

**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 1: Strait of Gibraltar to Bering Strait

Route	Distance (nautical miles)
Northern Sea Route 1	5424
Northern Sea Route 2	5160
Northwest Passage	5072

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 2: Current and Future Routes

Point A	Point B	Current Route	Future Alternative
East Coast US/Canada	West Coast US/Canada	Panama Canal	NWP
East Coast US/Canada	Oceania	Panama Canal	NWP
East Coast US/Canada	Asia	Panama Canal	NWP
Europe	Asia	Suez Canal	NSR
Europe	West Coast US/Canada	Panama Canal	NSR

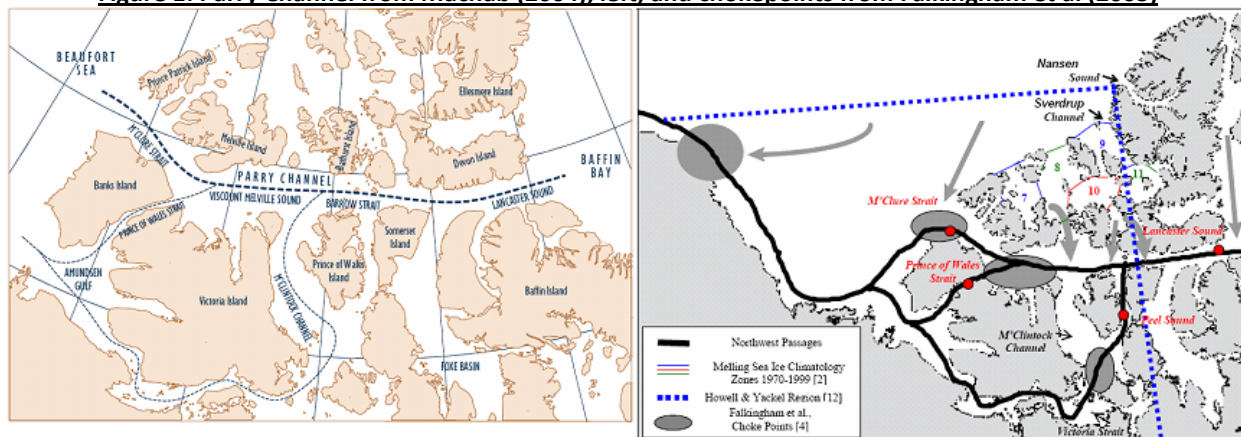
Both the Panama Canal (PC) and the NWP route distances were then found for those port connections involving the East Coast of the United States or Canada using Google Earth™'s "Ruler" function. For all port connections, the shortest *all-water* distance for each route was found by using the largest port 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.

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 $i = PC$, $TollCost_{PC} = tr_{PC} * w_{PC}$

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

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

and for $i = NWP$, $TollCost_{NWP} = tr_{NWP} * w_{NWP}$

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

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

Parameters³:

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)

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

Exogenous Variables:

tr_i = average toll rate for route i (\$US per long ton)⁴

w_i = cargo weight for route i (long tons)⁵

fp_i = fuel price for route i (\$US per metric ton)⁶

tt_i = passage or canal transit time for route i (hours)

l_i = length of passage or canal on route i (nautical miles)⁷

d_i = 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.

⁴ (Panama Canal Authority)

⁵ (Panama Canal Authority)

