Carbon Footprint Study

for the

Asia to North America Intermodal Trade

Port of Seattle

2711 Alaskan Way
Seattle, WA 98121

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Executive Summary

This April 2011 version of the "Carbon Footprint Study of the Asia to North America Intermodal Trade" builds upon the original study conducted by Herbert Engineering in May 2009, adding analysis for origin ports of Ho Chi Minh, Busan, and Tokyo; destination cities of New York, Atlanta, and Norfolk; vessel utilization from 60% to 90%, using 10% increments; slow steaming for vessel utilization from 60% to 90%, using 10% increments; and inland truck trips up to 300 miles.

The April 2011 "Carbon Footprint Study of the Asia to North America Intermodal Trade" 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 Asian ports of Shanghai, Hong Kong, Singapore, Tokyo, Busan, and Ho Chi Minh traveling to the North American ports of Seattle, Prince Rupert, Los Angeles / Long Beach, Houston, Savannah, Norfolk, and New York and progressing onward via Class I intermodal trains to the cities of Chicago, Columbus, Memphis, New York, Norfolk and Atlanta. Estimations of the total greenhouse gas emissions were also conducted for Class 8 Heavy Duty Diesel Vehicle (HDDV) truck deliveries of 300 miles from the North American port of entry.

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 from oceangoing container ships and domestic rail service indicates that marine transportation is 32% to 55% more efficient than rail transportation at typical operating conditions. This relationship favors shipping over rail transportation when total travel distances are comparable. However, the ocean distance from Asian ports to the West Coast ports, in particular the Pacific Northwest ports in the study, 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 to inland destinations.

Shipping via the port of Seattle under typical operating conditions (design service speed and 90% utilization) provides the lowest overall carbon emissions per TEU from all six Asian departure ports evaluated in this study, when the cargo continues to the inland container facilities at Chicago and Columbus. For cargoes leaving Tokyo, Busan, Shanghai, and Hong Kong and ending in New York and Norfolk the report also shows that Pacific Northwest ports are the best performing ports. Prince Rupert and Seattle have very similar emissions footprints since the ocean and rail distances are very similar.

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 29% lower when moving a container between Shanghai and Chicago via the port of Seattle on a 8,500 TEU container ship, as compared to moving the same container between Shanghai and Chicago via the Panama Canal and the port of New York on a 8,500 TEU Panamax container ship.

Finally, container ship parameters of speed and cargo utilization were varied separately and together within a realistic range of values to investigate the effect on key facts and findings. The results indicated that slow steaming container ships improved the transportation efficiency greatly for the ocean going leg of any trip. The ultimate result of this increase in efficiency is that longer ocean voyages to farther North American ports, particularly East Coast ports, are penalized less for the longer time at sea. With shorter rail trip than the West Coast, the East Coast becomes increasingly competitive with West Coast ports for total CO_2e / TEU over an intermodal shipment. On the other hand, as cargo utilization decreases for the vessels, the transportation efficiency worsens and the advantage swings stronger towards the Pacific Northwest ports, as they have the shortest ocean distances.

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Key Facts and Findings

2.1 General

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 under typical operating conditions. This finding is consistent over most of the scenarios involving the three smallest container ship sizes.

2. The transportation efficiency of trucking is calculated to be 0.54 kg CO_2e / TEU-km. Trucking is one third as efficient as rail transportation (at 0.17 kg CO_2e / TEU-km) and one fifth as efficient as the 8,500 TEU container ship (at 0.10 CO_2e / TEU-km).

3. Reducing vessel speed from 24 kts to 17 kts can cut total greenhouse gas emissions from vessels by as much as one half regardless of the size of the vessel.

4. A loss of cargo utilization, while greatly increasing the absolute emissions for all deliveries, favors the West Coast ports over the East Coast ports. The effect is less apparent for the larger ships as the efficiency gain from the economy of scale offsets the loss of efficiency from under-utilized ships. Pacific Northwest ports benefit the most from this behavior as they have the shortest ocean distances.

5. For many of the scenarios, the analyses indicate that the CO_2e efficiencies gained by moving the larger container ships through the Panama Canal are still not sufficient to offset the benefits of the shorter ocean legs to the West Coast ports. East Coast ports situated in the south stand to get the largest greenhouse gas emission improvement from the expansion of the Panama Canal.

2.2 Regional

2.2.1 Pacific Northwest (Prince Rupert and Seattle)

1. The Pacific Northwest has the shortest ocean distances of deliveries from Asia to North America. When this is matched with relatively short rail distances to Chicago and Columbus, deliveries travelling through the Pacific Northwest to those destinations have the smallest carbon footprint under typical operating conditions.

2. In most cases, with the exception of Asian departures from Singapore and Ho Chi Minh, Seattle is the best performing port for intermodal transport of goods to the final destinations of New York and Norfolk under typical operating conditions of speed and cargo utilization. This trend continues for slow steaming as long as speeds remain above 21 to 23 kts.

