Table 6-3 – Results from case study – fleet total.

Estimated potential for reduction of emissions from world fleet		
Reduction measures	Reduction of CO_2 emissions by implementation of measures on world fleet. [1]	
	2010	**2020**
M1. Efficiency rating ME, existing ships	2.3%	2.3%
M2. Efficiency optimised ME, new ships	1.9%	3.2%
M3. Stepwise switch from HFO to MDO.	1.6 %	3.0 %
H1. Optimal hull shape, new ships	6.4%	11.6%
H2. Propulsion system, new ships	3.1%	5.8%
H3. Maintenance (hull/propeller), existing ships	2.3%	2.3%
Theoretical max. from technical measures	**17.6%**	**28.2%**
O1. Speed reduction of 10%	23.3%	23.3%
O2. Weather routing	0.8%	0.8%

Estimated world fleet fuel consumption (no measures applied)

Scenario 1 - No measures, Annual growth of fleet 1.5%	**2010**	**2020**	**Scenario 2 - No measures, Annual growth of fleet 3.0%**	**2010**	**2020**
Fuel cons. (ME)	165.8 Mt	192.5 Mt	Fuel cons. (ME)	203.1 Mt	256.62 Mt
Increase from 2000[2]	19%	38%	Increase from 2000[2]	36%	72%

[1] Comparison with base line fleet development when no measures are applied.
[2] Based on model growth in fuel consumption
Denomination M - machinery measure, H - Hull/propulsion measure, O - Operational measure

The theoretical maximum when implementing all the considered technical measures for the entire fleet is a 17.6% reduction of the emissions in 2010 and 28.2% in 2020. Compared to the two scenarios these values are below the lower boundary for projected growth of fuel consumption and corresponding growth of CO_2 emissions. The fuel consumption increased by 46% during the period 1983 to 1993; hence, a growth in line with the scenarios has been experienced earlier during a period of 10 years.

The effect of the measures was found to be different for the different ship segments, and this is further described in Appendix 4.

The case scenario performed illustrates how the potential for various technical measures for reduction of CO_2 emissions can not be projected to apply proportionally when implemented for the entire fleet. Although the potential for a single technical measure may be significant, the effect on an aggregated level is reduced due to the applicability for different categories of ships. It further illustrates the need for long-term perspective in order to obtain quantifiable end results, due to the long period of time needed for effect of implementation of measures for new ships.

The case study indicates that the effect of technical measures will be different for different shipping segments. Technical measures may compensate growth in emissions due to growth of the fleet to a certain level, but limitations in reductions of emissions by introduction of technical measures have been identified.

Reduction of speed in general is identified as the single measure that results in highest reduction of CO_2 emissions. The reduction will be less if the transport capacity is kept constant, as number of vessels will increase. Even with increased number of vessels, reduced speed will result in reduced total consumption and emissions.

Implementation of new and improved technology is identified as the second best approach to reduce the emissions.

The results from this case study are only based on a technical approach to the task of reducing greenhouse gas emissions from ships. Economical or trade related issues are not properly dealt with, and will affect the above conclusions. Applicability of several measures will have to be considered based on more thorough marked analysis.

6.2. Comparison of freight transportation modes

6.2.1. Introduction

This chapter presents a comparison of international maritime transportation with other modes of freight transportation (truck and rail). Many previous studies exist that calculate these comparisons. Each of these studies tends to follow one of two approaches:

1. They calculate emissions by mode from national average data that may not represent specific regions or modal trade-offs [*Davis*, 1998; *International Chamber of Shipping*, 1997; *OECD and Hecht*, 1997; *Schipper and Marie-Lilliu*, 1999]; or
2. They develop a geographically-specific case study that may not be valid generally outside of the region considered [*Lipinski et al.*, 1999; *Newstrand*, 1992].

