Zero Emissions Vessels

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This paper proposes a LNG-fueled coastal RO/RO for the East Coast of the US trade to meet upcoming Emission Control Area (ECA) requirements. The exhaust system for this vessel is proposed to be a wet system so there is no airborne emission. The CO_2 *remaining in the exhaust system is removed in the exhaust stream, and remaining exhaust components are combined with cooling water to provide a cooling effluent that meets Environmental Protection Agency (EPA) requirements. The concept design is carried to the point of determining operating economics, and the environmental effect of operating such ships is assessed as compared to conventional truck traffic. It was found that each ship will reduce East Coast highway truck traffic by over 1900 trucks per week. Since there are no emissions from the ship, each ship will also bring environmental advantages. It appears the ship would be economically competitive with conventional truck transport: the cost for transporting a single 53' trailer via ship is roughly $996, compared to $1245 via truck. Furthermore, the proposed three vessel shipping service could potentially remove nearly 300,000 vehicles from the road annually.*

Keywords

Zero-Emission Vessel; Coastal RO/RO; Short Sea Shipping; Marine Highway; Shipping Economics; Trucking.

1. Introduction

Highways in the United States have become increasingly congested with traffic, especially compounded by large trucks carrying goods along the coasts. Not only is this a logistics issue for the business sector, but it also has major ramifications for the well being of the general public: 42,000 citizens die every year in fatal highway accidents. Roughly $800 billion in tax money is spent every year, both federally and locally, on improving the US infrastructure that has deteriorated by the passage of these trucks Furthermore, the excessive numbers of trucks emitting oxides of nitrogen and sulfur (NOX and SOX) and carbon dioxide (CO2) into the atmosphere continue to alarm scientists with concerns of acid rain and global warming, respectively. Finally, with the cost of oil fluctuating, and ultimately rising, economists wonder if a fleet of trucks, each transporting a single container, is truly an effective economic endeavor.

At the behest of government officials, environmentalists, and businessmen, economists have begun thinking of viable alternatives to the nation's current trucking system. Perhaps the most under-utilized resource available for intra-national containerized transportation is the ocean itself. Currently, it is primarily used for international trade, but the prospects for shipping containers along the coasts of the US and moving goods between American cities are very promising. The US eastern seaboard, with its large industrial cities near the coast and its frequently-congested freeway, Interstate 95 (I-95), is potentially a prime location for such a short sea shipping (S3) route.

2. Background

2.1 Rising Environmental Concerns

Beginning with the fully-realized effects of the Industrial Revolution in the mid-1800s, industrial emissions have increased substantially, releasing undesirable byproducts into the atmosphere. Particularly detrimental byproducts include nitrous oxides (NO_X), sulfurous oxides (SO_X), and carbon dioxide (CO_2). Figure 1 illustrates the enormous increase in global CO_2 emissions over the past 150 years.

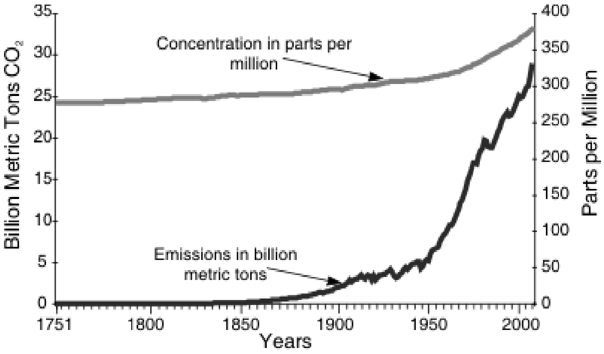


Figure 1. Global CO_2 Emission, 1751-2000

Source: Energy Information Administration

Today, vehicles on land, sea, and air are still large sources of emissions. Data from the year 2000 indicate that the US transportation industry alone accounted for 55% of the total man-made sources of NO_X, 40% of the total unburnt hydrocarbon, and 23% of the total particulate matter. At least 30% of the national fossil fuel-related CO_2 emissions in 1999 were attributed to the transportation industry. These pollutants, along with ozone (O_3) and lead, are significant contributors to poor air quality in the US and abroad.

Two other significant pollutants are sulfurous oxides (SOx) and carbon dioxide (CO2). Acid rain, for instance, is caused by NOx and sulfur dioxide (SO2), and it may adversely affect human respiration. Carbon dioxide is one of many greenhouse gases (GHG) that has been attributed with causing "climate change."

The International Convention for the Prevention of Pollution from Ships (MARPOL) was revised in 2008 to set stricter standards for the emissions from ships. Globally, sulfur content in fuels will be limited to 0.5% from 2020 and on (vs. 4.5% now). New limitations will also be imposed on NOx emissions. The timing and amounts of sulfur in fuel for global and ECA (defined below) requirements are shown in Figure 2; requirements for NOX are shown in Figure 3.

