Cost-Minimizing Route Choice for Marine Transportation:

Expected Vessel Traffic through the Northwest Passage 2050 to 2100

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for

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INTRODUCTION

"By mid-century (September 2041–2060), most of the alternative routes in the Northwest Passage and Northern Sea Route are projected to be nearly ice-free...By the end of the 21st century, vast areas of the Arctic Ocean are projected to be ice-free in summer, increasing the possibility of shipping across the Arctic Ocean" (ACIA, 2005, p.923). Indeed, Somanathan, Flynn and Szymanski (2007) have shown that, even now, shipping through the Northwest Passage (NWP) is cost-effective for some routes even when faced with large incremental capital costs from the development of more structurally sound ships.

In this paper, I obtain an estimate of annual traffic levels through the NWP by modeling a shipper's cost-minimization problem. This model uses shipping distances, gathered using Google Earth™, between some main trading regions for both the Panama Canal (PC) route and the NWP route, as well as current and expected future commodity flow data from the Panama Canal Authority (Panama Canal, 2007).

Conditional on Canada’s sovereignty over the waters of the Arctic Archipelago, an accurate estimate of traffic levels would contribute to a cost-benefit analysis of the decision of whether or not to restrict foreign passage given predicted toll revenues, employment opportunities, and infrastructure requirements of a NWP shipping route. This is also very important for northern communities as they work toward the development of climate change adaptation policies.
PRELIMINARIES

When investigating the port connections which would be expected to substitute toward the NWP, the shipper's decision problem involves the minimization of a cost function which includes fuel costs, operating costs, and toll costs. However, the problem can be refined by first considering the opening of other new routes.

The Arctic waters north of Russia will be ice-free before those of the Arctic Archipelago (ACIA, 2005). Furthermore, "while direct (across the North Pole) trans-arctic voyages are unlikely by mid-century, voyages may be possible north of the arctic island groups (such as those along the Russian Arctic coast) and away from shallow continental shelf areas that restrict navigation"(ACIA, 2005, p.925). Therefore the Northern Sea Route (NSR), and a shorter route, NSR2, are hypothesized and are shown in the Google Earth™ capture of Figure 6 (orange) in Appendix A. Table 1 shows the nearly equivalent distances of the NWP and NSR routes from the Strait of Gibraltar to the Bering Strait, which leads to the expectation that all port connections involving Northern Europe and the Bering Strait would, under the condition of similar toll rates between NWP and NSR, choose the shorter NSR over the NWP. Port connections involving the rest of Europe and the Bering Strait would also substitute toward the NSR over the NWP due to the nearly equivalent distances and the earlier opening of the NSR; however, it is unrealistic to expect that any Arctic route will be considered for these port connections due to both the shorter distances and lower tolls available through use of the Suez Canal. Therefore, the historically more established Northern Sea Route (NSR) is expected to be a more realistic option for both Europe to Asia and Europe to West Coast US/Canada port connections.

<table>
<thead>
<tr>
<th>Table 1: Strait of Gibraltar to Bering Strait</th>
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<tbody>
<tr>
<td>Route</td>
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<td>Northern Sea Route 1</td>
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<td>Northern Sea Route 2</td>
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<td>Northwest Passage</td>
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Having considered the port connections over which future Arctic routes are expected to compete (those involving the Bering Strait), Table 2 summarizes the preceding arguments and shows the port connections of interest in this paper. The NWP is expected to provide a strategic advantage only to those connections which involve the East Coast of the United States or Canada.

<table>
<thead>
<tr>
<th>Point A</th>
<th>Point B</th>
<th>Current Route</th>
<th>Future Alternative</th>
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<td>East Coast US/Canada</td>
<td>West Coast US/Canada</td>
<td>Panama Canal</td>
<td>NWP</td>
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<td>Panama Canal</td>
<td>NSR</td>
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Both the Panama Canal (PC) and the NWP route distances were then found for those port connections involving the East Coast of the United States or Canada using Google Earth™’s "Ruler" function. For all port connections, the shortest all-water distance for each route was found by using the largest port of each region outlined in the Panama Canal Authority (2008) data. Current cargo data then obtained from the Panama Canal Authority (Panama Canal, 2008) for all port connections, and both the distances and cargo weights are shown in Tables 3 and 4 in Appendix A.