3. Although the Prince Rupert has smaller ocean distances than Seattle, its correspondingly longer rail distances to inland destinations 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 CO_2e emission from ship and rail. Sensitivity analyses demonstrate that small changes in assumptions can change the relative ranking between these ports.

2.2.2 California Ports (Los Angeles / Long Beach and Oakland)

1. Los Angeles/Long Beach generally has the lowest emissions for container shipments to Memphis under typical conditions. Los Angeles/Long Beach is closer to Memphis by rail by as much as 600 miles when compared to the Pacific Northwest ports due to its southern location in the United States. Los Angeles/Long Beach has the smallest carbon footprint for deliveries to Atlanta under typical operating conditions for all Asian departures with the exception of Singapore and Ho Chi Minh for all vessel sizes. As vessel speeds slow down, Los Angeles/Long Beach continues to perform the best.

2. Deliveries through the Port of Oakland have the smallest carbon footprint when continuing on to Memphis and departing the Western Asian ports of Singapore and Ho Chi Minh on vessels smaller than 12,500 TEU container ships.

2.2.3 Southern East Coast (Houston and Savannah)

1. Savannah has the lowest CO_2e per TEU to containers heading to Atlanta when vessels are using slow steaming strategies at the slowest speeds and the largest ships. This is particularly evident for container ships travelling at slower than 21 kts on 6,500 TEU, 8,500 TEU, and 12,500 TEU vessels.

2. Houston has the lowest greenhouse gas emissions for containers destined for Memphis, transported on 8,500 TEU vessels, transiting at 17 - 18 kts, and departing from the ports of Busan, Tokyo, Shanghai, and Hong Kong. On 12,500 TEU ships, the highest speed that container ships can transport goods and still retain a Houston advantage is about 21 kts.

2.2.4 Northern East Coast (New York and Norfolk)

1. All water deliveries to New York and Norfolk emit the least amount of CO_2e per TEU on voyages originating from Western Asia (Singapore and Ho Chi Minh) on 6,500 and 8,500 TEU vessels when traveling via the Suez Canal. This finding applies to all 12,500 TEU ships departing any Asian ports in this study.

2. New York and Norfolk's advantages under an all-water scenario increase as the speed decreases from current typical transit speed when traveling through the Suez Canal. For west Asian departures (Singapore and Ho Chi Minh) with cargo going to the city of Columbus, Norfolk is the port with the smallest carbon footprint under most of the scenarios when the vessels are slow steaming.

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:

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

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 (CO_2), methane (CH_4), and nitrous oxide (N_2O) 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 (CO_2e) by multiplying the emissions by the Global Warming Potential values found in the latest Fourth Assessment Report of the IPCC[2].

Table 1: Global Warming Potentials (100 years), expressed as Carbon Dioxide Equivalents (CO_2e)

Global Warming Potentials (CO_2e)	
CO_2	1
CH_4	25
N_2O	298

[1] Puget Sound Maritime Air Emissions Inventory, Starcrest Consulting Group, April 2007
[2] Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4), 2007

3.1 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 vessels. The container ship particulars are shown below:

Table 2: Vessel Characteristics

	Vessel #1	Vessel #2	Vessel #3	Vessel #4
Vessel Capacity (TEU)	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
In-Port 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 typical 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. For this analysis, it is assumed that each ship carries a container load at 90% utilization.

[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

3.1.1 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.

3.1.2 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

Engine Type	At Sea	Maneuvering	In-Port
Propulsion	0.80	0.03	0.00
Auxiliary	0.13	0.50	0.17

3.1.3 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, Singapore, Ho Chi Minh, Busan, and Tokyo to the selected North American ports 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,and 12,500 TEU) were directed through both the Suez Canal and Panama Canal to East Coast ports. Vessels transiting the Suez or Panama Canal were assigned a factor to account for changes in the operations when passing 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.

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

Despite the importance to local emission impacts, 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. The impact of cold ironing 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 power plants. With this assumption, the overall emission reduction for a 8,500 TEU vessel would only be approximately 0.5% of the total emissions from the supply chain.

In addition to cold ironing, another initiative taken by the Port of Los Angeles and Long Beach is the Green Flag Program. This program provides a financial incentive for vessels that call the area to reduce their speed to 12 kts or less when they are 40 nm seaward from the entrance to harbor. As a large percentage of vessels are voluntarily participating, 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.

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	5,067
	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
Ho Chi Mihn	Seattle		6,574
	Oakland		6,868
	Los Angeles		7,379
	Prince Rupert		6,195
	Savannah	Panama	11,623
	Savannah	Suez	11,357
	New York	Panama	12,033
	New York	Suez	10,803
	Norfolk	Panama	11,842
	Norfolk	Suez	10,962
	Houston	Panama	11,600
	Houston	Suez	12,381
Busan	Seattle		4,608
	Oakland		4,936
	Los Angeles		5,253
	Prince Rupert		4,173
	Savannah	Panama	9,709
	Savannah	Suez	13,210
	New York	Panama	10,119
	New York	Suez	12,656
	Norfolk	Panama	9,928
	Norfolk	Suez	12,815
	Houston	Panama	9,686
	Houston	Suez	14,234
Tokyo	Seattle		4,255
	Oakland		4,549
	Los Angeles		4,849
	Prince Rupert		3,873
	Savannah	Panama	9,298
	Savannah	Suez	13,607
	New York	Panama	9,708
	New York	Suez	13,053
	Norfolk	Panama	9,517
	Norfolk	Suez	13,212
	Houston	Panama	9,275
	Houston	Suez	14,631

3.1.4 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.