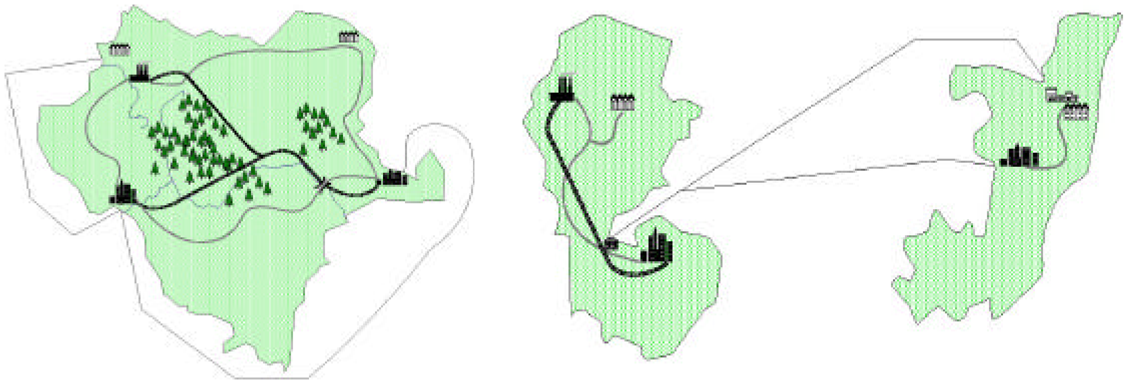
In fact, some studies contradict each other by ranking the modes differently. The analysis presented here attempts to resolve these two approaches by developing a common model that can address both approaches in one framework.

In addition, a comparison of international shipping with other modes of freight transportation in developed nations is presented. Modal shares (by tonne-kilometre) for national freight movement in Western Europe, the United States, and Central and Eastern European countries are reported. Total tonne-km in international shipping is presented by general category of cargo.

6.2.2. Methodology

International maritime shipping is a critical element in the global freight transportation system that includes ocean and coastal routes, inland waterways, railways and roads. In some cases, the freight transportation network connects locations by multiple modal routes, functioning as modal substitutes (see Figure 6-3a). In this case, the cargo shipper has some degree of choice how to move freight between locations. However, it is more common for international maritime transportation to function as a modal complement to other modes of transportation. International shipping connects roads, railways, and inland waterways through ocean and coastal routes (see Figure 6-3b).

To identify explicitly the most important energy and environmental performance factors for international shipping, a Freight Transportation Model was developed. The conceptual framework is shown in Figure 6-4.



(a) (b)

Figure 6-3. Interdependence of Mulit-modal Freight Transportation System as (a) Potential Substitute Modes and (b) Complementary Modes

This idealised Freight Transportation Model defines an equal amount of cargo to be moved by each mode (ship, rail, and truck) across the same distance. It does not specify one type of cargo, but rather an equal tonnage of cargo that could be carried by each mode. By defining an equal tonnage of cargo and an equal distance, the tonne-km in the denominator are identical for all modes and all modes of freight transportation can be compared directly.

The Model estimates explicitly the energy-use and emissions during "open-ocean" or "highway" or "line-haul" transit, and estimates separately the average energy-use and emissions during manoeuvring, docking, and cargo transfer operations for each mode.

Four types of ships are modelled: 1) oil tanker; 2) bulk carrier; 3) container; and 4) general cargo. This Model use the same baseline characteristics assumed for the case-average ships presented in the case study above.

Some assumptions are mode-specific. By setting the annual cargo movements by each mode equal, the Model includes an estimate of time and energy consumption associated with each "turn-around", i.e. terminal approach, cargo transfer, and departure. In this regard, each mode is unique. For example, the Model assumes mode-specific times for ship terminal loading/unloading that begin when the vessel passes the "arrival-buoy" and end when the vessel passes the "departure-buoy". For a truck, this would represent the period beginning when the vehicle leaves the highway to enter the surface-street traffic near the terminal and ending when the vehicle resumes highway driving. For rail, this represents the period off the main rail line and in the switchyard, while the engine is de-coupled and re-coupled to railcars.

The Freight Transportation Model allows the distance between cargo movements (points A and B in Figure 6-4) to vary, but for baseline conditions a distance of 3,218 km (2,000 miles) was chosen. In the Model, 32.2 Million tonnes of cargo is moved by each mode in one year.

This tonnage is arbitrary, but roughly represents the amount of cargo moved in a moderately large port annually. Lastly, the carbon content of petroleum fuels (distillate and residual) is nearly constant [*Flagan and Seinfeld*, 1988; *Heywood*, 1988; *Lloyd's Register*, 1990; *Taylor*, 1995], well within the uncertainty bounds of the IPCC emission factor for CO_2 [*Houghton et al.*, 1996] as discussed in Chapter 1. Therefore, the Model applies the same emission factor for CO_2 across all modes. Table 6-4 summarises these common assumptions.