Given current cargo weights, the next step was to predict the growth rate of trade for each port connection. DRI-WEFA (2002) published expected trade growth rates for imports and exports for selected countries currently using the Panama Canal. I use these values, in combination with a cautiously assumed 3% annual growth for those regions not included in DRI-WEFA (2002), in order to derive a geometric mean for the growth rate of trade for each port connection.

Despite the expectation that the NWP will be open to shipping by about mid-century (ACIA, 2005), "sea ice conditions are highly variable and there will still be summers of occasional heavy ice conditions" (Wilkinson, Falkingham, Melling & De Abreu, 2004, p.4). Furthermore, the western end of the NWP may see more pack ice as it shifts southward, along with increased drifting multi-year (thicker)
ice which could create choke points in narrow channels (Wilkinson, Falkingham, Melling & De Abreu, 2004). This implies the use of icebreaker support at the western end of Parry Channel - the route through the NWP "most likely to attract the attention of the international shipping community on account of its east-west orientation and its broad passages" (Macnab, 2004, p.2). To address the possibility of chokepoints, the two chokepoints outlined by Falkingham, Chagnon, and McCort (2003) are used in the model. These chokepoints are shown in Figure 1, with one occurring in Viscount Melville Sound, and one occurring in M’Clure Strait. According to Google Earth’s "Ruler" function, the distance from the eastern end of Viscount Melville Sound to the western end of M’Clure Strait is approximately 330 nautical miles. It is assumed that beginning in 2050, shipping through the NWP will occur for 4 months of the year through the Parry Channel with the mandatory assistance of icebreakers over this 330 nautical mile stretch.

**Figure 1: Parry Channel from Macnab (2004), left, and chokepoints from Falkingham et al (2003)**

According to Ragner (2000), icebreaker fees on the NSR do not depend on the number of days of icebreaker support, and could be as low as $5 US per gross register ton while still covering operating costs.¹ I assume that the NWP toll structure will be $5 US per long ton of cargo weight in order to have a straight comparison between the NWP and the PC toll structure.

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¹ The gross tonnage is a function of the moulded volume of all enclosed spaces of the ship.
Unpredictable ice conditions on Arctic shipping routes cause frequent and unavoidable delays even with icebreaker support, thus prohibiting the use of these routes by liner operations with containerized cargo which tends to have strict time schedules (Ragner, 2000, p.551). Furthermore, the recent and projected growth of the North American intermodal transportation infrastructure may, by the time the NWP is likely to be considered as shipping route, provide liner operations with containerized cargo sufficient capacity to bypass the NWP and PC altogether, not to mention at a lower cost. For these reasons, I am able to avoid the use of the Panama Canal Authority's cumbersome Panama Canal/Universal Measurement System (PC/UMS) net tonnage conversion which is used to assess tolls for containerized cargo. Therefore, I use only the traffic data from the Panama Canal Authority (2007) which deals with non-containerized cargo, and is enumerated in long tons.²

The shipper’s decision was then modeled in Matlab for the years 2050 to 2100 in order to find the cargo weight and number of vessels expected to transit the NWP given its opening in the year 2050.