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

Fuel Emission Factor (kg pollutant/tonne of fuel)		
Pollutant	**Propulsion**	**Auxiliary**
CO_2	3,134	3,134
CH_4	0.28	0.28
N_2O	0.08	0.08

3.1.5 Speed- Power Curve

The relationship between speed and propulsion power required is critical in the determination of the fuel consumption for ocean-going vessels. Generally speaking, the power required is related to the speed of the vessel to the 3rd power and is often regarded as the "propeller law." However, there are many other hydrodynamic effects related to the movement of ships through the water that are not captured in this equation that can have a significant effect on the power prediction at a particular speed. In order to develop a more robust method for the determination of the power required, HEC has used its Ship Evaluation Program (SEP) software to develop curves for the various sizes of the container ships evaluated in this study.

The speed-power relationship for a given vessel is influenced by the efficiency of the hull and propeller. SEP generated speed-power curves are based on the well-known Holtrop-Mennen method[15] and standard Wagenagen "B" series propellers. The Holtrop formulas are based on regression of data from model tests conducted at MARIN on a variety of hull forms and models dating back to the 1970's. It is recognized that more modern vessels perform better than the Holtrop predictions. Based on benchmarking of Holtrop

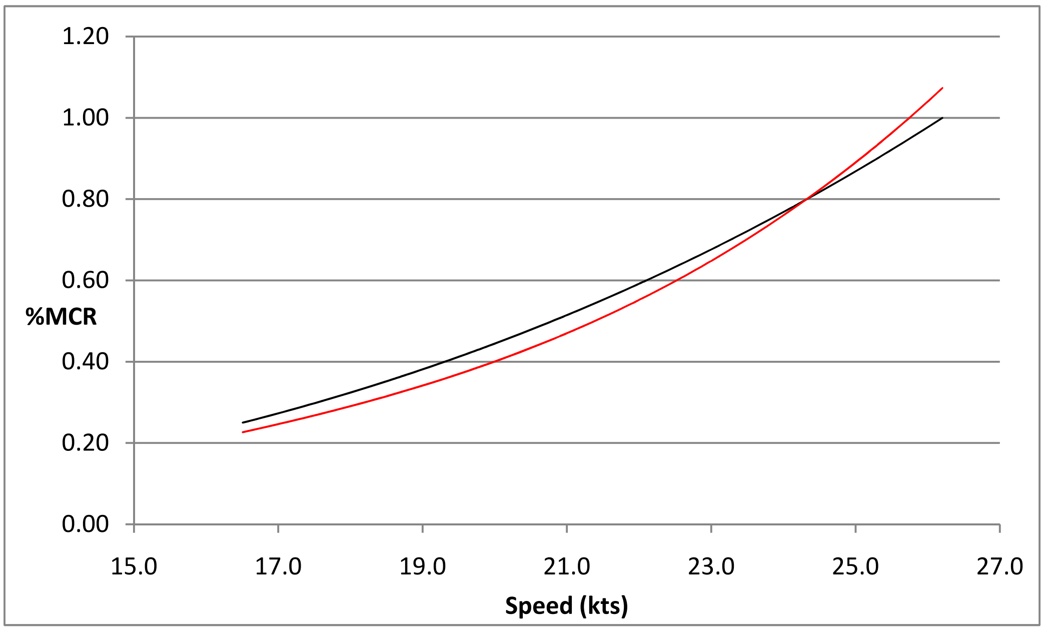
[14] 2006 IPCC Guidelines For National Greenhouse Gas Inventories
[15] A Statistical Resistance Prediction Method with a Speed Dependent Form Factor", by J. Holtrop, MARIN, 1988

analyses against model tests and trial data of container ships built in the last 10 years, a correction factor was applied to adjust power requirements to reflect modern container ship design practice.

Figure 1 illustrates the difference between a speed power developed from the propeller law versus a curve derived from the SEP software. For ease of use in these calculations power is represented as a load factor, or percentage of MCR of the propulsion engine.

For this study, speed-power curves were initially developed for calm water conditions (referred to as the trial condition), and then adjusted for average weather conditions by applying a service margin.