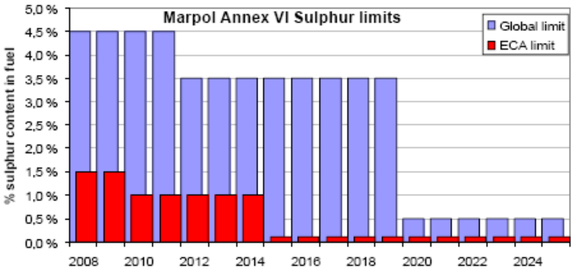


Figure 2: MARPOL Limits on Fuel Sulfur Content

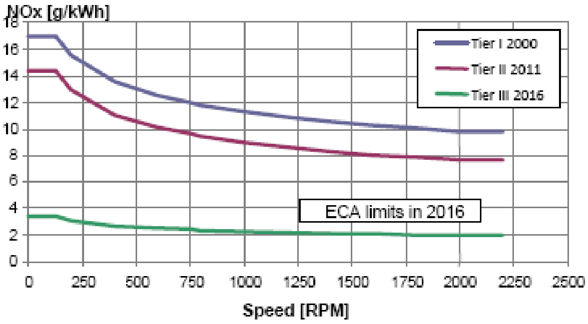


Figure 3: NOx Emission Limits, MARPOL Annex VI

In addition to these limits, the US-based Marine Environmental Protection Committee has also given approval for plans to declare certain areas of the US and Canada's coastal waters as an Emission Control Area (ECA). The North and Baltic Seas are already ECAs and the initial US/Canadian ECA is likely to become effective in July 2010. While the initial area will be restrictive, it is expected that nearly the entire coast line could become an ECA within the next 10 years. Depending on how far out this ECA extends (possibly 200 miles), coastal US shipping may eventually operate entirely within the ECA.

In order to meet future limitations within ECAs, much cleaner fuels will be required, in addition to exhaust treatment. It is estimated that these fuels could cost 70% to 100% more than conventional bunker fuel.

2.2 Possibilities of LNG

LNG (liquefied natural gas) has been proposed as an alternative solution to the challenge of cleaner shipping fuels, for scheduled trades in Northern Europe, and particularly those within the ECA. The environmental qualities of LNG are superior to those of any liquid petroleum fuel. The technical and operational viability of LNG as a fuel for ships has already been demonstrated in Norway, where a number of coastal ferries and other ships have operated on LNG for several years, with more under way. The use of LNG effectively eliminates the need for exhaust treatment, due to very low NOx formation in the engines, as well as the absence of sulfur. Table 1 demonstrates the differences in emissions among LNG and other liquid petroleum fuels.

Table 1. LNG Emission Comparison

Fuel type	SOx (g/kWh)	NOx (g/kWh)	PM (g/kWh)	CO2 (g/kWh)
Residual oil 3.5% sulphur	13	9-12	1,5	580-630
Marine diesel oil, 0,5%S	2	8-11	0,25-0,5	580-630
Gasoil, 0.1% sulphur	0,4	8-11	0,15-0,25	580-630
Natural gas (LNG)	0	2	~0	430-480

Notably, LNG as a fuel emits no SOx, very little NOx, and no particulate matter, but it does emit $CO_{2,}$ albeit 20-25% less than liquid fuels. Since CO2 may contribute to climate change, it is the focus for commercial and technical proposals related to climate change mitigation.

There is precedence to using LNG as a fuel in coastal trade: as of 2008 in Norway, six car ferries, three offshore supply vessels, and one coast guard vessel used LNG. The total of ships, including vessels on order or planned, is to exceed 20 LNG-powered vessels. One such RO/RO vessel, intended for service among western Norway, the United Kingdom, and the European continent, is shown in Figure 4.

Figure 4: Norway's Sea-Cargo LNG-Fueled RO/ROs Source: Rolls Royce

Some of these vessels plan to use engines with spark ignition. Other LNG-fueled ships are powered by engines that use ignition by a small diesel portion in the fuel, and can alternatively run on diesel oil alone. Wärtsilä and Rolls Royce Marine are currently the leading manufacturers of gas, or dual-fuel, powered engines for ships. In addition, a number of established diesel engine manufacturers have developed, or are developing, gas versions of their engines.

The logistics of LNG fueling is often cited as a reason why LNG-fueled ships will be difficult to implement. The implication is that a special LNG bunkering port would have to be constructed for LNG fueling. There are four existing East Coast LNG terminals: Nova Scotia, Boston, Maryland, and Savannah that have tanker truck loading capability.

Since LNG is 1/600th of its gaseous volume and has a specific gravity of 0.4, it occupies little volume and has a weight less than liquid fuel. It is estimated that the RO/RO depicted in this paper would need about 200 M3 to complete the round trip between Boston and Charleston. As an LNG tanker truck carries about 55 M3, only four truck loads would be required to bunker the vessel for a round trip.

Barges are also possible for fueling, either carrying tank trucks on deck, or fitted with permanently mounted deck tanks.

In the case of this RO/RO, one could also consider LNG tanker trucks staying on board, in the cargo area, and not installing fuel tanks in the vessel.

3. Route Selection

The proposed coastal RO/RO is envisioned as a 2-port vessel which could operate between the following ports, as possible locations:

- Boston to Savannah – 910 miles
- New York to Jacksonville – 792 miles
- New York to Miami – 981 miles
- Boston to Jacksonville -1000 miles
- Boston to Miami – 1223 miles
- Boston to Charleston – 838 miles

Therefore, vessel notional maximum route is 1223 miles. The route selected for this paper is between Boston, MA, and Charleston, SC. As mentioned, an LNG fueling terminal exists already in Boston.

It is important to mention that no market sizing study was done for the route; it is assumed that enough cargo is moved to warrant a coastal shipping trade.