² 1 long ton = 2240 pounds = 1016.0469 kg
**ECONOMIC MODEL**

In order to estimate expected traffic through the NWP, it is necessary to model a shipper's decision problem. Given a total cargo weight, a shipper solves the following problem in order to minimize costs:

Ship through the NWP if: $TC_{NWP} < TC_{PC}$ and total cost for route $i$,

$$TC_i = (TollCost_i + OperatingCost_i + FuelCost_i)$$

where for $i = PC$,

$TollCost_{PC} = tr_{PC} \cdot w_{PC}$

$$OperatingCost_{PC} = \left(\frac{d_{PC} - l_{PC}}{v_{ow}} + tt_{PC}\right) \cdot \frac{c}{24}$$

$$FuelCost_{PC} = \frac{d_{PC}}{v_{ow}} \cdot fc \cdot pp \cdot \left(\frac{1}{10^6}\right) \cdot fp_{PC}$$

and for $i = NWP$,

$TollCost_{NWP} = tr_{NWP} \cdot w_{NWP}$

$$OperatingCost_{NWP} = \left(\frac{d_{NWP} - l_{NWP}}{v_{ow}} + tt_{NWP}\right) \cdot \frac{c}{24}$$

$$FuelCost_{NWP} = \frac{d_{NWP}}{v_{ow}} \cdot fc \cdot pp \cdot \left(\frac{1}{10^6}\right) \cdot fp_{NWP}$$

**Parameters**: 3

$v_{ow} =$ openwater ship velocity (20 nautical miles per hour)

$c =$ operating costs ($4000-$5000 per day) includes crew wages, provisions, maintenance, and stores

$fc =$ fuel consumption (160-171 grams/kWh)

$pp =$ propulsion power (19,600-25,200 KW)

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3 All parameters from Somanathan, Flynn, and Szymanski (2007, pp.327-328)
Exogenous Variables:

\[ tr_i = \text{average toll rate for route } i \text{ ($US per long ton)} \]

\[ w_i = \text{cargo weight for route } i \text{ (long tons)} \]

\[ fp_i = \text{fuel price for route } i \text{ ($US per metric ton)} \]

\[ tt_i = \text{passage or canal transit time for route } i \text{ (hours)} \]

\[ l_i = \text{length of passage or canal on route } i \text{ (nautical miles)} \]

\[ d_i = \text{total distance of PC route (nautical miles)} \]

COMPUTATIONAL MODEL

The shipper's decision problem was modeled in Matlab due to the efficiency with which Matlab is able to handle matrices. The code was broken up into three cost functions and a main body. The first cost function generates a toll cost vector, with an element for both the PC route and the NWP route. The second and third cost functions perform the same analysis for the operating cost vector and the fuel cost vector, respectively.

In the main body of the code, the parameters are first listed along with the route-dependent variables. Next the matrices of distances for port connections are listed for both the PC and NWP routes, as well as a matrix for the current PC cargo weights. Next comes two matrices of expected growth rates from DRI-WEFA (2002), with an elementwise multiplication and subsequent elementwise square-root in order to derive a matrix of geometric mean expected growth rates. The three cost functions are then called, and a new total cost function is created for each route by summing the elements of the three cost component functions.

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4 (Panama Canal Authority)  
5 (Panama Canal Authority)  
6 (Bunkerworld)  
7 (Panama Canal Authority) and (Macnab, 2004)
The code then begins the solution process which is performed using a while loop and two nested for loops. The two for loops find the minimum cost route for each element of the cargo weight matrix and assign to the element of a control matrix, \( u_{pc} \), a 1 if the PC is found to be a lower cost route and a 0 otherwise. Once these for loops have completed their task, the matrix \( u_{pc} \) is subtracted from a previously defined matrix of ones, \( \text{onesmatrix} \), and the resulting matrix is multiplied elementwise by the cargo weight matrix to find the cargo expected to transit the NWP for each port connection for the year in question. The year is then increased by one and the cargo weight matrix is multiplied elementwise by the cargo growth matrix, and the while loop completes another cycle. This is done until the horizon year of 2100 is reached.

RESULTS

Using the model as described, the main objective was to obtain a realistic estimate of the expected cargo weight and vessel traffic through the NWP. Based on the uncertainties of climate models, as well as the uncertainties associated with the unprecedented large-scale use of an Arctic shipping route, these results should be looked upon as one of many possible scenarios. The results are presented here in graphical form, and are analyzed in the Discussion section.

