques to monthly spot price data, Gülen (1997), finds strong evidence against the regionalization hypothesis as spot prices for similar quality crude oils in different regions move together. Extending Gülen (1997) to weekly spot price data and allowing for a one-time exogenously determined structural break, Gülen (1999), finds further evidence against the regionalization hypothesis as oil prices do not deviate from each other in short horizons. At the higher frequency, surprisingly, results indicate co-movement between crude oils of different qualities as well. Interestingly, it appears that the co-movement is stronger during periods of rising prices than during periods of falling prices.

More recently, Hammoudeh et al. (2008) apply symmetric and asymmetric cointegration tests to daily spot price data. They find a long-run, stable relationship between benchmarks, regardless of their properties and locations. They also find asymmetric adjustment towards long-run equilibrium. Similarly, Fattouh (2010) models crude oil price differentials as a two-regime threshold autoregressive process. Using weekly spot price data, he finds, the price differential adjustment process depends on whether the crude oils are of similar or different quality. For crude oils of differing quality, when the price differential is below an estimated threshold, the price differential follows a random walk. When the price differential crosses the estimated threshold, the price differential is stationary. Results also suggest that the presence of a highly liquid futures market for one or both of the crude oils affects the adjustment process for the price differential by eliminating the threshold effects.

Maslyuk and Smyth (2009) and Wilmot (2013) consider the cointegration of crude oil prices with an endogenously determined structural break following Gregory and Hansen (1996). Maslyuk and Smyth (2009) examine the co-movement of Brent and WTI spot and futures prices using daily data. They find spot and futures prices are cointegrated with a structural break. Their results support the 'one great pool' hypothesis as the cointegration between WTI spot and Brent futures prices and Brent spot and WTI futures prices implies a high degree of integration between the two markets. Most of the break points occur in 2003 and reflect events that directly relate to oil markets, in particular the Second Gulf war, events in major oil-producing countries or events directly related to oil markets in the United States.

Wilmot (2013) focuses on the relationship between regional benchmarks (Edmonton Par, WCS, Bonny Light, and Mexican Maya). Using monthly spot price data, Wilmot finds, crude oil prices of similar and different qualities are cointegrated with a structural break, adding support for the 'one great pool' hypothesis. His estimated break points, between 2008 and 2009, occur much later than those found by Maslyuk and Smyth (2009). Later dates are chosen because Wilmot's sample period includes the boom and bust in oil prices.

2.3 Methodology

Cointegration analysis provides the natural tool to investigate the 'one great pool' hypothesis. Standard econometric analysis and inference lead to spurious results when applied to nonstationary time series. As a result, a number of residual-based cointegration methods have been used to test for a long-run relationship between crude oil prices including Engle and Granger (1987), Gregory and Hansen (1996), and Enders and Siklos (2001). In this article, the Engle-Granger and Gregory-Hansen cointegration tests are used to test for a cointegrating relationship between crude oil prices while the Kejriwal and Perron (2010) sup-Wald test is used to test for structural changes in the cointegrating vector.

Two cointegration models are considered in this article. The first model, denoted the Restricted model or RM, is the standard Engle-Granger cointegration model,

$$y_t = \alpha + \beta x_t + u_t, \tag{2.1}$$

where the cointegrating vector is $(1, -\alpha, -\beta)$. The second model, denoted the Unrestricted model or UM, allows for a one-time shift in the intercept and slope,

$$y_t = \alpha_1 + \alpha_2 \varphi_t + \beta_1 x_t + \beta_2 \varphi_t x_t + u_t, \tag{2.2}$$

where φ_t is a dummy variable, defined as,

$$\varphi_t = \begin{cases} 0 & \text{if} \quad t \leq \tau, \\ 1 & \text{if} \quad t > \tau. \end{cases}$$

and τ is the break date. With a pre-break cointegrating vector $(1, -\alpha_1, -\beta_1)$ and a post-break cointegrating vector $(1, -(\alpha_1 + \alpha_2), -(\beta_1 + \beta_2))$.

In the traditional sense, two variables, x_t and y_t, are cointegrated if a linear combination of the variables is stationary. We use the augmented Dickey-Fuller (ADF) test to test the OLS residuals from equation (2.1), $\hat{u}_t$, for a unit root. A failure to reject the null hypothesis of a unit root implies crude oil prices are not cointegrated while a reject of the null in favour of the alternative (i.e. stationarity) implies prices are cointegrated. Critical values for the ADF test are provided by Engle and Granger (1987) in Table 2 (p. 269).

Gregory and Hansen (1996) extend conventional cointegration tests to include a larger class of models. They propose ADF, and Phillips-Perron (Z_α and Z_t) type tests designed to test the null hypothesis of no cointegration against the alternative of cointegration in the presence of a structural change. OLS residuals are obtained from equation (2.2) and test statistics are estimated for all possible break dates, $[0.15T] \leq \tau \leq [0.85T]$. The test statistic is then determined where the estimated statistics reaches its smallest value.

$$ADF^* = \inf_{\tau \in T} ADF(\tau) \quad Z_\alpha^* = \inf_{\tau \in T} Z_\alpha(\tau) \quad Z_t^* = \inf_{\tau \in T} Z_t(\tau)$$

The null hypothesis of no cointegration is reject if the test statistic is less than the critical values provided by Gregory and Hansen (1996) in Table 1 (p. 109). Here, results are based on the Z_t statistic which is described by Gregory-Hansen as the most powerful statistic.

Kejriwal and Perron (2010) extend Bai and Perron's (1998) structural change tests to allow for both I(0) and I(1) variables. They derive the limiting distribution of the sup-Wald test under the null hypothesis of no structural change against the alternative of a given number of structural changes. They show that the limiting distribution is not the same as would prevail in a stationary framework. Their tests maintain correct size in finite samples and are much more powerful than the commonly used LM tests.

The sup-Wald test has a null hypothesis of no structural change, equation (2.1), against the alternative of a given number of structural changes, equation (2.2). Under the alternative, the estimates of the parameters are obtained by minimizing the global sum of squared residuals. For each break date, τ_i, estimate equation (2.2) by OLS and denote the resulting sum of squared residuals as $SSR(\tau_i)$, the estimate of the break date is $\hat{\tau} = \arg\min_{\tau} SSR(\tau)$. The sup-Wald test is then defined as

$$\sup F_{\hat{\tau}} = (T-2) \times \frac{RSSR - USSR(\hat{\tau})}{USSR(\hat{\tau})} \tag{2.3}$$

where $RSSR$ is the sum of squared residuals from the RM and $USSR(\hat{\tau})$ is the sum of squared residuals from the UM with $\hat{\tau}$ obtained by minimizing the global sum of squared residuals. The null hypothesis of no structural change is rejected if sup $F_{\hat{\tau}}$ is greater than the critical values provided by Kejriwal and Perron (2010) in Table 1 (p. 509). If the error term is serially correlated, Kejriwal and Perron offer the following adjustment

$$F^* = \left(\hat{\sigma}_u^2/\hat{\sigma}^2\right)F \tag{2.4}$$

where $\hat{\sigma}_u^2 = T^{-1}\sum_{t=1}^{T}\hat{u}_t^2$ and $\hat{\sigma}^2$ is a consistent estimate of σ^2. They propose a new estimator of the long-run variance that is constructed using a hybrid method that involves residuals determined under both the null and alternative hypotheses. The proposed estimator is

$$\hat{\sigma}^2 = T^{-1}\sum_{t=1}^{T}\tilde{u}_t^2 + 2T^{-1}\sum_{j=1}^{T-1} w(j/\hat{h}) \sum_{t=j+1}^{T} \tilde{u}_t\tilde{u}_{t-j}, \tag{2.5}$$

where $\tilde{u}_t$ and $\hat{u}_t$ are the residuals obtained under the null and alternative hypotheses. The kernel function $w(\cdot)$ is the quadratic spectral with an estimated bandwidth given by $\hat{h} = 1.3221(\hat{a}(2)T)^{1/5}$, where $\hat{a}(2) = 4\hat{\rho}^2/(1-\hat{\rho})^4$ and $\hat{\rho} = \sum_{t=2}^{T}\hat{u}_t\hat{u}_{t-1}/\sum_{t=1}^{T}\hat{u}_{t-1}^2$. Kejriwal-Perron show the sup-Wald test based on this estimator is able to by-pass the problem of nonmonotonic power while maintaining an exact size close to the nominal size.

