

Carbon Footprint Study
for the
Asia to North America Intermodal
Trade

for

Port of Seattle

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Seattle, WA 98111

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1 Executive Summary

This study provides estimates of the greenhouse gas emissions from the delivery of a cargo load of containers from four different size vessels (4,500 TEU, 6,500 TEU, 8,500 TEU, and 12,500 TEU) originating in the ports of Shanghai, Hong Kong, and Singapore and traveling to the North American ports of Seattle, Prince Rupert, Los Angeles / Long Beach, Houston, Savannah, Norfolk, and New York / New Jersey and progressing onward via Class I intermodal trains to the cities of Chicago, Columbus, and Memphis. The analysis was performed using an emissions analysis methodology which estimates the mass of carbon dioxide, methane, and nitrous oxide. Emission factors, vessel and locomotive data, publicly available sea and rail routes, and assumptions based on previous emission studies are utilized to estimate carbon dioxide equivalent emissions. Methane and nitrous oxide emissions are converted to carbon dioxide equivalents so that their overall impact on climate change can be assessed.

A comparison of the emissions of oceangoing containerhips and domestic rail service shows that marine transportation emits about 1.5 to 2.25 less carbon dioxide equivalent emissions (CO₂e) per TEU-km than rail transportation. This relationship favors shipping over rail transportation when travel distances are comparable. However, the ocean distance from Asian ports to the West Coast ports and in particular the ports of Prince Rupert and Seattle are so much shorter than the distances to the East Coast ports that this more than offsets the detrimental impact of the longer rail distances from the West Coast ports.

Shipping via the port of Seattle provides the lowest overall carbon emissions from all three Asian departure ports evaluated in this study, when the cargo continues to the inland container facilities at Chicago and Columbus. With comparable ocean and rail distances, Prince Rupert has a very similar emissions footprint. The ports of Los Angeles / Long Beach and Oakland have the lowest emissions when shipping containers to Memphis. West Coast ports have lower emissions than East Coast ports for all but one of the cases investigated in this study.

The carbon footprint advantages of the West Coast ports can be quite significant. For example, carbon emissions expressed in terms of emissions per TEU moved are approximately 41% lower when moving a container between Shanghai and Chicago via the port of Seattle on a 8,500 TEU containerhip, as compared to moving the same container between Shanghai and Chicago via the Panama Canal and the port of New York / New Jersey on a 4,500 TEU Panamax containerhip. A 4,500 TEU containerhip, with its 32.2 meter beam, is the largest size vessel that can transit the Panama Canal at this time.

For Far East to U.S. East Coast voyages, lower carbon emissions per container moved are realized for Post-Panamax vessels traveling via the Suez Canal as compared to Panamax vessels traveling via the Panama Canal. Recognizing that efforts to expand the Panama Canal are now underway, a supplementary analysis, located in Appendix B, of Post-Panamax vessels transiting through the Panama Canal has been carried out. This analysis indicates that Post Panamax vessels departing from Shanghai and Hong Kong will have reduced carbon emissions when heading to East Coast ports by way of the Panama Canal rather than the Suez Canal. Routing through the Suez Canal continues to be the more CO₂e efficient alternative per TEU for voyages originating in Singapore. Even after the expansion of the Panama Canal enables transit of larger vessels, the total carbon emissions associated with shipments moving through West Coast ports to the inland facilities remain below those levels attained when transiting the Panama Canal to East Coast ports. For example, total CO₂e emissions per TEU moved between Shanghai and Chicago via the port of Seattle on a 12,500 TEU containerhip are approximately 31% less than if the

container is carried on the same vessel via the Panama Canal to the port of New York / New Jersey, and then by rail to Chicago.

2 Methodology

The methodology used in this analysis is an emissions estimate method similar to what is detailed in the *Puget Sound Maritime Air Emissions Inventory*¹. The same basic equation is applied both to the container ship engine emissions and the locomotive engine emissions. The primary equation used to estimate emissions is:

$$\text{Emissions} = \text{MCR} \times \text{LF} \times \text{A} \times \text{EF} \text{ (kg)}$$

Where:

- MCR = Maximum Continuous Rating of the combustion engine in use (kW)
- LF = Load factor
- A = Activity time (hours)
- EF = Power based emission factor (kg/ kW-hr) for the greenhouse gas

The emissions of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) are calculated from published power based emission factors available for each greenhouse gas. Emissions of methane and nitrous oxide are then converted to Carbon Dioxide Equivalents (CO₂e) by multiplying the emissions by the Global Warming Potential values found in the latest Fourth Assessment Report of the IPCC².

Table 1: Global Warming Potentials (100 years), expressed as Carbon Dioxide Equivalents (CO₂e)

	Global Warming Potentials
CO ₂	1
CH ₄	25
N ₂ O	298

2.1 Container Ships

Container ships were selected such that they represent common operational characteristics from modern 4,500 TEU, 6,500 TEU, 8,500 TEU, and 12,500 TEU ships. The container ship particulars are shown below:

¹ Puget Sound Maritime Air Emissions Inventory, Starcrest Consulting Group, April 2007

² Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4), 2007

Table 2: Vessel Characteristics

	Vessel #1	Vessel #2	Vessel #3	Vessel #4
Vessel Capacity (TEUs)	4,444	6,402	8,214	12,500
Propulsion Rated Power (kW)	43,920	57,100	68,640	80,080
Auxiliary Rated Power (kW)	7,140	8,500	12,200	14,000
Propulsion Fuel Consumption (g/kW-hr)	175	175	175	175
Auxiliary Fuel Consumption (g/kW-hr)	197	190	190	190
Transit Speed (kts)	23.94	24.11	24.33	24.04
Inport Time (hrs)	33	52	50	60

A representative vessel was selected for each size category. Power, engine type, and transit speeds were obtained from available vessel details.^{3,4,5} Fuel consumption data was taken from manufacturers' data^{6,7} for the engine in question and adjusted from ISO conditions to account for use of heavy fuel oil in normal operating conditions. Transit speeds were calculated by adjusting given 90% MCR design speeds to 80% MCR speeds by using the propeller law relationship. Maneuvering speeds were approximated from port emission inventories.^{8,9} In-port times were estimated by the Port of Seattle. It is assumed that each ship carries a full container load with 90% utilization.

2.1.1 Maximum Continuous Ratings of Propulsion and Auxiliary Engines

MCR engine power data was obtained from specific vessel information. The MCR represents the maximum power output of the engines and is seldom used in the actual operation of the vessel.

2.1.2 Load Factors for Container Ships

Load factors used in this study are the same as found in the *Puget Sound Maritime Air Emissions Inventory*¹⁰. Load factors represent a percentage of maximum power used in the at sea, maneuvering, and in-port operational modes.

Table 3: Load Factors for Ship's Main Propulsion and Auxiliary Machinery

Load Factors	At Sea	Maneuvering	In-port
Propulsion	0.80	0.03	0.00
Auxiliary	0.13	0.50	0.17

³ Significant Ships 2003, Royal Institution of Naval Architects

⁴ Significant Ships 2004, Royal Institution of Naval Architects

⁵ Significant Ships 2005, Royal Institution of Naval Architects

⁶ Man B&W website and 2008 Programme

⁷ Sulzer website, www.sulzer.com

⁸ Puget Sound Maritime Air Emissions Inventory, Starcrest Consulting Group, April 2007

⁹ Port of Los Angeles Inventory of Air Emissions CY 2005, September 2007

¹⁰ Sound Maritime Air Emissions Inventory, Starcrest Consulting Group, April 2007

2.1.3 Activity Time in Mode

The activity time for the propulsion engines was calculated by dividing the ocean distance from the ports of Shanghai, Hong Kong, and Singapore to the North American port in question by the assumed transit speed. Ocean route distances were obtained from *Distance Between Ports*¹¹. The 4,500 TEU vessel is a Panamax ship that is capable of transiting through the Panama Canal to North American East Coast ports. The Post-Panamax ships (6,500 TEU, 8,500 TEU, 12,500 TEU) were directed through the Suez Canal on westbound routes to East Coast ports. East Coast bound vessels using either the Suez or Panama Canal were assigned a factor to account for changes in the operations when transiting through the canals. The factor was developed by calculating the greenhouse gas emissions from reduced transit speeds in the canal and the average canal waiting times outside the canal using appropriate load factors to represent the vessel in each of these modes. Specific canal data was obtained from the canal authorities^{12,13}.

No specific provisions were made for ships utilizing onshore power systems, or cold ironing, in any of the ports. While there are significant plans for shore power infrastructure for container vessels, few berths (and ships) are equipped with this technology today. Typically, vessels will have a total of 3 to 4 hours of power on shipboard generators while the shore power equipment is being connected and disconnected.

In addition, the influence of cold ironing on the total emissions of the entire supply chain is quite small. It is understood that it is quite important for emissions in the local area. Its impact was determined by conservatively assuming that a particular ship had no emissions while connected to shore power, omitting connection and disconnection times and emissions from shore powerplants. With this assumption, the overall emission reduction for a 12,500 TEU vessel would only be approximately 0.6% of the total emissions from the supply chain.

In addition to cold ironing, another major initiative taken by the Port of Los Angeles and Long Beach is the Green Flag Program. This program rewards vessels that call the area to reduce their speed to 12 kts when they are 20 nm seaward from the entrance to harbor. As a large percentage of vessels are operating accordingly, the calculations for vessels bound for Los Angeles take into account the change in speed with the corresponding reduction in load factor from vessel speed reduction.

¹¹ "Publication 151 - Distance Between Ports." National Imagery and Mapping Agency, 2001

¹² Monthly Canal Operations Summary 2008-2009, Autoridad Del Canal de Panama

¹³ Suez Canal Authority website, <http://www.suezcanal.gov.eg/>

Table 4: Distance Between Ports

Origin Port	Destination Port	Canal	Nautical Miles
Shanghai	Seattle		5,067
	Oakland		5,399
	Los Angeles		5,699
	Prince Rupert		4,607
	Savannah	Panama	10,172
	Savannah	Suez	12,915
	New York	Panama	10,582
	New York	Suez	12,357
	Norfolk	Panama	10,391
	Norfolk	Suez	12,520
	Houston	Panama	10,149
	Houston	Suez	13,939
Hong Kong	Seattle		5,768
	Oakland		6,047
	Los Angeles		6,380
	Prince Rupert		5,286
	Savannah	Panama	10,801
	Savannah	Suez	12,162
	New York	Panama	11,211
	New York	Suez	11,604
	Norfolk	Panama	11,020
	Norfolk	Suez	11,767
	Houston	Panama	10,778
	Houston	Suez	13,186
Singapore	Seattle		7,062
	Oakland		7,356
	Los Angeles		7,867
	Prince Rupert		6,683
	Savannah	Panama	12,111
	Savannah	Suez	10,708
	New York	Panama	12,521
	New York	Suez	10,150
	Norfolk	Panama	12,330
	Norfolk	Suez	10,313
	Houston	Panama	12,088
	Houston	Suez	11,732

2.1.4 Emission Factors

Fuel based emissions factors are taken from *2006 IPCC Guidelines for National Greenhouse Gas Inventories*¹⁴. These emissions factors have been used as the basis for numerous other greenhouse gas emission studies and inventories. It was assumed that both propulsion and auxiliary engines are operating solely on heavy fuel oil. Fuel based emission factors (kg / tonne fuel) were converted to power based emission factors (kg/ kW-hr) by multiplying the appropriate fuel based emission factor by the specific fuel consumption in each mode.

Fuel-based emission factors from IPCC are listed in Table 5

¹⁴ 2006 IPCC Guidelines For National Greenhouse Gas Inventories

Table 5: Fuel Emission Factors for Main Propulsion and Auxiliary Machinery

	Fuel Emission Factor (kg pollutant/tonne fuel)	
	Propulsion	Auxiliary
CO ₂	3,134	3,134
CH ₄	0.28	0.28
N ₂ O	0.08	0.08

Fuel based emission factors based on the fuel consumption of the engine are listed in Table 6.

Table 6: Power Emission Factors for Ship's Main Propulsion and Auxiliary Machinery

	Power Emission Factors (kg pollutant / kW-hr)		
	Shipboard Propulsion	Shipboard Auxiliary	
	Vessels #1,2,3,&4	Vessel #1	Vessel #2/3/4
CO ₂	0.548	0.617	0.595
CH ₄	0.00005	0.00006	0.00005
N ₂ O	0.00001	0.00002	0.00002

2.2 Locomotives

In order to estimate the emissions from locomotives, a calculation for the required number of locomotives to transport the cargo from the ship to its destination was performed. It was assumed that all the cargo was carried on double stack railcars where each railcar was capable of holding 4 TEUs (4 x 20' containers or 2 x 40ft containers). Each TEU was assumed to weigh 10 MT.¹⁵ A railcar, the Maxi-Stack IV, was used for rail car tare weight¹⁶. A common locomotive, EMD's SD-70, was selected to perform the hauling duties¹⁷. An average speed of 30 mph was selected based on performance measures from Association of American Railroads and Railroad Performance Measures¹⁸. A horsepower per ton (HPT) ratio of 2 was selected¹⁹ for a typical intermodal train covering a range of grades at this average speed.

