GENERALIZED COST FUNCTIONS OF CRUDE OIL PIPELINE SHIPMENTS IN CANADA

Adam Morrison; Chris Bachmann; Frank Saccomanno

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Introduction

The cost-effective and safe shipping of crude oil is increasingly important as Canada seeks to increase its total oil production and export. The National Energy Board (NEB) suggests that most major pipelines are currently at over 80% utilization (National Energy Board, 2016), while the Canadian Association of Petroleum Producers (CAPP) forecasts a large increase in future production, partly from the Alberta oil sands (Canadian Association of Petroleum Producers, 2016). Meanwhile, recent North American crude oil pipeline projects, such as the Keystone XL pipeline and the Dakota Access pipeline are regularly subject to controversy in the media (e.g., BBC, 2017; The Globe and Mail, 2017; CTV, 2017). Limited pipeline capacities along major routes have already increased dependence on rail as the second-best alternative mode of shipping crude oil (Green and Jackson, 2015). Rail shipments of petroleum bulk crude are expected to increase significantly over the next 10-20 years, especially if globally crude oil prices experience a turnaround and bring new sources into production (e.g., heavier Alberta oil sands) and especially if new pipelines are not built to serve this expected demand.

Previous studies indicate a mode switch to rail may be problematic. For example, a review of US crude oil incidents from 2005 to 2009 indicates that rates for pipelines per ton-miles are overwhelmingly lower than rail, with only 0.58 pipeline incidents compared to 2.08 rail incidents, per billion ton-miles (Furchtgott-Roth & Green, 2013). The Fraser Institute presented similar conclusions for Canada, finding that between 2003 and 2013, there were 0.049 pipeline incidents compared to 0.226 rail incidents, per million barrel of oil equivalent (Mboe) (Green & Jackson, 2015). Risk is expressed as a function of both probability of hazardous incident as well as its consequences in terms of deleterious health and environmental impacts.

For rail incidents, the effects on the population and environment will depend on the density, nature and location of people in the vicinity of the release, and whether some form of sheltering or evacuation plan has been put into effect. And while pipeline incidents may be less frequent, the environmental consequences of such incidents could be substantial if a spill or leak were to occur and remain undetected for a period of time. Streams, lakes, rivers and groundwater could be contaminated, posing long term threats to human and animal populations. In this light, the relative risks between shipping crude oil need to be determined on a route-specific basis, to capture the conditions under which these shipments take place. Before a comprehensive Quantitative Risk Assessment (QRA) can be developed, accurate forecasts of crude oil shipments by mode and route are required, for different scenarios of potential infrastructure investments and operating characteristics. A more in-depth discussion of QRA principles can be found in Leeming & Saccomanno (1994) and Saccomanno & Cassidy (1993).

Although freight demand modelling is now a well-established field of research and practice, pipelines are scarcely included. For example, even recent textbooks on freight demand modelling make no mention of modelling pipeline transportation (e.g., L. A. Tavasszy & Jong, 2014). Not surprisingly, freight demand models focus on the most prevalent modes: truck and rail in urban, regional, and national models, and marine and air in international models. The focus of much research has been on pushing freight demand models beyond the basic four-step paradigm borrowed from travel demand models, for example by linking freight demand models to economic models (e.g., Kockelman, Jin, Zhao, & Ruíz-Juri, 2005), incorporating supply chain and logistics behaviours (e.g.,Tavasszy & Jong, 2013), and fully representing the diversity of actors in the freight system (e.g., Cavalcante & Roorda, 2013). As for pipelines, research has primarily occurred outside of transportation engineering, instead focusing on mechanical properties (e.g.,Herrán, de la Cruz, & de Andrés, 2010; Ribas, Yamamoto, Polli, Arruda, & Neves-Jr, 2013; and Abbasi & Garousi, 2010). Research on crude oil shipments in pipeline networks is particularly scarce. One paper focuses on the optimization of crude oil packaging in a Chinese pipeline network (Zuying, Yuan, Kelong, & Lisha, 2014), but complete freight demand models that include the pipeline mode are absent from the literature. To accurately model mode and route choice decisions for crude oil shipments, pipelines must be considered and this requires accurate estimates of the costs borne by shippers over each route.