2.4 Data

With virtually hundreds of different grades of crude oil traded in world markets, we focus the analysis on seven crude oil streams: WTI, Brent, Dubai, Maya, WCS, LLS and ESS. This will allow us to analyze the impact unconventional crude oil production has had on the relationship between North American landlocked crude oils (WTI, WCS, and ESS) and tidewater crude oils (Brent, Dubai, Maya, and LLS). For example, if the relationship between tidewater crude oils is stable but the relationship between land-locked and tidewater crude oils changes then we may be able to attribute this change to the boom in unconventional crude oil. The data comprises weekly closing spot prices for the seven crude oils, it is collected from Bloomberg for the period from May 2, 2008 to February 26, 2016, and all prices are expressed in U.S. dollars per barrel.

Crude oils are divided into groups based on two basic physical properties: API gravity and sulfur content. API gravity is the standard measure for specific gravity, a crude oil can be grouped into one of three categories: light, medium, and heavy.[5] Crude oils with relatively low sulfur content (less than 0.42 percent) are classified as sweet crudes and crude oils with relatively high sulfur content are classified as sour crudes. Typically, lighter and sweeter crude oils receive higher prices on world markets because they are easier to refine and result in a more valuable output mix. Other factors that affect the price of crude oil include its location and transportation costs, i.e. a crude oil located near a refinery will receive a higher price than one that is further away.

Table 2.1 presents the summary statistics for the seven crude oils considered. It also contains information about physical properties and location. Light, sweet and heavy, sour crude oils with access to tidewater (Brent, LLS, Dubai, and Maya) have a higher average price than landlocked light, sweet and heavy, sour crude oils (WTI, WCS, and ESS) over the sample period. Surprisingly, Dubai, a medium sour crude oil, has a higher average price than WTI. It is also surprising how large the average price difference is between WTI and LLS. WTI is a higher quality crude oil than LLS, yet, it averages \$7.63 less than LLS over the sample period.

[5] Light crude oil has an API gravity higher than 31.1°. Medium crude oil has an API gravity between 22.3°and 31.1°. Heavy crude oil has an API gravity below 22.3°.

Table 2.1: Summary Statistics Weekly Spot Prices

	WTI	Brent blend	Dubai Fateh	Mexican Maya	WCS	LLS	ESS
Mean	81.91	88.79	86.25	78.26	64.69	89.54	82.50
St Dev.	23.27	26.91	25.73	24.75	20.64	26.59	24.49
Max	145.29	144.38	139.89	129.77	129.63	149.42	148.09
Min	29.42	27.93	25.27	21.68	15.12	30.67	28.17
Skew	-0.32	-0.42	-0.49	-0.49	-0.20	-0.39	-0.16
Kurt	-0.32	-1.02	-0.88	-0.87	0.07	-0.84	-0.44
API gravity	39°	>35°	31°	21.1°	20.3°	35.7°	33.5°
Sulfur content	0.34%	<1%	1.7%	3.38%	3.43%	0.44%	0.15%
Location	Cushing, OK	Sullom Voe, U.K.	Dubai, U.A.E.	Cayo Arcas, MX	Hardisty, AB	St. James, LA	Edmonton, AB
Obs.	409	409	409	409	409	409	409

Note: The data comprises weekly closing crude oil spot prices for the seven crude oils over the period from May 2, 2008 to February 26, 2016.

2.5 Empirical Results

This section presents the empirical results for the twenty one possible price pairs. Interest lies in the timing of the structural breaks. Our null hypothesis is land-locked North American crude oil markets are segmented from world markets because of the large technology shock that is the unconventional crude oil boom and the resulting infrastructure and logistic constraints. Our alternative is that prices are cointegrated with a structural change caused by the unconventional crude oil boom. This corresponds to the technical null hypothesis that crude oil prices are not cointegrated. Crude oil prices are not cointegrated if we fail to reject the null hypothesis of both the Engle-Granger and Gregory-Hansen cointegration tests. Rejection of the null hypothesis implies these markets are still part of the world oil market. Crude oil prices have a stable long-run relationship if we fail to reject the null hypothesis of the Kejriwal-Perron test. Prices are cointegrated with a structural change if we reject the null hypothesis.

To perform the proposed cointegration tests we must first establish that each price series has a unit root. The ADF, PP, Kwiatkowski, Phillips, Schmidt, and Shin

(KPSS), and Zivot and Andrews (ZA) tests were applied to the natural log of each series and its difference. The ADF, PP, and ZA tests all have a null hypothesis of a unit root with an alternative of stationarity. The ZA tests differs from the ADF and PP tests as its alternative allows for an endogenously determined structural break. The KPSS test has a null hypothesis of stationarity and an alternative of a unit root. The results, reported in Table 2.2, indicates that each series is integrated of order one.

Table 2.2: Unit Root Tests

	ADF	PP	KPSS	ZA	Break Point
WTI	-1.62	-4.250	1.21***	-3.34	09/26/2014
Δ WTI	-5.38***	-470.1***	0.2	-23.28***	12/19/2008
Brent	-1.35	-2.41	1.28***	-2.8	09/19/2014
Δ Brent	-5.57***	-460.19***	0.26	-22.3***	12/19/2008
Dubai	-1.48	-1.95	1.28***	-2.55	09/05/2014
Δ Dubai	-5.42***	-404.65***	0.29	-20.09***	12/19/2008
WCS	-1.92	-8.48	1.42***	-3.62	10/03/2014
Δ WCS	-6.23***	-429.83***	0.13	-21.57***	12/19/2008
Maya	-1.62	-2.7	1.32***	-2.65	09/26/2014
Δ Maya	-5.46***	-475.35***	0.26	-21.96***	12/19/2008
LLS	-1.45	-2.81	1.37***	-2.92	09/26/2014
Δ LLS	-5.37***	-473.99***	0.24	-22.94***	12/19/2008
ESS	-2.02	-7.32	1.24***	-3.63	09/26/2014
Δ ESS	-5.91***	-456.62***	0.120	-22.49***	12/19/2008

Note: *, **, *** indicates significance at the 90%, 95%, and 99% level, respectively.

Next the Engle and Granger (1987) and Gregory and Hansen (1996) cointegration tests are applied to each price pair, the results are presented in Table 2.3. Results from the Engle-Granger cointegration test show four price pairs are not cointegrated with four pairs cointegrated at the 10 percent level. WTI is not cointegrated with tidewater crude oils (Brent, LLS, Maya, and Dubai at 10 percent) but is cointegrated with other land-locked crude oils (WCS and ESS). While tidewater crude oil price pairs (Brent - Dubai, Brent - LLS, Maya - Brent, Maya - Dubai, Maya - LLS, and LLS - Dubai) are cointegrated at the 1 percent level. This evidence lends support the claim that North American crude oil markets are segmented from world markets as previous studies have found evidence of a long-run relationship between these crude oil prices (Hammoudeh et al. (2008) and Maslyuk and Smyth (2009)).

Allowing for a structural break, the results from the Gregory and Hansen (1996) cointegration test are less favorable to the null hypothesis of no cointegration. Of the four price pairs that were not cointegrated, two are cointegrated with a structural break at the 5 percent level. All four price pairs that were cointegrated at the 10 percent level are now cointegrated with a structural break at the 1 percent level. Three price pairs fail to reject the null hypothesis. WTI - Maya and WTI - LLS also failed to reject the null hypothesis of the Engle-Granger cointegration test and are therefore not cointegrated. Surprisingly, Maya - Brent failed to reject the null hypothesis Gregory-Hansen cointegration test given that it rejected the null hypothesis of the Engle-Granger cointegration test at the 1 percent level.