In addition to emissions from the line haul locomotives, an additional factor was applied to the line haul greenhouse gas emissions to account for emissions from switching locomotives. An additional 10% was applied to the line haul emissions to account for necessary switching both on and off port. The factor was determined by comparing the fuel consumptions of freight and yard switching activities as reported by the major railroads companies in their annual R-1 Annual Reports to the Surface Transportation Board²⁰. While total freight fuel consumption in the R-1 Reports includes cargo other than intermodal, it is assumed for the purposes of this study that the relative percentage of yard switching fuel consumption is the same for all types of cargo.

¹⁵ "Interim Guidelines for Voluntary Ship CO₂ Emissions Indexing for Use in Trials", MEPC/Circ.471, International Maritime Organization.

¹⁶ www.grbx.com

¹⁷ www.uprr.com

¹⁸ Association of American Railroads website, www.aar.org

¹⁹ Correspondence with Class I railroads

²⁰ <http://www.stb.dot.gov/econdata.nsf/f039526076cc0f8e8525660b006870c9?OpenView>

The results of this calculation are presented below:

Table 7: Train Characteristics

Typical Train Characteristics	
Average Speed	30 mph
Horsepower / Ton Ratio	2
Horsepower per Locomotive	4000 hp
Brake Specific Fuel Consumption	235 kg/kW-hr
Weight per Locomotive	207 tons
Tare Weight of Railcar	22.6 tons

2.2.1 Maximum Continuous Ratings for Locomotives

Using the HPT ratio, an estimated weight of the cargo, and the combined weight of the locomotives and rail cars, a calculation was performed to determine the required locomotive horsepower to move the container load. It was assumed that all track conditions exhibit similar environmental, gradient, and curvature characteristics.

Table 8: Required Locomotive Power per Container Load for Representative Vessels

	4500 TEU Vessel	6500 TEU Vessel	8500 TEU Vessel	12500 TEU Vessel
Locomotive Power (kW)	128,262	181,954	235,645	354,959
Number of Locomotives	43	61	79	119

2.2.2 Load Factors for Locomotives

The load factor used for rail operations was determined using weighted time in notch settings as per recent port emission inventories^{21,22}. The load factor applied in this study is 0.28²³. This load value is based on operation data taken from 63 trains from 4 Class I railroads over many sections of the country with various types of terrain.²⁴ Since this load factor represents the emissions from the engine operation and average speed over the entire transit, the analysis was performed on just one 'average' operational mode (speed, grade, HP requirement).

To better understand the impact of the 'average' grade assumption on the results a sensitivity check was performed. The concern was that the fuel consumption of intermodal trains traveling over high grade tracks, such as areas in the Cascades, Sierras, or Rocky Mountains, may be sufficiently higher than the fuel consumption of trains traveling over grades faced by East Coast ports and alter key findings. To account for the higher than average grades, a 30% fuel

²¹ Puget Sound Maritime Air Emissions Inventory, Starcrest Consulting Group, April 2007.

²² Port of Los Angeles Inventory of Air Emissions CY 2005, September 2007.

²³ Puget Sound Maritime Air Emissions Inventory, Starcrest Consulting Group, April 2007.

²⁴ Locomotive Emission Standards – Regulatory Support Document, US Environmental Protection Agency, April 1998.

consumption penalty was given to the West Coast ports while no additional factor was applied to the East Coast ports. This 30% figure was based on EPA research comparing the fuel consumption on zero grade routes with the consumption on the highest grades in the U.S.²⁵ This very conservative assumption ignores the fact that trains traveling over the Appalachian mountain range would also experience an increase in fuel consumption over a zero grade baseline. When evaluated on this basis, East Coast ports outperform the West Coast ports only for intermodal trips heading to Columbus and Memphis from Singapore.

2.2.3 Activity Time in Mode

The time to deliver the cargo was determined by dividing the rail distance from each coastal port to the cities of Chicago, Memphis, and Columbus by the assumed speed of the locomotive. Rail distances were determined by selecting the rail mileages found in the 2006 Public Use Waybill File²⁶ between the required destinations. The Public Use Waybill File, provided by the Surface Transportation Board, collects a sample of railroad shipment waybills within North America and gives the information in an electronic data file. Information regarding the commodity shipped, origin of shipment, destination of shipment, and mileage are all listed on the waybill. Listed distances are the ramp to ramp distances and may vary somewhat based on the carrier, the location of the carrier's container terminal, and any transfers between carriers that may occur. In several cases, shipments terminated at the extent of a carrier's track on certain routes. In these cases, distances were calculated by summing the mileages of the first trip to the intermediate point and then from the intermediate point to the final destination. This primarily occurs with cargo coming from the West Coast and terminating in Kansas City, Memphis, or Chicago without continuing further east to cities such as Columbus. It was assumed that all major Class I rail tracks have the necessary weight and clearance requirements for double stack intermodal shipments.

Rail distances used in this study are presented in Table 9.

Table 9: Rail Distances Between Ports and Inland Facilities

	Rail Distances (Statute Miles)		
	Chicago	Columbus	Memphis
Seattle	2,200	2,520	2,710
Oakland	2,370	2,690	2,400
Los Angeles	2,100	2,420	2,100
Norfolk	1,000	660	960
Savannah	1,080	1,400	710
Prince Rupert	2,592	2,902	3,070
New York	950	760	1,150
Houston	1,100	1,250	560

2.2.4 Emission Factors for Locomotives

²⁵ Development of Railroad Emission Inventory Methodologies – Report No. SR2004-06-02, Sierra Research Inc, June 2004.

²⁶ 2006 Public Use Waybill, Surface Transportation Board.

Fuel based emissions factors were taken from *2006 IPCC Guidelines for National Greenhouse Gas Inventories*²⁷. It was assumed that locomotives operate on standard U.S. off-road diesel. These emission factors were converted to power based emission factors by multiplying the appropriate fuel based emission factor by the specific fuel consumption.

Fuel-based and power specific emission factors from IPCC are listed in Table 10.

Table 10: Rail Emission Factors

	Railway Emission Factors	
	kg pollutant/tonne fuel	kg pollutant / kW-hr
CO ₂	3,164	0.744
CH ₄	0.18	0.00004
N ₂ O	1.22	0.00029

2.2.5 Port Operations and Drayage

Marine containers require additional equipment in order to be moved from the containerships to the intermodal line haul locomotives that will ultimately deliver them to their final inland destination. This process is quite complex and can differ greatly depending on the specific cargo handling equipment (CHE), location, and layout of the ports and terminals. While some ports have extensive on dock rail capabilities and short drays to off dock facilities, other ports have minimal port rail operations and therefore a large percentage of the containers are drayed as much as 25 miles away via Heavy Duty Diesel Vehicles (HDDV).

To determine the emissions from CHE, calculations were initially performed using available emission inventories^{28,29,30} that estimated total CO₂e emissions from CHE's at container terminals. Using this information in conjunction with TEU throughput from AAPA statistics³¹, an approximation of greenhouse gas emissions during drayage operations per TEU could be determined. This, in turn, could be applied to the amount of TEUs for each case to determine the amount of CO₂e that would be emitted by CHE in the handling of the containers. The factor was calculated to be 0.025 MT CO₂e/ TEU.

To determine the amount of emissions from drayage trucks transporting containers to near dock or off dock rail yards, a more detailed calculation of emissions per HDDV was required. This was done because within port emissions inventories, it was difficult to separate specific data to determine which shipments represented container traffic bound for intermodal transfer facilities and which traffic was bound for distribution centers and local use.

In order to understand the range of emissions from drayage trucks transporting containers bound for intermodal facilities two extreme assumptions were considered: 1) 90% of containers required

²⁷ 2006 IPCC Guidelines For National Greenhouse Gas Inventories

²⁸ Port of Long Beach Inventory of Air Emissions Inventory - 2006, Starcrest Consulting Group, June 2008

²⁹ Puget Sound Maritime Air Emissions Inventory, Starcrest Consulting Group, April 2007

³⁰ Port of Long Beach Inventory of Air Emissions Inventory - 2007, Starcrest Consulting Group, Jan 2009

³¹ <http://www.aapa-ports.org/>

drayage, and 2) 10% of containers required drayage. It was assumed that one truck carried one container (or 2 TEUs). The average dray distance and average idling time was selected to be 10 miles and 1 hour, respectively. This drayage calculation utilized emission factors for HDDVs in running and idling modes presented as g/mile drayed and g/hours idling³². Given a certain amount of containers departing for off-dock facilities with the HDDVs having assumed distances and idling times, the amount of emissions could be estimated.

The result for the case with 90% drayage was 0.012 MT CO₂e/ TEU. For the case with 10% drayage, the corresponding emission was calculated to be 0.001 MT CO₂e/ TEU. Doubling the average dray distance to 20 miles nearly doubles the MT CO₂e/ TEU. A range from 0.001 MT CO₂e/ TEU to 0.025 MT CO₂e/ TEU could be possible depending on the characteristics of the port being evaluated.

Total emissions from drayage, considering both CHE and trucks, are projected to be, on average, no more than 0.037 MT CO₂e/ TEU. This is less than 3% of the total carbon footprint of even the shortest intermodal trip. If we consider that deviation from this average value is no more than a 1.5% added benefit or cost, it can be said that drayage and CHE considerations have little if any noticeable impact on key conclusions. For the calculations presented herein, the average value of 0.037 CO₂e/ TEU is applied for all trips and port combinations.

³² Port of Long Beach Inventory of Air Emissions Inventory - 2006, Starcrest Consulting Group, June 2008

3 Emission Estimate Calculations

Summaries of CO₂e emissions for the various combinations of ship size and route configurations are provided in Appendix A (Table A-1 through Table A-4). Analyses for four different containerships of sizes 4,500, 6,500, 8,500, and 12,500 TEU capacities are presented. The matrix includes containership departures from Shanghai, Hong Kong, and Singapore going to Chicago, Columbus, and Memphis through the various North American ports. The summary tables provide CO₂e emission figures for containerships including the voyage leg plus in-port emissions (identified as Ocean CO₂e), for locomotives covering rail movements between the container port and inland facilities (identified as Rail CO₂e), and the total CO₂e emissions. Total emissions include the ocean and rail contributions plus a factor for drayage.

Emissions are given for East Coast bound vessels transiting through both the Panama Canal and the Suez Canal for all Asian departures. Currently, the Panama Canal size restrictions do not permit the passage of containerships larger than about 4,500 TEU. The figures for Post-Panamax vessels are provided for informational purposes. It should be noted that vessels traveling to East Coast ports from Singapore have shorter ocean distances via the Suez Canal than by going through the Panama Canal.

Appendix B (Table B-1 through Table B-3) gives CO₂e emission figures with the assumption that larger containerships are able to transit the Panama Canal. Work to expand the Panama Canal to accommodate these larger vessels is currently underway, with expected completion in 2014. Once this work is completed, containerships up to approximately 12,500 TEUs in capacity will be able to transit the canal. This will significantly reduce ocean distances for vessels departing the ports of Shanghai and Hong Kong heading to North American East Coast ports. East Coast ports have been preparing for the upcoming expansion by improving their current port infrastructure so that the ports have enough navigable depth, crane reach, and capacity to handle the potential new traffic.

4 Key Facts and Findings

1. West Coast ports have a distinct advantage in total mass of greenhouse gas emitted as compared to East Coast ports, when considering single intermodal shipments from Asian ports to internal U.S. cities. This finding is consistent over all four container ship sizes. The primary reason is that the West Coast port ocean distances from China are considerably shorter than the East Coast distances.
2. Amongst the West Coast ports, Prince Rupert has the shortest ocean distance with the distances increasing as the ports move south with the Port of Los Angeles having the longest ocean trip. For example, the voyage from Shanghai to Seattle is about 632 nautical miles or about 11% shorter than the voyage from Shanghai to Los Angeles. East Coast ports have longer ocean distances and shorter rail distances than any of the West Coast ports. For example, the distance from Shanghai to New York via the Panama Canal is about 5,515 nautical miles further, or more than twice the distance, when compared to the voyage from Shanghai to Seattle. As the Asian departures move further south from Shanghai to the ports of Hong Kong and Singapore, the difference in ocean distance between East and West Coast ports becomes less significant.
3. A comparison of the emissions of oceangoing containerships and domestic rail service shows that marine transportation emits about 1.5 to 2.25 less CO₂e per TEU-km than rail transportation. As an example, a 12,500 TEU containership at 90% utilization emits approximately 0.07 kg / TEU-km while rail would transport the offloaded containers with emissions of 0.17 kg / TEU-km. This relationship favors shipping over rail transportation, all things being equal. However, the ocean distance from Asian ports to the West Coast ports and, in particular, the ports of Prince Rupert and Seattle are so much shorter than the ocean distances to the East Coast ports that this more than offsets the detrimental impact of the longer rail distances from the West Coast ports.
4. The mileage benefit offered by West Coast ports is amplified with Post-Panamax vessels since they are currently unable to transit the Panama Canal, thereby increasing their ocean distances by as much as 2,500 nm when departing from northern Asia ports. Post-Panamax containerships are significantly more CO₂e efficient per TEU than the smaller Panamax containerships, which are constrained by the beam and draft restrictions of the Panama Canal.
5. While West Coast ports have a significant CO₂e over the East Coast ports, the differences among the West Coast ports are smaller. The ports of Seattle and Prince Rupert offer the shortest shipping distances to the Far East ports and therefore offer lower carbon footprints for specific origins and destinations. As a consequence, Pacific Northwest ports have the lowest amount of CO₂e emission over all the shipments to Columbus and Chicago. For example, total CO₂e emissions per TEU moved between Shanghai and Chicago via the port of Seattle on a 8,500 TEU containership is estimated at 1.52 MT/ TEU. The corresponding figure for total CO₂e emissions per TEU moved between Shanghai and Chicago via the Panama Canal and New York on an 8,500 TEU containership is estimated at 2.57 MT per TEU. For this scenario, the Pacific Northwest option offers a 41% reduction in overall CO₂e emissions.