For any coastal shipping route, it is desirable to be as time competitive, as possible, with truck transit times. As indicated later, truck transit is 31.3 hours and to roughly match that transit time, the ship would be required to cruise at well over 26 knots. This nearly four day round trip would involve a vessel of great HP and fuel consumption. It was determined that going to about 56 hours instead of 31.3 hours would allow a much more reasonable vessel speed of 15 knots. Thus, a 6-day round trip voyage time has been used for analysis.

4. Concept Design

4.1 Basic Features

For a RO/RO, one of the most important design points is the loading and unloading capabilities of the vessel. Figures 5, 6, and 7 show the concept design developed and the cargo transfer loading and unloading ramp arrangement for the RO/RO, called the *CLR.*

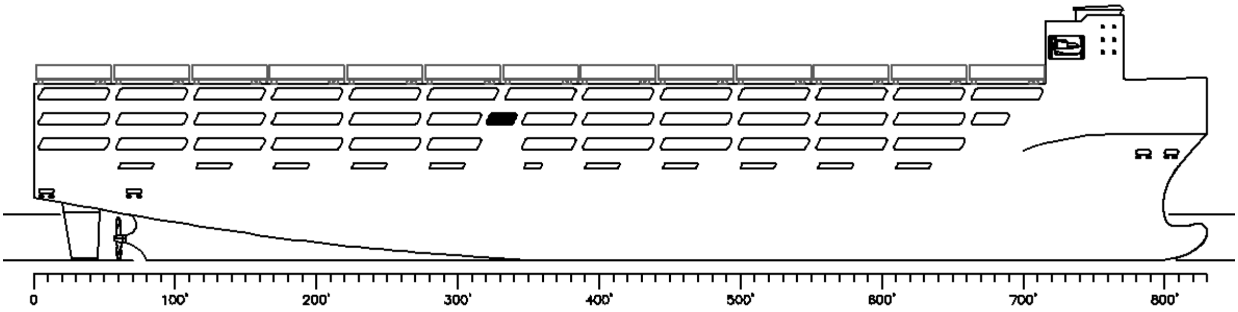
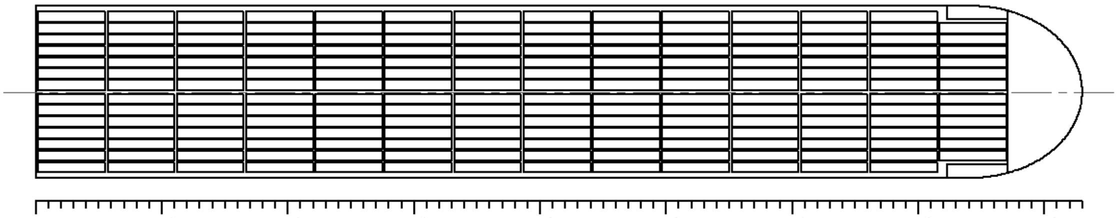
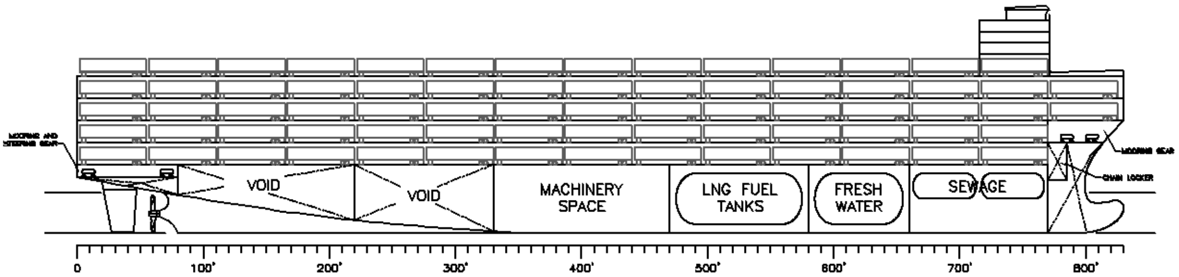


Figure 5: Outboard Profile View

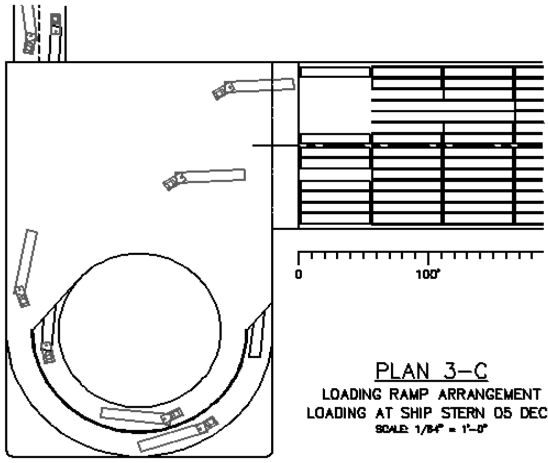


PLAN 2-C
05 DECK PLAN WITH CARGO TRAILERS
SCALE: 1/64" = 1'-0"

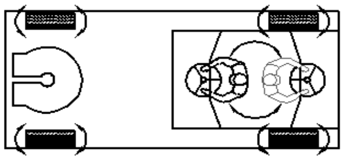


PROFILE 2-A
INBOARD PROFILE
SCALE: 1/64" = 1'-0"

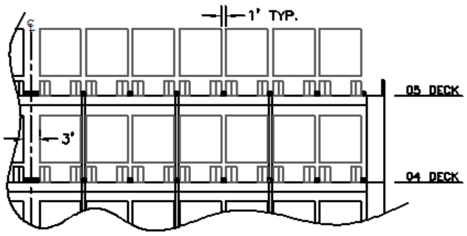
Figure 6: Plan View and Inboard Profile View