Having established that a crude oil price pair is at least cointegrated, we then test parameter stability using the sup-Wald test. The residuals from equations (2.1) and (2.2) were tested for serial correlation using the Box-Ljung test. First, the results of the test, which are not reported, show that residuals are serially correlated for all price pairs, as a result, we adjust the sup-Wald test as described above. Test results and estimated break dates are presented in Table 2.3. Results show that Maya - Brent and Maya - LLS are cointegrated without a structural break. WTI - WCS and LLS - ESS are cointegrated with a structural break at the 10 percent level. The remaining price pairs are cointegrated with a structural break at the 5 percent level or better. The earliest break date selected is July 7, 2010 and the last break date is selected is December 26, 2014.[6]

Table 2.3 shows the estimated break dates estimated following Kejriwal and Perron (2008). Break dates between land-locked North American crude oils and tidewater crude oils range from December 31, 2010 to June 10, 2011. These dates correspond to the start of the unconventional crude oil boom and suggest that the unconventional crude oil boom may have caused the relationship between land-locked crude oils and tide-water crude oils to change. Figure 2.2 plots crude oil price series along with

[6]The earliest possible break date is June 26, 2009 and the latest possible break date is December 26, 2014

Table 2.3: Cointegration Test Results

	Engle-Granger	Gregory-Hansen	Kejriwal-Perron
WTI - WCS	-5.4***	-5.3**	11.72*
		12/26/2012	07/30/2010
WTI - Maya	-2.7	-4.25	8.7
		03/11/2011	01/28/2011
WTI - Brent	-2.73	-5.2**	20.6***
		12/17/2010	12/31/2010
WTI - LLS	-2.98	-3.93	6.96
		05/31/2013	12/31/2010
WTI - ESS	-4.6***	-5.29**	5.63
		12/09/2011	08/30/2013
WTI - Dubai	-3.48*	-7.22***	27.35***
		12/24/2010	01/14/2011
WCS - Maya	-3.32*	-5.82***	21***
		01/14/2011	12/31/2010
WCS - Brent	-3.32*	-5.4**	18.61***
		09/17/2010	12/31/2010
WCS - LLS	-3.53**	-5.11**	12.81**
		01/31/2014	07/30/2010
WCS - ESS	-3.2	-5.46**	16.68**
		09/19/2014	01/31/2014
WCS - Dubai	-3.5*	-6.51***	23.23***
		12/17/2010	12/31/2010
Maya - Brent	-4.28***	-4.59	4.59
		12/19/2014	08/23/2013
Maya - LLS	-4.6***	-5.01**	5.59
		11/28/2014	10/21/2011
Maya - ESS	-3.54**	-5.2**	14.25**
		07/22/2011	06/10/2011
Maya - Dubai	-4.86***	-8.22***	14.89**
		08/30/2013	09/27/2013
Brent - LLS	-4.76***	-9.88***	49.83***
		08/30/2013	08/16/2013
Brent - ESS	-4.36***	-5.9***	19.44***
		06/17/2011	05/27/2011
Brent - Dubai	-3.92**	-13.09***	50.5***
		12/12/2014	12/26/2014
LLS - ESS	-4.61***	-5.62***	10.34*
		07/22/2011	05/27/2011
LLS - Dubai	-4.51***	-11.49***	50.12***
		08/30/2013	09/06/2013
ESS - Dubai	-3.56**	-7.3***	24.86***
		07/22/2011	08/12/2011

Note: *, **, *** indicates significance at the 90%, 95%, and 99% level, respectively.

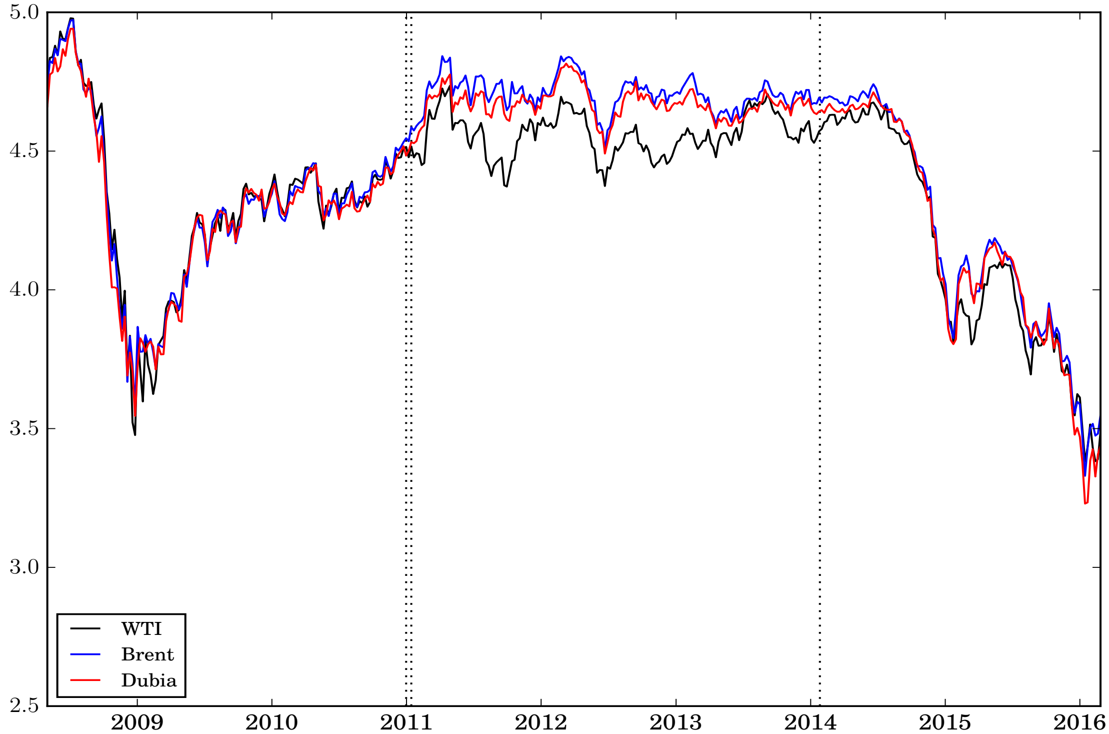
the estimated break dates. Figure 2.2a shows that prior to the estimated breaks; Brent, Dubai, and WTI followed each other very closely. Following the break, WTI is discounted relative to Brent and Dubai; however, it appears that the three crude oils still move together as they seem to increase and decrease together. Similar results can be seen in Figure 2.2b.

Break dates between tidewater crude oils range from August 16, 2013 to December 26, 2014. With Maya - Dubai, Brent - LLS, and LLS - Dubai occurring between August and September 2013. These breaks may correspond to low demand caused by weak global economic growth. Land-locked North American crude oils seem to have a stable cointegrating relationship. WTI - WCS and WTI - ESS are cointegrated at the 1 percent level according to the Engle-Granger cointegration test, however, only the WTI - WCS pair rejects the Kejriwal-Perron null hypothesis of no structural change, at the 10 percent level. WCS and ESS are cointegrated with a structural break but the break date, January 31, 2014, does not correspond to the rise in unconventional crude oil production.

