Contents

1. Introduction

This report documents the CO_2 pipeline transportation cost models developed by MIT Carbon Capture and Sequestration Program for the Carbon Management Geographical Information System (GIS) project under the contract DE-FC26-02NT41622.

Figure 1 Pipeline Transport Overview Diagram

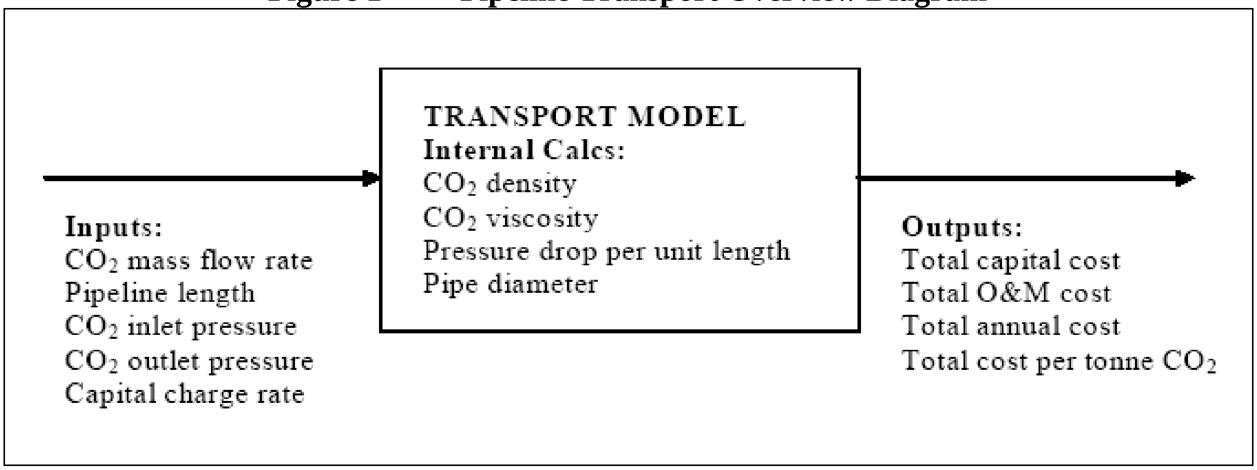

Figure 1 gives an overview of the transportation cost model. The model can be broken down into three steps, documented in the following sections of this report.

- Section 2 presents the methodology to calculate the pipeline diameter as a function of maximum CO_2 flow rate in design capacity.
- Section 3 lists the obstacle layers considered in the CO_2 transport cost model and the relative weights assigned to each obstacle.
- Section 4 describes the method of identifying least-cost pipeline route between sources and sinks based on the obstacle layers listed in section3.
- Section 5 presents two cost calculation models: MIT correlation and CMU correlation. In these two models, the pipeline capital cost is calculated as functions of diameter, length, and pipeline length with different function forms. The comparison of these two methods is also discussed in this section.

2. Pipeline Diameter Calculation

The pipeline design capacity is one of the first design criteria needed for CO_2 transport cost estimation. Pipeline capacity is a factor of both pipeline diameter and operating pressure, and pipelines need to be appropriately sized for the CO_2 transport requirements of their corresponding CO_2 emissions sources. Therefore, the CO2 transport package calculates the pipeline diameter as a function of pressure drop allowance per unit length, friction, CO_2 density and CO_2 mass flow rate.

Equation (1) gives the relationship among pipeline diameter (D), maximum allowable pressure drop ($\Delta P/\Delta L$), CO_2 mass flow rate ($\dot{m}$), CO_2 density (ρ), and the Fanning friction pressure (f) can be characterized by the following formula (Heddle *et.al.*, 2003):

$$\frac{\Delta P}{\Delta L} = \frac{32 f \dot{m}^2}{\pi^2 \rho D^5} \qquad (1)$$

In equation (1), the default maximum allowable pressure drop per unit length ($\Delta P/\Delta L$) is set to be 49Pa/m. The default CO_2 density (ρ) is assumed to be 884 kg/m^3[i]. calculated from MIT CO_2 property calculator, The Fanning friction pressure is found by using the relationship based on the Moody chart (see Heddle *et.al.*, 2003).