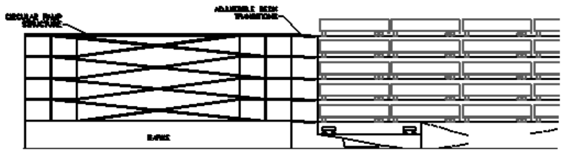
PLAN 3-C
LOADING RAMP ARRANGEMENT
LOADING AT SHIP STERN 05 DECK
SCALE: 1/64" = 1'-0"



DETAIL 1-C
LOADING TRACTOR WITH ROTATING DRIVER POSITION
4 WHEEL DRIVE WITH 4 WHEEL STEERING
SCALE: 1/32" = 1'-0"



SECTION 1-A
04 AND 05 DECK TRAILER STOWAGE
MIDSHIP LOOKING FORWARD
SCALE: 1/16" = 1'-0"



ELEVATION 3-A
LOADING RAMP WITH TRANSITIONS
LOADING AT SHIP STERN
SCALE: 1/64" = 1'-0"

Figure 7: Trailer Loading Details

As can be seen in Figure 6, all cargo is located above the freeboard deck; from Figure 7, it can be seen that cargo is loaded and discharged from the stern. The five cargo levels of the ship are mated to a five level floating transfer facility (Plan 3-C) that is permanently moored in each port.

Port time is reduced by arranging the loading / discharge facility so there is no crossing traffic. The cargo removal operations are started on the starboard side; once the outside lane trailers have been removed, each tractor bringing a trailer up turns and drives aft, so that the rig is aligned with the lane to be filled. The driver of tractor can then swivel his driving position 180 degrees (Detail 1-C) such that backing into the lane is carried out with the driver facing the lane entry point. Four-wheel steering assists entry into the lanes. Curbing between the lanes (Section 1-A) assists in aligning the parked trailer and minimizes lashing. Once a loaded trailer is parked, the tractor proceeds to the next lane, to port, to remove a trailer to shore. All 5 decks are intended to be loaded and unloaded simultaneously.

As both the ship and transfer ramp facility are floating (Elevation 3-A), alignment between the two is not affected by tides. The floating facility also makes it possible for the ship operator to change ports, without major infrastructure changes. The ship and floating transfer ramp facility would not necessarily require fully developed pier facilities to start operations.

By opening the sides of the ship at the 5 cargo levels, cargo ventilation requirements are nearly eliminated. Furthermore, it should be noted there is no stack or casings. Air inlet is provided on each side, amidships, between side frames.

It is proposed that the only built-in tankage, using ships structure, will be the forepeak and aft peak tanks. These are intended to be the only ballast tanks, as the fine hull form should be easy to trim for required drafts. Fresh Water and Sewage tankage will be provided by standard manufactured baffled cylindrical tanks. The LNG tanks can be provided from a number of sources, coming fully outfitted.

The desired capacity of the RO/RO is 2500 TEU, or the equivalent of roughly 943 53-foot trailers. Based on this condition, along with port requirements of possible ports, principal characteristics were derived and are shown in Table 2.

Table 2. *CLR* Principal Characteristics

Item	Value
Length Overall	830 ft
Length, Waterline	730 ft
Beam	134 ft
Draft	32 ft
Displacement	47,000 LT
Trailer Capacity	2500 TEU
Block Coefficient	0.48
Midship Coefficient	0.95
Prismatic Coefficient	0.50
Propeller Diameter	22.5 ft
SHP @ 15 kts	15,000 hp

4.2 Exhaust Stream Possibilities

To provide a clear path for RO/RO trailers on all decks it is proposed to bring in air for propulsion through side ducts located between side web frames. It is also proposed to eliminate the conventional exhaust stack and to replace the exhaust stack with a wet exhaust system that includes a loop (again, within the side frame structure) that carries the exhaust above the freeboard deck, before going over the side.

Wet exhaust systems have traditionally resulted in back pressure for engines and have either reduced performance or caused improper operation.

The authors propose that the ship shown be fitted with a longitudinally orientated cooling water system with a scoop forward and suction exit that would accelerate flow through the loop. A Bernoulli type restriction in the loop would give a low pressure point at the restriction and exhaust gas would be entered at that point. Pressure at that point would be slightly below atmospheric pressure.

4.2.1 CO2 Extraction

The exhaust gases, before being injected into the cooling water stream, will be bubbled through a chemical, or ionic, process that will remove CO2 from the exhaust gas. Proven systems exist where the medium is constantly circulated, giving up the CO2 in a separate part of the process where the CO2 is captured. The captured CO2 will be compressed and retained on board for shore discharge, via a trailer mounted pressure vessel. While the cost for the extraction process is included in the ship cost, the cost for removal and disposal is assumed to be offset by carbon credits.

5. Shipping Operation

In the sea shipping model, the mode of transportation switches twice, causing time delays not seen by the truck-only transportation model. A short-distance trucker starts from a manufacturing plant in South Carolina and drives some distance until he reaches the port in Charleston; this intermediate transit step is termed drayage. Once the truck reaches the port, trailer is loaded onto a yard tractor. Stevedores place the trailer onto the RO/RO vessel, the main mode of transportation. When fully loaded, the vessel motors at full speed to Boston, slowing down slightly to maneuver through both ports. Its cargo is unloaded in the same manner as it was loaded. Finally, a short-distance trucker picks up the trailer and delivers it to its final destination in the Northeast.