Figure 1: Comparison of Propeller Law and SEP Power Curves

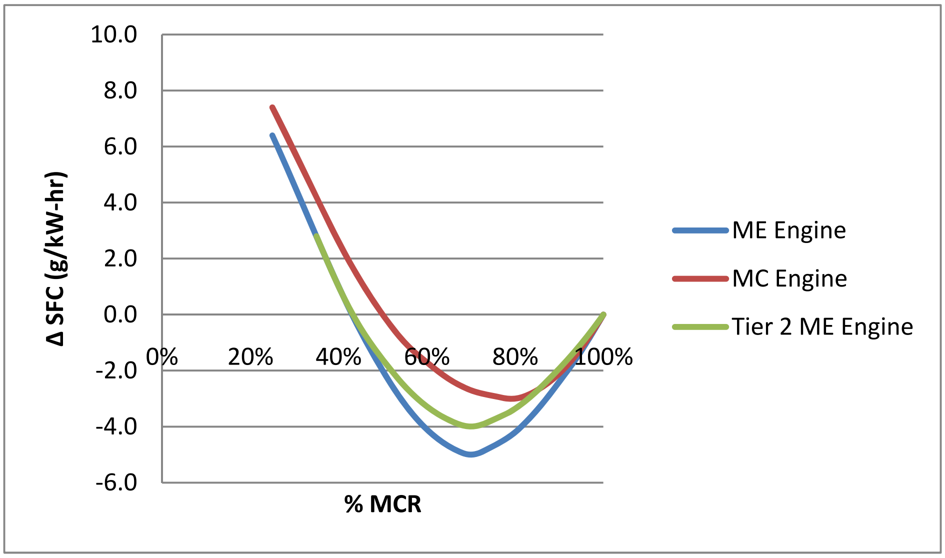


3.1.6 Fuel Consumption

Emission factors used in this study were determined by multiplying the specific fuel consumption (SFC) values by the fuel based emission factors given in Section 3.1.4 Emission Factors. Specific fuel consumptions were selected for mechanically controlled, or “MC” , Tier 1 compliant, 2 stroke diesel engine.

In this study, changes in vessel speed were analyzed with the corresponding adjustments in the engine load factor (% MCR). As the load factor varies, the specific fuel consumption will also change. For an “MC” engine, the minimum specific fuel consumption is achieved at the 80% MCR load condition. Figure 2 shows the change in the specific fuel consumption relative to the 100% MCR condition, taken as a function of the loading on the engine. Also included in the plot are curves representing newer electronically controlled "ME" engine in both current Tier 1 and upcoming Tier 2 configurations for additional reference.[16]

Figure 2: Change in Fuel Consumption versus Engine Load



It should be noted that electronically controlled engines offer improved specific fuel consumption over a larger range of engine loadings with the minimum value at 70% MCR. As more stringent diesel engine regulations come into effect, such as Tier 2 standards, specific fuel consumptions will increase as the engines are configured to reduce NO_x emissions.

3.1.7 Utilization

Under typical circumstances, cargo utilizations were assumed to be 90% to represent common operating conditions. As part of this study, a range of utilizations between 90% to 60% were considered in order to better understand the influence of this parameter on key results.

When utilizations are reduced, there is a subsequent reduction in draft and displacement, which generally leads to less power being required to move the ship at a given speed. HEC's SEP software was used to estimate the change in powering requirements as a function of vessel utilization.

3.2 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

[16] Vendor Data from MAN B&W, 2005

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.[17] A railcar, the Maxi-Stack IV, was used for rail car tare weight[18]. A common locomotive, EMD's SD-70, was selected to perform the hauling duties[19]. An average speed of 30 mph was selected based on performance measures from Association of American Railroads and Railroad Performance Measures[20]. A horsepower per ton (HPT) ratio of 2 was selected[21] 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 Board[22]. 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.

The results of this calculation are presented below:

Table 6: Train Characteristics

Typical Train Characteristics	
Average Speed	30 mph
Horsepower/Ton Ratio	2
Horsepower per Locomotive	400 hp
Brake Specific Fuel Consumption	235 kg/kW-hr
Weight per Locomotive	207 tons
Tare Weight of Railcar	22.6 tons

[17] "Interim Guidelines for Voluntary Ship CO_2 Emissions Indexing for Use in Trials", MEPC/Circ.471, International Maritime Organization.
[18] www.grbx.com
[19] www.uprr.com
[20] Association of American Railroads website, www.aar.org
[21] Correspondence with Class I railroads
[22] http://www.stb.dot.gov/econdata.nsf/f039526076cc0f8e8525660b006870c9?OpenView

3.2.1 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 7: Required Locomotive Power per Container Load for Representative Vessels

	4,500 TEU Vessel	6,500 TEU Vessel	8,500 TEU Vessel	12,500 TEU Vessel
Locomotive Power (kW)	128,262	181,954	235,645	354,959
Number of Locomotives	43	61	79	119

3.2.2 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[23,24]. The load factor applied in this study is 0.28[25]. 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.[26] 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 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.[27]. 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.

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23 Puget Sound Maritime Air Emissions Inventory, Starcrest Consulting Group, April 2007.
24 Port of Los Angeles Inventory of Air Emissions CY 2005, September 2007.
25 Puget Sound Maritime Air Emissions Inventory, Starcrest Consulting Group, April 2007.
26 Locomotive Emission Standards – Regulatory Support Document, US Environmental Protection Agency, April 1998.
27 Development of Railroad Emission Inventory Methodologies – Report No. SR2004-06-02, Sierra Research Inc, June 2004.