Table 6-4. Common Model Assumptions across Modes

Cargo Movement Distance	3,218 km (2,000 miles)
Cargo Total Movement	32.2 Million Tonnes
CO_2 (kg/tonne fuel)[a)]	3,170

a) Fuel-carbon content is nearly equal (within 2%) for diesel fuel used in truck, rail, and marine engines and for residual fuel used in marine engines. Uncertainty reported in emission factor (refer to DNV chapter) exceeds variation between transportation modes.

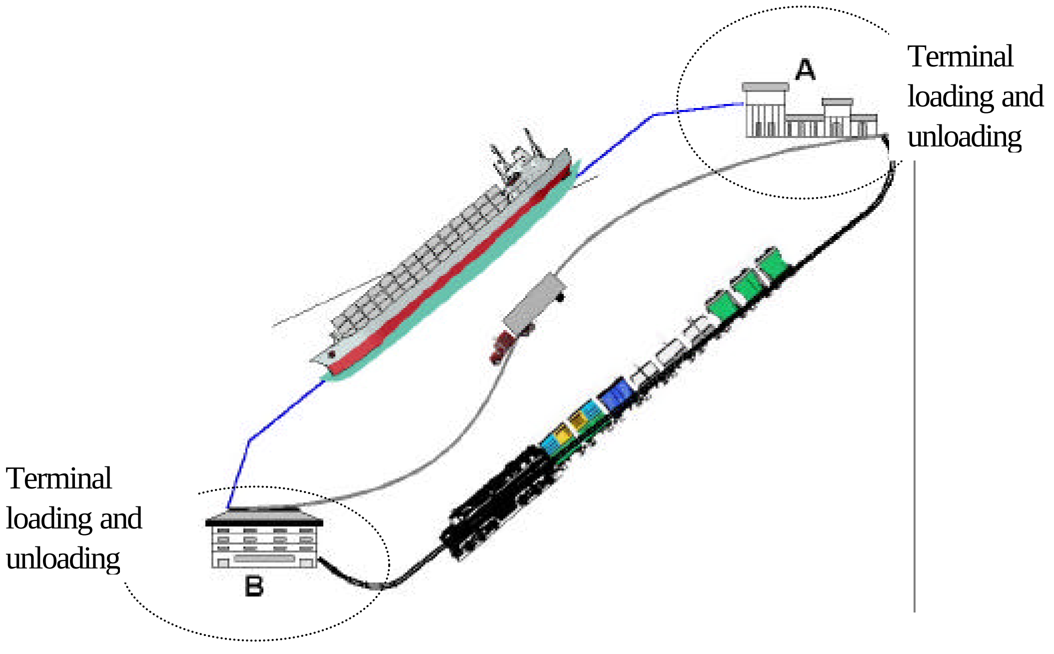


Figure 6-4. Freight Transportation Model Design Framework: Each Mode Performs the Same Work in One Year (Equal Tonnage Moved Equal Distance)

The Model calculations begin by estimating the cargo that can be carried on each case ship (or truck or train). Because DWT describes more than the cargo carrying capacity of a ship, the DWT reported in Lloyds was multiplied by 80% to obtain an estimate of the maximum cargo tons that could be carried; this is consistent with typical voyage estimating factors [*Packard*, 1991]. This value was multiplied by the capacity factor.

Rated vessel speed and the Model distance of 3,218 km (1,739 nautical miles or 2,000 miles) were used to estimate transit times. The slower average manoeuvring speed of 10 knots was applied during the assumed turn-around time in port. From this information, the number of hours per trip, annual number of trips per vessel, and number of ships required to move the total cargo in one year were calculated.

Engine power at cruising speed was used to estimate average daily fuel consumption during transit. Daily fuel-use during manoeuvring into and out of port regions was estimated as presented in Appendix 4. Total fuel consumed per trip was estimated by multiplying the daily fuel consumption for transit and turn-around periods by the amount of time spent underway and manoeuvring, respectively. The entire E3 duty cycle was not used in these calculations because turn-around performance was modeled separately. Similar procedures were used for rail and truck.

By multiplying the fuel consumed each trip by the annual number of trips per ship and by the number of ships required, the Model estimates the annual fuel consumption required to move the total cargo tonnage. Total fuel use divided by the total cargo moved results in an estimate of the annual energy intensity, measured as fuel use per ktonne cargo. From this value, conversions can be applied to estimate energy intensity in MJ per ktonne cargo, or to estimate emissions per ktonne cargo.