**Figure 2**

Total Cargo Weight (Long Tons) Transiting the NWP by Year
The number of vessels expected to transit the NWP in the year 2100 was found to be only 31\(^8\). This is surprisingly low, but is explained by the high degree of sensitivity of the shipper's decision to the NWP toll structure, as well as the geographic location of most of the East Coast US/Canada maritime trade - the vast majority of which involves the Gulf Coast of the United States, a region very close to the Panama Canal. If the cargo weights flowing from and to the Gulf Coast of the US were present on the East Coast of Canada, the number of vessels would of course be much higher. The re-routings of interest, however, are shown in Figure 3.

Figure 3

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\(^8\) Obtained by dividing cargo weight by current average long tons per PC transit (Panama Canal Authority, 2008)
EXPERIMENTS

Two conditions were investigated:

1. The current state of a hypothetical *all-year ice-free NWP with* Canadian sovereignty which allows the administration of a toll structure identical to that of the PC, and

2. The current state of a hypothetical *all-year ice-free NWP without* Canadian sovereignty which allows free foreign passage through the Parry Channel.

**Figure 4: Results of Condition 1**

*Total Current Cargo Transiting the PC by Inter-Regional Connection if NWP ice-free with PC Toll Structure*

*Total Current Cargo Transiting the NWP by Inter-Regional Connection if NWP ice-free with PC Toll Structure*
From the results of Condition 1, it can be seen that, even with an ice-free NWP, under an identical toll-structure to that of the PC the NWP results in no re-routings for those connections involving the Gulf Coast of the United States. This is important, since the majority of maritime cargo on the East Coast of US/Canada involves the Gulf Coast. Therefore, even if no ice were to be present in the NWP, this route would not capture the majority of the East Coast US/Canada maritime cargo trade unless it charged a cheaper toll than the PC.
Under Condition 2, Canada is assumed to lack the ability to impose tolls on vessels transiting the NWP. In effect, Canada has lost the battle for sovereignty over the waters of the NWP, and Parry Channel has been deemed an international strait. Canada is unable to enforce a toll, and with no impediments to transiting the NWP such as hazardous ice conditions, even the Gulf Coast of the United States finds it cheaper to ship through the NWP than the PC.

**CONCLUSION**

Under the toll structure of Ragner (2002), only those connections involving either the Great Lakes or the East Coast of Canada re-route from the PC to the NWP. Only 4 vessels are expected to transit the NWP in 2050, growing to 31 vessels by 2100. It is unlikely that these low traffic volumes would be sufficient to justify the infrastructure and operating costs associated with the development of a NWP shipping route. If the toll structure could be lowered below the estimate of Ragner (2002), traffic volumes through the NWP will rise. However, in order to capture the traffic involving the Gulf Coast of the United States, the NWP toll structure *must* be cheaper than the PC toll structure. It is those port connections involving the Gulf Coast of the United States which make up the majority of possible NWP traffic, therefore the most important question as to the feasibility of a NWP shipping route is by how much the NWP toll must undercut the PC toll in order to capture the Gulf Coast traffic and if this toll revenue would be sufficient to support the development of the NWP as a shipping route.
REFERENCES


Wilson, K. J., Falkingham, J., Melling, H., & De Abreu, R. (2004). *Shipping in the Canadian Arctic: Other possible climate change scenarios*. Ottawa and Victoria, Canada: Canadian Ice Service and Fisheries and Oceans Canada.
APPENDIX A

Figure 6: Bering Strait to Strait of Gibraltar by NWP(green), NSR(red), NSR2(red with orange leg)

Table 3: Total Distances for PC route and NWP route for all port connections involving the EC US/Canada