3.2.3 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, Columbus, New York, Norfolk, and Atlanta by the assumed speed of the locomotive. Rail distances were determined by selecting the rail mileages found in the 2006 Public Use Waybill File[28] 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 8.

Table 8: Rail Distances Between Ports and Inland Facilities

	Rail Distances (Statute Miles)					
	Chicago	**Columbus**	**Memphis**	**New York**	**Atlanta**	**Norfolk**
Seattle	2,200	2,520	2,710	3,150	2,930	3,200
Oakland	2,370	2,690	2,400	3,160	2,720	3,240
Los Angeles	2,100	2,420	2,100	2,920	2,400	3,000
Prince Rupert	2,592	2,902	3,070	3,542	3,322	3,562
Savannah	1,080	1,400	710	900	280	710
New York	950	760	1,150	0	860	480
Norfolk	1,000	660	960	480	650	0
Houston	1,100	1,250	560	1,710	940	1,550

[28] 2006 Public Use Waybill, Surface Transportation Board.

3.2.4 Emission Factors for Locomotives

Fuel based emissions factors were taken from *2006 IPCC Guidelines for National Greenhouse Gas Inventories* [29]. 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 9.

Table 9: Rail Emission Factors

Railway Emission Factors		
Pollutant	**kg pollutant/tonne fuel**	**kg/pollutant/kW-hr**
CO_2	3,164	0.744
CH_4	0.18	0.00004
N_2O	1.22	0.00029

3.3 Heavy Duty Diesel Vehicles

3.3.1 Trucks

Greenhouse gas emissions from trucks were estimated using fuel based emission factors from the IPCC and estimated fuel consumption values for Class 8 Heavy Duty Diesel Vehicles (HDDV). For the calculation of carbon dioxide emissions from trucks, the same fuel based emission factor for distillate fuel, as applied for locomotives, was used. Emission factors for nitrous oxide and methane are those as presented in an EPA report[30] with units of grams emission per mile travelled.

[29] 2006 IPCC Guidelines For National Greenhouse Gas Inventories
[30] Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles – Report No. EPA420-P-04-016, Environmental Protection Agency, November 2004

$$\text{Emissions} = EF \times D \text{ (g)}$$

Where:

EF = Emission factor (g/mile) for the greenhouse gas derived from truck fuel consumption in (g/mile) multiplied by the fuel based emission factor (kg emission per kg fuel)

D = Distance travelled by the truck (miles)

Fuel consumption was selected as a representative value of a HDDV carrying a single 40' container, equaling 2 TEUs, for a distance of 300 statute miles consisting of travel at typical line haul highway speeds[31] under the California Heavy-Duty Diesel Truck Drive Cycle. Principal characteristics for the representative trucks are given in Table 10.

Table 10: Truck Fuel Consumption Values

Truck Fuel Consumption Values	
Fuel Consumption	553 g fuel/mile
CO_2 Emission Factor	3,164 kg CO_2/tonne fuel
N_2O Emission Factor (g N_2O/mile)	0.0048 g N_2O/mile
CH_4 Emission Factor	0.0051 g CH_4/mile

3.3.2 Port Operations and Drayage

Marine containers require additional equipment in order to be moved from the container ships 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[32,33,34] that estimated total CO_2e emissions from CHE's at container terminals. Using this

[31] "Reducing Heavy Duty Combination Truck Fuel Consumption and CO2 Emissions", Northeast States Center for a Clean Air Future (NESCCAF), International Council on Clean Transportation (ICCT), Southwestern Research Institute, TIAX, LLC, October 2009.
[32] Port of Long Beach Inventory of Air Emissions Inventory - 2006, Starcrest Consulting Group, June 2008
[33] Puget Sound Maritime Air Emissions Inventory, Starcrest Consulting Group, April 2007
[34] Port of Long Beach Inventory of Air Emissions Inventory - 2007, Starcrest Consulting Group, Jan 2009

information in conjunction with TEU throughput from AAPA statistics[35], 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 CO_2e that would be emitted by CHE in the handling of the containers. The factor was calculated to be 0.025 MT CO_2e/ 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 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 idling[36]. 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.

Total emissions from drayage, considering both CHE and trucks, are projected to be, on average, no more than 0.037 MT CO_2e/ 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 CO_2e/ TEU is applied for all trips and port combinations.

[35] http://www.aapa-ports.org/
[36] Port of Long Beach Inventory of Air Emissions Inventory - 2006, Starcrest Consulting Group, June 2008

Emissions Calculations

Summaries of CO_2e emissions for the various combinations of ship size and route configurations are provided in Appendices A through D found in a separate companion document *Carbon Footprint Study for the Asia to North America Intermodal Trade – Data Table Appendices*. Analyses for four different container ships of sizes 4,500 TEU, 6,500 TEU, 8,500 TEU, and 12,500 TEU capacities are presented. The matrix includes container ship departures from Shanghai, Hong Kong, Singapore, Tokyo, Busan, and Ho Chi Minh going to Chicago, Columbus, Memphis, New York, Norfolk, and Atlanta through the various North American ports of Prince Rupert, Seattle, Los Angeles/ Long Beach, Savannah, Houston, Norfolk, and New York. The summary tables provide CO_2e emission figures for container ships including the voyage leg plus in-port emissions (identified as Ocean CO_2e), for locomotives covering rail movements between the container port and inland facilities (identified as Rail CO_2e), and the total CO_2e emissions. Total emissions include the ocean and rail contributions plus a factor for drayage.