Figure2.1 plots the relationship between the maximum mass flow rate and the pipeline diameter. A power function closely models this relationship. In this study it is assumed that standard type gas industry pipelines will be used for CO_2 transportation. Based on the power function in Figure 2.1, Table 1 gives the breakdown of the CO_2 flow rate for each pipeline standard diameter within the range from 4 to 36 inches. For any given maximum CO_2 flow rate, Table 1 provides a look-up table to determine the appropriate pipeline diameter. The package also allows users to define the maximum allowable pressure drop.

The calculation is found to be consistent with most literatures on pipeline diameter design (Vandeginste and Piessens, 2008). At this stage we did not consider elevation difference and pumping station.

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[i] According to the MIT CO2 property calculator, the CO2 density of 884 kg/m^3 corresponds to the status of a temperature of 25 ºC and a pressure of 158 bar.

Figure 2.1 Maximum Mass CO_2 Flow Rate as a Function of Pipeline Diameter

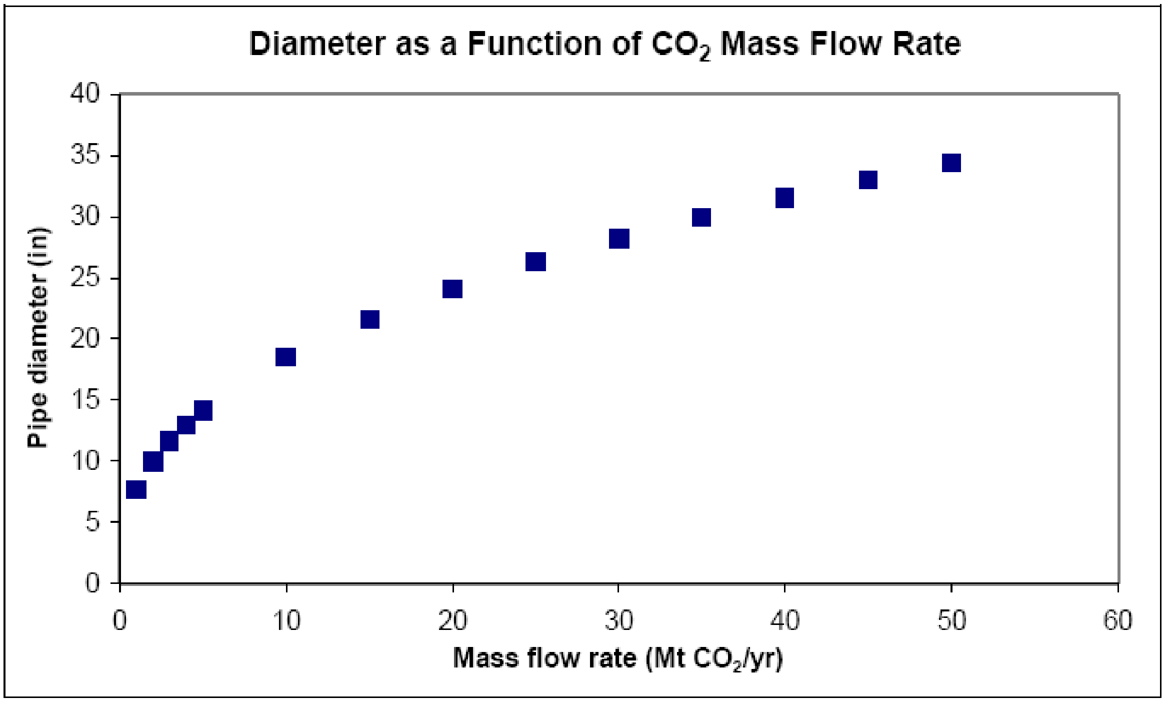


Table 1 Pipeline Diameter and the CO_2 Flow Rate Range

Pipeline Diameter (inch)	CO_2 Flow Rate (Mt/yr)	
	lower bound	upper bound
4		0.19
6	0.19	0.54
8	0.54	1.13
12	1.13	3.25
16	3.25	6.86
20	6.86	12.26
24	12.26	19.69
30	19.69	35.16
36	35.16	56.46

3. Obstacle Layer Construction

In addition to the diameter and capacity, the terrain being traversed by a pipeline is another significant pipeline construction cost variable. These costs vary considerably according to the local terrain and are also affected by the presence of buildings or infrastructure. Pipeline construction is more expensive in hilly areas than on flat plains. In order to reduce complications and costs, a pipeline's route should avoid passing through populated places[ii], wetlands, and national or state parks. In order to account for such obstacles in the study, the locations and characteristics of these obstacles were loaded into Geographic Information System (GIS) software. Using the GIS software the costs for traversing such obstacles during pipeline construction were combined into a single obstacle data layer. This obstacle layer reflected three types of general obstacles: land slope, protected areas, and crossings and three line type obstacles: waterways, railroads, and highways.