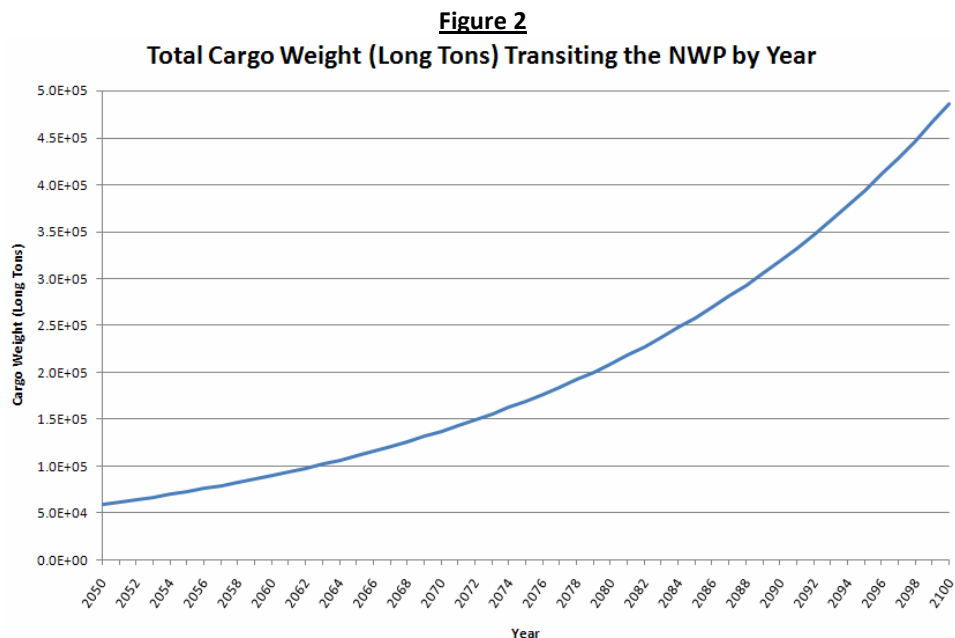
⁶ (Bunkerworld)

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, *upc*, 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 *upc* is subtracted from a previously defined matrix of ones, *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.