6.2.3. Results

The Freight Transportation Model can be used to compare modes while varying important input parameters such as capacity factor. Figure 6-5 shows that capacity factor has significant effect on the fuel consumption per ktonne cargo, and that the effect is greatest for trucks. This confirms the qualitative insights from previous analyses about the importance of capacity factor, presented in Section 5.1. Using average capacity factors, trucks consume more than twice as much fuel per ktonne as rail. (All model runs presented in this section use a cargo transportation distance of 3,218 km. The effect of changing transportation distance is discussed in Section 5.4.)

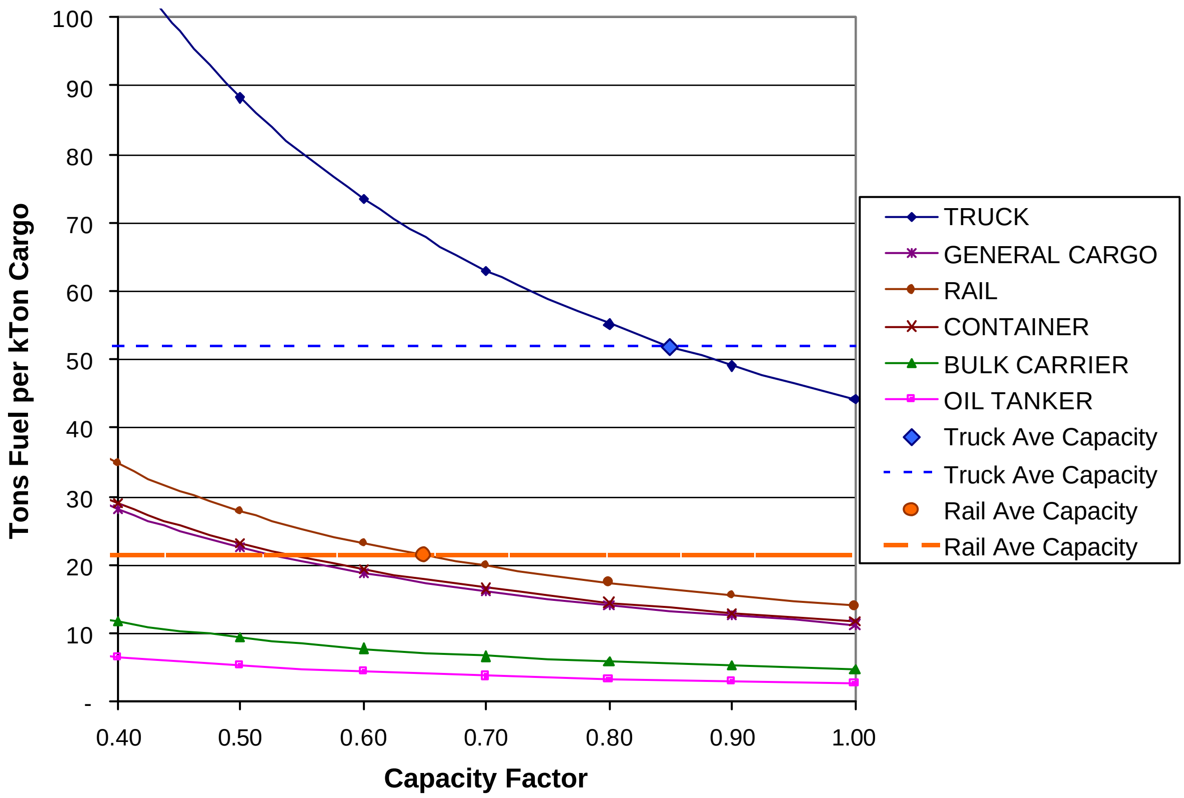


Figure 6-5. Fuel Consumption by Freight Transportation Mode as a Function of Capacity Factor

Figure 6-6 presents similar results for CO_2 emissions per ktonne cargo, including error bars representing the variability introduced by including different speed and power combinations. Three important points should be noted. First, even with error bars the truck mode produces the highest CO_2 emissions per ktonne cargo. Second, rail does not always perform significantly worse than ships, if different speed and power relationships are used for ships of the same type and size as the case-average container and general cargo ships. Third, bulk carriers and oil tankers in the case-average size ranges do perform significantly better than other ships, rail and truck.

When other pollutants are considered, the results can be different. NO_x comparisons varied by capacity factor are presented in
Figure 6-7. Ships still perform better than truck or rail modes, but this difference is not always large. Because significant NO_x controls have been required for trucks, their NO_x performance improves relative to the other modes. Additionally, more fuel-efficient diesel engines in rail and marine applications tend to operate at higher temperatures and pressures than truck engines, and therefore produce more NO_x for the same power. Most interestingly, under average truck and rail capacity factors (85% for truck and 65% for rail), the NO_x performance of these modes is nearly identical.