In order to use this land obstacle data to help calculate optimal pipeline routes, the continuous obstacle data layer was rasterized into 1km by 1km cells. If there were no transportation obstacles contained within a given 1 km^2 cell, then the construction costs of a pipeline traversing the cell was assumed to be "1". From this base case construction cost, relative weights were then assigned to each obstacle in Table 3.1 according to the difficulty of traversing the obstacle. These relative weights were then added to the base case construction cost to form a combined pipeline construction cost factor.

The total pipeline construction cost factor for a cell is then the sum of the base case cost factor and the cost factors of all of the obstacles that exist in that cell. For example, the relative cost of a 8 inch pipeline crossing a river in the national park would be 41: 1 (base case) + 30 (national park) + 10 (river crossing). Using the weighted cost layer calculated above, the spatial analysis function in ArcGIS was used to determine the least cost pipeline path for connecting each source and sink.

[ii] The populated places data is from US Land Use and Land Cover (LULC) data set, which adopts the census definition of "populated place areas" that include census designated places, consolidated cities, and incorporated places within United States identified by the U.S. Bureau of the Census.

Table 3.1 Estimated Relative Construction Cost Factor

Construction Condition		**Cost Factor**
Base Case		1
Slope		
	10-20%	0.1
	20-30%	0.4
	>30%	0.8
Protected Area		
	Populated Area	15
	Wetland	15
	National Park	30
	State Park	15
Crossing		
	Wateway Crossing	10
	Railroad Crossing	3
	Highway Crossing	3

Note: The relative weights are calculated as the ratios of the additional construction costs to cross those obstacles and the base case construction cost for an 8 inch pipeline.

4. Least-cost Pipeline Route Selection and Length Calculation

The total pipeline construction cost factor for a cell is the sum of the base case cost factor and the cost factors of all of the obstacles that exist in the cell. The CO_2 transport package assumes that the ***absolute*** additional obstacle costs are independent of pipeline diameter. So the ***relative*** cost factors have a reverse relationship with pipeline diameter. Using the weighted cost layer calculated above, the CO_2 transport package calls the spatial analysis function in ArcGIS determine the least-cost pipeline route for connecting source and sink. Figure 4.1 shows the procedures to identify the least-cost CO_2 pipeline transport route in ArcGIS. The least-cost route length and the pipeline diameter will be used in the CO_2 transport economic model to determine the pipeline construction and O&M costs.

Figure 4.1 Procedures to Identify the Least-cost Route

1. Pipeline diameter is calculated based on CO_2 flow rate;
2. Obstacle layers' relative cost factors are adjusted according to pipeline diameters;
3. All obstacle layers are aggregated to get a total cost raster layer;
4. Direction (back link) raster layer is calculated;
5. Least-cost path is identified by using *CostPath* function in ArcObject;
6. Least-cost route length is fed back to the total cost model to get the total cost.

5 CO_2 Pipeline Transport Cost Calculation Methods

The amount of cost data on CO_2 pipelines in the open literature is very limited. But there is an abundance of cost data for natural gas pipelines. For this reason, land construction cost data for natural gas pipelines were used to estimate the construction costs for CO_2 pipelines. This should be adequate for the screening study as there is little difference between land construction costs for these two types of pipelines. It is worthy noting, however, that CO_2 pipelines might be slightly more expensive because of the greater wall thickness needed to contain CO_2, which is transported at higher pressures.