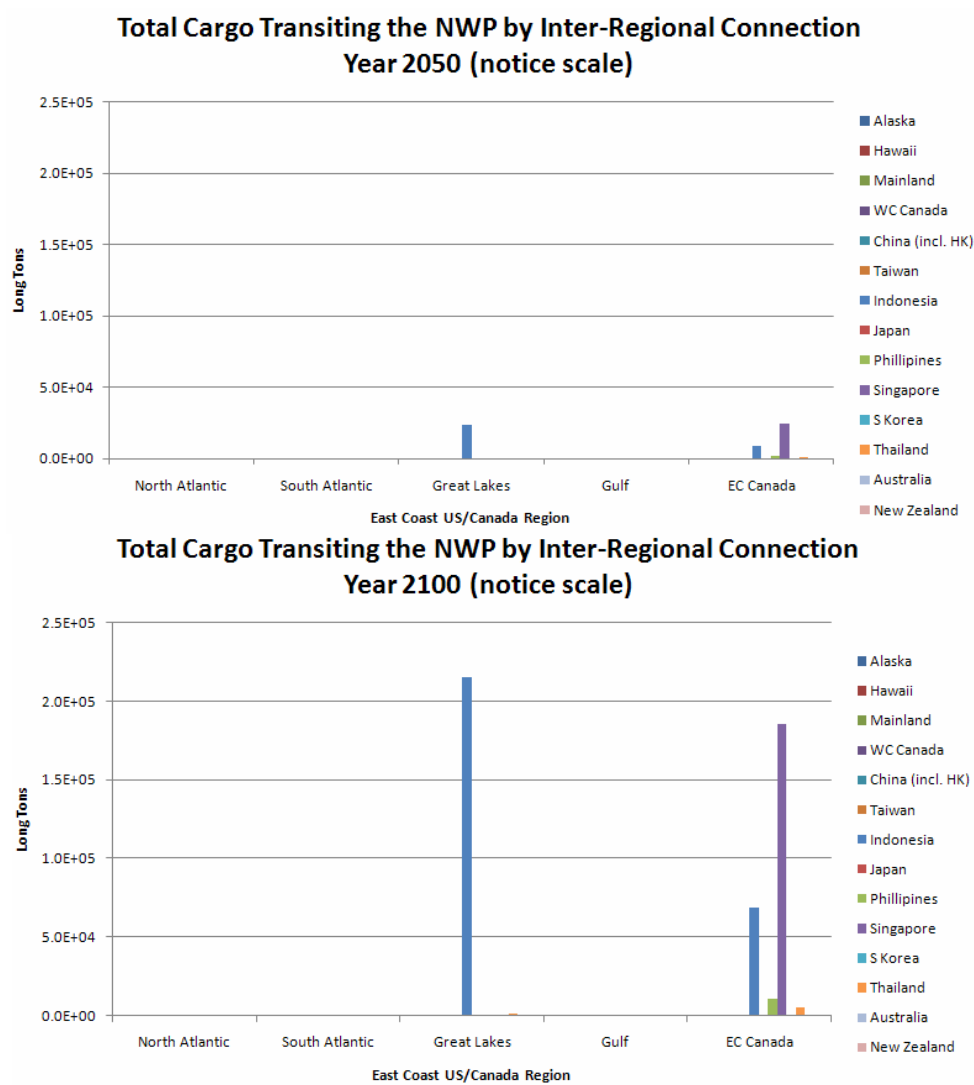
RESULTS

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.



The number of vessels expected to transit the NWP in the year 2100 was found to be only 31⁸. 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.