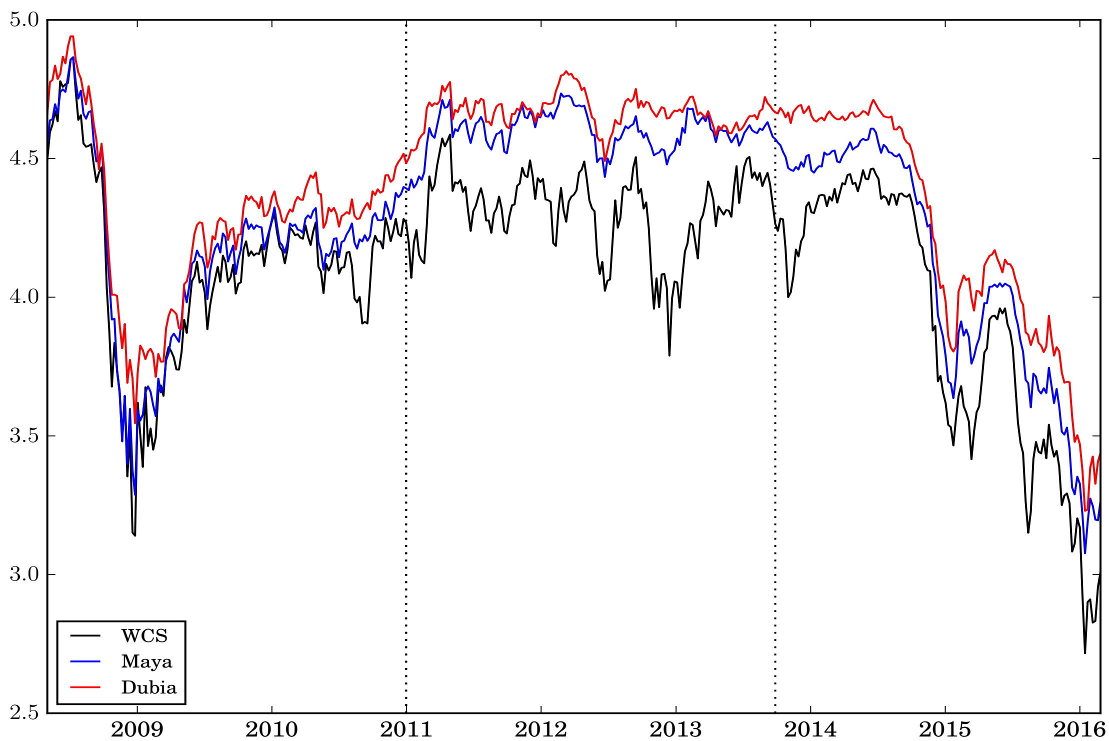
2.6 Conclusion

The large discount faced by land-locked North American crude oils relative to tidewater crude oils has received a lot of attention. Many believe the rapid increase in production from unconventional reserves segmented North American markets from world markets as constrained transportation capacity restricted producers ability to move production away from regions with excess supply. This article examines the spatial pricing relationship between weekly crude oil spot prices for the period from May 2008 to February 2016. Focus is given to the relationship between land-locked North American crude oils and international benchmarks with access to tidewater. The sup-Wald test proposed by Kejriwal and Perron (2010) is used to test for an endogenously determined structural break in the cointegrating vector between crude oil prices. Results show that weekly crude oil spot prices are cointegrated with a structural break; suggesting land-locked North American markets are still integrated

Figure 2.2: Endogenously Determined Structural Breaks



(a) WTI - Brent: 12/31/2010, WTI - Dubai: 1/14/2011, Brent - Dubai: 12/26/2014



(b) WCS - Dubai: 12/31/2010, WCS - Maya: 12/31/2010, Dubai - Maya: 9/27/2013 with world markets and the large price differences may reflect constrained capacity in North America. In order to increase prices and investment, the results found in this article, support policies designed to reduce the large price differences i.e. expand pipeline capacity.

The cointegration of crude oil prices has received much attention in the literature, however, most authors assume a stable cointegrating relationship between crude oils in different locations. Maslyuk and Smyth (2009) and Wilmot (2013) find that crude oil prices are cointegrated with a structural break. They argue that multiple break should be examined as a number of factors can cause the relationship between crude oil prices to change including technological shocks, policy and regime changes. We find unconventional crude oil production in North America has cause the relationship between land-locked North American crude oils and tidewater crude oils to change.

2.7 Tables

Table 2.4: Engle and Granger (1987) Cointegration Test Results

	ADF	PP
WTI - WCS	-5.4***	-51.49***
WTI - Maya	-2.7	-20.62
WTI - Brent	-2.73	-26.74**
WTI - LLS	-2.98	-17.78
WTI - Dubai	-3.48*	-52.52***
WCS - Maya	-3.32*	-34.63***
WCS - Brent	-3.32*	-30.52**
WCS - LLS	-3.53**	-28.78**
WCS - Dubai	-3.5*	-45.02***
Maya - Brent	-4.28***	-34.37***
Maya - LLS	-4.6***	-39.53***
Maya - Dubai	-4.86***	-95.740***
Brent - LLS	-4.76***	-143.72***
Brent - Dubai	-3.92**	-203.41***
LLS - Dubai	-4.51***	-156.04***
WTI - ESS	-4.6***	-47.88***
WCS - ESS	-3.2	-30.79**
Maya - ESS	-3.54**	-39.43***
Brent - ESS	-4.36***	-54.21***
LLS - ESS	-4.61***	-51.42***
ESS - Dubai	-3.56**	-58.44***

Table 2.5: Gregory and Hansen (1996) Cointegration Test Results

	ADF	Z_α	Z_t
WTI - WCS	-5.25**	-52.76**	-5.3**
	02/17/2012	12/26/2012	01/13/2012
WTI - Maya	-3.660	-33.04	-4.25
	04/08/2011	03/11/2011	03/11/2011
WTI - Brent	-3.920	-51.18**	-5.2**
	11/05/2010	12/17/2010	12/17/2010
WTI - LLS	-3.95	-29.01	-3.93
	06/14/2013	05/31/2013	05/31/2013
WTI - Dubai	-4.8*	-91.74***	-7.22***
	03/25/2011	12/24/2010	12/24/2010
WCS - Maya	-4.97**	-62.95***	-5.82***
	03/04/2011	01/14/2011	01/14/2011
WCS - Brent	-5.04**	-55.55**	-5.4**
	10/29/2010	09/17/2010	09/17/2010
WCS - LLS	-4.95**	-49.62**	-5.11**
	10/29/2010	01/31/2014	01/31/2014
WCS - Dubai	-5.24**	-77.42***	-6.51***
	10/29/2010	12/17/2010	12/17/2010
Maya - Brent	-4.53	-39.06	-4.59
	05/21/2010	12/19/2014	12/19/2014
Maya - LLS	-5.15**	-45.03*	-5.01**
	08/19/2011	11/28/2014	11/28/2014
Maya - Dubai	-5.45**	-116.79***	-8.22***
	08/09/2013	08/30/2013	08/30/2013
Brent - LLS	-5.24**	-160.27***	-9.88***
	07/12/2013	08/30/2013	08/30/2013
Brent - Dubai	-5.26**	-262.56***	-13.09***
	11/07/2014	12/12/2014	12/12/2014
LLS - Dubai	-5.76***	-208.47***	-11.49***
	07/19/2013	08/30/2013	08/30/2013
WTI - ESS	-5.08**	-55.7**	-5.29**
	07/05/2013	12/09/2011	12/09/2011
WCS - ESS	-4.64	-56.15**	-5.46**
	10/31/2014	09/19/2014	09/19/2014
Maya - ESS	-4.14	-52.51**	-5.2**
	07/22/2011	07/22/2011	07/22/2011
Brent - ESS	-4.91*	-66.5***	-5.9***
	06/17/2011	06/17/2011	06/17/2011
LLS - ESS	-5.02**	-60.88***	-5.62***
	06/17/2011	07/15/2011	07/22/2011
ESS - Dubai	-5.35**	-96.07***	-7.3***
	11/04/2011	07/08/2011	07/22/2011