The CO_2 transport package divides the pipeline transport cost into two components: the land construction cost and the O&M cost. Equation (2) gives the formula to annualize the land construction cost over the operating life of the pipeline:

$$\text{Annualized Cost} = \text{Land Construction Cost} * \text{Capital Charge Factor} + \text{O\&M Cost} \tag{2}$$

The package uses a default capital charge of 0.15 and assumes the pipeline O&M cost to be \$5,000/mile per year, independent of pipeline diameter (Heddle, *et.al.*, 2003). The package adopts two correlations to estimate the land construction costs for CO_2 pipelines: the MIT correlation and the CMU correlation, which are discussed in details below.

5.1 MIT Correlation

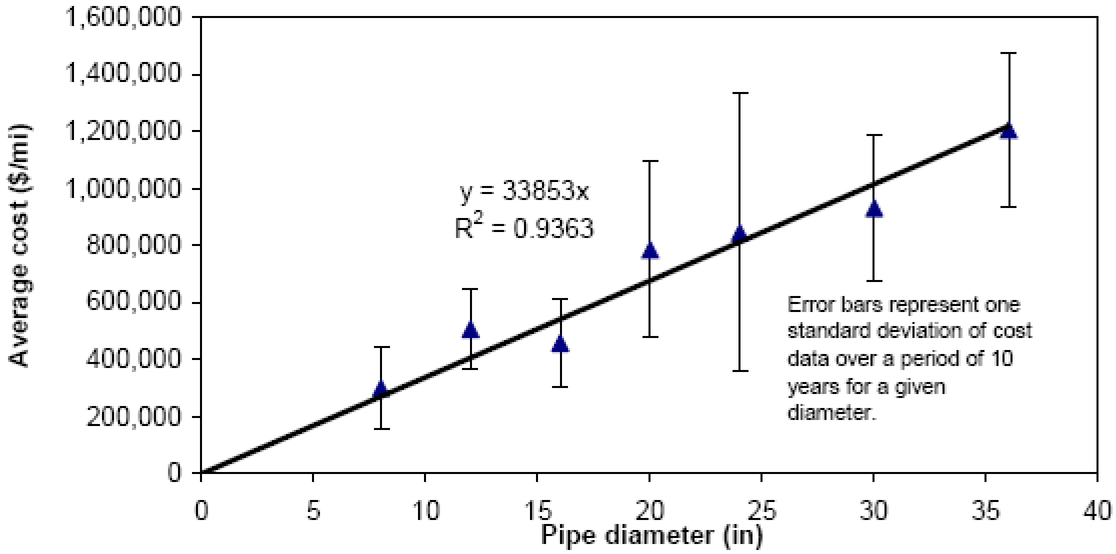
The MIT correlation was developed by the Carbon Capture and Sequestration Technologies Program (CCSTP) at the Massachusetts Institute of Technology. It assumes that the CO_2 pipeline land construction cost has a linear correlation with pipeline diameter and length. Using data for natural gas pipelines consists of cost estimates filed with the United States' Federal Energy Regulatory Commission (FERC) and reported in the Oil and Gas Journal between 1989 and 1998, Heddle *et.al.* (2003) estimate the CO_2 pipeline construction cost to be \$33,900/in/mile. Figure 5.1 shows the regression analysis of pipeline land construction cost data. Equation (3) provides the formula for the MIT correlation used in the transport package:

$$LCC = \alpha * D * L \tag{3}$$

where α = \$33,853;
D: pipeline diameter in inches (function of CO_2 flow rate);
L: least-cost pipeline route length in miles;

In addition, the package also allows users to replace parameter α with their self-defined values.

Figure 5.1 Regression Analysis of Pipeline Land Construction Cost Data



Due to increased costs and inflation, the land construction costs of pipeline construction have increased since the original LCC was calculated (based on data between 1989 and 1998). New data from the Oil and Gas Journal shows the costs of pipeline construction up to 2007. These new values were used in order to obtain a more accurate, up to date number. The equation is the same; it is just calculated by an Index.