Additional calculations were peformed varying vessel speeds (from 17 kst to 24 kts in 1 kt increments) across each of the four ship utilization scenarios (90% through 60 in 10% increments). This information will be available on the Port of Seattle Green Gateway Carbon Footprint web calculator. This data is provided to give users of the web calculator a wider range of realistic operational scenarios for their use as the additional data allows comparison of scenarios where speeds may be different than typical design speed on under-utilized vessels.

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 container ships larger than about 4,500 TEU. Work to expand the Panama Canal to accommodate these larger vessels is currently underway, with expected completion in 2014. Once this work is completed, container ships up to approximately 12,500 TEUs in capacity will be able to transit the canal. 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.

Appendix A provides data table for typical operating conditions for the various ship sizes and origin-destination pairs.

Appendix B provides summaries of CO_2e emissions of shipboard transfer between ports and a final truck delivery of 300 miles from the arrival port. No inter-port or locomotive transfers are assumed.

Appendix C provides results for a single representative route for each of the three sizes of container ships with service speed being adjusted from 17 kts to 24 kts in one knot increments.

Appendix D provides CO_2e emission estimates with the ships travelling at the design speed and having the shipboard cargo capacity utilizations adjusted from 60% to 90% in 10% increments.

Results and Discussion

5.1 Typical Operations

For 'typical operations' the vessels were assumed to be operating at the design service speed with a cargo utilization of 90%. This is representative of standard operations for a transpacific service.

Vessels with the shortest distance between from the closest Asian ports (Tokyo, Busan, Shanghai, and Hong Kong) and the West Coast of North America indicate that transit through the Pacific Northwest ports have the lowest greenhouse gas emissions when going to the final destinations of Chicago, Columbus, New York, and Norfolk. Final rail destination that are further south on the continent (Memphis and Atlanta) give the advantage to the cargo entering Californian ports and having left from the closest Asian ports.

The departure ports of Ho Chi Minh City and Singapore are at least 800 nm further from the US West Coast than the next closest port of Hong Kong. This difference gives a carbon advantage for all water shipments to New York and Norfolk, when cargo is routed through the Suez Canal.

The behavior can be explained by examining the differences in transportation efficiencies of the different modes and the relative distances between the ports. Calculated transportation efficiencies for the container ships vary from 0.07 to 0.11 kg CO_2e / TEU-km as the ships get smaller in capacity. In comparison, the rail transportation efficiency was calculated to be 0.17 kg CO_2e / TEU-km. Ocean voyages to the East Coast are significantly longer than those going to the West Coast. In most cases, the much smaller rail distance for East Coast ports (with its lower transportation efficiency) is not able to overcome the emissions from the longer, but more efficient ocean voyage.

5.2 Truck Deliveries

As some of the deliveries will be made by truck when shorter distances are involved, an additional section was added to evaluate the effect of this assumption on total CO_2e for the entire trip. It was assumed that truck travelled 300 miles from the port of entry.

The transportation efficiency of trucking is calculated to be 0.54 kg CO_2e / TEU-km. This value is one third as efficient as rail transportation (at 0.17 kg CO_2e / TEU-km) and over one fifth as inefficient as the largest 8,500 TEU container ship (at 0.10 CO_2e / TEU-km). The same intermodal cargoes moving 300 miles on a truck can be moved nearly 950 miles on efficient double stack intermodal rail service.
While trucks are not nearly as efficient in their transport of cargo as other modes, they serve an integral part of the overall supply chain as they are able to provide deliveries to locales that do not have adequate rail or navigable waterway access.

5.3 Vessel Slow Steaming

It is widely recognized that speed reduction in ships is one of the most effective ways to lower fuel consumption and thus reduce greenhouse gas emissions. Because of the slope of the speed –power curve, speed reductions on transpacific container ships on the order of 6 to 8 knots can reduce the required engine loading and the related fuel consumption by as much as half.

As fuel costs make up a large part of the total operating costs of a ship, speed reduction is a strategy that is often implemented when fuel prices increase during market events such as the Suez crisis of the 1980s or the surge in demand experienced in 2007-2008. Recently, operators have resorted to slow steaming as a way to deal with the oversupply of ships as a result of the recent worldwide economic downturn.