Table 2.6: Kejriwal and Perron (2010) Cointegration Test Results

	sup Wald	Robust sup Wald
WTI - WCS	136.23	11.72*
	07/30/2010	07/30/2010
WTI - Maya	166.94	8.7
	01/28/2011	01/28/2011
WTI - Brent	348.58	20.6***
	12/31/2010	12/31/2010
WTI - LLS	149.98	6.96
	12/31/2010	12/31/2010
WTI - ESS	51.77	5.63
	08/30/2013	08/30/2013
WTI - Dubai	224.19	27.35***
	01/14/2011	01/14/2011
WCS - Maya	265.47	21***
	12/31/2010	12/31/2010
WCS - Brent	270.19	18.61***
	12/31/2010	12/31/2010
WCS - LLS	171.1	12.81**
	07/30/2010	07/30/2010
WCS - ESS	194.56	16.68**
	01/31/2014	01/31/2014
WCS - Dubai	231.9	23.23***
	12/31/2010	12/31/2010
Maya - Brent	53.95	4.59
	08/23/2013	08/23/2013
Maya - LLS	58.83	5.59
	10/21/2011	10/21/2011
Maya - ESS	177.88	14.25**
	06/10/2011	06/10/2011
Maya - Dubai	70.59	14.89**
	09/27/2013	09/27/2013
Brent - LLS	280.21	49.83***
	08/16/2013	08/16/2013
Brent - ESS	221.43	19.44***
	05/27/2011	05/27/2011
Brent - Dubai	121.78	50.5***
	12/26/2014	12/26/2014
LLS - ESS	95.54	10.34*
	05/27/2011	05/27/2011
LLS - Dubai	174.35	50.12***
	09/06/2013	09/06/2013
ESS - Dubai	182.2	24.86***
	08/12/2011	08/12/2011

Chapter 3

Regime Switching for the WTI-WCS Price Spread

3.1 Introduction

It is well established that the price of a commodity critically depends on its quality and its location. Samuelson (1952) and Takayama and Judge (1971) have shown that spatial arbitrage ensures the price of a commodity in one location is equal to the price of the commodity in another location less transport costs between the two locations (i.e. the price difference equals transport costs). More recently, in a spatial arbitrage model with transport capacity constraints, Coleman (2009) found that on rare occasions the price difference between two locations can exceed transport costs when capacity is fully utilized. His results suggest two regimes govern the price difference process. In one regime, the price difference fluctuates around transport costs as inventories and excess transport capacity are sufficient to smooth fluctuations in supply and demand. In the other regime, when capacity is fully utilized, the price difference exceeds transport costs as excess supply cannot be moved from one region to the other causing higher prices in the importing region and lower prices in the exporting region.

Motivated by Coleman's findings, this article examines the impact constrained transport capacity may have on the distribution of the WTI-WCS spread.[1] Historically, the WTI-WCS spread has reflected transport costs and quality differences. The average monthly WTI-WCS spread from January 2005 to December 2010 was \$13.13. The National Energy Board (2014) estimates the cost of shipping oil via pipeline from Hardisty to Cushing is about \$5 to \$6.55 per barrel, depending on the quality of the crude oil and the system used. Using the average Brent-Mexican Maya spread as an estimate of the light-heavy crude oil discount,[2] over the same period, the value of the quality difference is \$6.92. Given these values, transport costs and quality difference are about \$11.92 to \$13.47. However, from 2011 to 2014, the WTI-WCS spread increased to an average of \$20.61 which exceeds transport costs and quality differences. Many observes believe the increase in the WTI-WCS spread is the result of constrained transportation capacity as pipelines are generally full and more crude oil is being shipped by rail to avoid bottlenecks despite its high cost.[3] Galay (2016) has shown that a large sustained spread reduces the value of operating projects and projects in the planning stages. Excess spread above quality differences and transport costs represents substantial lost revenue for producers and revenues for government through royalties, income taxes, and leased crown land.

In this article, the WTI-WCS spread is modeled as a two regime Markov-switching model where sufficient capacity and constrained capacity are the unobserved state variables. Markov-switching models are used for series that are believed to transition over a finite set of unobserved regimes, allowing the process to evolve differently in each regime. Markets generally take the view that some spare capacity is desirable; however, the point at which the markets view of capacity switches from sufficient to constrained is not known with certainty. The transition between sufficient and constrained capacity regimes occurs according to a Markov process.

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[1] WTI is a light, sweet crude oil located in Cushing, Oklahoma. It is the benchmark crude oil in North American. WCS is a heavy, sour crude oil that is located in Hardisty, Alberta.

[2] Brent is a light, sweet crude oil similar in quality to WTI and Mexican Maya is a heavy, sour crude oil similar in quality to WCS. Both Brent and Mexican Maya have access to tidewater and therefore face much lower transport costs.

[3] According to McKeown et al. (2016), in 2013, crude oil transported by rail reached 200,000 bbl/d. Compared to the previous year, exports by rail increased by 177%. The National Energy Board estimates that rail costs are roughly double or triple the cost of pipelines.

The results of this article corroborate the finding of Coleman and others in the spatial arbitrage and commodity storage literature including Samuelson (1971), who showed the theory generates a non-linear first-order Markov process for prices. When there is sufficient transport capacity, the WTI-WCS spread reflects transport costs and quality differences. There is a high degree of correlation between periods and the standard deviation is small. When capacity is constrained, the spread is larger than transport costs and quality differences. There is less correlation between periods as supply cannot be moved to smooth supply and demand imbalances, and the standard deviation is much higher.

Recently, Fritsche and Suvankulov (2015) used a threshold vector autoregression (TVAR) model to quantify the effect pipeline capacity utilization and crude-by-rail shipments have on determining the WTI-WCS spread. Their results are qualitatively similar to those presented here. They find the WTI-WCS spread responses differently across regimes to changes in pipeline capacity utilization and crude-by-rail. Under the less congested pipeline regime, a shock to pipeline capacity utilization has a small and statistically insignificant impact on the spread. By contrast, under a tight regime, shocks to pipeline capacity utilization lead to significant changes in the WTI-WCS spread.

The results of this article indicate additional pipeline capacity could be necessary for long-run growth in oil sands production. If global crude oil prices return to levels seen from 2011 to 2014, then an expansion of pipeline capacity may be necessary to transport crude oil to market. The National Energy Board (2013) estimated Canadian crude oil production could increase by as much as 75 percent compared to 2012 levels and reach 5.8 million barrels per day by 2035. However, the WTI-WCS spread has returned to previous levels as a result of the fall in global crude oil prices in 2015. If prices remain low, there will be no need to expand pipeline capacity. At current prices there is little incentive to invest in new oil sands projects and current capacity is sufficient to transport current production.

The rest of the article is organized as follows. Section 3.2 presents the two regime Markov-switching model. Sections 3.3 and 3.4 presents the data, results and provides a discussion. Section 3.5 concludes.

3.2 Model

The Markov-switching model was initially developed by Goldfeld and Quandt (1973) for linear regression equations. Hamilton (1989) extended Goldfeld and Quandt's Markov-switching regression to allow for autoregressive processes and provided a non-linear filter for estimation. Following Hamilton's seminal paper, Markov-switching models have become widely applied in economics. Hamilton modeled the growth rate of GDP as a switching process to capture the asymmetric behavior observed over expansions and recessions. Garcia and Perron (1996) modeled real interest rates under three regimes, Engel and Hamilton (1990) model US exchange rates, and Kim et al. (1998) model monthly stock returns. More recently, Zhang and Zhang (2015) modeled Brent, WTI, and the Brent-WTI spread pre and post financial crisis use a three regime Markov switching model.

Guided by the conclusions of Coleman (2009), the WTI-WCS spread is specified as following a two-regime Markov switching model. Let y_t denote the WTI-WCS spread. The spread follows the two-regime Markov-switching model:

$$y_t - \mu_{s_t} = \rho_{s_t}(y_{t-1} - \mu_{s_{t-1}}) + \epsilon_t, \tag{3.1}$$

where μ_{s_t} is the regime specific mean spread, ρ_{s_t} is the regime specific autoregressive coefficient, ϵ_t is independent and identically distributed error term with regime specific variance $\sigma^2_{s_t}$, and $s_t = 1$ or 2 denotes the regime. Regime 1, $s_t = 1$, represents the normal times when there is sufficient transportation capacity in place. Regime 2, $s_t = 2$, represents constrained times when there is insufficient transportation capacity. The state of the regime is not directly observable, if it was, we could simply estimate equation (3.1) with the use of dummy variables. However, we do not know with certainty which regime prevails, therefore, the transition probabilities are defined as

$$\Pr[s_t = j | s_{t-1} = i] = p_{i,j}, \quad (i, j = 1, 2) \tag{3.2}$$

where $p_{i,1} + p_{i,2} = 1$, $i = 1, 2$.