The objective of this research is to develop cost functions for shipping crude oil by pipeline in Canada. These cost functions are a form of "link-performance functions" applied to pipeline route segments for a given mix of shipping conditions. This objective involves several important steps:

1. Researching the relevant explanatory variables that impact the cost of shipping crude oil by pipeline.
2. Collecting data on the relevant explanatory variables (identified in 1.); and
3. Obtaining empirical cost functions based on the Canadian data (collected in 2.)

Data Collection

The first source of data was the National Energy Board (NEB), who regulate pipelines, energy development and trade in the Canadian public interest. The NEB has publically available data on the tariffs/tolls charged by Canadian pipeline companies, including the fees charged to crude shippers, which consist of usage fees as well as surcharges (National Energy Board, 2017). In addition to these quantitative data, the NEB also provides information about the corresponding rules and regulations (e.g., what is an acceptable shipment and what capacity limitations may be in place aside from the physical system constraints). Other NEB reports describe the current state of the pipeline transportation system, upcoming projects for all major pipeline companies, and trends in tolls over time (National Energy Board, 2016; and National Energy Board, 2014). The trends in tolls compared to the pipeline utilization over multiple years gives insight into how utilization along with recent construction can affect the costs of shipments. For example, the steady increase in tolls since 2010 on the Enbridge mainline system directly correlates with the increase in capacity of the system. These coupled price and capacity increases are due to the construction costs associated with network expansion increasing the capital costs of the pipeline, and subsequently the tolls required for capital cost recovery.

The next source of data was Natural Resource Canada (NRCan), who develop policies and programs related to enhancing the natural resources sector of the Canadian economy. NRCan has Geographic Information System (GIS) data for both the Canadian rail and pipeline transportation networks. These data were used for determining distances between the Origin-Destination (OD) pairs given by the NEB toll and tariff documents. For some pipelines not covered in the NRCan GIS data, the Canadian Energy Pipeline Association (CEPA) liquids pipeline maps were used (CEPA, 2014; and CEPA, 2017).

Remaining data were gathered from pipeline company websites. These companies consisted of Enbridge Inc. (Enbridge Inc., 2017), Kinder Morgan (Kinder Morgan, 2015), Plains Midstream Canada (Plains Midstream Canada, 2017), Spectra Energy Corp. (Spectra Energy Corp., 2017), and TransCanada Corp. (TransCanada Corp., 2017). These data include pipeline specifications, such as age and diameter.

Data from all sources were collected manually, through the reading of the reports and documents, and summarized into an Excel database. Note that OD path distances were first estimated by the sum of all used pipeline links in ArcMap (ArcGIS, 2017) , where the NRCan GIS data was imported and refined along with the CEPA maps.

In summary, nine documents related to the tolling were used (Enbridge Pipelines Inc., 2011; Kinder Morgan Cochin LLC & Kinder Morgan Cochin ULC, 2015; Kinder Morgan Cochin ULC, 2015; Trans Mountain Pipeline ULC, 2013b; TransCanada Keystone Pipeline Limited, 2015b ; Express Pipeline Ltd., Express

Pipeline LLC, & Platte Pipe Line Company, LLC, 2015; Plains Midstream Canada ULC, 2013c; Plains Midstream Canada ULC, 2013d; and Plains Midstream Canada ULC, 2013b), and another six for the rules and regulations (Enbridge Pipelines Inc., 2011; Kinder Morgan Cochin LLC & Kinder Morgan Cochin ULC, 2015; TransCanada Keystone Pipeline Limited, 2015a; Express Pipeline Ltd., 2014; Plains Midstream Canada ULC, 2013a; and Trans Mountain Pipeline ULC, 2013a). Distances required two maps and the GIS data set of approximately 900 segments. As some companies own multiple pipelines, only 6 companies were uniquely identified for data collection. In total, the resulting database includes 323 observations of pipeline shipping costs and corresponding explanatory variables to complete the regression models estimated in the next section.

Regression Analysis

Regression models are used to estimate the cost of crude oil shipments in Canada as a function of selected pipeline characteristics, crude oil type, and destination contractual factors. This research implements linear regression models since they are commonly used for rail freight cost functions.