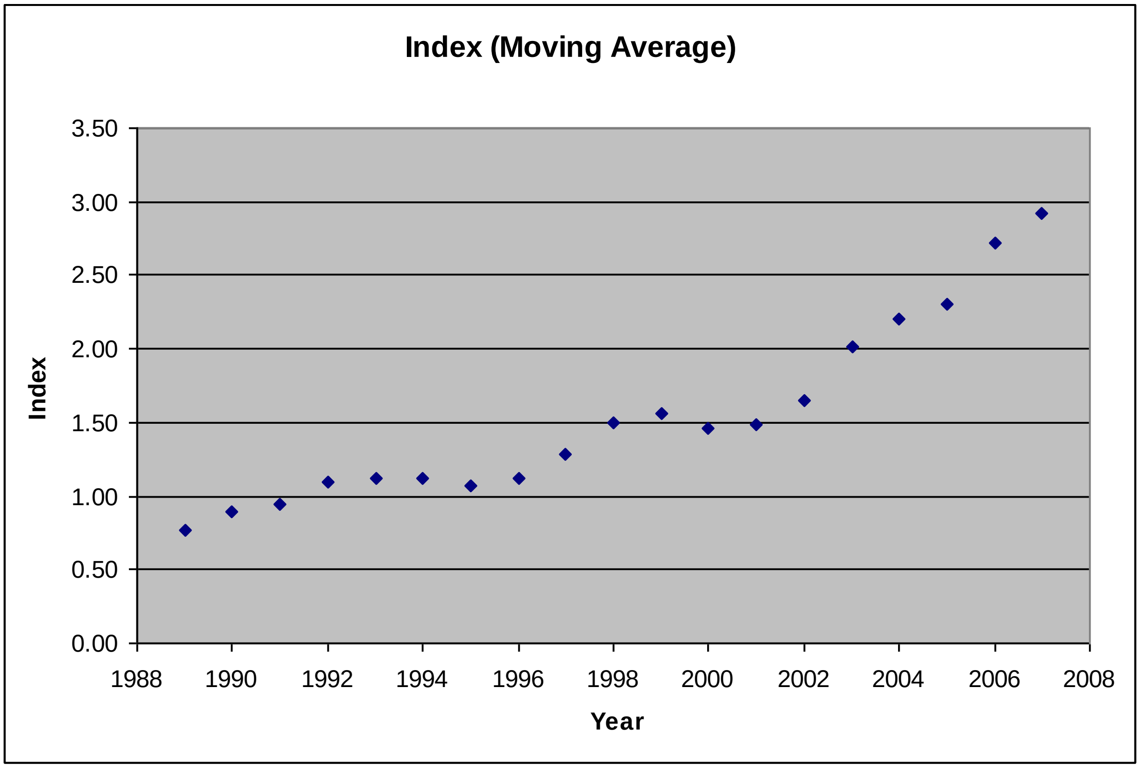
$$LCC= \alpha * D * L * Index_t \quad (4)$$

The new Index for year 2007 equals to 2.92. See Table 5.1 and Figure 5.2. This value is an optional addition when calculating the LCC for post 2007.

Table 5.1 Price Index for MIT Correlation

Year	Index	Running Average
1989	0.83	0.83
1990	0.71	0.90
1991	1.15	0.95
1992	0.98	1.10
1993	1.17	1.12
1994	1.20	1.12
1995	1.00	1.07
1996	1.02	1.12
1997	1.34	1.28
1998	1.48	1.51
1999	1.69	1.56
2000	1.51	1.47
2001	1.20	1.48
2002	1.74	1.65
2003	2.00	2.01
2004	2.30	2.20
2005	2.31	2.30
2006	2.30	2.71
2007	3.53	2.92