The conditional density of an observed value of y_t is:

$$f(y_t|s_t, s_{t-1}, \psi_{t-1}) = \frac{1}{\sqrt{2\pi\sigma_{s_t}^2}} \exp\left\{\frac{-[y_t - \mu_{s_t} - \rho_{s_t}(y_{t-1} - \mu_{s_{t-1}})]^2}{2\sigma_{s_t}^2}\right\}, \tag{3.3}$$

where ψ_{t-1} is all information available up to time $t-1$. The conditional likelihood value for each observation y_t can be written as a weighted average of the conditional densities in (3.3) as follows:

$$\begin{aligned} L_t(\theta) = f(y_t|\psi_{t-1}) &= \sum_{s_t=1}^{2} \sum_{s_{t-1}=1}^{2} f(y_t, s_t, s_{t-1}|\psi_{t-1}) \\ &= \sum_{s_t=1}^{2} \sum_{s_{t-1}=1}^{2} f(y_t|s_t, s_{t-1}, \psi_{t-1})\Pr[s_t, s_{t-1}|\psi_{t-1}] \end{aligned} \tag{3.4}$$

where the weights are the joint probability of regime s_t and s_{t-1} occurring given all past information up to $t-1$

$$\Pr[s_t, s_{t-1}|\psi_{t-1}] = \Pr[s_t|s_{t-1}]\Pr[s_{t-1}|\psi_{t-1}]$$

with the probability of regime s_{t-1} conditional on all information up to $t-1$

$$\Pr[s_{t-1}|\psi_{t-1}] = \sum_{s_{t-2}} \Pr[s_{t-1}, s_{t-2}|\psi_{t-1}]$$

and the joint probability of regime s_{t-1} and s_{t-2} given all available information at time $t-1$

$$\Pr[s_{t-1}, s_{t-2}|\psi_{t-1}] = \frac{f(y_{t-1}, s_{t-1}, s_{t-2}|\psi_{t-2})}{f(y_{t-1}|\psi_{t-2})}.$$

The log-likelihood function is then

$$\begin{aligned} \mathcal{L}(\theta) &= \sum_{t=1}^{T} \ln L_t(\theta) \\ &= \sum_{t=1}^{T} \ln \left\{ \sum_{s_t=1}^{2} \sum_{s_{t-1}=1}^{2} f(y_t|s_t, s_{t-1}, \psi_{t-1})\Pr[s_t, s_{t-1}|\psi_{t-1}] \right\} \end{aligned} \tag{3.5}$$

where $\theta = (\mu_1, \mu_2, \rho_1, \rho_2, \sigma_1^2, \sigma_1^2)$ is a vector of parameters. The model parameters and probabilities are computed using the nonlinear filtering algorithm for maximum likelihood as described in Hamilton (1994) and Kim and Nelson (1999).[4]

3.3 Data

Weekly crude oil spot price data covering a period of 9 years from May 2, 2008 to February 26, 2016 is used in this study. The spot prices are measured in US dollars per barrel. The data was obtained from Bloomberg. The WTI-WCS spread is simply the difference between WTI and WCS.

Table 3.1: Descriptive Statistics

	WTI	WCS	Price Spread	Price Spread/WTI
Mean	81.91	64.69	17.22	0.218
St.Dev	23.27	20.64	6.78	0.080
Min	29.42	15.12	5.80	0.086
Max	145.29	129.63	42.50	0.490
Skew	-0.32	-0.20	0.95	0.943
Kurt	2.67	3.05	3.90	3.313
AR(1)	0.98	0.97	0.92	0.910
AR(2)	0.95	0.93	0.86	0.830
AR(3)	0.93	0.90	0.81	0.757
Number of Observations = 409				

Correlation

	WTI	WCS	Price Spread	Price Spread/WTI
WTI	1	0.96	0.51	-0.34
WCS		1	0.25	-0.57
Price Spread			1	0.58
Price Spread/WTI				1

Table 3.1 presents the descriptive statistics and correlation for WTI, WCS, the WTI-WCS spread, and the WTI-WCS spread as a percentage of WTI. WTI and WCS are highly correlated. The series minimum and maximum values occur on the same days. They reach their minimum values of 29.42 and 15.12 on January 15, 2016 and they reach their maximum value of 145.29 and 129.63 on July 4, 2008. The WTI-WCS spread reaches its minimum value of 5.80 on March 6, 2009 following

[4]The Stata program mswitch is used to estimate the parameters of the model.

the start of the financial crisis. It reaches its maximum value of 42.50 on December 14, 2012. All series have a high degree of serial correlation. WTI and WCS are negatively skewed while the WTI-WCS spread and the spread as a percentage of WTI are positively skewed. The WTI-WCS spread is positively correlated with WTI and WCS. However, as a percentage of WTI it is negatively correlated with both WTI and WCS. The spread increases as spot prices increase just at a slower rate.

3.4 Results

Before estimating the Markov-switching model, we first establish the WTI-WCS spread data is stationary using the augmented Dickey-Fuller (ADF) test. The ADF tests for a unit root in a time series against the alternative of stationarity. Table 3.2 presents the results of the ADF. Over the sample period WTI and WCS fail to reject the null hypothesis of a unit root. The WTI-WCS spread rejects the null hypothesis of a unit root at the 1 percent level.

Table 3.2: Augmented Dickey-Fuller Test

	WTI	WCS	Price Spread	Price Spread/WTI
Test Statistic	-2.45	-3.01	-4.18	-5.23
p-value	0.39	0.15	0.01	0.01

The estimated results are presented in Table 3.3. Before discussing the results, we first test for two regimes using the likelihood ratio (LR) test proposed by Garcia (1998). Standard tests are not applicable because under the null hypothesis transition probabilities are not defined. Garcia derives the asymptotic null distribution of the LR test for two-state Markov-switching models. The test has a null hypothesis of one regime (autoregressive model) versus an alternative of two regimes (Markov-switching model). The LR ratio test is specified as

$$LR = 2 * (\mathcal{L}(\hat{\theta}, \hat{\phi}) - \mathcal{L}(\tilde{\theta}))$$

where $\mathcal{L}(\hat{\theta}, \hat{\phi})$ is the log-likelihood from the unrestricted model (Markov switching model) with $\phi = (p_{11}, p_{22})$ and $\mathcal{L}(\tilde{\theta})$ is the log-likelihood from the restricted model

Table 3.3: The estimated results of two-regime Markov switching model

	Full Change model	Fixed Autoregressive term	Fixed Sigma term
ρ_1	0.948*** (0.023)	0.933*** (0.019)	0.918*** (0.02)
ρ_2	0.878*** (0.049)		1.11*** (0.049)
μ_1	15.157*** (1.744)	14.329*** (1.26)	13.964*** (1.606)
μ_2	20.352*** (1.879)	19.372*** (1.475)	18.782*** (1.852)
σ_1	1.397 (0.067)	1.397 (0.067)	1.85 (0.08)
σ_2	3.729 (0.263)	3.771 (0.263)	
p_{11}	0.978 (0.01)	0.978 (0.01)	0.947 (0.014)
p_{21}	0.054 (0.026)	0.054 (0.026)	0.424 (0.163)
p_{12}	0.022 (0.01)	0.022 (0.01)	0.053 (0.014)
p_{22}	0.946 (0.026)	0.946 (0.026)	0.576 (0.163)
Log likelihood	-875.988	-876.783	-917.648
AIC	1767.975	1767.565	1849.296
BIC	1800.065	1795.644	1877.375

Note: ρ_i is the autoregressive parameter in each regime. μ_i is the mean of the WTI-WCS spread in each regime. σ_i is the standard deviation of the WTI-WCS spread in each regime. The sample period is May 2, 2008 - February 26, 2016. Standard errors are reported in parentheses. *, **, *** indicates significance at the 90%, 95%, and 99% level, respectively.