Figure3



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

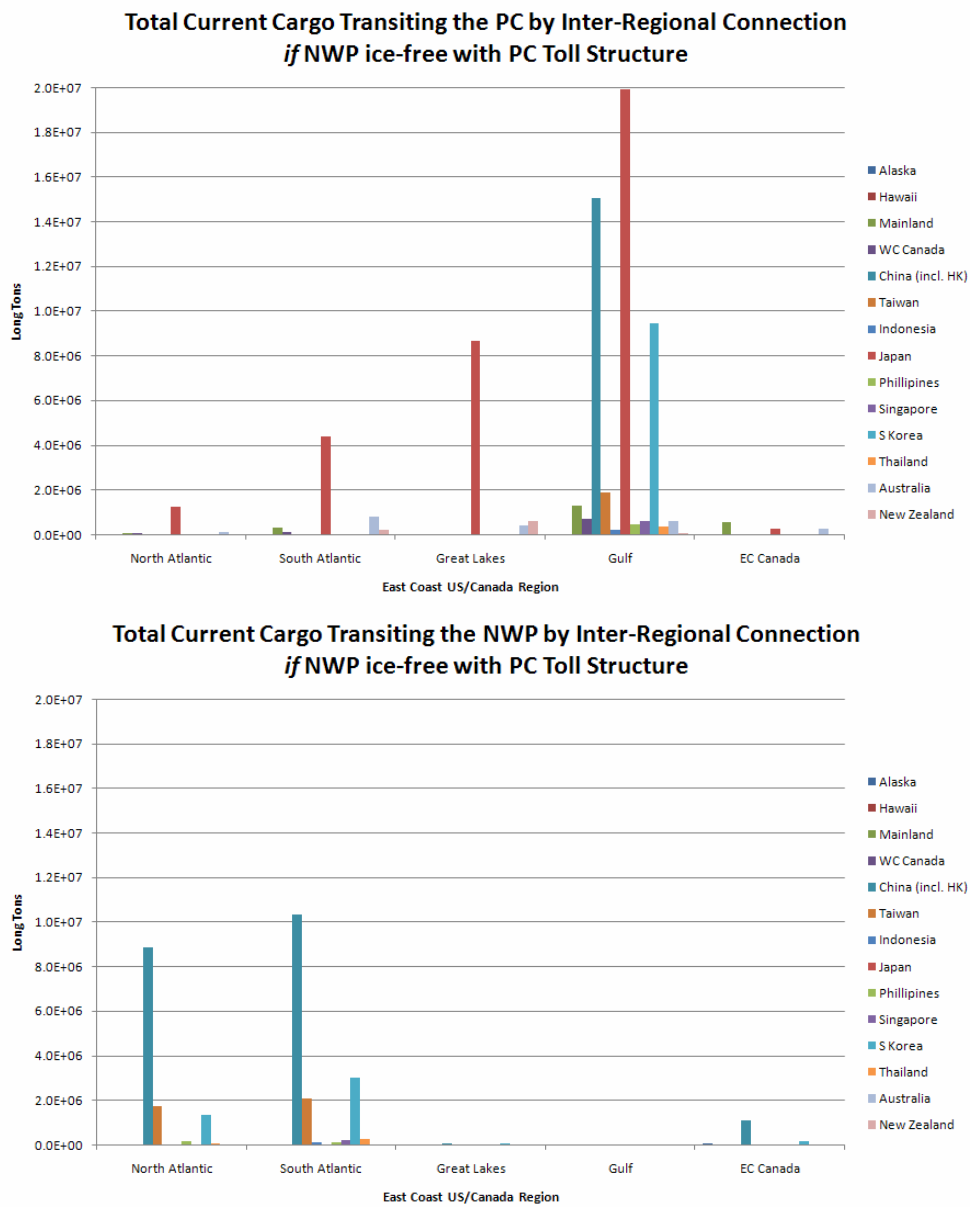
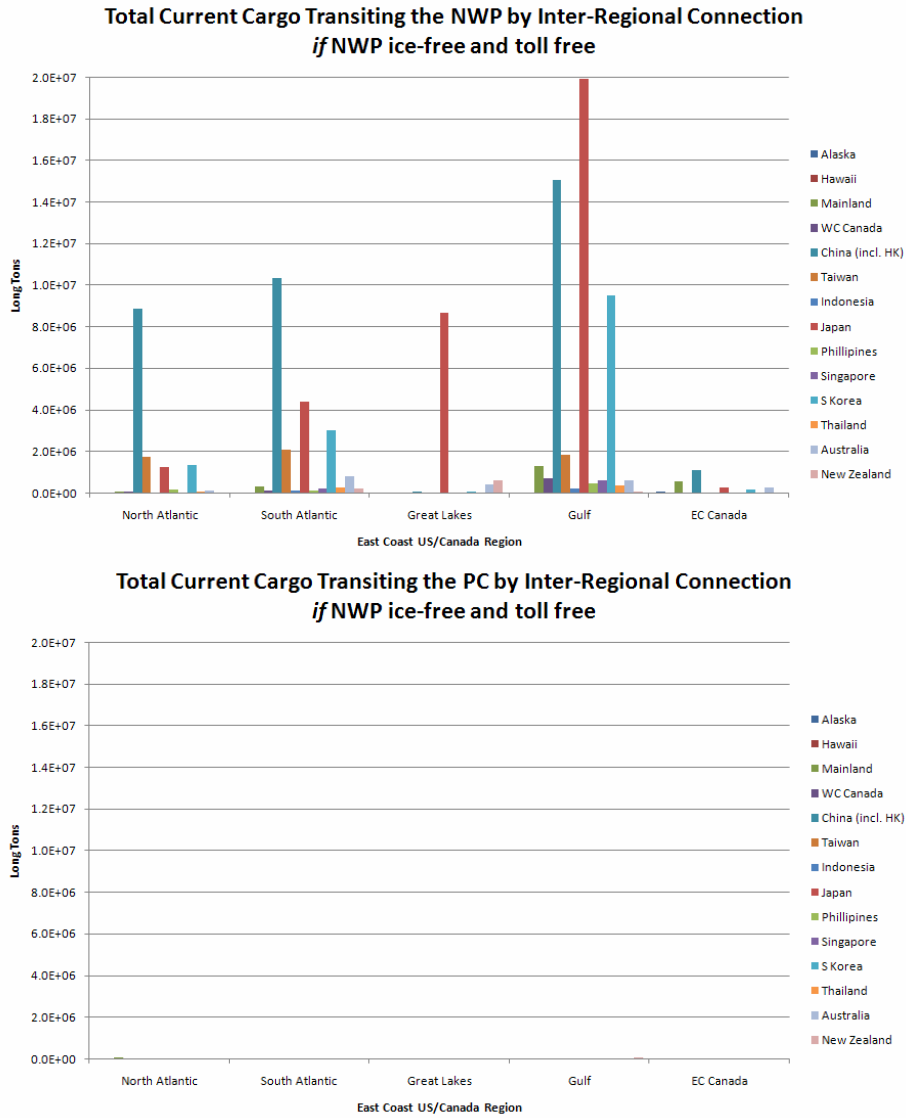


Figure 5: Results of Condition 2



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.