Regression models are most often evaluated in terms of their ability to replicate observed outcomes. In particular, R^2 values indicate the proportion of variance in the dependent variable that is explained by the independent variables (i.e., the ratio of explained variance to total variance). The statistical significance of individual parameters is assessed using a t-statistic (or p-values less than 0.05 or 5% level of significance). The two-tailed t-statistics suggests that only parameters that are significant are used in the resultant performance function, such that other factors would have negligible effects on pipeline costs. The parameters also should reflect expected positive or negative relationships based on intuitive logic (makes sense test).

Before hypothesizing explanatory variables, it is necessary to develop an understanding of how costs are actually determined in the real-world. A general equation takes the form:

$$Toll = Base\ Rate + (\beta \times Distance) + Surcharges \qquad \textbf{(1)}$$

where

$$Base\ Rate = \frac{Capital\ Cost + Opera \qquad and\ Maintenance}{Throughput} \qquad \textbf{(2)}$$

and β is a parameter applied to the distance. All companies will determine the costs associated with the ownership and usage of the pipeline, referred to as the "Capital Costs" (CC) and "Operation and Maintenance" (OM), respectively. The CC is associated with the depreciation, interest expense, return on equity and forecasted tax allowance. The OM is associated with wages, construction and property taxes. To create a market in which all shippers are fairly charged, the total shipment amount, "Throughput", then divides the total cost to create the "Base rate".

Since pipelines are owned by different companies, there is a large variability of other costs that they may include in their tolls, referred to as surcharges. The most prevalent charge attributed to the tolls is the abandonment surcharge: to account for the possibility of a pipeline being shut down, and the numerous costs associated with its decommissioning, all shippers are required to pay a small additional fee. Companies are expected to determine a fair abandonment surcharge, to be approved by the NEB, and added to all shipments (on a per cubic meter basis).

Canadian pipeline shipping features

For companies that ship internationally (predominantly to the US) there is an additional payment captured by International Joint Tolls (IJT). Canadian Local Tariffs (CLT) are the tolling rates applied only to Canadian receipt and terminal locations, while IJTs are the tolls applied to crude shipments from Canada to the US.

Additionally, some companies may have special cost structures, such as the Enbridge tankage fees and Kinder Morgan Firm Service Fee (FSF). Enbridge is unique in that they own their own tanks for oil storage, allowing them to charge additional fees for storing crude oil. These fees are applied separately from the shipment tolls and are only applicable in the case that the shipper is using the tank farms associated with Enbridge. The Kinder Morgan FSF stems from the Westridge Docks that are connected to this pipeline. Kinder Morgan decided that due to the large amount of shipments that are being sent to this dock, a specific amount of capacity would be allocated to these shipments. If a shipper was to occupy some of this capacity, then an additional fee, dependent on the percentage of the separate capacity, is set on top of the existing net toll. Due to this allocated capacity, an additional complication was added to the tolling process, known as toll bidding. The companies who are to acquire a portion of this capacity must bid on the volume and toll rate they are to pay. However, the final decision on the allocation comes down to the ranking of the companies, based on the bid premium (i.e., $bid\ toll \times bid\ volume$), with the highest bidding companies receiving the capacity.

Finally, not all crude shippers have contracts for their shipments, which differentiates the tolls into committed and uncommitted rates. Committed toll rates refer to the rates applied to contracted shippers, which are typically determined through negotiated toll settlements. Committed toll rates are the primary focus of this study, as there is a large variance in how uncommitted shipment tolls are determined (due to the pipeline owners giving varying incentives to contracted shippers).

With the above understanding developed from the toll applications and regulatory documents described previously, a set of explanatory variables was hypothesized. First, and perhaps most important, is distance. When comparing distance to tolls by crude oil type (Condensate, Light, Medium, Heavy) and destination (CLT, IJT), distance explains a high proportion of the variance in tolls. If companies are examined individually, distance (along with a base rate) accounts for over 90% of the variance in tolls. These early analyses suggested that notwithstanding differences between crude types, destinations, and companies, distance is a key factor in determining the cost of crude oil shipments (with a positive parameter value).