TOTE’s RO/RO service from Washington to Alaska is by far the most successful S3 operation the US has seen. Thus, to simulate an East Coast route, the operational experience of TOTE on the West Coast was heavily consulted. Instead of TOTE’s Orca Class vessel, the *CLR* was used in the model.

5.1 Time Estimate

The delivery time of the S3 route is defined as the time for a single trailer to leave its point of origin and arrive at its final warehouse. Table 3 below shows the summation of shipping time. The final row indicates the number of one-way trips that are possible given that vessel speed. (Annual vessel usage of 98%, or 357 days per year, is assumed.)

The cargo handling and “Other Port Time” categories provide the time it takes for the service to load and unload all trailers and any unforeseen delays, termed “dead time", respectively. This data was obtained by analyzing loading data of the TOTE RO/RO M.V. Midnight Sun, taken over 8 port calls between January 17, 2008 and February 21, 2008.

The dead time encountered in Charleston and Boston is a result of unexpected slowdowns. Ideally, this time should be as close to zero as possible, and the ship will be ready to leave as soon as all cargo is aboard. However, as was seen in TOTE's operation, this dead time can range anywhere from 10 minutes (a successful turnaround) to 6 hours (when repairs were made on the engine). The 120-minute figure is a mean estimate based on TOTE's turnaround times in Anchorage and Tacoma.

Maneuvering times are based on data from the port authorities of Boston and Charleston. For each city, a map of the harbor was reviewed and a possible location for an S3 terminal was selected. The port of Charleston provides a time estimate for ship transit to open water. The time for the RO/RO vessel to reach its dock is Boston was determined by Boston's port speed limit, 10 knots, constituting an additional 90 minutes of maneuvering time.

Finally, the drayage category is calculated by assuming a mean distance from the origin of the goods to the port, or from the port to its final destination. Data on drayage distance to and from the Boston and Charleston ports were derived from an EPA study that estimates an average drayage short-haul truck covers 32 miles at 25 miles per hour.

Table 3. Total Time for One-Way Shipping Operation

Activity	Time (minutes)
Cruising Speed	15 kts.
Cargo Handling	480
Maneuvering (x2)	240
Other Port Time	120
At Sea Time	3200
Drayage (x2)	154
Totals	4040 67.3 hr
Possible Ship round trips /yr. @ 6 days/ RT	**60**

Note that the total time (67.3 Hr.) for the shipping operation includes drayage time. However, when calculating the total number of trips possible each year, this drayage time is not included, because the ship itself is unaffected by the drayage time and can leave port as soon as all of its cargo is offloaded.

Each ship can carry out 120 one-way trips each year, as consistent with the 6 day round trip service. Assuming there are 3 vessels in the fleet, this equates to 360 one-way voyages, or 180 round-trip voyages. With roughly 943 trucks on board carrying 53-ft-long trailers, this RO/RO service could potentially remove 340,000 trucks from the road annually.

5.2 Cost Estimate

As in the trucking cost estimate, costs were itemized into periodical and per-trip categories. The original start-up costs are quite substantial for the construction of the 830-foot-long RO-RO vessel, but they become less noticeable as the ship's service life continues.

Table 4 tabulates an estimate of the cost of the short sea shipping operation.

Table 4 . Total Cost for Shipping Operation, Per Trailer

Item	Cost ($)
Ship Construction	195
Insurance	13
Repair/Maintenance	14
Crewing	38
Stevedoring	78
Drayage	360
Navigation and Port	98
Fuel	100
Miscellaneous	100
Total	**$996**

The ship construction cost displayed in Table 4 indicates the initial cost for the *CLR*'s construction, broken into monthly payments. A price tag of $195 million is roughly market value for a US-built and flagged RO/RO vessel with similar principal characteristics. Included in the overall capital cost is the cost of the two floating terminals used in the route. The terms of the loan for this large initial investment are applied over a 20-year period, and the estimated service life is 30 years. Based on current market rates for RO/ROs of comparable size, a 20-year loan was assumed to have an interest rate of roughly 5.0%.

Since the *CLR* is a Jones Act vessel, its crew must be US Citizens. The crew size would be determined by US Coast Guard regulations and union agreements, however we have assumed 22 crew members (12 crew and 10 officers) as a conservative estimate for a ship of the *CLR's* size. The estimated wage rates, including benefits, are $150k annually for crew and $255k annually for officers. Feeding costs are estimated at from $90k to $160k annually. In total, the daily crew cost is roughly $12.3k per day. Table 4 displays these costs as a single per-trailer sum in the "Crewing" category.

Stevedoring cost estimates were taken from a study on US West Coast ports completed by TranSystems. Drayage costs, like drayage time, depend on the distance of the dray. This model assumes that cargo is delivered within 50 miles of the port, an average figure for East Coast drayage distances; a new load is picked up on the way back to the port. Ultimately, a cost of $180 per dray was used as the standard one-way drayage cost for Atlantic Coast ports; this figure is based on typical drayage rates. This charge occurs in both Charleston and Boston, so a single trailer incurs $360 in drayage costs in the S3 route.