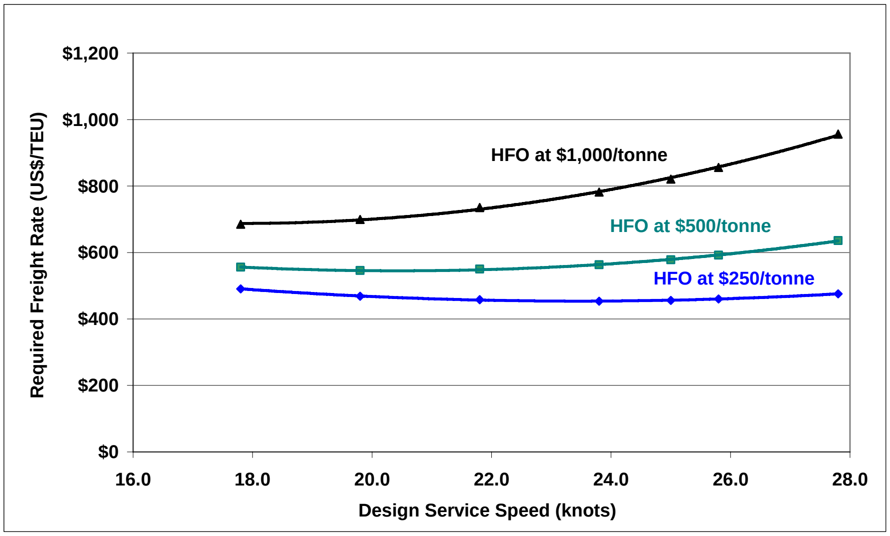
However, selecting the optimal operating speed involves not only fuel cost considerations but also the expectations of the shipper for timely delivery of cargo, the number of ships required in a given trade route to provide regular service, and other supply-demand factors. To capture all the capital costs, operating costs, and inventory costs of onboard cargo the monetary measure Required Freight Rate (RFR) is often used. To shed light on the value of slow steaming it is instructive to consider the RFR over a range of speeds and fuel costs. Figure 3, taken from joint study by ABS and HEC[37], shows the RFR expressed in terms of US$ per TEU, for container ships operating in the Transpacific service. In that study, a parametric series of container ship designs having design speeds ranging from 18 to 27 knots were developed, and the required freight rate determined for different fuel prices.

The optimal operating point is the speed that corresponds to the lowest RFR. In the above example, the optimal speed when fuel is $250 / tonne is in the 24 to 26 knot range. As fuel approaches $1,000 / tonne, this optimal speed decreases to 17 to 19 knots. Optimal speeds of 17 to 19 knots are achieved when fuel costs approach $1,000 / tonne.

Since escalating fuel prices appear to be a longer term trend it is expected that slower design and operating speeds for container ships will become the norm. This trend will be further encouraged by environmental regulations. For instance, in the newly established North American Emission Control Area (ECA), vessels will be required to burn distillate fuels with lower sulfur content or use equivalent measures to reduce emissions starting in August 2012. The lower sulfur fuels are considerably more expensive than the heavy fuel oils commonly burned on ocean-going ships. Another contributing factor to the increase in fuel price may stem from domestic and international greenhouse gas regulatory efforts that may eventually place a real or virtual tax realized through a mandated market based measure.

[37] "Parametric Study of 'Baby' Neo-Panamax Container ships", American Bureau of Shipping and Herbert Engineering Corp., 2008.

Figure 3: Sensitivity of RFR to Fuel Oil Price (Approx. 5,500 TEU Container ship in Transpacific Service



5.3.1 Analysis of Results

In this study, the entire matrix of origin-destination emission calculations was performed for ships operating at speeds from 17 kts to 24 kts. At 17 kts, the engine loading is approximately 25% MCR (load factor). This is currently at the low end of engine operation which is suitable for the long term service. Speeds below that threshold would require engine modifications in order to get efficient and reliable continuous operation.

The results reveal that as the vessel speed is reduced, the transport efficiency is improved, and greenhouse gas emissions go down. The emission reductions for the East Coast ports are greater than those for the West Coast ports because of the longer voyage distances and correspondingly higher mass emissions per voyage.

In the case of a 8,500 TEU container ship, the vessel transport efficiency at 24 kts is 0.09 kg CO_2e / TEU-km. Reducing the speed to 17 kts equates to a new transport efficiency of 0.05 kg CO_2e / TEU-km. The speed power curves indicate that load factors on the propulsion engine can be halved from their 80% values at typical transit speed (~24-25 kts) to 40% by reducing speed to 19-20 kts.

The results show that within the speed range investigated, regardless of the vessel size, Seattle generally remains the port with the smallest footprint per TEU for deliveries to Chicago (the destination city with shortest rail distance from Seattle). The only exception to this is for Singapore departures going through New York and the Suez Canal at the speeds below 20 kts for 8,500 TEU ships.

For other port/destination pairs, emission advantages are decidedly mixed as speed and vessel size are varied. For deliveries to Columbus, Seattle has the lowest footprint for East Asian departures with smaller (<8,500 TEU) container ships at the faster design speeds, whereas Norfolk gains the advantage once the ships are large enough, starting at 8,500 TEU and the speeds are slow enough. Norfolk has the advantage for departures from Singapore under all speeds and ship sizes with exception of speeds higher than 21 kts on 4,500 TEU ships, 22 kts on 6,500 TEU ships, and 23 kts for 8,500 TEU ships when transiting the Suez Canal.