<table>
<thead>
<tr>
<th>Total Distance by Panama Canal</th>
<th>EC US/Can</th>
<th>North Atlantic</th>
<th>South Atlantic</th>
<th>Great Lakes</th>
<th>Gulf</th>
<th>EC Canada</th>
<th>Port of NY/NJ</th>
<th>Port of Hampton Roads, VA</th>
<th>Port of Duluth, Mn</th>
<th>Port of South Louisiana (Laplace)</th>
<th>Port of St John, NB</th>
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</thead>
<tbody>
<tr>
<td>WC US/Can</td>
<td>Alaska</td>
<td>Port of Valdez</td>
<td>6952.90</td>
<td>6788.70</td>
<td>9222.18</td>
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<td></td>
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<td>Australia</td>
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<td>11426.41</td>
<td>12144.50</td>
<td>12827.45</td>
<td>10951.07</td>
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<tr>
<td></td>
<td>New Zealand</td>
<td>Port of Auckland</td>
<td>10671.82</td>
<td>10806.22</td>
<td>11524.31</td>
<td>12207.26</td>
<td>10330.88</td>
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</table>
### Table 4: 2007 Cargo Weights (long tons) from Panama Canal Authority (Panama Canal, 2008)

<table>
<thead>
<tr>
<th>WC US/Can</th>
<th>EC US/Canada</th>
<th>North Atlantic</th>
<th>South Atlantic</th>
<th>Great Lakes</th>
<th>Gulf</th>
<th>Port of South Louisiana (Laplacette)</th>
<th>EC Canada</th>
<th>Port of St John, NB</th>
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<tbody>
<tr>
<td>Alaska</td>
<td>Port of Valdez</td>
<td>0</td>
<td>0</td>
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<td>360727</td>
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<td>Port of Honolulu</td>
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<td>0</td>
<td>1569</td>
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<td>1263954</td>
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<td>539906</td>
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<tr>
<td>WC Canada</td>
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<td>60103</td>
<td>137346</td>
<td>0</td>
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<td>China (incl. HK)</td>
<td>Port of Shanghai</td>
<td>8847400</td>
<td>1038498</td>
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<td>15038226</td>
<td>1100562</td>
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<td>Taiwan</td>
<td>Port of Kaohsiung</td>
<td>1750133</td>
<td>2091138</td>
<td>40261</td>
<td>1848011</td>
<td></td>
<td>58657</td>
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<tr>
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<td>Port of Tanjung Priok (Jakarta)</td>
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<td>93610</td>
<td>10402</td>
<td>1880097</td>
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<td>4711</td>
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</tr>
<tr>
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<td>18625991</td>
<td>19912244</td>
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<td>232520</td>
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<tr>
<td>Philippines</td>
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<td>103825</td>
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<td>421838</td>
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<td>43467</td>
<td>9458017</td>
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<td>162762</td>
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<tr>
<td>Thailand</td>
<td>Port of Laem Chabang</td>
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<td>236792</td>
<td>63</td>
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<td>375</td>
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<td>792976</td>
<td>410635</td>
<td>588542</td>
<td>247463</td>
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<tr>
<td>New Zealand</td>
<td>Port of Auckland</td>
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<td>203599</td>
<td>625014</td>
<td>59783</td>
<td></td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>


**Title:** Cost-Minimizing Route Choice and Expected Vessel Volumes  
**Program name:** panamacanalversusnorthwestpassage.m  
**by Andrew Barnes**

---

**Preliminaries**

\[
t = 2100;  \quad \text{% horizon year}
\]
\[
eports = 5; \quad \text{% number of East Coast US/Canada ports}
\]
\[
otherports = 14; \quad \text{% total number of other ports in WC US/Can(4), Asia(8), and Oceania(2)}
\]
\[
onesmatrix=ones(otherports,ecports);
\]

---

**For Toll Cost Function**

\[
trpc=3.65; \quad \text{% toll rates by route (US$/long ton)}
\]

---

**For Operating Cost Function**

\[
lpc=43.2; \quad \text{% Panama Canal length; and Northwest Passage (Parry Channel) length (naut. mi.)}
\]
\[
ttpc=24; \quad \text{% Currently from Panama Canal Authority webpage;}
\]
\[
ttnwp=38.91; \quad \text{% Based on (720 minus 330) naut.mi.(Meridian Article) @ 20 naut.mi./hr openwater speed and 330 nau. mi. @ 17 naut.mi./hr icebreaker speed}
\]