Ship Speed (knots)	15
CO_2 Emitted (kg)	0
SO_X Emitted (kg)	0
NO_X Emitted (kg)	>0
Fuel Consumed (kg)	**167**

Navigation and port charges, totaling $98 in Table 4, is comprised of multiple charges levied by the ports of Charleston and Boston. Dockage and pilotage fees are based on the size of a ship, whereas wharfage and usage fees are charged per trailer. Dockage is defined as the charge assessed against a vessel for berthing at a wharf, pier, or bulkhead structure or for mooring to a berthed vessel. Pilotage is the amount paid for harbor pilots to navigate in through the local channels. Wharfage is a charge assessed on a vessel for all cargo passing or conveyed over, onto, or under wharves. The usage fee is levied on shippers when they perform their own loading or unloading at a port facility (South Carolina State Ports Authority).

Fuel costs were calculated by estimating the fuel consumption (FC) of the *CLR* during both maneuvering and cruising speeds. (The method for obtaining the FC is detailed in the Emissions Estimate section.) At its cruising speed of 15 knots, the vessel uses approximately 100 gallons of fuel per trailer. The *CLR's* engines are running on LNG at a cost of $0.75 per gallon.

Finally, a category of miscellaneous charges was created to track costs that do not easily fit into other categories. One component is the Harbor Maintenance Tax (HMT), which is levied on the shipper based on the value of the cargo. Since the cargo's value is highly uncertain, an estimate of $47,800 was used for the value of goods in a single FEU (National Ports and Waterway Institute). Also in this category are MG&A (Management, General, and Administrative) costs. These cover expenses related to marketing, accounting, legal issues, and human resources. MG&A costs are estimated at 1.5% of total expenses per trailer. In all, the miscellaneous costs were conservatively set at $100 to include the aforementioned expenses in addition to other unforeseen expenses.

5.3 Emissions Estimate

Until recently, only steam-turbine ships would have burned LNG in their main propulsion plants, but as discussed earlier, there are a number of new and more efficient technologies being developed which will allow for the more widespread use of LNG as a fuel. MAN B&W, Wärtsilä, and Rolls Royce Marine have all developed diesel engines which can burn the gas. The Rolls Royce Bergen engines can burn the gas alone, but the MAN B&W and Wärtsilä engines are dual-fuel which require the injection of a small amount of fuel oil with the gas. In striving to minimize the emissions of the ship, the Bergen engines will be considered in this analysis. First, the *CLR's* per trip power consumption is calculated, and then the emissions profile of each trip is determined using estimated emissions data from Rolls Royce.

5.3.1 Power Consumption

A ship-powering regression was used to estimate the required SHP for the *CLR* at the investigated speeds. Port and Maneuvering loads were also estimated and the total power consumed per trip was calculated. Table 5 below shows this tabulation and results.

Ship Speed (knots)	15
Max Required Power	(kW)
SHP Cruising	11200
Electrical Load	1700
Tot Required Power	12900
Load Estimates	(kW)
At-Sea	12900
Maneuvering & Port	4900
Power Consumption	**(kW-hr)**
At-sea	748200
Maneuvering & Port	45960
TOTAL	794160

Table 5. *CLR* Power Consumption

As shown in Table 5, the power consumption of the voyage from Charleston to Boston is divided into two components: at-sea consumption (i.e., at cruising speed), and maneuvering and port consumption. The ship spends the majority of its time cruising the 800-nautical-mile (920-mile) buoy-to-buoy distance. The at-sea load is the shaft horsepower (SHP) required to make cruising speed, in addition to the electrical load, estimated at 1700 kW. The maneuvering load is the SHP of the RO/RO at a reduced speed of ten knots in each port, plus the electrical load. Lastly, port loads are simply an electrical load of 1000 kW, slightly reduced from 1700 kW while docked. Together, maneuvering and port power consumptions account for only 5 to 6% of the total power consumption, depending on vessel speed.

5.3.2 Emissions Profile

For the emissions estimate of the ship, emissions factors for the Rolls Royce Bergen engines were used.

The emission factors were provided in the form of gram per kilowatt-hour; these factors were multiplied by power consumption figures from Table 6 to estimate the mass of undesirable emissions. For comparison to the trucking emissions, these totals were divided by the number of trailers in a typical load, 900, to present the data in emissions per trailer. The results are shown in Table 6.

Table 6. *CLR* Emissions Profile, Per Trailer

The Bergen engines produce no sulfurous oxides, and very few nitrous oxides. Furthermore, a relatively low amount of carbon dioxide is emitted. All of these pollutant levels are compared to the trucking emissions in a later analysis.

The emissions profile of the ship decreases as its operating speed decreases. By carrying out emissions estimates above and below 15 knots, it can be shown that the ideal speed (lowest possible emissions per trip) is just slightly lower than 15 knots.

6. Trucking Operation

A long-haul truck begins its journey from a manufacturing center in Charleston, South Carolina, and travels northbound along I-95 until it reaches its final destination near Boston, Massachusetts, a distance of approximately 1020 miles. Along the way, it encounters weigh stations, traffic slowdowns around major industrial centers, and other unforeseen stops. This trip must fit into a trucker's overall schedule to ensure that he follows federally-mandated rest regulations. In terms of cost, the trucker incurs per-trip costs (tolls, fuel, and depreciation), but also monthly costs (insurance and licensing fees) independent of this single journey.

In the trucking model, the tractor-trailer is of standard size and weight, roughly 25,000 lbs when empty. Each truck carries a single 53 foot trailer with a cargo weight of approximately 10 tons, or 20,000 lbs, for a fully-loaded weight of 45,000 lbs. These trucks are considered heavy-duty trucks, categorized as Class 8 in the US Department of Transportation's (USDOT) weight rating system, since their gross vehicle weight rating (GVWR) exceeds 30,000 lbs.