6. Although the Prince Rupert has smaller ocean distances than Port of Seattle, correspondingly longer rail distances to inland destinations more than offset the lesser ocean emissions. The differences between these two ports are quite small and neither port has a distinct advantage over the other with regards to combined CO₂e emission from ship and rail. Sensitivity analyses demonstrate that small changes in assumptions can change the relative ranking between these ports.
7. Los Angeles generally has the lowest emissions for container shipments to Memphis. Los Angeles is closer to Memphis by rail by as much as 600 miles when compared to the North West Coast ports due to its southern location in the US. For a few scenarios, Oakland has the least amount of emissions to Memphis. This occurs in the cases of 4,500, 6,500, and 8,500 TEU ships departing Singapore. With rail transport being less efficient (MT CO₂e/ TEU / mile) as compared to ocean shipping, any ocean route advantage held by the northern West Coast ports is eroded during the rail leg of these shipments.
8. In one scenario, a 12,500 TEU shipment that originates in Singapore bound for Columbus shows lower emissions when transiting through Norfolk than West Coast ports. In this case, the West Coast ports are at a disadvantage because a higher volume of containers are traveling a relatively longer distance via rail while the ocean distance advantage is lower for the southern Asia ports. Vessels leaving from southern Asian ports traveling to North East Coast ports through the Suez Canal have ocean distances that are within 4,000 nm of the closest Pacific Northwest ports. The reduced ocean distance differential, short rail distances, and large container payloads may give the North East Coast ports the carbon footprint advantage in these particular cases, especially in instances of large container loads.
9. Terminal operations and drayage emissions are not a major contributor to total intermodal transport emissions.
10. Once the Panama Canal expansion project is completed allowing larger ships to transit the canal, oceangoing distances for Post Panamax size ships departing the Asian ports of Shanghai and Hong Kong will be significantly reduced for voyages to East Coast ports. West Coast ports still retain their carbon emission advantage, however, especially for North Asia originated shipments. Ocean distances to the East Coast ports via the Panama Canal are nearly double the distances to the Pacific Northwest ports when departing from Shanghai. Analyses demonstrate that the CO₂e efficiencies gained by moving the larger containerships through the Panama Canal are still not sufficient to offset the benefits of the shorter ocean legs to the West Coast ports. For example, total CO₂e emissions per TEU moved between Shanghai and Chicago via the port of Seattle on a 12,500 TEU containership is estimated at 1.32 MT per TEU. The corresponding figure for total CO₂e emissions per TEU moved between Shanghai and Chicago via the Panama Canal and the port of New York on a 12,500 TEU containership is estimated at 1.73 MT /TEU. For this scenario, the Seattle option offers a 31% reduction in overall CO₂e emissions.

Appendix A: DATA TABLES

A.1 4,500 TEU Container Ships

Origin Port	Destination Port	Via Canal	Ocean CO ₂ e (MT)			Rail CO ₂ e (MT)			Total CO ₂ e (MT)			Total CO ₂ e per TEU (MT/TEU)		
			Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis
Shanghai	Seattle		4,269	2,352	2,934	2,728	2,934	6,800	7,146	7,352	1,700	1,787	1,838	
	Oakland		4,547	2,566	2,598	2,912	2,598	7,262	7,608	7,294	1,816	1,902	1,824	
	Los Angeles		4,764	2,274	2,274	2,620	2,274	7,186	7,533	7,186	1,797	1,883	1,797	
	Prince Rupert		3,884	2,806	3,142	3,324	3,324	6,839	7,175	7,357	1,710	1,794	1,839	
	Savannah	Panama	8,557	1,169	1,516	1,516	769	9,875	10,222	9,475	2,469	2,556	2,369	
	Savannah	Suez	10,823	1,169	1,516	1,516	769	12,141	12,488	11,741	3,036	3,122	2,936	
	New York	Panama	8,900	1,029	823	1,245	1,245	10,078	9,872	10,294	2,520	2,468	2,574	
	New York	Suez	10,356	1,029	823	1,245	1,245	11,534	11,328	11,750	2,884	2,832	2,938	
	Norfolk	Panama	8,740	1,083	715	1,039	1,039	9,972	9,604	9,929	2,493	2,401	2,482	
	Norfolk	Suez	10,456	1,083	715	1,039	1,039	11,687	11,319	11,644	2,922	2,830	2,911	
	Houston	Panama	8,538	1,191	1,353	606	606	9,878	10,040	9,293	2,470	2,510	2,323	
	Houston	Suez	11,680	1,191	1,353	606	606	13,020	13,183	12,436	3,255	3,296	3,109	
Hong Kong	Seattle		4,856	2,382	2,934	2,728	2,934	7,387	7,733	7,939	1,847	1,933	1,985	
	Oakland		5,089	2,566	2,598	2,912	2,598	7,804	8,151	7,837	1,951	2,038	1,959	
	Los Angeles		5,334	2,274	2,274	2,620	2,274	7,756	8,103	7,756	1,939	2,026	1,939	
	Prince Rupert		4,452	2,806	3,142	3,324	3,324	7,408	7,743	7,925	1,852	1,936	1,981	
	Savannah	Panama	9,083	1,169	1,516	1,516	769	10,402	10,748	10,001	2,601	2,687	2,501	
	Savannah	Suez	10,156	1,169	1,516	1,516	769	11,474	11,821	11,074	2,869	2,955	2,769	
	New York	Panama	9,426	1,029	823	1,245	1,245	10,604	10,398	10,821	2,651	2,600	2,705	
	New York	Suez	9,689	1,029	823	1,245	1,245	10,867	10,661	11,083	2,717	2,665	2,771	
	Norfolk	Panama	9,267	1,083	715	1,039	1,039	10,498	10,130	10,455	2,625	2,533	2,614	
	Norfolk	Suez	9,825	1,083	715	1,039	1,039	11,057	10,689	11,014	2,765	2,673	2,754	
	Houston	Panama	9,064	1,191	1,353	606	606	10,404	10,566	9,819	2,601	2,642	2,455	
	Houston	Suez	11,013	1,191	1,353	606	606	12,353	12,515	11,768	3,089	3,129	2,942	
Singapore	Seattle		5,939	2,382	2,934	2,728	2,934	8,470	8,816	9,022	2,118	2,204	2,256	
	Oakland		6,185	2,566	2,598	2,912	2,598	8,900	9,246	8,932	2,225	2,312	2,233	
	Los Angeles		6,578	2,274	2,274	2,620	2,274	9,001	9,348	9,001	2,250	2,337	2,250	
	Prince Rupert		5,622	2,806	3,142	3,324	3,324	8,577	8,913	9,094	2,144	2,228	2,274	
	Savannah	Panama	10,180	1,169	1,516	1,516	769	11,498	11,845	11,098	2,875	2,961	2,775	
	Savannah	Suez	8,939	1,169	1,516	1,516	769	10,108	10,455	9,708	2,527	2,614	2,427	
	New York	Panama	10,523	1,029	823	1,245	1,245	11,701	11,495	11,917	2,925	2,874	2,980	
	New York	Suez	8,472	1,029	823	1,245	1,245	9,500	9,295	9,717	2,375	2,324	2,429	
	Norfolk	Panama	10,363	1,083	715	1,039	1,039	11,595	11,227	11,552	2,899	2,807	2,888	
	Norfolk	Suez	8,608	1,083	715	1,039	1,039	9,691	9,323	9,648	2,423	2,331	2,412	
	Houston	Panama	10,160	1,191	1,353	606	606	11,501	11,663	10,916	2,875	2,916	2,729	
	Houston	Suez	9,796	1,191	1,353	606	606	10,987	11,149	10,402	2,747	2,788	2,601	

Table A-1 4,500 TEU CO₂e Emission Calculations

Figure A-1: Total CO₂e Emissions per 4,500 TEU Intermodal Delivery from Shanghai

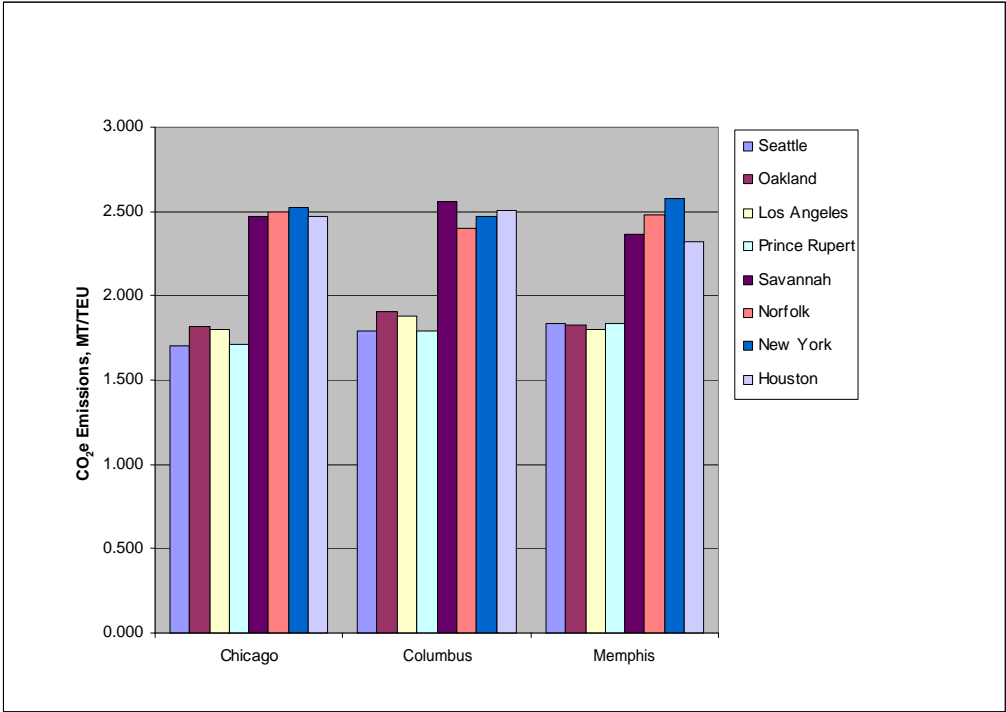


Figure A-2: Total CO₂e Emissions per 4,500 TEU Intermodal Delivery from Hong Kong

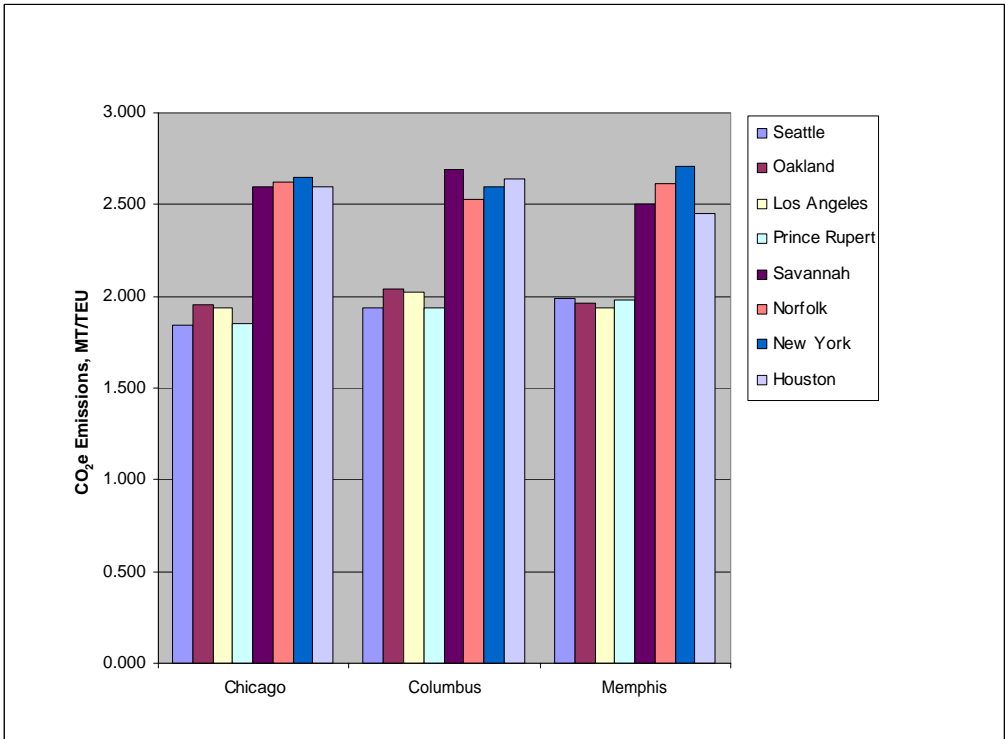


Figure A-3: Total CO₂e Emissions per 4,500 TEU Intermodal Delivery from Singapore