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APPENDIX A

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

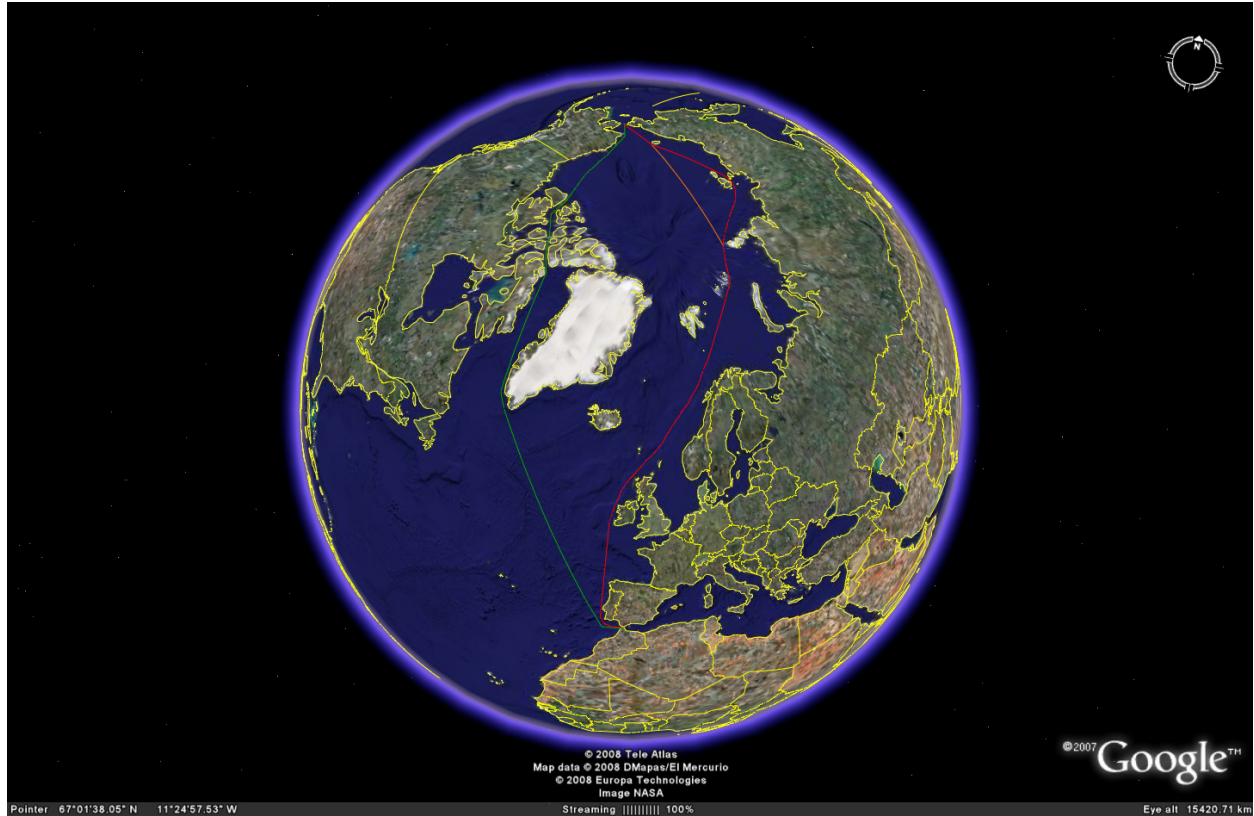


Table 3: Total Distances for PC route and NWP route for all port connections involving the EC US/Canada