Figure 5.2 Price Index (Running Average) for MIT Correlation



5.2 CMU Correlation

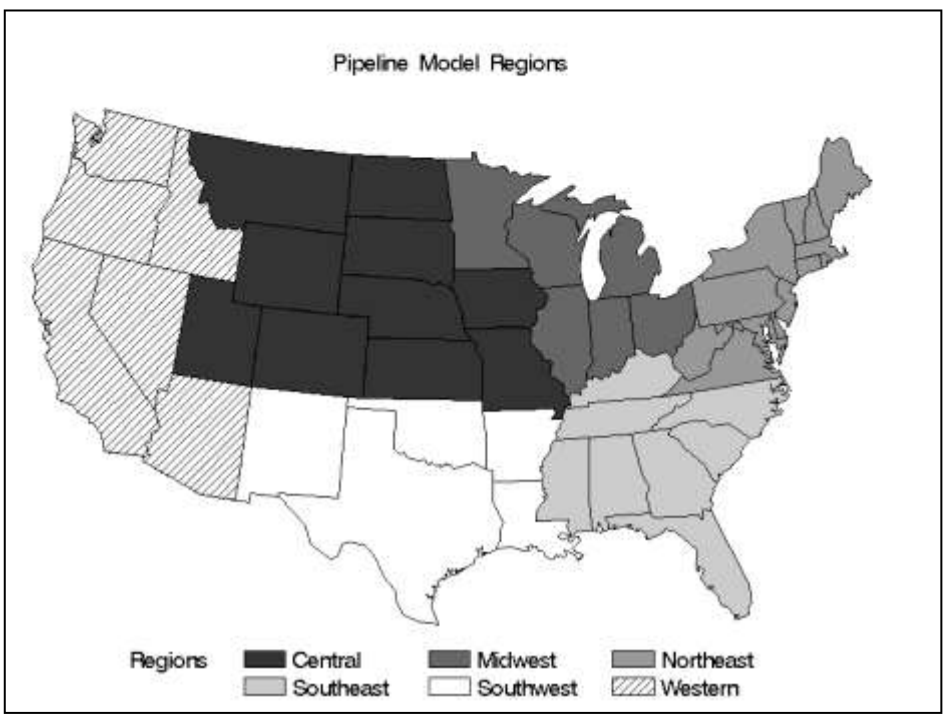
A recent study by Sean McCoy (2006) at the Carnegie Mellon University reexamines the CO_2 pipeline land construction cost using an updated data set—natural gas pipeline project costs published in the Oil and Gas Journal between 1994 and 2003. The CMU correlation looses the linearity restriction in the MIT correlation and allows a double-log (nonlinear) relationship between pipeline land construction cost and pipeline diameter and length. In addition, the CMU correlation takes into account regional differences in CO_2 pipeline land construction costs by using regional dummy variables (see Figure 5.3 for region definitions). Equation (5) provides the formula for the CMU correlation used the transport package:

$$LCC = \beta * D^x * L^y * z \quad (5)$$

where β = \$42,404;
x = 1.035
y = 0.853
z: regional weights

Region	Central	Southwest	West	Midwest	Southeast	Northeast
z values	1.000	1.248	1.341	1.516	1.687	1.783

Figure 5.3 CMU CO2 Pipeline Model Regions



Due to increased costs and inflation, the land construction costs of pipeline construction have increased since the original LCC was calculated (based on data between 1994 and 2003). New data from the Oil and Gas Journal shows the costs of pipeline construction up to 2007.
These new values were used in order to obtain a more accurate, up to date number. The equation is the same; it is just calculated by an Index.

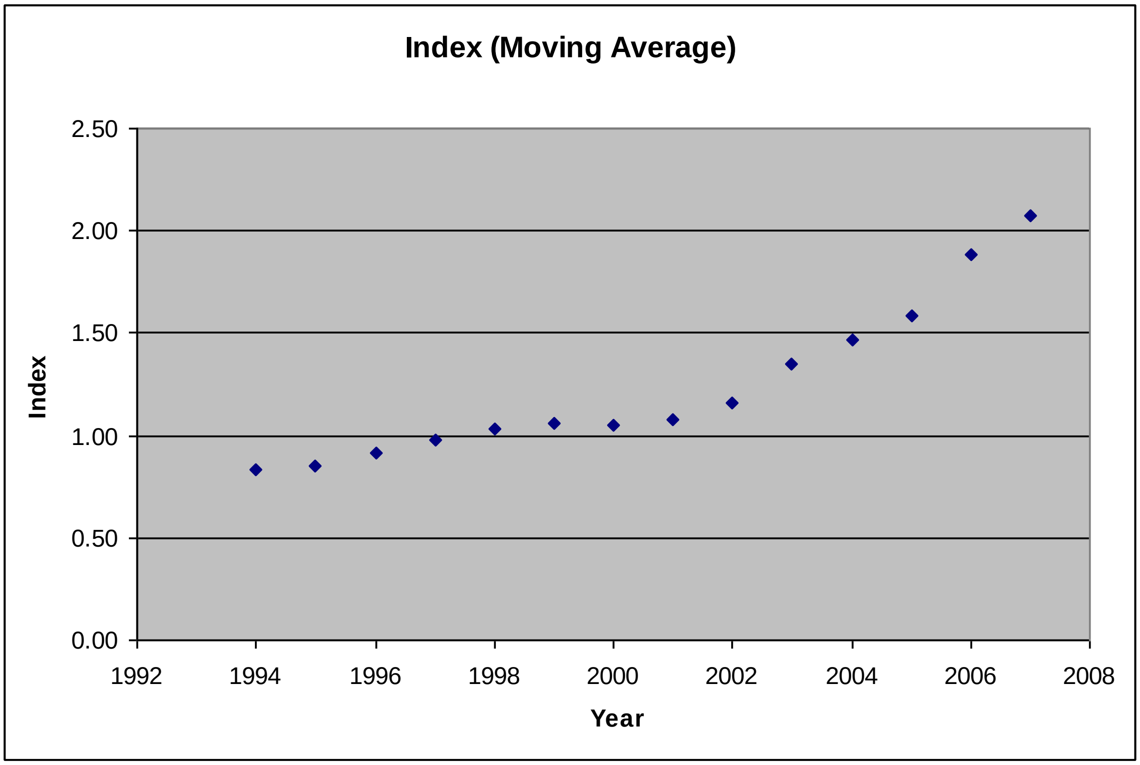
$$LCC = \beta * D^x * L^y * z * Index_t \qquad (6)$$