Seattle also has the lowest CO_2e / TEU emissions for many of final deliveries to Norfolk and New York on 4,500 and 6,500 TEU container ships when the ocean distances are closest (Hong Kong, Shanghai, Busan, and Tokyo) and speeds remain higher. Otherwise, all water deliveries to New York and Norfolk achieve lower greenhouse gas emissions. For 4,500 TEU ships departing from the Tokyo and Busan, the shift from Seattle to Norfolk and New York occurs at 20-22 kts and 21-22 kts respectively. On 6,500 TEU ship, the transition occurs for speeds in the range of 21-23 kts. An 8,500 ship at the highest speeds of 22 to 24 knots has the smallest footprint via Seattle for cargo departing Hong Kong, Shanghai, Busan, or Tokyo and travelling to New York and Norfolk.

For deliveries to Memphis, Los Angeles scenarios offer the smallest CO_2e emission / TEU for most of the 4,500 TEU and 6,500 TEU vessels. Depending on the departure point in Asia, the advantage shifts to Savannah once the ship size increases to 6,500 TEU (for Singapore and Ho Chi Minh departures through the Suez Canal) or the speed is reduced to 19 kts on 4,500 TEU ships departing Singapore. 8,500 TEU container ships departing the Eastern Asian ports, including also Ho Chi Minh, to Los Angeles have the lowest carbon footprint up to approximately 17-19 kts service speed. Below those speeds, Houston via the Panama Canal becomes the best performing port. In the case of Singapore (throught the Suez Canal), Savannah is the optimal port for all speeds below 22 - 23 kts.

For deliveries to Atlanta, arrivals through Los Angeles are optimal for ships up to 8,500 TEU capacity, particularly at higher speeds. As the ship size increases and service speed is reduced, Savannah becomes the optimal port of entry for CO_2e emission / TEU when for transits through the Suez Canal.

5.3.2 Adding Ships to the Fleet

One strategy used by ship operators when slowing vessels down is to add ships to a particular service in order to maintain a identical cargo throughput as before. The concern with this action is that adding ships to the fleet would tend to increase the overall emissions and lessen the effect of speed reduction as a measure for reduction of greenhouse gas emissions.

An investigation into this scenario was carried out using a typical transpacific trade consisting of 5 vessels in a weekly delivery service. The investigation compared the annual CO_2e per annual TEU delivered at typical service speeds and also when ships are slowed down to a speed where it would be necessary to add an additional ship in order to preserve the same annual cargo throughput. Assuming full utilization on all vessels, 5 ships with a service speed of 23 knots deliver the same cargo annually as 6 ships with a service speed of approximately 19 kts.

The calculation indicates that a fleet of vessels on a single trade route slowing down to 19 kts from an original service speed of 24.5 kts and adding a ship in the service results in a 25% reduction in the fleetwide CO_2e / TEU if utilization is maintained at 90%. This is the same reduction in CO_2e / TEU that is achieved by a single ship slowing to 19kts. This demonstrates that adding a ship while maintaining utilization does not increase emissions per TEU.

Adding ships to the fleet occurs when market forces are strong enough to slow vessels speeds down. Initially, operators will slow down slightly with the understanding that they will not deliver the same annual amount of cargo. Once the loss of cargo throughput impact market competitiveness, additional ships will be added to keep up with market demand.

5.4 Reduction in Ship Utilization

The analysis confirms that a loss of utilization decreases the greenhouse gas transportation efficiency. In the case of an 8,500 TEU ship delivery from Shanghai to Chicago passing through Seattle, the total transportation efficiency improves from 0.14 to 0.12 kg CO_2e / TEU-km as the utilization increases from 60% to 90%. The vessel component of the overall transport efficiency improves from 0.12 to 0.10 kg CO_2e / TEU-km. As the change in transport efficiency greatly affects the ocean mode of delivery, the change in total emissions will be heavily dependent on the length of the ocean voyage. Rail transport efficiency will not change because rail utilizations will remain the same regardless of the number of containers that are delivered by each vessel. As a result, East Coast deliveries, with significantly longer ocean voyages, will have longer exposure in a less efficient transportation mode than the West Coast ports.

5.5 12,500 TEU Container Ships

The results for the 12,500 TEU ship demonstrate that the difference between the East and West Coast ports is much less significant than that for the smaller ships. 12,500 TEU container ships have a transportation efficiency of 0.07 kg CO_2e / TEU-km which lowers the impact of the longer ocean voyages on total emissions. For example, under standard sailing conditions, 12,500 TEU ship scenarios with final destinations to New York and Norfolk will have the lowest overall carbon footprint regardless of the port of entry. If these large vessels slow down significantly from their design speeds, the lowest greenhouse gas emission for nearly all scenarios will mostly shift to the East Coast ports. However, a loss of cargo utilization will deteriorate the transportation efficiency and shift their emission performance toward that of a smaller container ship.

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