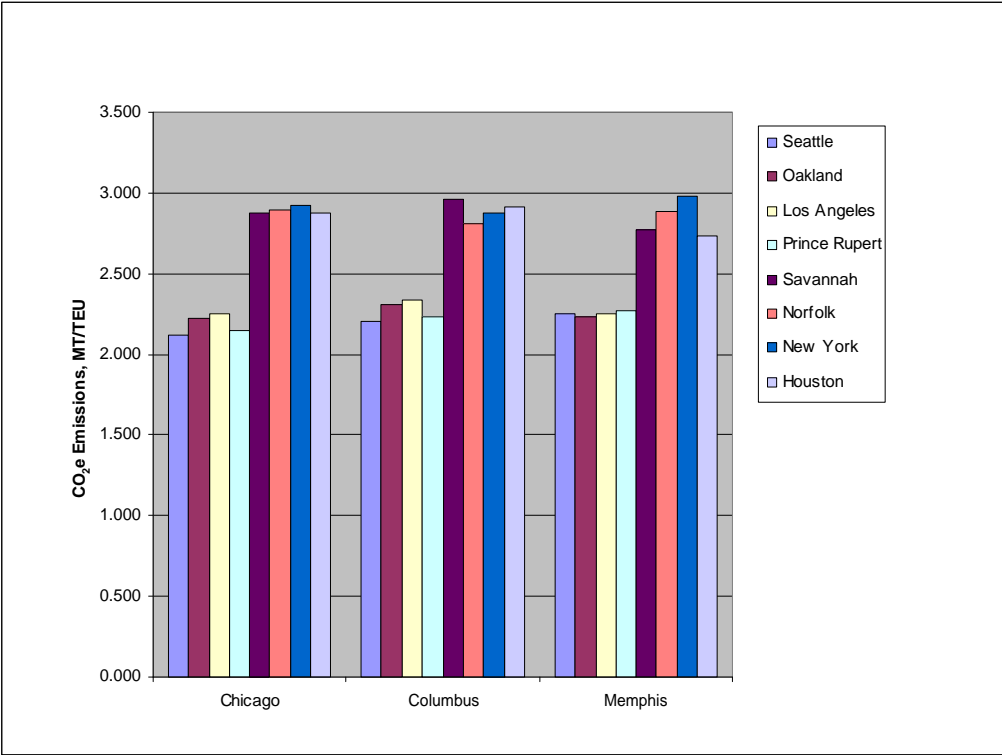
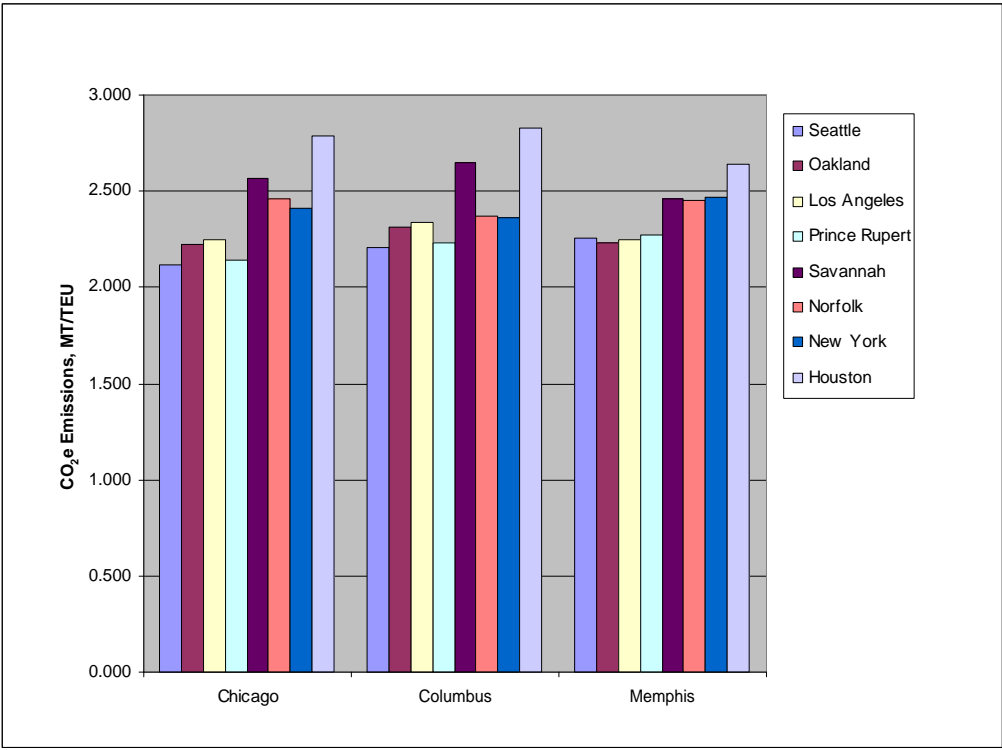


Figure A-4: Total CO₂e Emissions per 4,500 TEU Intermodal Delivery from Singapore (East Coast Bound Ships Through the Suez Canal)



A.2 6,500 TEU Container Ships

Origin Port	Destination Port	Via Canal	Ocean CO ₂ e (MT)			Rail CO ₂ e (MT)			Total CO ₂ e (MT)			Total CO ₂ e per TEU (MT/TEU)		
			Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis
Shanghai	Seattle		3,379	3,870	4,162	9,098	9,590	9,881	1,579	1,664	1,715			
	Oakland		3,640	4,131	3,686	9,717	10,208	9,763	1,686	1,772	1,694			
	Los Angeles		3,225	3,717	3,225	9,580	10,072	9,580	1,663	1,748	1,663			
	Prince Rupert		3,981	4,457	4,715	9,205	9,681	9,939	1,598	1,680	1,725			
	Savannah	Panama		1,659	2,150	1,090	12,890	13,382	12,322	2,237	2,322	2,139		
	Savannah	Suez		1,659	2,150	1,090	15,761	16,252	15,192	2,735	2,821	2,637		
	New York	Panama		1,459	1,167	1,766	13,132	12,840	13,439	2,279	2,229	2,332		
	New York	Suez		1,459	1,167	1,766	14,960	14,668	15,267	2,596	2,546	2,650		
	Norfolk	Panama		1,536	1,014	1,474	13,003	12,481	12,942	2,257	2,166	2,246		
	Norfolk	Suez		1,536	1,014	1,474	15,213	14,690	15,151	2,640	2,550	2,630		
	Houston	Panama		1,689	1,920	860	12,896	13,127	12,067	2,238	2,278	2,094		
	Houston	Suez		1,689	1,920	860	16,894	17,124	16,065	2,932	2,972	2,788		
Hong Kong	Seattle		3,379	3,870	4,162	9,853	10,344	10,636	1,710	1,795	1,846			
	Oakland		3,640	4,131	3,686	10,414	10,906	10,460	1,807	1,893	1,815			
	Los Angeles		3,225	3,717	3,225	10,313	10,805	10,313	1,790	1,875	1,790			
	Prince Rupert		3,981	4,457	4,715	9,936	10,412	10,670	1,724	1,807	1,852			
	Savannah	Panama		1,659	2,150	1,090	13,568	14,059	12,999	2,355	2,440	2,256		
	Savannah	Suez		1,659	2,150	1,090	14,950	15,441	14,382	2,595	2,680	2,496		
	New York	Panama		1,459	1,167	1,766	13,809	13,518	14,116	2,397	2,346	2,450		
	New York	Suez		1,459	1,167	1,766	14,150	13,858	14,457	2,456	2,405	2,509		
	Norfolk	Panama		1,536	1,014	1,474	13,680	13,158	13,619	2,374	2,284	2,364		
	Norfolk	Suez		1,536	1,014	1,474	14,402	13,880	14,340	2,500	2,409	2,489		
	Houston	Panama		1,689	1,920	860	13,573	13,804	12,744	2,356	2,396	2,212		
	Houston	Suez		1,689	1,920	860	16,083	16,314	15,254	2,791	2,831	2,647		
Singapore	Seattle		3,379	3,870	4,162	11,246	11,738	12,029	1,952	2,037	2,088			
	Oakland		3,640	4,131	3,686	11,824	12,315	11,870	2,052	2,137	2,060			
	Los Angeles		3,225	3,717	3,225	11,914	12,406	11,914	2,068	2,153	2,068			
	Prince Rupert		3,981	4,457	4,715	11,440	11,916	12,174	1,986	2,068	2,113			
	Savannah	Panama		1,659	2,150	1,090	14,978	15,469	14,410	2,600	2,685	2,501		
	Savannah	Suez		1,659	2,150	1,090	13,384	13,876	12,816	2,323	2,408	2,224		
	New York	Panama		1,459	1,167	1,766	15,220	14,928	15,527	2,642	2,591	2,695		
	New York	Suez		1,459	1,167	1,766	12,584	12,292	12,891	2,184	2,133	2,237		
	Norfolk	Panama		1,536	1,014	1,474	15,091	14,569	15,030	2,619	2,529	2,608		
	Norfolk	Suez		1,536	1,014	1,474	12,836	12,314	12,775	2,228	2,137	2,217		
	Houston	Panama		1,689	1,920	860	14,984	15,214	14,155	2,601	2,641	2,457		
	Houston	Suez		1,689	1,920	860	14,518	14,748	13,688	2,520	2,560	2,376		

Table A-2 6,500 TEU CO₂e Emission Calculations

Figure A-5: Total CO₂e Emissions per 6,500 TEU Intermodal Delivery from Shanghai

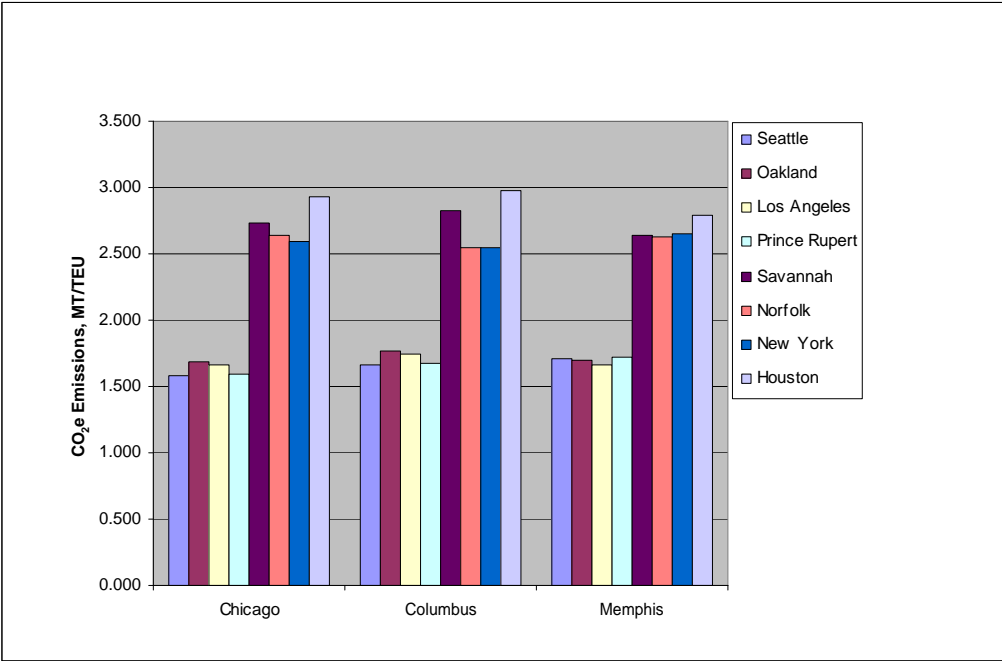


Figure A-6: Total CO₂e Emissions per 6,500 TEU Intermodal Delivery from Hong Kong