---

**For Fuel Cost Function**

\[
fppc=507; \quad \text{% fuel price by route ($US/metric ton)}
\]
\[
vow=20; \quad \text{% openwater velocity (naut. mi. per hour)}
\]
\[
c=4500; \quad \text{% operating cost per day including wages, meals, maintenance ($US/day)}
\]
\[
fc=165.5; \quad \text{% fuel consumption (grams/kWhr)}
\]
\[
pp=22400; \quad \text{% propulsion power (kWhr)}
\]

---

**pcdist** = [6952.896544 6788.696544 9322.176544 6375.076544 7271.466544;  
6703.556544 6539.356544 9072.836544 6125.736544 7022.126544;  
4935.296544 4771.096544 7304.576544 4357.476544 5253.866544;  
5100.216544 4936.016544 7469.496544 4522.396544 5418.786544;  
11410.94654 11246.74654 13780.22654 10833.12654 11729.51654;  
12530.49654 12366.29654 14899.77654 11952.67654 12849.06654;  
10133.09654 9968.896544 12502.37654 9559.696544 10451.66654;  
8535.486544 8371.286544 10904.76654 7957.666544 8854.056544];
nwpdist=[5966.34000 6100.74000 6818.83000 7501.78000 5625.40000; 7185.49000 7319.89000 8037.98000 8720.93000 6844.55000; 7490.38000 7624.78000 8342.87000 9025.82000 7149.44000; 6822.33000 6956.73000 7674.82000 8357.77000 6481.39000; 7894.35000 8028.75000 8746.84000 9429.79000 7553.41000; 8385.45000 8519.85000 9237.94000 9920.89000 8044.51000; 10393.9600 10528.3600 11246.4500 11929.4000 10053.0200; 10241.0400 10375.4400 11093.5300 11776.4800 9900.10000; 8843.51000 8977.91000 9696.00000 10378.9500 8502.57000; 9988.02000 10122.4200 10840.5100 11523.4600 9647.08000; 11292.0100 11426.4100 12144.5000 12827.4500 10951.0700; 10671.8200 10806.2200 11524.3100 12207.2600 10330.8800];

cargo0=[0.000000 0.000000 0.000000 487.00000 60727.0000; 52697.0000 283183.000 10454.0000 1263954.00 539906.000; 60103.0000 135746.000 0.0000000 721470.000 26874.0000; 8847400.00 10308498.0 72806.0000 15033226.0 1100562.00; 1750133.00 2091138.00 40261.0000 1848011.00 58657.0000; 21434.0000 93610.0000 10402.0000 186007.000 4711.00000; 1246466.00 4355909.00 8625991.00 19912244.0 232520.000; 131300.000 103825.000 0.0000000 421838.000 745.000000; 18447.0000 217762.000 0.0000000 588385.000 12708.0000; 112359.000 792976.000 410635.000 588542.000 247463.000; 16606.0000 203599.000 625014.000 59783.0000 0.00000000];

eportgr=[1.061 1.061 1.061 1.061 1.053; 1.061 1.061 1.061 1.061 1.053; 1.061 1.061 1.061 1.061 1.053; 1.061 1.061 1.061 1.061 1.053; 1.061 1.061 1.061 1.061 1.053; 1.061 1.061 1.061 1.061 1.053; 1.061 1.061 1.061 1.061 1.053; 1.061 1.061 1.061 1.061 1.053];

ecportgr=[1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061];