6.1 Time Estimate

Table 7 below breaks down the various times for each of a truck's stops and slowdowns on its journey, in addition to the full-speed driving time; ultimately, a final time estimate is displayed.

Table 7. Total Time for One-Way Trucking Operation

Item	Time Spent [min]
Driving Full Speed	967
City Traffic	179
Weigh Station(s)	30
Required Rest	660
Comfort Stop(s)	45
Total	1881 min 31.35 hr
Trips	**120/yr**

The category entitled "Driving Full Speed" is comprised of two components: first, the majority of driving time, spent on I-95; and second, the small amount of time required driving from the manufacturing center to I-95 in Charleston and from I-95 to the distribution center in Boston. This time, on average, was set at 30 minutes in each port city.

As shown in the table, traffic buildups are quite significant, accounting for the 179 minutes of "city traffic" shown. A truck meets these slowdowns while approaching major industrial hubs, such as Washington D.C., New York City, and Providence. This congestion time estimate was calculated using factors of expected time delay provided by the USDOT.

Weigh stations account for an almost negligible amount of time in the trucker's journey. In the past, truckers were required to stop at weigh stations at the border of each state they traversed; but with recent technology, truckers can use an electronic weigh station pass and visit a single weigh station at the beginning of their journey (Pre Pass). A small allowance was also made for comfort stops, which include eating and restroom breaks.

Interestingly, one of the most time-consuming steps for a trucking operation is the required rest of the trucker. To alleviate problems of driver fatigue, the Federal Motor Carrier Safety Administration (FMCSA) stipulates that all commercial motor vehicle operators spend no more than 70 hours per week operating their vehicle. Changes in 2003 required drivers to maintain a minimum 21-hour cycle, with 11 hours of driving mandatorily followed by 10 hours of rest (Federal Motor Carrier Safety Administration). For this particular route, the trucker's required rest accounts for a significant portion of the entire journey time; for a route with shorter distance, such as from Los Angeles to Oakland, this rest time would not be an issue.

For this analysis, it was assumed that the truck drivers do abide by the rules and regulations specified by the FMCSA. Although it is understood that truckers may ignore the hours of service required, it is very difficult to quantify this effect. Also, although some trucks exceed the speed limit, other trucks do drive considerably slower than the posted speed limit; it was assumed that, on average, the truckers drive at the speed limit. After accounting for required breaks and other furloughs, it is estimated that an average trucker drives roughly 10,000 miles per month. Thus, for the 1020-mile journey from Charleston to Boston, it is reasonable to assume that the truck would complete this route 10 times each month, or 120 times per year.

6.2 Cost Estimate

The frequency of the trucking route directly affects the cost of delivery. Certain costs, called fixed costs, represent the money that a trucker pays each month regardless of his load and route. Even if his truck is sitting in a parking lot, the trucker still must pay a monthly fee for his truck and trailer and various insurance packages. Thus, it is beneficial for a trucker to deliver as much cargo per month as possible, thereby effectively driving down these fixed costs.

Table 8 below calculates the cost for a one-way trip from Charleston to Boston, the voyage cost

Table 8. Total Cost for One-Way Trucking Operation, Per Trailer

Item	**Cost ($)**
Tractor Payment	231
Trailer Payment	104
License / Fees	5
Collision Insurance	33
Personal Insurance	80
Office Costs	150
Truck Maintenance	85
Trailer Maintenance	20
Cargo Insurance	60
Communication	20
Tolls	114
Fuel	344
Driver Cost	0
Total	**$1245**

In today's market, the cost of a new 18-wheeler ranges from $80k to $120k, while a trailer can be found for $30k to $60k (The Trucker's Report). For this analysis, an initial cost of $100k was selected, paid over a period of 5 years with 12% interest; this common financing structure requires monthly payments of $2312. The trailer, bought at $45k, uses the same financing structure as well.

The cost of a license to operate a tractor-trailer depends on the state registry of the truck, as well as vehicle weight. The "License/Fees" category in Table 8 represents the licensing fees for a 45000-lb tractor-trailer to be registered in South Carolina (South Carolina Department of Motor Vehicles). The PrePass technology, which allows truckers to bypass weigh stations on I-95, has a monthly flat-rate charge of $16 for unlimited bypassing (PrePass).

The trucker himself is typically responsible for collision insurance and personal insurance. Collision insurance rates are typically 3% to 4% of the insured value of the cargo. Personal insurance includes health, life, and disability insurance, all important coverage for a full-time trucker. Fixed office costs are estimated at roughly $1500 per month; these include legal setup and financial management, usually performed by an accountant (Transportation Business Associates).

A truck's variable costs fluctuate from month to month depending on the amount of truck usage. The more often a trucker drives a vehicle, the higher the maintenance and repair costs will be, and the more often the tires will need to be replaced. Maintenance includes small items such as light bulbs, wipers, and windows, as well as larger mechanical components like brakes, clutches, and engines. Both scheduled maintenance and unscheduled repair of the tractor-trailer combination produce a cost of roughly $1050 per month (based on 10.5 cents per mile over the course of 10,000 miles). Not only must the condition of the cab be preserved, but that of the trailer too; a reasonable amount to allocate for trailer maintenance is roughly one fifth of the total maintenance cost (Minnesota Department of Transportation).