Total Distance by Panama Canal			EC US/Can	South Atlantic	Great Lakes	Gulf	EC Canada
			North Atlantic	Port of Hampton Roads, VA	Port of Duluth, Mn	Port of South Louisiana (Laplace)	Port of St John, NB
WC US/Can	Alaska	Port of Valdez	6952.90	6788.70	9322.18	6375.08	7271.47
	Hawaii	Port of Honolulu	6703.56	6539.36	9072.84	6125.74	7022.13
	Mainland	Port of Long Beach, CA	4935.30	4771.10	7304.58	4357.48	5253.87
	WC Canada	Port of Vancouver, BC	6064.45	5900.25	8433.73	5486.63	6383.02
Asia	China (incl. HK)	Port of Shanghai	10721.68	10557.48	13090.96	10143.86	11040.25
	Taiwan	Port of Kaohsiung	10991.25	10827.05	13360.53	10413.43	11309.82
	Indonesia	Port of Tanjung Priok (Jakarta)	12619.61	12455.41	14988.89	12041.79	12938.18
	Japan	Port of Nagoya	5100.22	4936.02	7469.50	4522.40	5418.79
	Philippines	Port of Manila	11410.95	11246.75	13780.23	10833.13	11729.52
	Singapore	Port of Singapore	12530.50	12366.30	14899.78	11952.68	12849.07
	S Korea	Port of Busan	10133.10	9968.90	12502.38	9555.28	10451.67
	Thailand	Port of Laem Chabang	12568.84	12404.64	14938.12	11991.02	12887.41
Oceania	Australia	Port of Melbourne	9937.52	9773.32	12306.80	9359.70	10256.09
	New Zealand	Port of Auckland	8535.49	8371.29	10904.77	7957.67	8854.06
Total Distance by Northwest Passage			EC US/Can	South Atlantic	Great Lakes	Gulf	EC Canada
			North Atlantic	Port of Hampton Roads, VA	Port of Duluth, Mn	Port of South Louisiana (Laplace)	Port of St John, NB
WC US/Can	Alaska	Port of Valdez	5966.34	6100.74	6818.83	7501.78	5625.40
	Hawaii	Port of Honolulu	7185.49	7319.89	8037.98	8720.93	6844.55
	Mainland	Port of Long Beach, CA	7490.38	7624.78	8342.87	9025.82	7149.44
	WC Canada	Port of Vancouver, BC	6822.33	6956.73	7674.82	8357.77	6481.39
Asia	China (incl. HK)	Port of Shanghai	7894.35	8028.75	8746.84	9429.79	7553.41
	Taiwan	Port of Kaohsiung	8385.45	8519.85	9237.94	9920.89	8044.51
	Indonesia	Port of Tanjung Priok (Jakarta)	10393.96	10528.36	11246.45	11929.40	10053.02
	Japan	Port of Nagoya	10241.04	10375.44	11093.53	11776.48	9900.10
	Philippines	Port of Manila	8843.51	8977.91	9696.00	10378.95	8502.57
	Singapore	Port of Singapore	9988.02	10122.42	10840.51	11523.46	9647.08
	S Korea	Port of Busan	7412.41	7546.81	8264.90	8947.85	7071.47
	Thailand	Port of Laem Chabang	9931.10	10065.50	10783.59	11466.54	9590.16
Oceania	Australia	Port of Melbourne	11292.01	11426.41	12144.50	12827.45	10951.07
	New Zealand	Port of Auckland	10671.82	10806.22	11524.31	12207.26	10330.88

Table 4: 2007 Cargo Weights (long tons) from Panama Canal Authority (Panama Canal, 2008)

			EC US/Can		Gulf		EC Canada
			North Atlantic	South Atlantic	Great Lakes		
			Port of NY/NJ	Port of Hampton Roads, VA	Port of Duluth, Mn	Port of South Louisiana (Laplace)	Port of St John, NB
WC US/Can	Alaska	Port of Valdez	0	0	0	487	60727
	Hawaii	Port of Honolulu	0	12032	0	1569	0
	Mainland	Port of Long Beach, CA	52697	283183	10454	1263954	539906
	WC Canada	Port of Vancouver, BC	60103	135746	0	721470	26874
Asia	China (incl. HK)	Port of Shanghai	8847400	10308498	72806	15033226	1100562
	Taiwan	Port of Kaohsiung	1750133	2091138	40261	1848011	58657
	Indonesia	Port of Tanjung Priok (Jakarta)	21434	93610	10402	186007	4711
	Japan	Port of Nagoya	1246466	4355909	18625991	19912244	232520
	Phillipines	Port of Manila	131300	103825	0	421838	745
	Singapore	Port of Singapore	18447	217762	0	588385	12708
	S Korea	Port of Busan	1313251	2995289	45467	9458027	162762
	Thailand	Port of Laem Chabang	62242	236792	63	340161	375
Oceania	Australia	Port of Melbourne	112359	792976	410635	588542	247463
	New Zealand	Port of Auckland	16606	203599	625014	59783	0