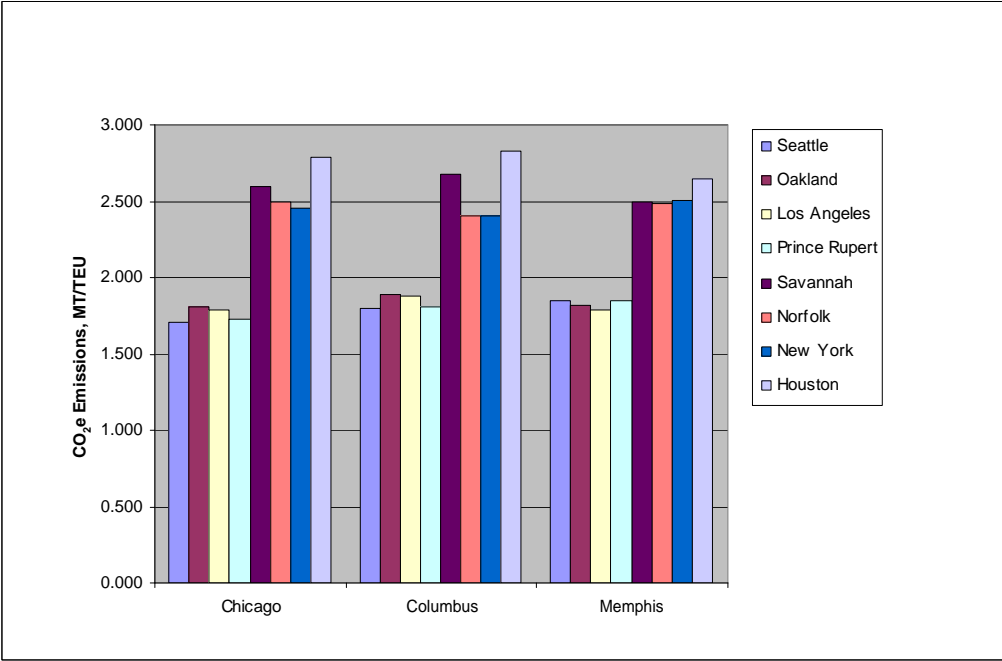
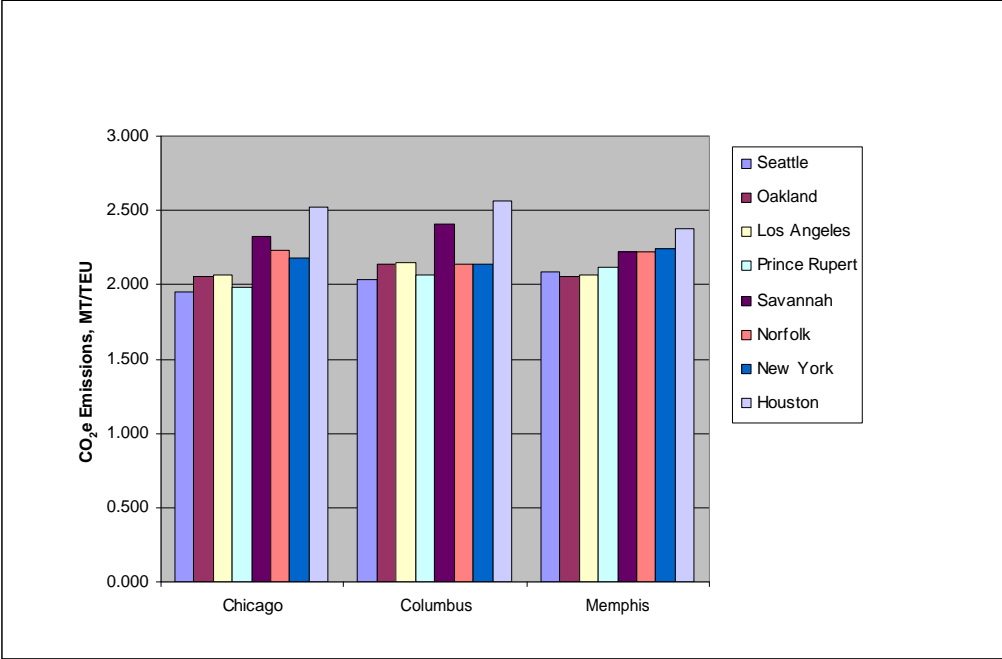


Figure A-7: Total CO₂e Emissions per 6,500 TEU Intermodal Delivery from Singapore



A.3 8,500 TEU Container Ships

Origin Port	Destination Port	Via Canal	Ocean CO ₂ e (MT)			Rail CO ₂ e (MT)			Total CO ₂ e (MT)			Total CO ₂ e per TEU (MT/TEU)		
			Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis
Shanghai	Seattle		6,601	5,012	5,390	11,252	11,889	12,267	1,522	1,608	1,659			
	Oakland		7,029	4,714	5,351	12,019	12,655	12,078	1,626	1,712	1,634			
	Los Angeles		7,362	4,177	4,814	11,815	12,452	11,815	1,598	1,684	1,598			
	Prince Rupert		6,008	5,156	6,106	11,439	12,055	12,390	1,547	1,631	1,676			
	Savannah	Panama	13,210	2,148	2,785	15,634	16,270	14,898	2,115	2,201	2,015			
	Savannah	Suez	16,642	2,148	2,785	19,066	19,702	18,330	2,579	2,665	2,479			
	New York	Panama	13,739	1,890	1,512	15,904	15,526	16,302	2,151	2,100	2,205			
	New York	Suez	15,922	1,890	1,512	18,088	17,710	18,486	2,447	2,396	2,501			
	Norfolk	Panama	13,492	1,989	1,313	15,757	15,081	15,677	2,131	2,040	2,121			
	Norfolk	Suez	16,133	1,989	1,313	18,397	17,721	18,318	2,489	2,397	2,478			
	Houston	Panama	13,180	2,188	2,486	15,644	15,942	14,570	2,116	2,157	1,971			
	Houston	Suez	17,962	2,188	2,486	20,426	20,724	19,352	2,763	2,803	2,618			
Hong Kong	Seattle		7,505	4,376	5,012	12,156	12,793	13,171	1,644	1,730	1,782			
	Oakland		7,864	4,714	5,351	12,854	13,491	12,914	1,739	1,825	1,747			
	Los Angeles		8,241	4,177	4,814	12,693	13,330	12,693	1,717	1,803	1,717			
	Prince Rupert		6,883	5,156	6,106	12,314	12,931	13,265	1,666	1,749	1,794			
	Savannah	Panama	14,021	2,148	2,785	16,445	17,081	15,709	2,224	2,311	2,125			
	Savannah	Suez	15,671	2,148	2,785	18,095	18,731	17,359	2,448	2,534	2,348			
	New York	Panama	14,550	1,890	1,512	16,715	16,337	17,113	2,261	2,210	2,315			
	New York	Suez	14,951	1,890	1,512	17,117	16,739	17,515	2,315	2,264	2,369			
	Norfolk	Panama	14,303	1,989	1,313	16,568	15,892	16,489	2,241	2,150	2,230			
	Norfolk	Suez	15,162	1,989	1,313	17,426	16,750	17,347	2,357	2,266	2,347			
	Houston	Panama	13,991	2,188	2,486	16,455	16,753	15,381	2,226	2,266	2,081			
	Houston	Suez	16,991	2,188	2,486	19,455	19,753	18,381	2,632	2,672	2,486			
Singapore	Seattle		9,173	4,376	5,012	13,825	14,461	14,839	1,870	1,956	2,007			
	Oakland		9,552	4,714	5,351	14,542	15,178	14,602	1,967	2,053	1,975			
	Los Angeles		10,158	4,177	4,814	14,611	15,247	14,611	1,976	2,062	1,976			
	Prince Rupert		8,684	5,156	6,106	14,116	14,732	15,066	1,909	1,993	2,038			
	Savannah	Panama	15,710	2,148	2,785	18,134	18,770	17,398	2,453	2,539	2,353			
	Savannah	Suez	13,796	2,148	2,785	16,220	16,857	15,484	2,194	2,280	2,095			
	New York	Panama	16,239	1,890	1,512	18,404	18,026	18,802	2,490	2,438	2,543			
	New York	Suez	13,077	1,890	1,512	15,242	14,864	15,640	2,062	2,011	2,116			
	Norfolk	Panama	15,993	1,989	1,313	18,257	17,581	18,178	2,470	2,378	2,459			
	Norfolk	Suez	13,287	1,989	1,313	15,552	14,875	15,472	2,104	2,012	2,093			
	Houston	Panama	15,680	2,188	2,486	18,144	18,442	17,070	2,454	2,495	2,309			
	Houston	Suez	15,117	2,188	2,486	17,580	17,879	16,506	2,378	2,418	2,233			

Table A-3 8,500 TEU CO₂e Emission Calculations

Figure A-8: Total CO₂e Emissions per 8,500 TEU Intermodal Delivery from Shanghai

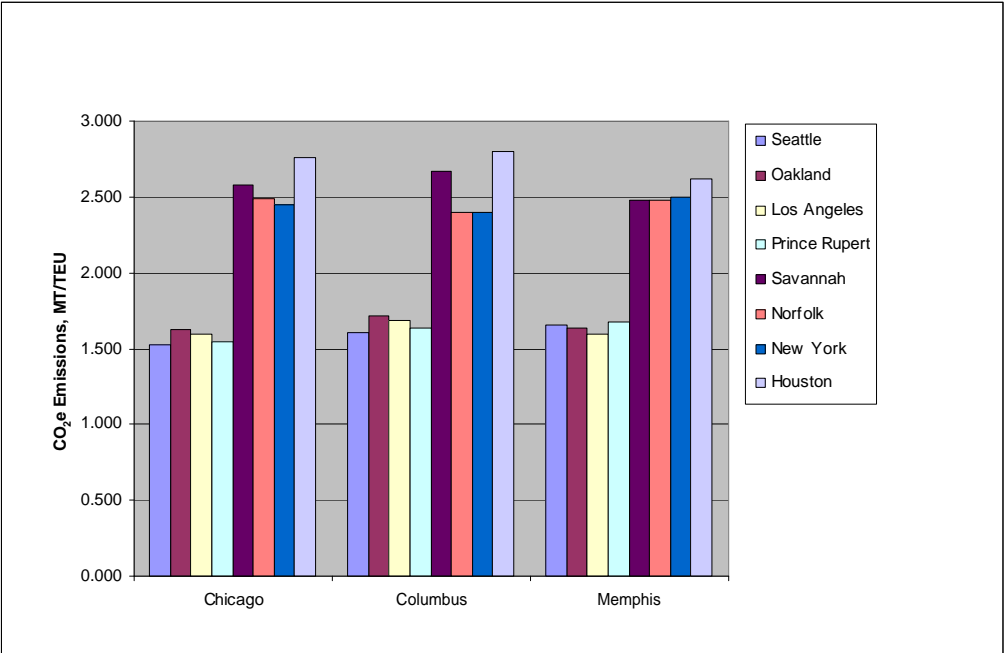


Figure A-9: Total CO₂e Emissions per 8,500 TEU Intermodal Delivery from Hong Kong

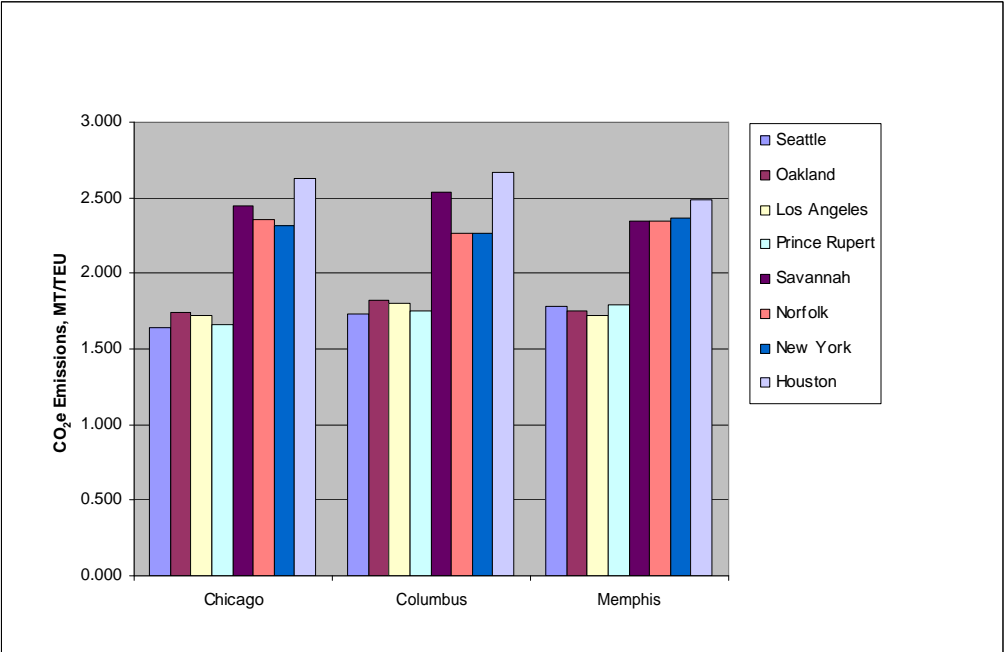
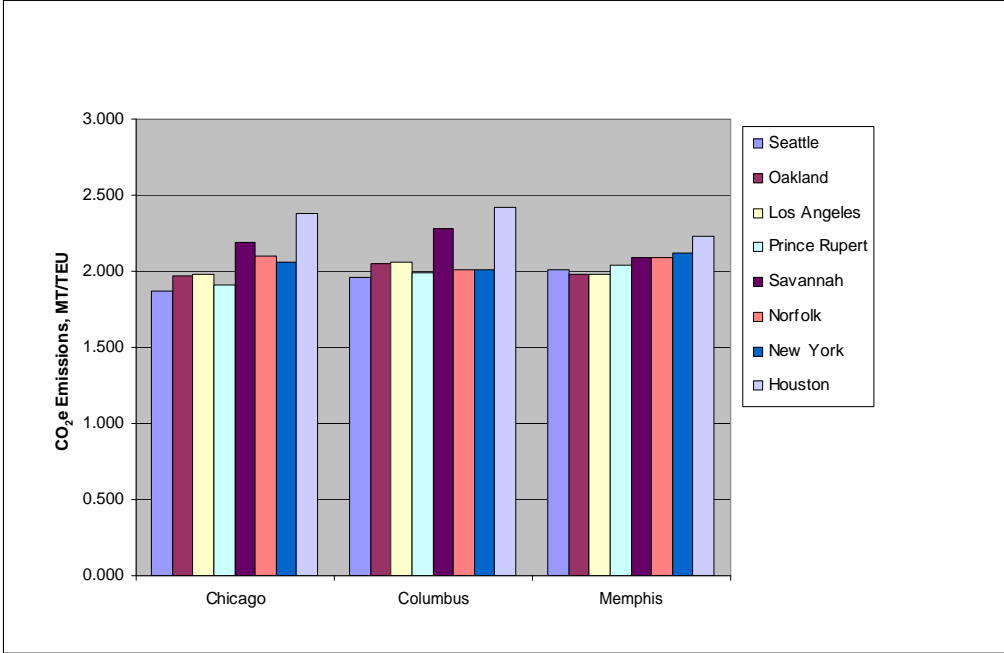