(autoregressive model). From the results in Tables 3.3 and 3.6, the LR statistic calculated to test the null in specification 1 gives 167.858. The estimation of ρ for the autoregressive model is 0.925. These values exceed Garcia's 95 and 99% asymptotic critical values for $\rho = 0.95$ of 8.48 and 12.08 respectively from Garcia (1998) (Table 3, p. 776). This suggests that the null of an autoregressive model should be rejected in favor of the Markov switching model at both significance levels.

The maximum likelihood estimates of the Markov-switching models, reported in Table 3.3, shows the regime dependent means, standard deviations, autoregressive coefficients, and transition probabilities are all individually statistically significant. There are two WTI-WCS spread regimes. One regime is characterized by a low mean and low standard deviation. The mean WTI-WCS spread in regime 1 of \$15.16 is roughly consistent with transport costs and quality differences and has a relatively small standard deviation of \$1.397 per week. The other regime is characterized by a high mean and high standard deviation. The mean spread in regime 2 is \$20.35, which exceeds transport costs and quality differences and the standard deviation is \$3.729 per week. The results from Table 3.3 also show that, the autoregressive coefficients varies across regimes. In regime 1, the WTI-WCS spread is highly correlated with previous values, $\rho_1 = 0.948$. In regime 2, the spread is less correlated with past value, $\rho_2 = 0.878$. The estimated values of μ_1, μ_2, σ_1, σ_2, ρ_1, and ρ_2 support Coleman's (2009) predictions and the results of Fritsche and Suvankulov (2015). In one regime there is a smaller mean spread, less variability, and more correlation between periods as spare transport capacity can be used to smooth supply and demand shocks. In the other regime the mean spread increases, the spread is more variable and less correlated between periods as prices in each region are affected by supply and demand shocks that cannot be smoothed because of capacity constraints.

Along with estimating equation (3.1), we estimate two alternative Markov-switching models. In one the autoregressive coefficient is fixed across regimes, $\rho_1 = \rho_2$. In the other the standard deviation is fixed across regimes, $\sigma_1 = \sigma_2$. The results are presented in Table 3.3. Like the results for equation (3.1), all parameter values for both alternative specifications are statistically significant.

The alternative specifications support the hypothesis that constrained transportation capacity increases the mean and variance of the WTI-WCS spread. The fixed autoregressive coefficient Markov-switching model has a mean spread of \$14.33 in regime 1 and \$19.37 in regime 2. The fixed standard deviation Markov-switching model has a mean spread of \$13.96 in regime 1 and \$18.78 in regime 2. In all three estimated models the difference between means in each regime is roughly \$5. Similar to the full Markov-switching model, the fixed autoregressive coefficient Markov-switching model predicts lower volatility in regime 1, $\sigma_1 = 1.397$ than regime 2, $\sigma_2 = 3.771$. The estimated standard deviation for the fixed standard deviation Markov-switching model is $\sigma_1 = 1.85$. It is larger than regime 1 standard deviations for the full and fixed autoregressive coefficient models but smaller than regime 2 standard deviations. The autoregressive coefficient, $\rho_1 = 0.933$, indicates a high degree of serial correlation in the fixed autoregressive coefficient Markov-switching model. Less serial correlation than the full Markov-switching model in regime 1 but more than regime 2. Surprisingly, the fixed standard deviation Markov-switching model, estimates a regime 2 autoregressive coefficient of 1.11. This implies the WTI-WCS spread would increase without bound in regime 2. In regime 1 the autoregressive coefficient is similar to those estimated for the full and fixed autoregressive coefficient models.

A LR test is used to compare the alternative specifications against the full Markov-switching model. The LR test tests the restricted model, fixed autoregressive and fixed standard deviation Markov-switching models, against the unrestricted model, full Markov-switching model. The LR test statistics are 1.59 and 83.32 for the fixed autoregressive coefficient and the fixed standard deviation Markov-switching models, respectively. We cannot reject the null hypothesis of a fixed autoregressive coefficient but we can reject the null hypothesis that the standard deviation is fixed across regimes. The results of the LR tests verify the WTI-WCS spread mean and variance are not constant across regimes. These test results are supported by the Akaike information criterion (AIC) and Bayesian information criterion (BIC). Both criteria favor the fixed autoregressive coefficient Markov-switching model over the full and fixed standard deviation Markov-switching models.

Table 3.4: The expected duration and observation ratio

	Full Change model		Fixed AR term		Fixed Sigma term	
	Regime 1	Regime 2	Regime 1	Regime 2	Regime 1	Regime 2
Expected Duration	45.45	18.52	45.45	18.52	18.87	2.36
Count	287	122	288	121	367	42
Observation Ratio	70.2%	29.8%	70.4%	29.6%	89.7%	10.3%

Note: Count is the number of weeks the WTI-WCS spread was in regime 1, $Pr[s_t = 1|\psi_T] > 0.5$.

Transition probabilities represent the likelihood that the WTI-WCS spread will stay in its current regime or switch to the other regime. The transition probabilities for each model specification are reported in Table 3.3. The full Markov-switching model and the fixed autoregressive coefficient model have the same transition probabilities.

$$p_{11} = 0.978 \quad p_{21} = 0.054$$
$$p_{12} = 0.022 \quad p_{22} = 0.946$$

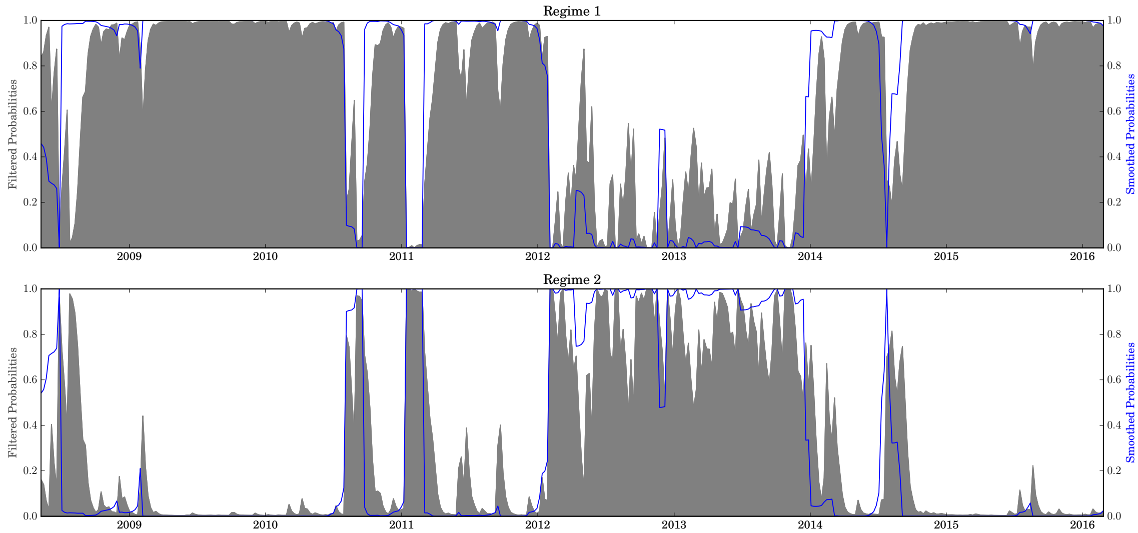
The transition probabilities for the fixed standard deviation Markov-switching model are as follows

$$p_{11} = 0.947 \quad p_{21} = 0.424$$
$$p_{12} = 0.053 \quad p_{22} = 0.576$$

For all three model specifications, regime 1 is the most stable regime. In the full and fixed autoregressive coefficient Markov-switching models the probability of remaining in regime 1 is 97.8 percent and the probability of remaining in regime 2 is 94.6 percent. In the fixed standard deviation Markov-switching model the probability of remaining in regime 1 is 94.7 percent and the probability of remaining in regime 2 is 57.6 percent. The full and fixed autoregressive coefficient Markov-switching models are characterized by relatively few regime changes as the expected duration of regime 1 is 46 weeks and the expected duration of regime 2 is 19 weeks. Table 3.4 shows that 70 percent of observations were in regime 1 and 30 percent were in regime 2, with the majority of those observation occurring between 2012 and 2014.