Since data on individual pipeline throughputs was not available, pipe diameter was used as a surrogate. The underlying assumption is that larger pipelines have larger capacities and therefore larger throughputs. Based on the general equation presented previously (1), it is hypothesized that larger diameter pipelines would decrease the toll cost, all else being equal (since the larger throughput splits the total cost among more shippers). In the future, inclusion of throughputs would be preferred, since the toll could then vary as function of usage in the associated transport network model.

Initially, it was thought that the age of a pipeline might be correlated to the capital costs, reflecting the significance of capital recovery costs for carriers in setting their tolls on individual lines. Since capital costs are based on depreciation, and depreciation occurs over time, the age of the pipeline was hypothesized to impact the associated tolls. However, it was found that the age of the pipeline was not meaningful to the capital costs, since there are constant expansions and additional costs to the pipeline which are not reflected in its age. For example, the likelihood of an expansion to a pipeline may increase with age. For this reason, although the ages of pipelines were collected, they are not used as explanatory variables in this study.

Disaggregate Cost Functions

The initial cost functions are expressed in disaggregate form per shipper, resulting in eight separate functions. These functions represent different crude oil types (Condensate, Light, Medium, Heavy), and destination-based tolling agreements (CLT, IJT). The estimated functions are linear in form, such that:

$$y = \beta_0 + \beta_1 d + \beta_2 \phi \qquad \textbf{(3)}$$

where,

y is the toll value for a specific OD pair ($CND/m^3)

d is the OD distance (km)

ϕ is the maximum pipeline diameter for an OD pair (inches)

The results of the estimated cost functions described by **(3)** are summarized in Table 1 below:

Table 1: Summary of Coefficients for Equation (3)

Crude Oil Type	Toll Type	t_0	β_0	t_1	β_1	t_2	β_2	$t_{2.5\%}$	R^2	Data Quantity
Condensate	CLT	1.12*	0.51	41.51	0.008	1.71	0.03	2.12	0.99	20
	IJT	5.02	29.52	1.64*	0.003	-3.52	-0.54	2.23	0.58	13
Light	CLT	2.83	4.28	9.97	0.005	-0.34*	-0.02	2.01	0.66	56
	IJT	4.69	11.28	9.63	0.005	-2.36	-0.15	2.00	0.66	61
Medium	CLT	-1.38*	-1.14	24.89	0.010	3.05	0.07	2.05	0.96	31
	IJT	4.46	13.58	6.74	0.005	-2.21	-0.15	2.03	0.63	39
Heavy	CLT	5.23	10.19	7.56	0.005	-2.55	-0.14	2.02	0.64	42
	IJT	5.90	15.67	8.52	0.005	-3.62	-0.19	2.00	0.72	61

** indicates parameter estimate is not significant*

The intercept coefficient, β_0, should take positive values as the intercept should be representative of the average base rate plus the average of all surcharges applicable to crude oil shipments via pipeline for the given crude and toll type. However, the value should remain relatively small as the observed data set has small base rates for distances that are close to zero.

The regression results indicate that there is high variation in coefficients among crude types. The tolling types coefficients were found to be consistently lower for the CLT in comparison to the IJT. From the above analysis, there are two discrepancies in the expected value from the Medium CLT and Condensate IJT, in which the first is a negative value and the second is quite large. Also, the Condensate CLT intercept is not significant (t-statistic).

The distance coefficients were found to be as expected (i.e. positive) and significant, but for Condensate IJT the coefficient was found to be not statistically significant. The coefficients for this variable are very consistent throughout the eight models, demonstrating very little sensitivity to both crude and toll type.

The diameter coefficients usually have their expected sign (negative), except for the Medium and Condensate CLT values (positive). Also, note the Light CLT coefficient is not statistically significant. The diameter coefficients have some similar values, but are mostly inconsistent.

The R^2 values averaged about 73%, indicating that these functions explain just over 70% of the variance in observed toll values. The Condensate IJT model has the lowest goodness-of-fit, however, primarily due to a lack of observations.

Since there are some not statistically significant and unexpected parameter estimates within this set of models, additional forms are considered, which combine the models through interval (or “dummy”) variables, thereby increasing the number of observations used for each regression analysis.