Figure A-10: Total CO₂e Emissions per 8,500 TEU Intermodal Delivery from Singapore



A.4 12,500 TEU Container Ships

Origin Port	Destination Port	Via Canal	Ocean CO ₂ e (MT)			Rail CO ₂ e (MT)			Total CO ₂ e (MT)			Total CO ₂ e per TEU (MT/TEU)		
			Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis
Shanghai	Seattle		6,592	7,550	8,120	14,813	15,771	16,341	1,317	1,402	1,453			
	Oakland		7,101	8,060	7,191	15,827	16,786	15,917	1,407	1,492	1,415			
	Los Angeles		6,292	7,251	6,292	15,413	16,371	15,413	1,370	1,455	1,370			
	Prince Rupert		7,766	8,695	9,198	15,287	16,216	16,719	1,359	1,441	1,486			
	Savannah	Panama	3,236	4,195	2,127	19,254	20,213	18,146	1,711	1,797	1,613			
	Savannah	Suez	3,236	4,195	2,127	23,306	24,264	22,197	2,072	2,157	1,973			
	New York	Panama	2,846	2,277	3,446	19,489	18,919	20,088	1,732	1,682	1,786			
	New York	Suez	2,846	2,277	3,446	22,067	21,498	22,666	1,962	1,911	2,015			
	Norfolk	Panama	2,996	1,977	2,876	19,348	18,329	19,228	1,720	1,629	1,709			
	Norfolk	Suez	2,996	1,977	2,876	22,465	21,446	22,345	1,997	1,906	1,986			
	Houston	Panama	3,296	3,745	1,678	19,279	19,729	17,661	1,714	1,754	1,570			
	Houston	Suez	3,296	3,745	1,678	24,924	25,373	23,306	2,215	2,255	2,072			
Hong Kong	Seattle		6,592	7,550	8,120	15,879	16,838	17,407	1,411	1,497	1,547			
	Oakland		7,101	8,060	7,191	16,813	17,772	16,903	1,494	1,580	1,502			
	Los Angeles		6,292	7,251	6,292	16,438	17,396	16,438	1,461	1,546	1,461			
	Prince Rupert		7,766	8,695	9,198	16,320	17,249	17,752	1,451	1,533	1,578			
	Savannah	Panama	3,236	4,195	2,127	20,211	21,170	19,103	1,797	1,882	1,698			
	Savannah	Suez	3,236	4,195	2,127	22,160	23,119	21,051	1,970	2,055	1,871			
	New York	Panama	2,846	2,277	3,446	20,446	19,876	21,045	1,817	1,767	1,871			
	New York	Suez	2,846	2,277	3,446	20,921	20,352	21,520	1,860	1,809	1,913			
	Norfolk	Panama	2,996	1,977	2,876	20,305	19,286	20,185	1,805	1,714	1,794			
	Norfolk	Suez	2,996	1,977	2,876	21,319	20,300	21,199	1,895	1,804	1,884			
	Houston	Panama	3,296	3,745	1,678	20,236	20,686	18,618	1,799	1,839	1,655			
	Houston	Suez	3,296	3,745	1,678	23,778	24,227	22,160	2,114	2,154	1,970			
Singapore	Seattle		6,592	7,550	8,120	17,848	18,807	19,376	1,587	1,672	1,722			
	Oakland		7,101	8,060	7,191	18,805	19,764	18,895	1,672	1,757	1,680			
	Los Angeles		6,292	7,251	6,292	18,711	19,670	18,711	1,663	1,748	1,663			
	Prince Rupert		7,766	8,695	9,198	18,446	19,375	19,878	1,640	1,722	1,767			
	Savannah	Panama	3,236	4,195	2,127	22,205	23,163	21,096	1,974	2,059	1,875			
	Savannah	Suez	3,236	4,195	2,127	19,947	20,906	18,839	1,773	1,858	1,675			
	New York	Panama	2,846	2,277	3,446	22,439	21,870	23,038	1,995	1,944	2,048			
	New York	Suez	2,846	2,277	3,446	18,709	18,139	19,308	1,663	1,612	1,716			
	Norfolk	Panama	2,996	1,977	2,876	22,298	21,280	22,178	1,982	1,892	1,971			
	Norfolk	Suez	2,996	1,977	2,876	19,107	18,088	18,987	1,698	1,608	1,688			
	Houston	Panama	3,296	3,745	1,678	22,230	22,679	20,612	1,976	2,016	1,832			
	Houston	Suez	3,296	3,745	1,678	21,565	22,015	19,947	1,917	1,957	1,773			

Table A-4 12,500 TEU CO₂e Emission Calculations

Figure A-11: Total CO₂e Emissions per 12,500 TEU Intermodal Delivery from Shanghai

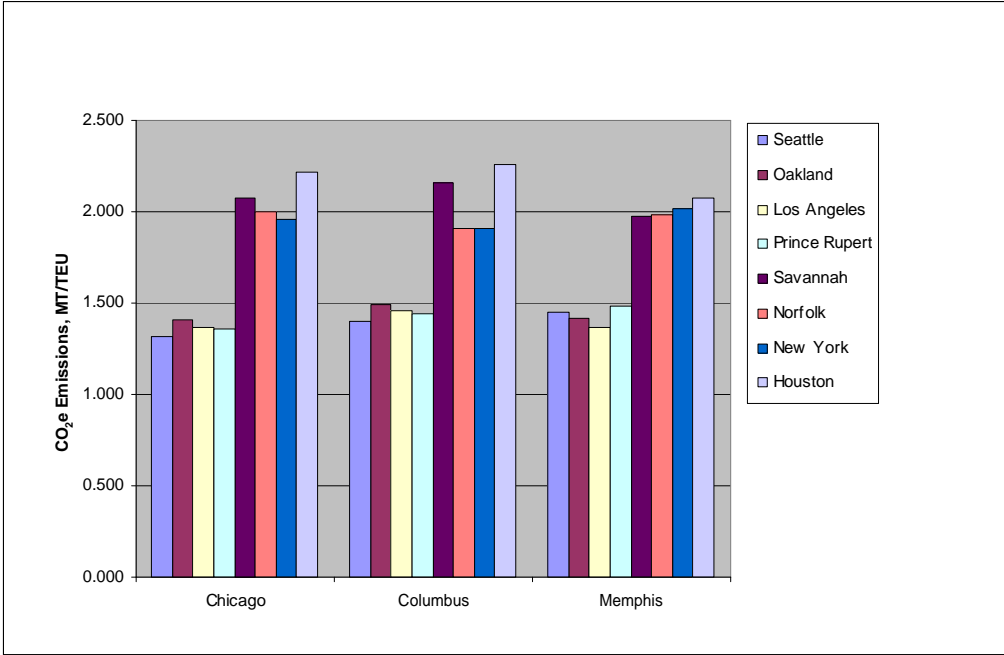


Figure A-12: Total CO₂e Emissions per 12,500 TEU Intermodal Delivery from Hong Kong

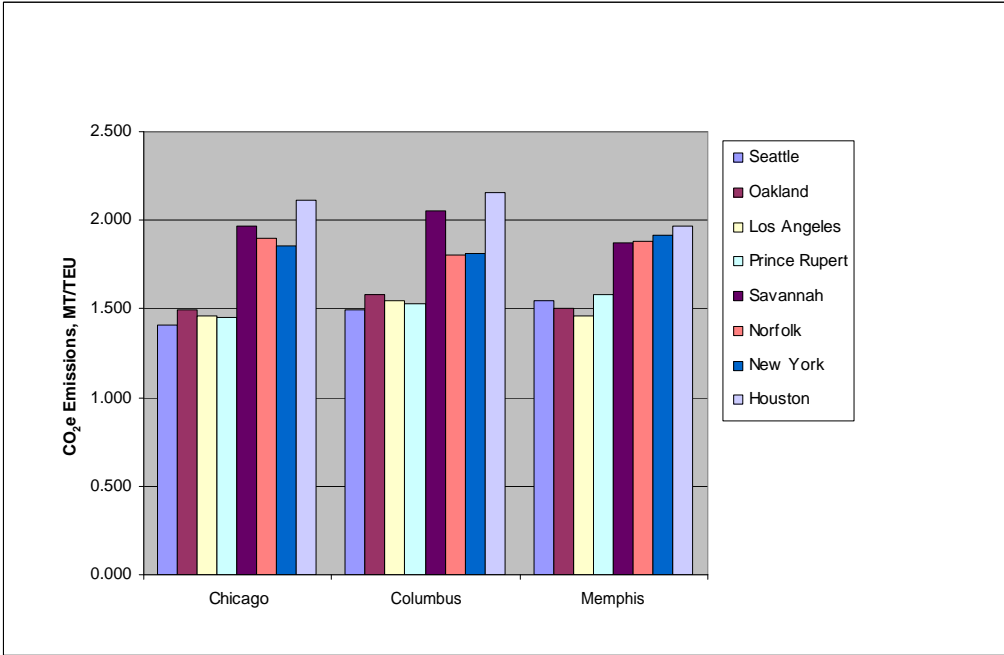
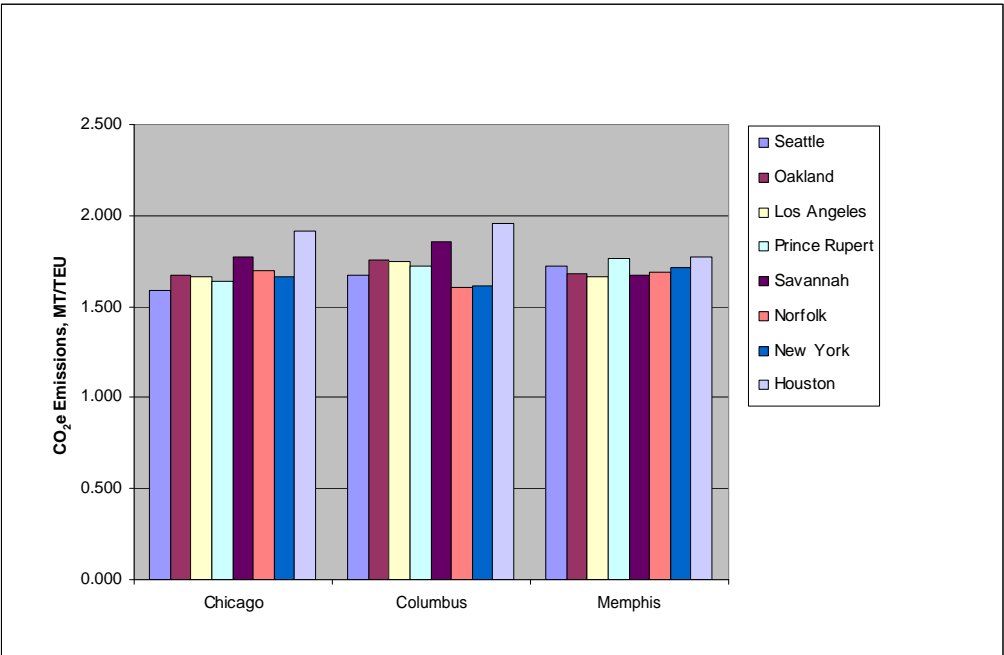


Figure A-13: Total CO₂e Emissions per 12,500 TEU Intermodal Delivery from Singapore