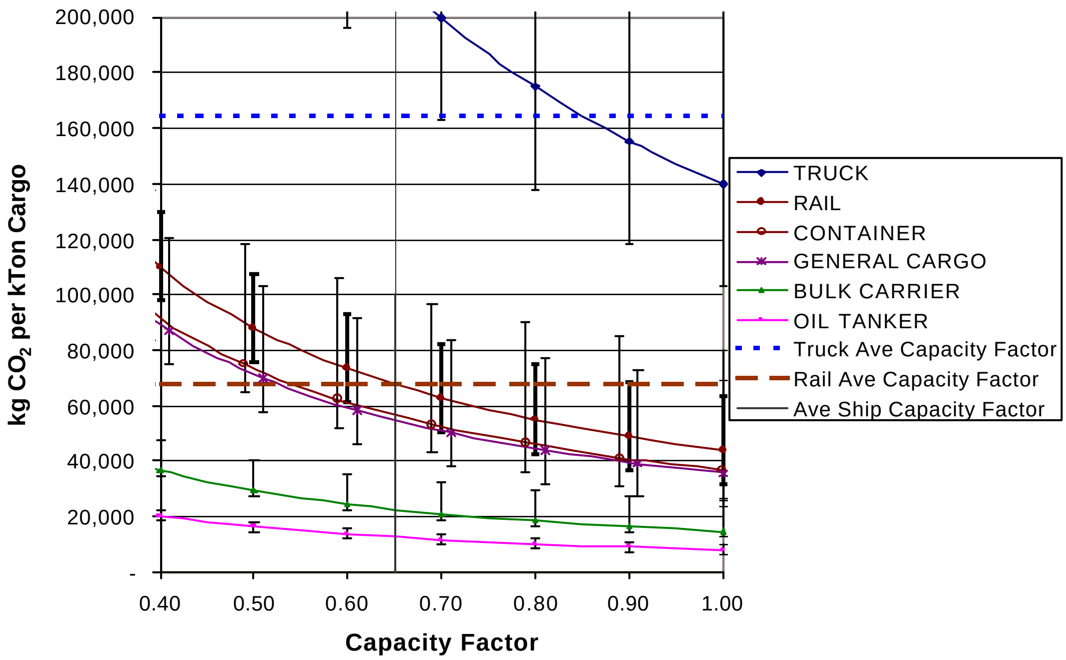


Figure 6-6. CO_2 Emissions Varied by Capacity Factor (with 5th and 95th percentile effects of variability shown)