Given the results presented in Table's 3.3 and 3.4 we can estimate the expected present value of profits for a barrel of transportation capacity. If we assume regime

Figure 3.1: Smoothed and Filtered Probabilities

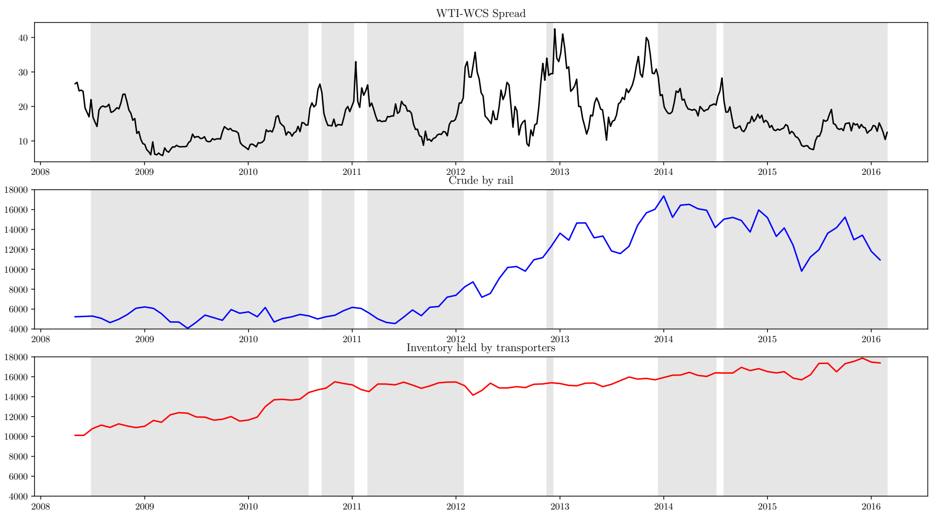


dependent mean minus quality difference represents the expected revenue for a transporter and the cost of shipping is \$5 to \$6.55 per barrel. Then expected profits are \$1.69 to \$3.24 in regime 1 and \$6.88 to \$8.43 in regime 2 for shipping a barrel of oil. Using the observation ratio as an unconditional probability measure and assuming a annual discount rate of 10 percent the expected present value of profits for a barrel of transportation capacity is \$32.36 to \$47.87. A new pipeline project that ships 500000 barrel per day would have an expected value of \$5.9 billion to \$8.7 billion.

Figure 3.1 plots the smoothed and filtered probability of being in each regime. The smoothed probability gives the probability of being in each regime using the full data sample, $Pr[s_t|\psi_T]$. The smoothed probability was computed using Kim's (1994) smoothing algorithm. The filtered probability gives the probability of being in each regime using only information available at $t-1$, $Pr[s_t|\psi_{t-1}]$. The probabilities can be used to understand the persistence of each regime and the most probable regime at each time period. The figures show the WTI-WCS spread is primarily in regime 1 for two extended periods from 2008 to 2012 and 2014 to 2016, except for two short periods around 2011. The spread is in regime 2 from 2012 to 2014. Regime changes seem to correspond to periods of constrained pipeline capacity.

Figure 3.2 plots WTI-WCS spread, monthly crude-by-rail shipments, and monthly

Figure 3.2: WTI-WCS Spread, Crude-by-rail, and Inventories



inventories held by crude oil transporters.[5] The shaded area represents periods when the WTI-WCS spread was likely to be in regime 1 (i.e. $Pr[s_t = 1|\psi_T] > 0.5$). Crude-by-rail shipments and inventories held by transporters may be indicators of capacity utilization. Shipping crude oil by rail is an expensive alternative to shipping crude oil by pipeline. A large WTI-WCS spread and constrained pipelines are required to justify the extra costs. High inventory levels during periods of high prices might indicate capacity constraints as there would be an incentive to take advantage of high prices if product could be moved to market and if the price spread covered transport costs. A cursory examination of Figure 3.2 suggests that regime 1 corresponds to periods when crude-by-rail shipments is relatively constant or decreasing. While regime 2 corresponds to periods when crude-by-rail shipments are increasing. It appears inventories held by transporters has little correlation with current regime as inventories appear elevated after 2010.

A preliminary examination of the relationship between WTI-WCS spread regime and crude-by-rail and inventories held by crude oil transporters is conducted by calculating correlations and regressing the log of smoothed probabilities on the log of

[5]The crude-by-rail shipments and inventory held by crude oil transporters data was collected from Statistics Canada Tables 126-0001 and 404-0002.

Table 3.5: OLS Regression Results

Dependant Variable: $Pr[s_t = 1 \mid \psi_T]$			
Constant	-0.003 (15.301)	16.78 (13.285)	8.31^{**} (3.851)
Crude-by-Rail	-1.29^{**} (0.616)		-1.04^{**} (0.425)
Inventory held by transporters	1.1 (1.964)	-1.87 (1.387)	
R-squared	0.065	0.019	0.061
Adj. R-squared	0.044	0.009	0.051
No. Observations	94	94	94

Note: Standard errors are reported in parentheses. *, **, *** indicates significance at the 90%, 95%, and 99% level, respectively.

crude-by-rail and inventories held by crude oil transporters. The monthly average smoothed probability is used for the analysis. The correlation between the smoothed probability and crude-by-rail is -0.22 and it is statistically significant at the 5 percent level. The correlation between smoothed probability and inventories held by transporters is -0.11 but it is not statistically significant. The negative relationship between smoothed probability and crude-by-rail is promising as a large spread between WTI and WCS is required to justify the high costs of transporting crude oil by rail. The OLS regression results are presented in Table 3.5. Using logged data allows the slope coefficients to be interpreted as elasticities. The results indicate crude oil inventories held by transporters has no effect on the probability of being in a given regime while crude-by-rail is statistically significant at the 5 percent level. The sign of the coefficient supports the notion that crude-by-rail shipments are more likely to occur during periods of constrained pipeline capacity than during periods of available capacity.

3.5 Conclusion

This article considers the impact constrained pipeline capacity may have on the WTI-WCS spread. Many participants in Canada's energy sector have been advocating for the expansion of Canada's pipeline transportation system because of the larger than normal spread that emerged between WTI and WCS from 2011 to 2015. The

WTI-WCS spread is modeled as a two regime Markov-switching model where one regime corresponds to normal times when there is sufficient transportation capacity and the other regime corresponds to times when there is insufficient transportation capacity. The results of this article are consistent with predictions in the spatial arbitrage literature. When there is sufficient transportation capacity the WTI-WCS spread reflects transport costs and quality differences, the spread is less volatile, and highly serially correlated. During periods of tight capacity the WTI-WCS spread exceeds transport costs and quality difference, the spread is more volatile, and serial correlation decreases as supply cannot be moved between regions to smooth supply and demand imbalances.

In this article we assume fixed transition probabilities when estimating equation (3.1). Ideally, transition probabilities would depend on a measure of pipeline capacity utilization. The preliminary correlation and OLS regression results, found in this article, suggest crude-by-rail may be an appropriate proxy for pipeline capacity utilization rates and warrants further investigation. Future research would incorporate crude-by-rail shipments into the transition probabilities.

3.6 Tables

Table 3.6: The estimated results of an AR(1) model

	AR(1)
ρ	0.925^{***} (0.019)
μ	1.258^{***} (0.345)
Log likelihood	-959.917
AIC	1923.834
BIC	1931.856

Note: The sample period is May 2, 2008 - February 26, 2016. Standard errors are reported in parentheses. *, **, *** indicates significance at the 90%, 95%, and 99% level, respectively.

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