Appendix B: ANALYSIS WITH PANAMA CANAL EXPANSION

B.1 6,500 TEU Container Ships

Origin Port	Destination Port	Via Canal	Ocean CO ₂ e (MT)			Rail CO ₂ e (MT)			Total CO ₂ e (MT)			Total CO ₂ e per TEU (MT/TEU)			
			Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	
Shanghai	Seattle		3379	3870	4162	9098	9590	9881	1579	1664	1715				
	Oakland		3640	4131	3636	9717	10208	9763	1686	1772	1694				
	Los Angeles		3225	3717	3225	9580	10072	9580	1663	1748	1663				
	Prince Rupert		3981	4457	4715	9205	9681	9939	1598	1680	1725				
	Savannah	Panama		1659	2150	1090	12890	13382	12322	2237	2322	2139			
	New York	Panama		1459	1167	1766	13132	12840	13439	2279	2229	2332			
Hong Kong	Norfolk	Panama	1536	1014	1474	13003	12481	12942	2257	2166	2246				
	Houston	Panama	1689	1920	860	12896	13127	12067	2238	2278	2094				
	Seattle		3379	3870	4162	9853	10344	10636	1710	1795	1846				
	Oakland		3640	4131	3636	10414	10906	10460	1807	1893	1815				
	Los Angeles		3225	3717	3225	10313	10805	10313	1790	1875	1790				
	Prince Rupert		3981	4457	4715	9936	10412	10670	1724	1807	1852				
Singapore	Savannah	Panama	1659	2150	1090	13568	14059	12999	2355	2440	2256				
	New York	Panama	1459	1167	1766	13809	13518	14116	2397	2346	2450				
	Norfolk	Panama	1536	1014	1474	13680	13158	13619	2374	2284	2364				
	Houston	Panama	1689	1920	860	13573	13804	12744	2356	2396	2212				
	Seattle		3379	3870	4162	11246	11738	12029	1952	2037	2088				
	Oakland		3640	4131	3636	11824	12315	11870	2062	2137	2060				
Singapore	Los Angeles		3225	3717	3225	11914	12406	11914	2068	2153	2068				
	Prince Rupert		3981	4457	4715	11440	11916	12174	1986	2068	2113				
	Savannah	Panama	1659	2150	1090	14978	15469	14410	2600	2685	2501				
	New York	Panama	1459	1167	1766	15220	14928	15527	2642	2591	2695				
	Norfolk	Panama	1536	1014	1474	15091	14569	15030	2619	2529	2608				
	Houston	Panama	1689	1920	860	14984	15214	14155	2601	2641	2457				

Table B-1 6,500 TEU CO₂e Emission Calculations with Expanded Panama Canal

Figure B-1: Total CO₂e Emissions per 6,500 TEU Intermodal Delivery from Shanghai

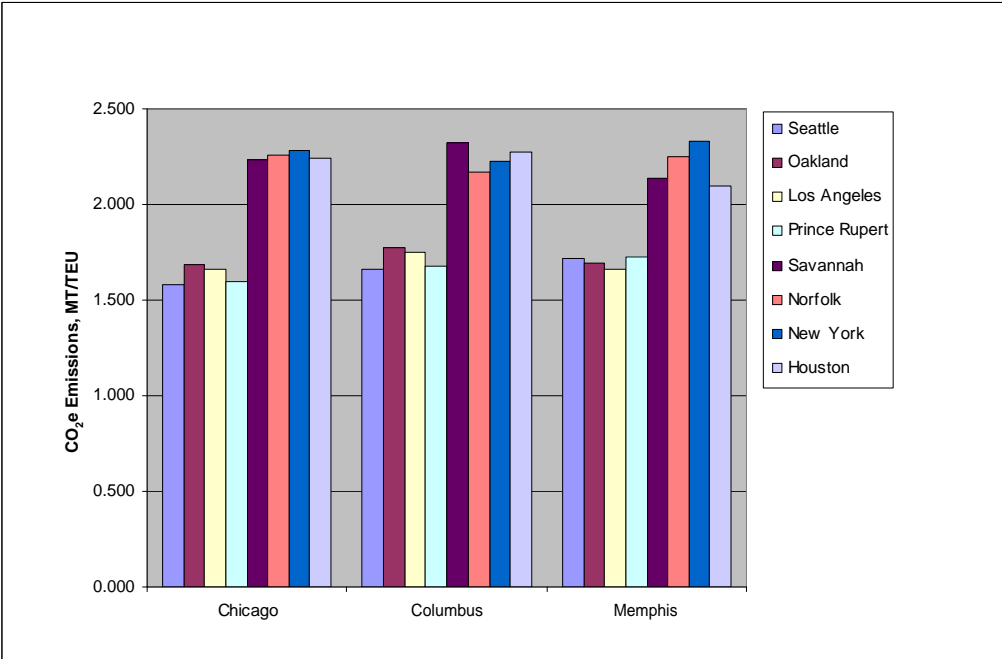


Figure B-2: Total CO₂e Emissions per 6,500 TEU Intermodal Delivery from Hong Kong

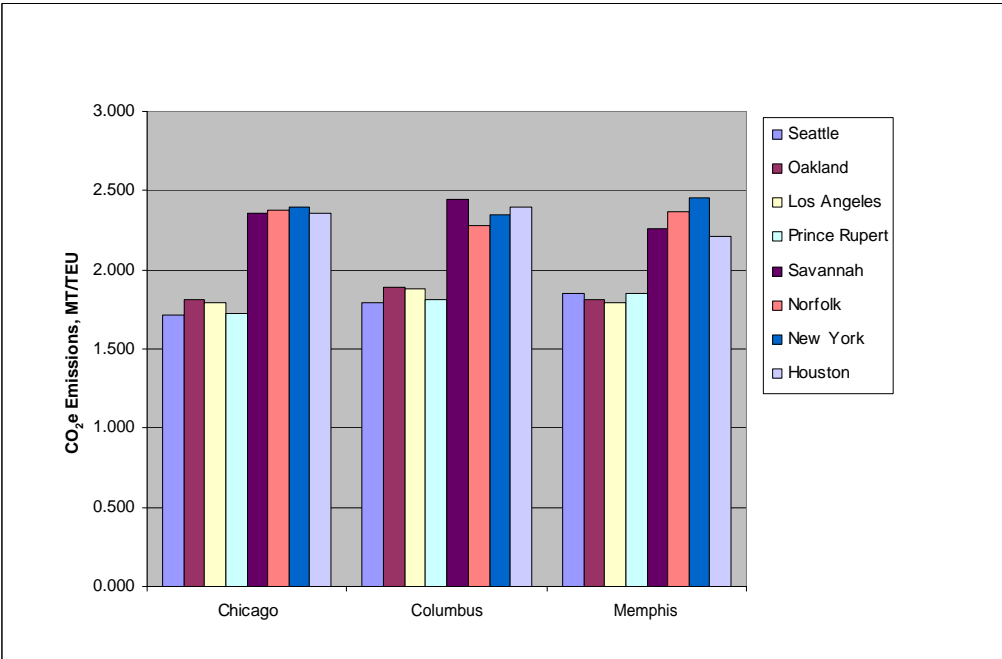
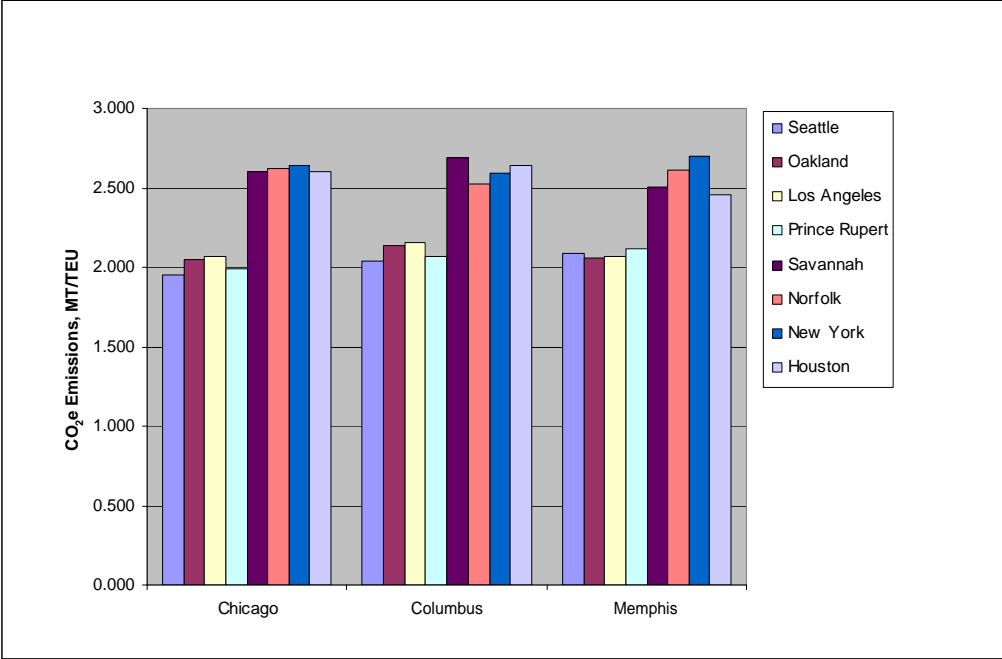


Figure B-3: Total CO₂e Emissions per 6,500 TEU Intermodal Delivery from Singapore



B.2 8,500 TEU Container Ships

Origin Port	Destination Port	Via Canal	Ocean CO ₂ e (MT)			Rail CO ₂ e (MT)			Total CO ₂ e (MT)			Total CO ₂ e per TEU (MT/TEU)		
			Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis
Shanghai	Seattle		6601	5012	5390	4376	5012	5390	11252	11889	12267	1.522	1.608	1.659
	Oakland		7029	5351	4774	4714	5351	4774	12019	12655	12078	1.626	1.712	1.634
	Los Angeles		7362	4814	4177	4177	4814	4177	11815	12452	11815	1.598	1.684	1.598
	Prince Rupert		6008	5156	6106	5156	5772	6106	11439	12055	12390	1.547	1.631	1.676
	Savannah	Panama		13210	2148	2785	2148	2785	15634	16270	14898	2.115	2.201	2.015
	New York	Panama		13739	1890	2287	1890	1512	15904	15526	16302	2.151	2.100	2.205
Hong Kong	Norfolk	Panama	13492	1989	1313	1989	1313	1910	15757	15081	15677	2.131	2.040	2.121
	Houston	Panama	13180	2188	2486	2188	2486	1114	15644	15942	14570	2.116	2.157	1.971
	Seattle		7505	5012	5390	4376	5012	5390	12156	12793	13171	1.644	1.730	1.782
	Oakland		7864	4714	4774	4714	5351	4774	12854	13491	12914	1.739	1.825	1.747
	Los Angeles		8241	4177	4814	4177	4814	4177	12693	13330	12693	1.717	1.803	1.717
	Prince Rupert		6883	5156	5772	5156	5772	6106	12314	12931	13265	1.666	1.749	1.794
Singapore	Savannah	Panama	14021	2148	2785	2148	2785	1412	16445	17081	15709	2.224	2.311	2.125
	New York	Panama	14550	1890	1512	1890	1512	2287	16715	16337	17113	2.261	2.210	2.315
	Norfolk	Panama	14303	1989	1313	1989	1313	1910	16568	15892	16489	2.241	2.150	2.230
	Houston	Panama	13991	2188	2486	2188	2486	1114	16455	16753	15381	2.226	2.266	2.081
	Seattle		9173	5012	5390	4376	5012	5390	13825	14461	14839	1.870	1.956	2.007
	Oakland		9552	4714	4774	4714	5351	4774	14542	15178	14602	1.967	2.053	1.975
Singapore	Los Angeles		10158	4177	4814	4177	4814	4177	14611	15247	14611	1.976	2.062	1.976
	Prince Rupert		8684	5156	5772	5156	5772	6106	14116	14732	15066	1.909	1.993	2.038
	Savannah	Panama	15710	2148	2785	2148	2785	1412	18134	18770	17398	2.453	2.539	2.353
	New York	Panama	16239	1890	1512	1890	1512	2287	18404	18026	18802	2.490	2.438	2.543
	Norfolk	Panama	15993	1989	1313	1989	1313	1910	18257	17581	18178	2.470	2.378	2.459
	Houston	Panama	15680	2188	2486	2188	2486	1114	18144	18442	17070	2.454	2.495	2.309