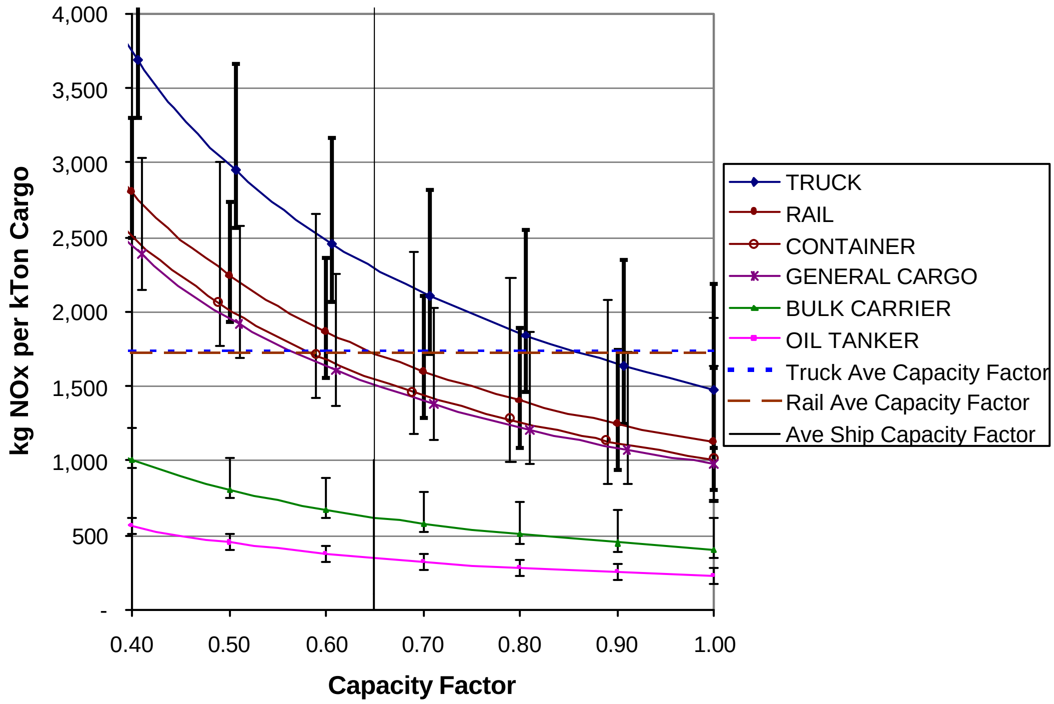


Figure 6-7. NOx Emissions Varied by Capacity Factor (with 5th and 95th percentile effects of variability shown)

Emissions differences between the modes are most noticeable for SO_x (Figure 6-8). The fuel-sulphur contents for marine bunkers are much greater than distillate diesel fuels used by truck and rail modes. This results in SO_x emissions per ktonne cargo that can be 6 to 26 times higher for ships than for land-based modes.

In summary, capacity-factor differences between the modes are significant, but modal differences between pollutants are much larger. The effects of changing capacity factors are not at all similar across pollutants. This is primarily due to modal differences in emission control, engine design, and fuel specifications. Under baseline model conditions, the CO_2 performance by ships is clearly better than other modes of freight transportation.

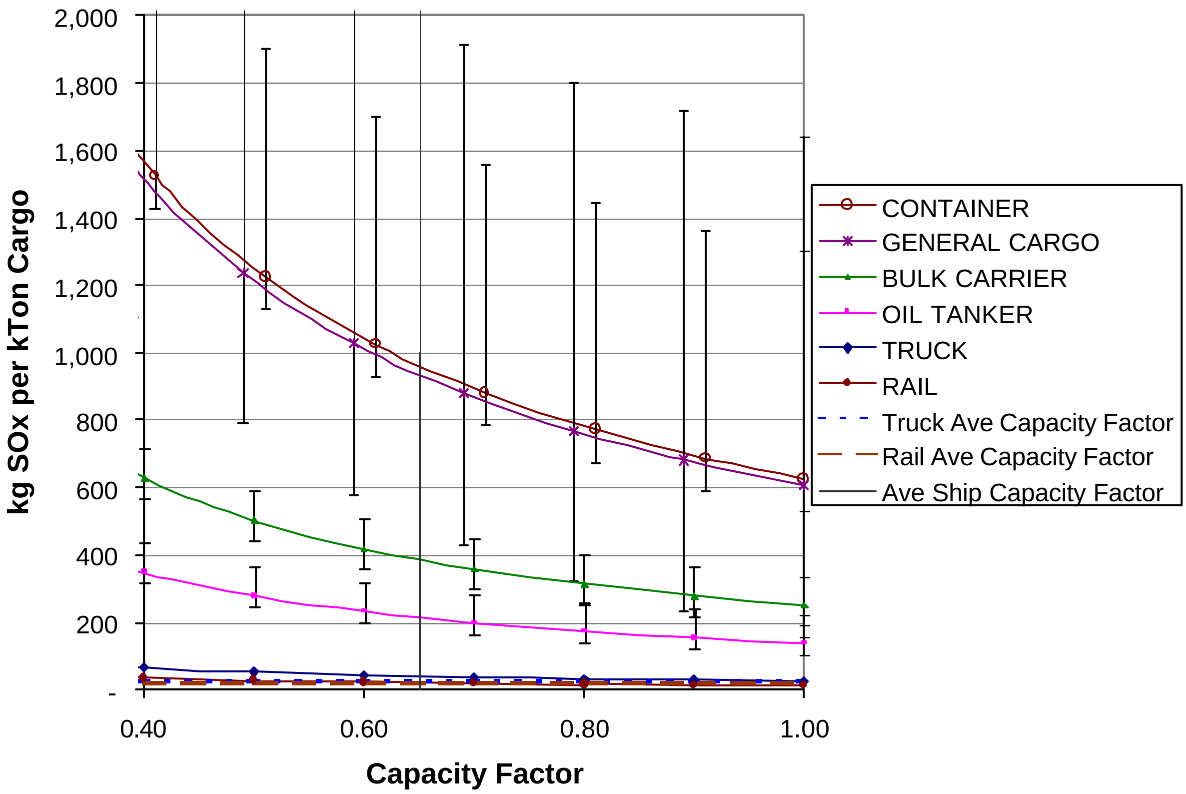


Figure 6-8. SOx Emissions Varied by Capacity Factor (with 5th and 95th percentile effects of variability shown, dominated by fuel-sulfur content)