Toll Type Combined Cost Functions

In this model, a dummy variable is introduced to combine the two tolling types, as shown below:

$$y = \beta_0 + \beta_1 d + \beta_2 \phi + \beta_3 D_T \quad \textbf{(4)}$$

where,

$D_T =$ Binary value for the toll type ($D_T = 0$ for a CLT and $D_T = 1$ for an IJT).

The results of the estimated cost functions described by **(4)** are summarized in Table 2 below:

Table 2: Summary of Coefficients for (4)

Crude Oil Type	t_0	β_0	t_1	β_1	t_2	β_2	t_3	β_3	$t_{2.5\%}$	R^2	Data Quantity
Condensate	4.23	11.56	4.15	0.005	-3.35	-0.31	2.84	7.53	2.045	0.864	34
Light	4.76	6.02	14.26	0.005	-2.14	-0.09	4.82	3.58	1.986	0.848	117
Medium	3.54	5.78	10.68	0.006	-1.46*	-0.07	2.08	2.55	2.014	0.848	70
Heavy	7.42	10.83	11.62	0.005	-4.79	-0.18	6.21	5.37	1.991	0.851	103

** indicates parameter estimate is not significant*

In these models, it is seen that these equations all have adequate and statistically significant coefficients and intercepts. There is an apparent improvement of the values of the intercepts. There appears to be some effect on cost for crude oil type. This is reasonable since typically the highest shipping products are medium and light crude, resulting in lower intercepts, than heavy crude with the highest associated costs and coefficient values.

The distance coefficients are adequate and significant. There, again, is no significant sensitivity across the crude oil types as there is alteration to the cost of shipment per distance based on a crude oil type. Most values are consistent with the previous regression models, with improvement in the uniformity of the coefficient values.

The diameter coefficients are all adequate, with only the Medium coefficient being not significant. This now presents a significant sensitivity to the crude oil type, as the medium and light values are quite low in magnitude compared to the other values. However, this makes sense given that the two largest throughputs are typically light and medium crude oil (i.e., with there being an expected higher utilization of the light and medium pipelines, the intercept will require a lower reduction in magnitude to accurately depict the base rate of the considered pipeline). This is a large improvement from the previous function as the coefficient values are now what was anticipated for this variable in terms of sign and magnitude.

The coefficient for the toll type dummy variable, β_3, should be positive and moderately small. This is because there is a small additional charge applied to the tolls as an international shipping tariff. From the above summary table, combining the previous models was appropriate since the coefficients for this dummy variable are all significant and are compatible with the assumption made. Across the crude oil types there is no discernible pattern or sensitivity to type, just a slight variance in the magnitudes.

The R^2 values have improved substantially since the previous function set, with an average value of 0.852. Overall, this is a better set of models, since they reduced the number of equations by half, as well as increased the accuracy of the models consistently. However, the equation set can still be further reduced in complexity while possibly retaining the degree of accuracy found with this set.

Fully Combined Cost Function

An additional regression was performed with a combination of the entire data set, using a linear function of the form:

$$y = \beta_0 + \beta_1 d + \beta_2 \phi + \beta_3 D_T + \beta_4 D_L + \beta_5 D_M + \beta_6 D_H \qquad \textbf{(5)}$$

Where,

D_L = Binary value for light crude, where $D_L = 1$ if the type is light crude, $D_L = 0$ for all others

D_M = Binary value for medium crude, where $D_M = 1$ if the type is medium crude, $D_M = 0$ for all others

D_H = Binary value for heavy crude, where $D_H = 1$ if the type is heavy crude, $D_H = 0$ for all others

The results of the estimated cost functions described by **(5)** are summarized in Table 3 below:

Table 3: Summary of Coefficients for (5)

t_0	β_0	t_1	β_1	t_2	β_2	t_3	β_3	t_4	β_4	t_5	β_5	t_6	β_6	$t_{2.5\%}$	R^2	Data Quantity
7.93	7.19	21.35	0.005	-6.12	-0.14	8.19	4.27	-0.59*	-0.38	2.01	1.40	4.05	2.69	1.967	0.85	323

** indicates parameter estimate is not significant*

From the above table, it is seen that this model has an adequate and significant coefficient for the intercept. It is relatively high in comparison to the previous values, but is still acceptably small to be representative of the tolls. Also, there is a larger magnitude given to the reduction based on the diameter which will decrease the base rate overall.