otherportgr=[1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061; 1.061 1.061 1.061 1.061 1.061];
1.061 1.061 1.061 1.061 1.061;  % US
1.061 1.061 1.061 1.061 1.061;  % US
1.053 1.053 1.053 1.053 1.053;  % Canada
1.073 1.073 1.073 1.073 1.073;  % China and Hong Kong averaged
1.062 1.062 1.062 1.062 1.062;  % Taiwan
1.030 1.030 1.030 1.030 1.030;  % Indonesia: 3 percent annual
growth rate of Panama Canal transits (Panama Study, 2005)
1.050 1.050 1.050 1.050 1.050;  % Japan
1.030 1.030 1.030 1.030 1.030;  % Phillipines: 3 percent
%annual growth rate of Panama Canal transits (Panama Study, 2005)
1.030 1.030 1.030 1.030 1.030;  % Singapore: 3 percent annual
growth rate of Panama Canal transits (Panama Study, 2005)
1.058 1.058 1.058 1.058 1.058;  % S. Korea
1.030 1.030 1.030 1.030 1.030;  % Thailand: 3 percent annual
growth rate of Panama Canal transits (Panama Study, 2005)
1.030 1.030 1.030 1.030 1.030;  % Australia: 3 percent annual
growth rate of Panama Canal transits (Panama Study, 2005)
1.030 1.030 1.030 1.030 1.030];  % New Zealand: 3 percent
%annual growth rate of Panama Canal transits (Panama Study, 2005)
cargogr=(ecportgr.*otherportgr).^(1/2);  % Provides a geometric mean for
trade growth by inter-region connection

Call the cost functions
[fuelcostpc, fuelcostnwp] = fuelcost(vow,fc,pp,fpnc,fpnwp,pcdist,nwpdist);
[opcostpc, opcostnwp] =
opcost(onesmatrix,vow,lpc,lnwp,c,pcdist,nwpdist,ttpc,ttnwp);
[tollcostpc,tollcostnwp] = tollcost(trpc, trnwp, cargo);
%Calculate total costs
totalcostpc = fuelcostpc + opcostpc + tollcostpc;
totalcostnwp = fuelcostnwp + opcostnwp + tollcostnwp;
k = 2050;  % Initial year of Northwest Passage Opening
while k <= t
cargo=(1/3).*cargo0.*(cargogr.^((k-2007)));
  % Estimates cargo weights for each
  %year (based on 4 month summer)
  for i=1:otherports
    for j=1:ecports
      if totalcostpc(i,j) < totalcostnwp(i,j)
        upc(i,j)=1;
      else
        upc(i,j)=0;
      end
    end
  end
  % upc;  % displays routes using panama canal as having a 1
  % upc.*cargo;  % displays cargo weights flowing through panama
  % canal for each inter-region connection
  (onesmatrix-upc).*cargo;  % displays cargo weights flowing through
  % northwest passage for each inter-region connection
  sum((onesmatrix-upc).*cargo)  % displays total cargo weight flowing through
  % northwest passage for each east coast US/Canada port
k = k+1;
end
MATLAB COST FUNCTIONS

% Title: total toll cost
% Function Name: tollcost.m
% Andrew Barnes

function [tollcostpc, tollcostnwp] = tollcost(trpc, trnwp, cargo)
    tollcostpc = trpc.*cargo;
    tollcostnwp = trnwp.*cargo;

% Title: operating cost
% Function Name: opcost.m
% Andrew Barnes

function [opcostpc, opcostnwp] =
opcost(onesmatrix, vow, lpc, lnwp, c, pcdist, nwpdist, ttpc, ttnwp)
    opcostpc = (c/24).*((1/vow).*(pcdist-(lpc.*onesmatrix))+(ttpc.*onesmatrix));
    opcostnwp = (c/24).*((1/vow).*(nwpdist-(lnwp.*onesmatrix))+(ttnwp.*onesmatrix));

% Title: fuel cost
% Function Name: fuelcost.m
% Andrew Barnes

function [fuelcostpc, fuelcostnwp] =
fuelcost(vow, fc, pp, fppc, fpnwp, pcdist, nwpdist)
    fuelcostpc = ((1/vow)*fc*pp*(1/1000000)*fppc).*pcdist;  % Divide by 10^6
    % to align units
    fuelcostnwp = ((1/vow)*fc*pp*(1/1000000)*fpnwp).*nwpdist; % Divide by 10^6
    % to align units