One important input assumption is the turn-around time, because the corresponding energy use during this period can account for 4% to 15% of total energy use per trip for ships under baseline model assumptions. Reducing turn-around time – or at least minimising the energy used by ships during turn-around time – can reduce total energy and emissions intensities in two different ways. The reduced turn-around time per ship can result in more trips per ship per year, thus requiring fewer ships to perform the work. Alternatively, reduced turn-around time can be used to make transit-speed adjustments that maintain constant trip duration; this results in reduced power with the same number of ships performing the cargo movements. Each of these is discussed below.

A 25% reduction in turn-around time can reduce CO_2 emissions by 1% to 4%, depending on the mode. In general, when turn-around times are a larger fraction of total energy use for each trip, reducing turn-around times has a larger effect in reducing CO_2 emissions. (It should be noted that reduced turn-around times also reduce other emissions and improve overall energy performance.)

On the other hand, using these reductions to adjust transit speeds can provide additional reductions in energy use, CO_2 emissions, and emissions of other pollutants. Figure 6-9 shows that given the baseline assumptions, a container ship can reduce transit speed by approximately 1 knot over a 3,218 km (2,000 mile) transit with a 6 hour (25%) reduction in turn-around time. The potential for turn-around time adjustments to reduce transit speed is greatest for faster vessels. For the case-average general cargo ship, the same reduction in turn-around time for the same 3,218 km transit allows for less than 1 knot speed reduction, and for the case-average tanker and bulk carrier the speed reduction is about 0.5 knots.

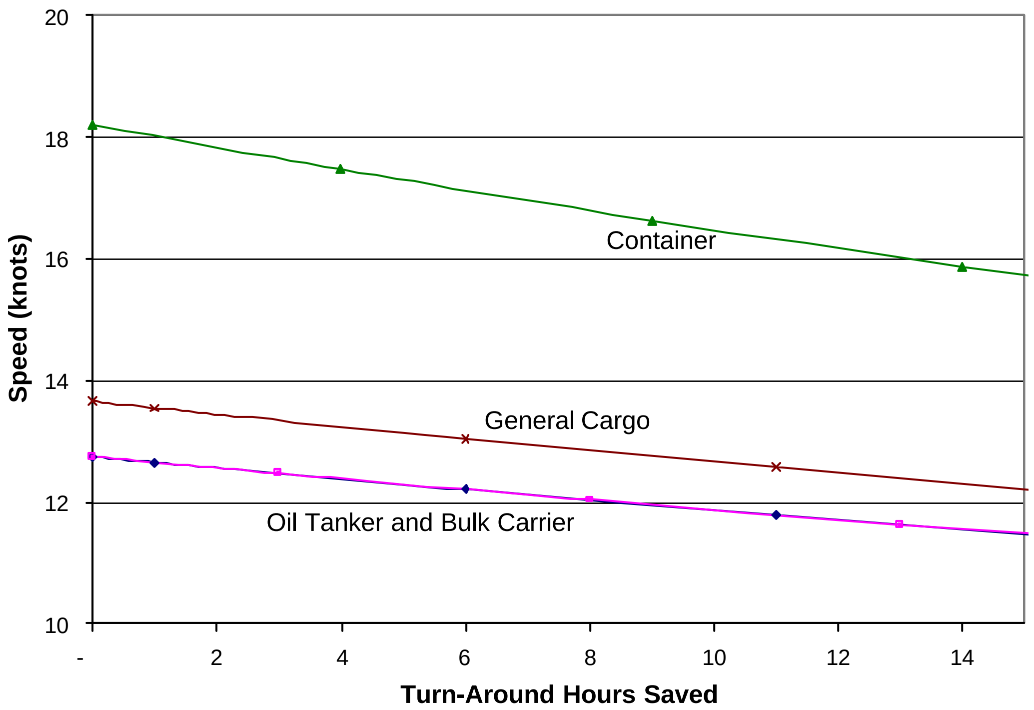


Figure 6-9. Speed Adjustment Potential to Maintain Constant Total Trip Time with Reduced Turn-Around Time for Baseline Scenario Distance of 3,218 km (2,000 miles)

The Freight Transit Model shows that these relatively small reductions in speed afforded by improved turn-around times have the potential to reduce emissions. Figure 6-10 compares the percent CO_2 reduction that results from reducing the required number of trips and ships with the percent CO_2 reduction from transit speed adjustments. While reducing turn-around time alone provides a modest reduction in emissions, additional reductions can be achieved by using these gains to reduce energy and emissions during transit. Under baseline model conditions, a 25% reduction in turn-around time with speed control can reduce CO_2 emissions by 14% to 17%, depending on ship type.