MAIN MATLAB CODE

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

t = 2100;           % horizon year
ecports = 5;       % number of East Coast US/Canada ports
otherports = 14;   % 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; trnwp=5; % toll rates by route (US$/long ton)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% - For Operating Cost Function%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
lpc=43.2; lnwp=720; % Panama Canal length; and Northwest Passage
%(Parry Channel) length (naut. mi.)
ttpc=24;           % Currently from Panama Canal Authority webpage;
ttnwp=38.91;       % Based on (720 minus 330) naut.mi.(Meridian
%Article) @ 20 naut.mi./hr openwater speed and 330 nau. mi. @ 17 naut.mi./hr
%icebreaker speed
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% - For Fuel Cost Function -%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fppc=507; fpnwp=553.5; % fuel price by route ($US/metric ton)
vow=20;           % openwater velocity (naut. mi. per hour)
c=4500; % operating cost per day including wages, meals, maintenance ($US/day)
fc=165.5;         % fuel consumption (grams/kWhr)
pp=22400;         % propulsion power (kWhr)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

pcdist=[6952.896544 6788.696544 9322.176544 6375.076544 7271.466544; % Table
%of distances between EC US/Can ports(columns)
        6703.556544 6539.356544 9072.836544 6125.736544 7022.126544; % and
%ports of WC US/Can(4), Asia(8), and Oceania(2) for Panama Canal route. (14x5)
        4935.296544 4771.096544 7304.576544 4357.476544 5253.866544;
        6064.446544 5900.246544 8433.726544 5486.626544 6383.016544;
        10721.67654 10557.47654 13090.95654 10143.85654 11040.24654;
        10991.24654 10827.04654 13360.52654 10413.42654 11309.81654;
        12619.60654 12455.40654 14988.88654 12041.78654 12938.17654;
        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 9555.276544 10451.66654;
        12568.83654 12404.63654 14938.11654 11991.01654 12887.40654;
        9937.516544 9773.316544 12306.79654 9359.696544 10256.08654;
        8535.486544 8371.286544 10904.76654 7957.666544 8854.056544];
```

```

nwpdist=[5966.34000 6100.74000 6818.83000 7501.78000 5625.40000; % Table of
%distances between EC US/Can ports(columns)
    7185.49000 7319.89000 8037.98000 8720.93000 6844.55000; % and ports
%of WC US/Can(4), Asia(8), and Oceania(2) for Northwest Passage route. (14x5)
    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;
    7412.41000 7546.81000 8264.90000 8947.85000 7071.47000;
    9931.10000 10065.5000 10783.5900 11466.5400 9590.16000;
    11292.0100 11426.4100 12144.5000 12827.4500 10951.0700;
    10671.8200 10806.2200 11524.3100 12207.2600 10330.8800];

```

```

cargo0=[0.00000000 0.00000000 0.00000000 487.000000 60727.0000; % Table of
&CURRENT cargo weights (long tons) between EC US/Can ports(columns)
    0.00000000 2032.00000 0.00000000 1569.00000 0.00000000; % and ports
%of WC US/Can(4), Asia(8), and Oceania(2) for Panama Canal route. (14x5)
    52697.0000 283183.000 10454.0000 1263954.00 539906.000;
    60103.0000 135746.000 0.00000000 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 0.00000000 421838.000 745.000000;
    18447.0000 217762.000 0.00000000 588385.000 12708.0000;
    1313251.00 2995289.00 45467.0000 9458027.00 162762.000;
    62242.0000 236792.000 63.0000000 340161.000 375.000000;
    112359.000 792976.000 410635.000 588542.000 247463.000;
    16606.0000 203599.000 625014.000 59783.0000 0.00000000];

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%- Growth Prospects-%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

ecportgr=[1.061 1.061 1.061 1.061 1.053; % Expected growth of imports and
%exports averaged (US and Canada )
    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;
    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];

```

```

otherportgr=[1.061 1.061 1.061 1.061 1.061; % Expected growth of imports
%and exports averaged (US)

```

```

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,fpcc,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
```