The new Index for year 2006 equals to 2.07. See Table 5.2 and Figure 5.4. This value is an optional addition when calculating the LCC for post 2007.

Table 5.2 Price Index for CMU Correlation

Year	$Index_t$	Running Average
1994	0.83	0.83
1995	0.82	0.85
1996	0.90	0.92
1997	1.02	0.97
1998	1.00	1.04
1999	1.08	1.06
2000	1.09	1.05
2001	0.99	1.08
2002	1.17	1.16
2003	1.33	1.35
2004	1.56	1.47
2005	1.52	1.59
2006	1.68	1.89
2007	2.46	2.07

Figure 5.4 Price Index (Running Average) for CMU Correlation



5.3 MIT-CMU Comparison

In the CMU correlation, a coefficient estimate of 1.035 for pipeline diameter indicates that the linearity assumption between land construction cost and diameter may be acceptable. However, the coefficient estimate for pipeline length is much less than 1, suggesting that there exist significant economies of scales for pipeline construction. The CMU correlation also indicates substantial regional differences in land construction cost. On average, the pipeline land construction cost in Northeast is 78 percent higher than in Central.

Table 3 compares the MIT and CMU prediction results. The CMU predictions of per inch-mile pipeline land construction cost are insensitive to the pipeline diameter but are very sensitive to pipeline length. Given that the pipeline lengths studied in the original MIT correlation range between 100km and 300km, the CMU predictions for pipeline length of 100 mile are more relevant for comparison purposes. It is easy to see that the MIT prediction ranks at the median of the CMU predictions of the 100 mile pipeline case for different regions, indicating that the two prediction results are indeed very similar.

Table 5.3 MIT-CMU Comparison

MIT Correlation Prediction ($/in/mile): $33,853

CMU Correlation Predictions ($/in/mile):

	Central		Southwest		West	
	100 mile	1,000 mile	100 mile	1,000 mile	100 mile	1,000 mile
8 inch	$23,210	$16,560	$28,962	$20,664	$31,117	$22,202
16 inch	$23,777	$16,965	$29,671	$21,170	$31,879	$22,745
24 inch	$24,116	$17,207	$30,093	$21,471	$32,332	$23,069

	Midwest		Southeast		Northeast	
	100 mile	1,000 mile	100 mile	1,000 mile	100 mile	1,000 mile
8 inch	$35,194	$25,111	$39,151	$27,934	$41,376	$29,522
16 inch	$36,055	$25,725	$40,108	$28,617	$42,388	$30,244
24 inch	$36,568	$26,091	$40,679	$29,024	$42,992	$30,674

References

Heddle, Gemma, Howard Herzog & Michael Klett. 2003. *The Economics of CO2 Storage.* MIT LFEE 2003-003 RP.

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Vandeginste V. and K. Piessens. 2008. Pipeline design for a least-cost router application for CO2 transport in the CO2 sequestration cycle. *International Journal of Greenhouse Gas Control*, doi:10.1016/j.ijggc.2008.02.001