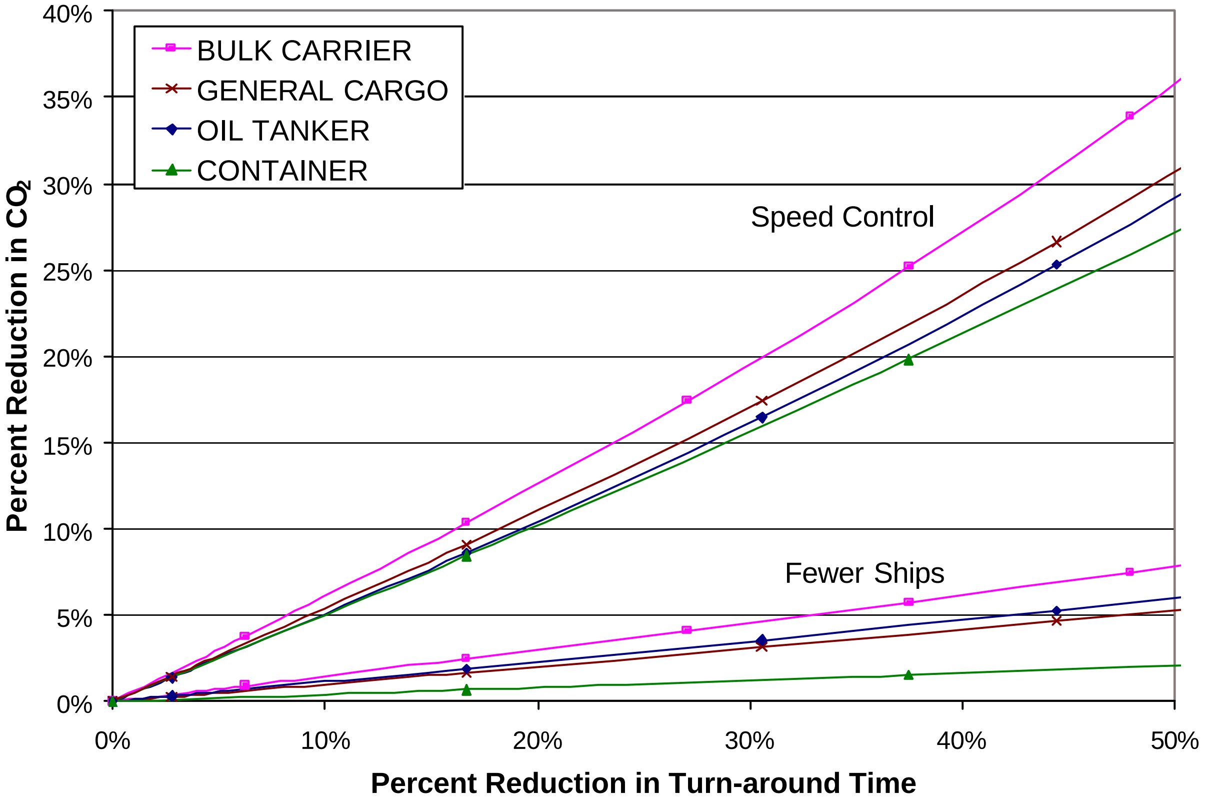


Figure 6-10. Comparison of Percent Fuel Consumption Variability with Terminal Turn-Around Time for Scenarios With and Without Open-Water Transit Speed Reduction

These results would be different under different model scenarios. Particularly, the transit distance has a significant effect on how much speed reduction can be achieved for a given reduction in turn-around time. To illustrate this, Figure 6-11 presents the same calculation for transit-speed reduction for three different distances. The baseline distance used in the model is 3,218 km (2,000 miles). For a distance of 805 km (500 miles), the same reduction in turn-around time can afford a much greater reduction in transit speed, because the turn-around time is a larger fraction of the total trip time. For a distance of 8,045 km (5,000 miles), the effect of reduced turn-around time on transit speed is much less.