Table B-2 8,500 TEU CO₂e Emission Calculations with Expanded Panama Canal

Figure B-4: Total CO₂e Emissions per 8,500 TEU Intermodal Delivery from Shanghai

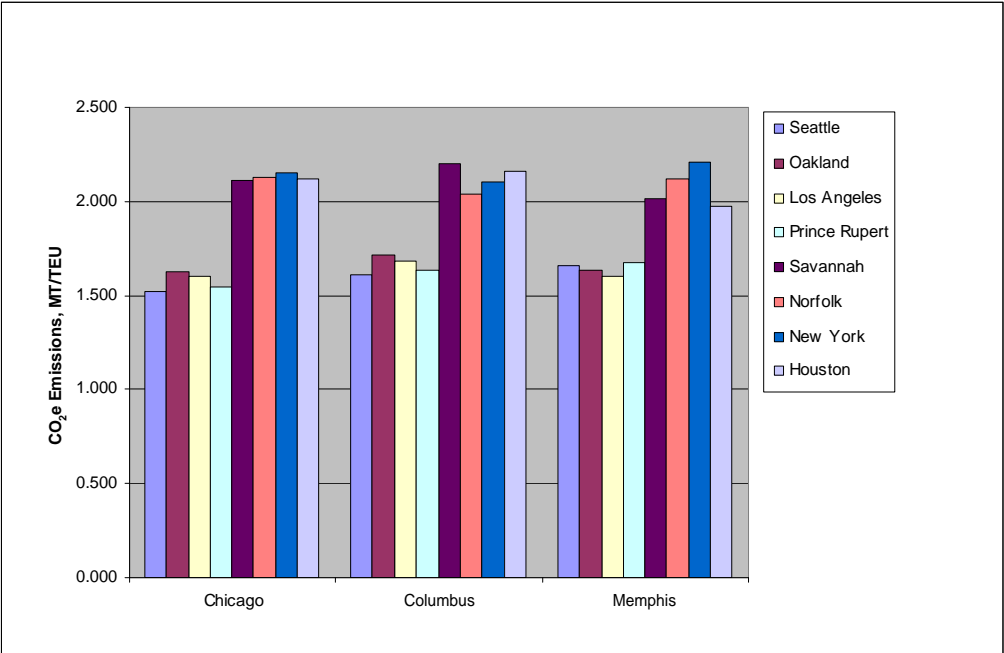


Figure B-5: Total CO₂e Emissions per 8,500 TEU Intermodal Delivery from Hong Kong

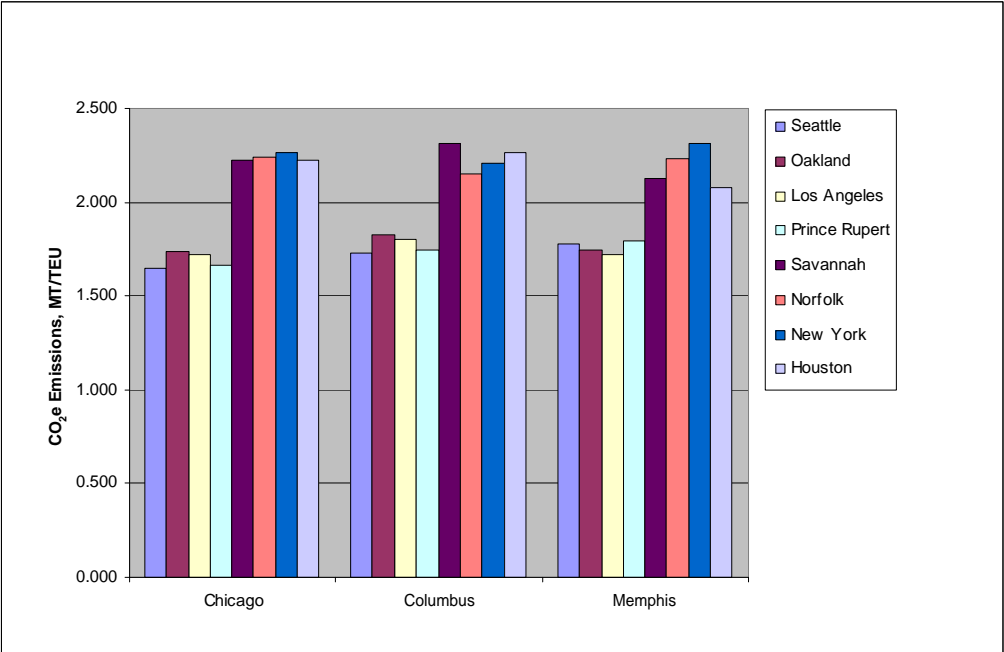
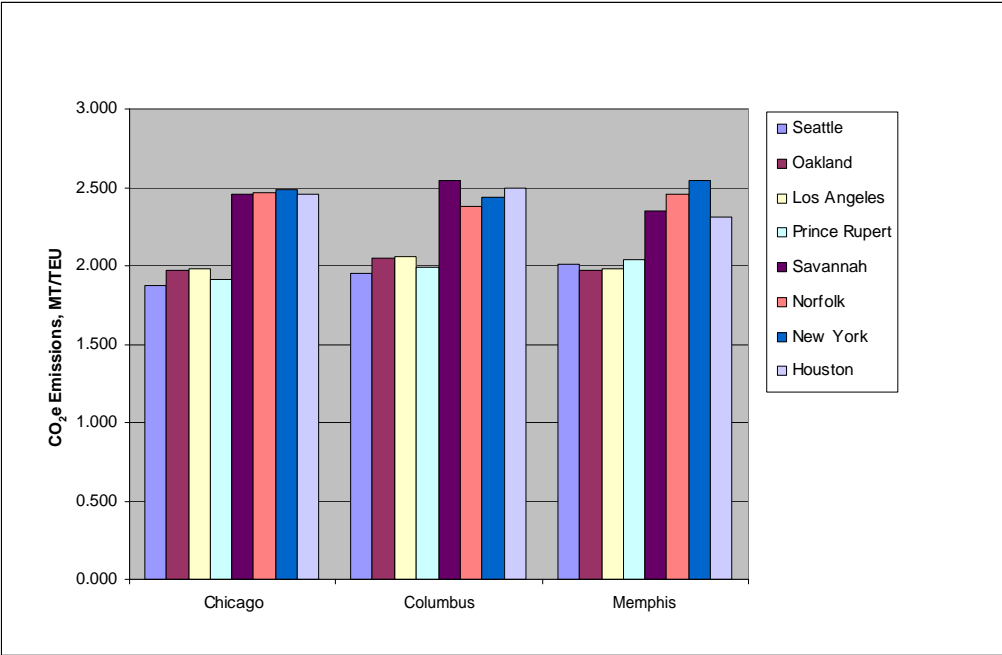


Figure B-6: Total CO₂e Emissions per 8,500 TEU Intermodal Delivery from Singapore



B.3 12,500 TEU Container Ships

Origin Port	Destination Port	Via Canal	Ocean CO ₂ e (MT)			Rail CO ₂ e (MT)			Total CO ₂ e (MT)			Total CO ₂ e per TEU (MT/TEU)			
			Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	Chicago	Columbus	Memphis	
Shanghai	Seattle		7801			6592	7550	8120	14813	15771	16341	1.317	1.402	1.453	
	Oakland		8307			7101	8060	7191	15827	16786	15917	1.407	1.492	1.415	
	Los Angeles		8701			6292	7251	6292	15413	16371	15413	1.370	1.455	1.370	
	Prince Rupert		7102			7766	8695	9198	15287	16216	16719	1.359	1.441	1.486	
	Savannah	Panama		15599			3236	4195	2127	19254	20213	18146	1.711	1.797	1.613
	New York	Panama		16223			2846	2277	3446	19489	18919	20088	1.732	1.682	1.786
Hong Kong	Norfolk	Panama	15932			2996	1977	2876	19348	18329	19228	1.720	1.629	1.709	
	Houston	Panama	15564			3296	3745	1678	19279	19729	17661	1.714	1.754	1.570	
	Seattle		8868			6592	7550	8120	15879	16838	17407	1.411	1.497	1.547	
	Oakland		9293			7101	8060	7191	16813	17772	16903	1.494	1.580	1.502	
	Los Angeles		9726			6292	7251	6292	16438	17396	16438	1.461	1.546	1.461	
	Prince Rupert		8135			7766	8695	9198	16320	17249	17752	1.451	1.533	1.578	
Singapore	Savannah	Panama	16556			3236	4195	2127	20211	21170	19103	1.797	1.882	1.698	
	New York	Panama	17180			2846	2277	3446	20446	19876	21045	1.817	1.767	1.871	
	Norfolk	Panama	16889			2996	1977	2876	20305	19286	20185	1.805	1.714	1.794	
	Houston	Panama	16521			3296	3745	1678	20236	20686	18618	1.799	1.839	1.655	
	Seattle		10837			6592	7550	8120	17848	18807	19376	1.587	1.672	1.722	
	Oakland		11284			7101	8060	7191	18805	19764	18895	1.672	1.757	1.680	
Singapore	Los Angeles		12000			6292	7251	6292	18711	19670	18711	1.663	1.748	1.663	
	Prince Rupert		10260			7766	8695	9198	18446	19375	19878	1.640	1.722	1.767	
	Savannah	Panama	18549			3236	4195	2127	22205	23163	21096	1.974	2.059	1.875	
	New York	Panama	19173			2846	2277	3446	22439	21870	23038	1.995	1.944	2.048	
	Norfolk	Panama	18883			2996	1977	2876	22298	21280	22178	1.982	1.892	1.971	
	Houston	Panama	18514			3296	3745	1678	22230	22679	20612	1.976	2.016	1.832	

Table B-3 12,500 TEU CO₂e Emission Calculations with Expanded Panama Canal

Figure B-7: Total CO₂e Emissions per 12,500 TEU Intermodal Delivery from Shanghai

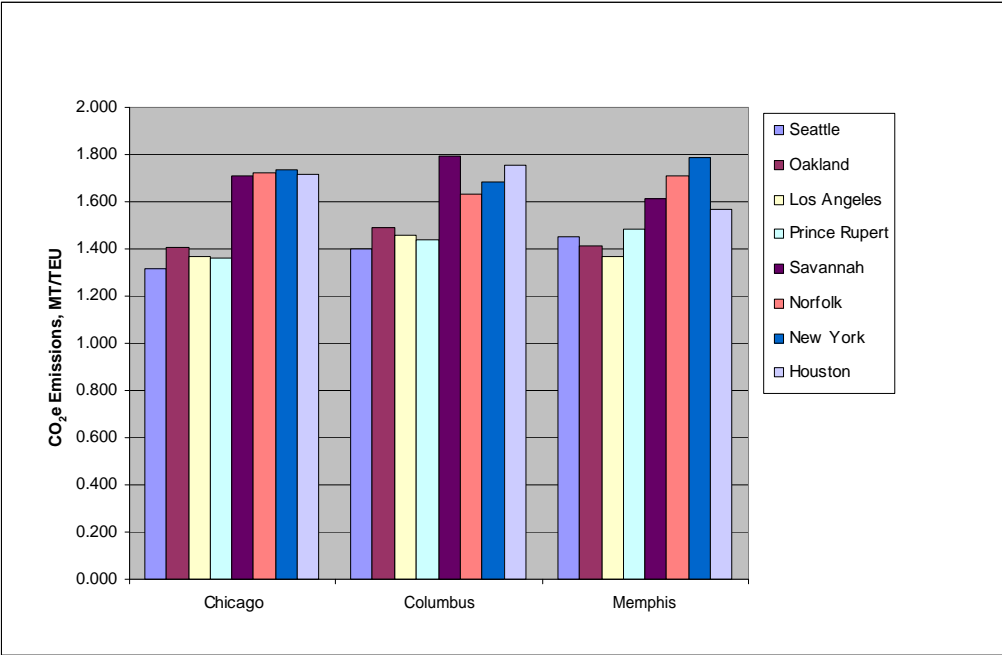


Figure B-8: Total CO₂e Emissions per 12,500 TEU Intermodal Delivery from Hong Kong

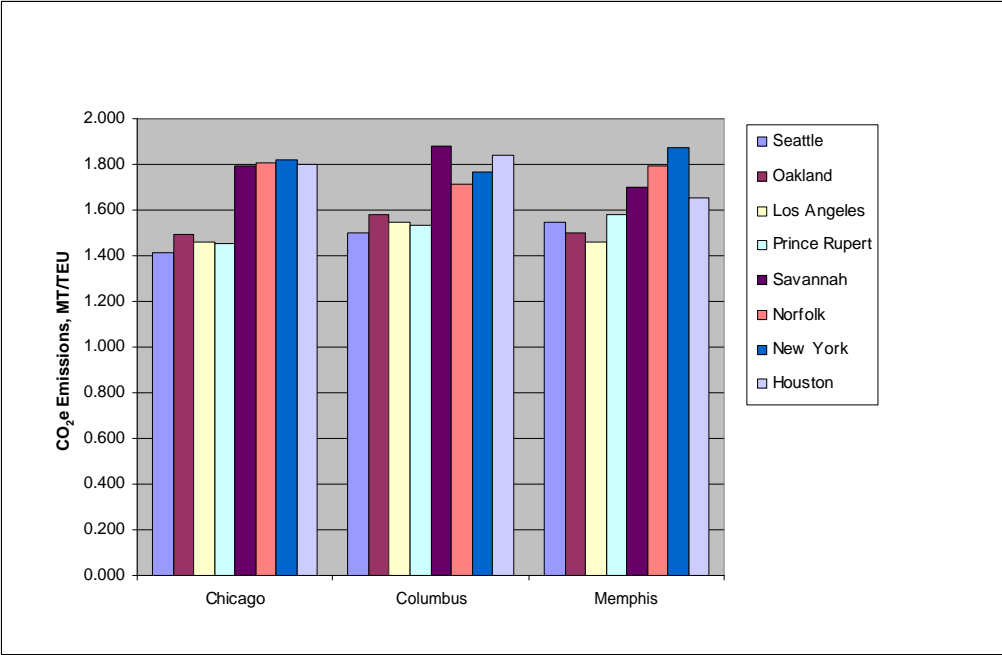


Figure B-9: Total CO₂e Emissions per 12,500 TEU Intermodal Delivery from Singapore