The distance coefficient is also adequate and significant, maintaining the same value as previously observed in all other formations of the general cost functions.

The diameter coefficient is statistically significant, with approximately an average of the previous coefficients, imparting a respectable influence to the effects of diameter of the pipeline to tolls costs.

The toll type coefficient has remained an adequate value, taking an expected average across all types for the increase of international shipping.

The coefficient for the crude type dummy variables, β_4 to β_6, should be positive and moderately small. This dummy variable was based on the changing viscosity of crude oil types, using condensate as the base value since it is the least viscous crude oil. These values should then be small and positive, increasing as you go from light to heavy, to compensate for the equivalent volume based on the compared viscosity. From the summary table, it is seen that the medium and heavy crude types have proper coefficients while the light crude type has an unintuitive coefficient. This is not an issue as the light crude coefficient is also not statistically significant in the model, and can therefore be removed.

The R^2 value has remained the same as the previous equations average value, indicating that this function is equivalent to the previous set of functions. While there were numerous equations developed, many of which with high R^2 values, the final cost function suggested in this study is a slight variation on the Fully Combined Cost Function (5). The alteration made to this function was the removal of the light crude dummy variable, since it is not statistically significant (R^2 remains at 0.85). The final equation then takes the form:

$$y = 6.92 + 0.005d - 0.142\phi + 4.26D_T + 1.70D_M + 3.00D_H \qquad \textbf{(6)}$$

Equation 6 is chosen because it has an equivalent goodness-of-fit as the Toll Combined Functions, while also reducing the number of equations by four. Although the Disaggregated Cost Functions do have some higher R^2 values, they are not consistently higher across all models. Most importantly, the resulting model can predict the tolls of all crude and toll types by itself, not requiring eight separate functions.

Conclusion

Interest in crude oil shipping is growing, as economic and environmental interests compete and conflict. The need for scientific and evidence-based decision making is evident, yet guidance that can be discerned from existing data and models is lacking. Unlike more commonly studied modes such as truck and rail, modelling techniques are not available to forecast future crude oil pipeline flows or to ask "what if" questions about modal attributes (e.g., changes in pipeline infrastructure) or shipment conditions (e.g., forecasted growth in crude oil shipments). Before a sound QRA can be undertaken, the domain of existing freight demand models must be expanded to model the unique complexities facing crude oil shippers on the pipeline transportation network. The research discussed in this paper takes an initial step in this direction.

This research developed empirical cost functions for shipping crude oil by pipeline in Canada. Results indicate that the distance shipped along each pipeline segment is statistically significant in establishing the shipper toll, as is the pipeline's diameter. Separate models estimated by toll type revealed that the effect of distance and diameter are relatively constant across toll types (i.e., same distance and diameter parameter signs across toll types), allowing for the effect of toll type to be captured by a statistically significant interval ("dummy") variable. Similarly, the effect of crude type was captured by interval variables in a combined cost function. The combined cost function has an R^2 value of 0.85, indicating good model fit. The resulting cost function can be used to model the cost of shipping crude oil of a certain type (condensate, light, medium, heavy) in a given diameter pipeline for a distance to a Canadian (CLT) or US (IJT) location.

Future work is needed to develop a complete crude oil shipment model. First, Origin-Destination (OD) flows are required at a zonal level that is consistent with the pipeline network. Current data collection efforts reveal there is a lack of public data available, and those data which are available are often supressed at a disaggregate level (e.g., Statistics Canada CANSIM data). Second, a new mode split and route assignment method is needed to represent the unique circumstances of crude oil shipping. Mode split models used for choosing between common freight modes (e.g., truck and rail), such as Random Utility-based Maximization (RUM) models, do not capture the complex interactions of crude shippers, pipeline carriers, and regulatory bodies, who all interact through contracts and regulations to determine the final mode and route assignments of crude oil shipments. Finally, only once a crude oil shipment model is developed, can a QRA for different infrastructure alternatives or operating characteristics be implemented.

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