Liability insurance, required by state and federal government regulations, protects against liability arising from damage or injuries to others in an accident. This constitutes the most expensive portion of an insurance package for trucks. In case of damaged or lost freight during transport, cargo insurance protects the trucker. To pay $600 each month is reasonable, as it is better for a trucker to be over-insured than deal with repaying face value for lost or damaged goods (Flying J Insurance Services).

Finally, with advances in technology, truckers have become increasingly equipped with telephones, laptops, GPS, satellite radio, Blackberries, and the like. These devices help truckers find their next load and communicate with dispatchers. Typical monthly communication costs, including these electronics packages, run at around $200 (Transportation Business Associates).

Tollbooths are located at five locations along the truck's journey: at the Delaware, New Jersey, and Massachusetts Turnpikes; across the Delaware Memorial Bridge; and through the Harbor Tunnel. It is assumed that a trucker will choose this particular route because it provides the shortest distance between Charleston and Boston. Prices range from $5 on the Massachusetts Turnpike to $32 on the New Jersey Turnpike.

Fuel prices fluctuate considerably, but can be a large percentage of the voyage cost. In Table 8, the fuel cost of $344 represents a price of $2.20 per gallon, the cost of diesel as of December 2008 (Bunker World). For this analysis, the mileage of an 18-wheeler is assumed to be 6.5 miles per gallon (this figure is established by the EPA MOBILE 6 program, which is used later in the environmental comparison). The fuel cost for the 1020-mile trip is calculated using this fuel mileage figure. The possibility of fuel price fluctuation and its ramification on trucking costs is an interesting topic to be developed later.

6.3 Emissions Estimate

MOBILE 6.2, an EPA emissions modeling program, was used for the trucking operation's emission analysis. The model produces emission factors, in units of grams of pollutant per mile, for different types of vehicles from 1952 to 2050. To account for the EPA's changing emission regulations, MOBILE 6.2 assumes that a reasonable distribution of both outdated and updated vehicles are driving on the highway annually. (The software for this emission calculator can be downloaded at http://www.epa.gov/OMS/m6.htm).

The model was used to calculate the emission factors for CO2, NOX, and SO2 for heavy-duty diesel vehicles weighing between 33,001 and 60,000 lbs, from the year 2009 until 2030. Emission factors for particulate matter (PM) and unburnt hydrocarbon (HC) were also collected.

Once the emission factors were determined, the overall footprint of the trucking operation was calculated on a per-trip basis. Since each truck travels roughly 1020 miles in its journey from Charleston to Boston, the emission factor was multiplied by 1020 miles to find the total emissions for each of the five pollutants. Figure 8 presents the final amount of pollutants that are emitted by a truck per trip as a function of the year of operation.

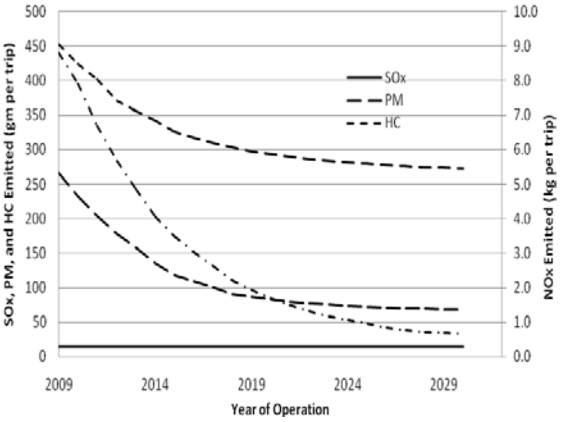


Figure 8: Emission of Pollutants: Trucking

As the trends in Figure 8 indicate, as older trucks are retired and newer, more-regulated trucks are brought into the operation, the overall environmental impact is significantly reduced. SOX emissions are not anticipated to decrease any further, since the final and most stringent regulation will fully come into effect this year (2009). Carbon dioxide emissions are expected to diminish from 1577 kg in 2009 to 1569 by 2030, a minute reduction of 0.4%. This difference is neither apparent nor significant, so CO2 emissions were not shown in Figure 8.

7. Logistics Comparison

Before considering the environmental effects of either transport mode, it is necessary to look at both routes from a businessman's perspective, as a money-making endeavor. If S3 can deliver a trailer in a timely fashion, and if it can function soundly by making a profit, only then is it a viable alternative to the current trucking system. To that end, this section presents the bottom line: final time and cost estimates for both S3 and trucking, as a potential investor would see them. Cost estimates are all normalized into units of cost per trailer, as this is a convenient unit of comparison.

One of the attractive points of short sea shipping is its ability to remove large trucks from the road. In the economic analysis, it was assumed that all three ships were nearly fully loaded in every voyage by 900 53-ft-long trailers. Table 9 below shows the bottom line for the ship: assuming other plausible loading conditions, it outputs the number of vehicles taken off the road annually.

Table 9. Trip Frequency

Loading Condition	Round Trips/yr	Trailers Removed/yr
Truck	120	--
500 Trailers	156	156,000
600 Trailers	156	187,200
700 Trailers	156	218,400
800 Trailers	156	249,600
900 Trailers	156	280,800

7.1 Time

In the shipping time estimate, different permutations of the shipping route were examined to see how quickly the *CLR* could deliver its cargo. Figure 9 below shows the final time estimates for the shipment via RO/RO, as compared to the trucking route.

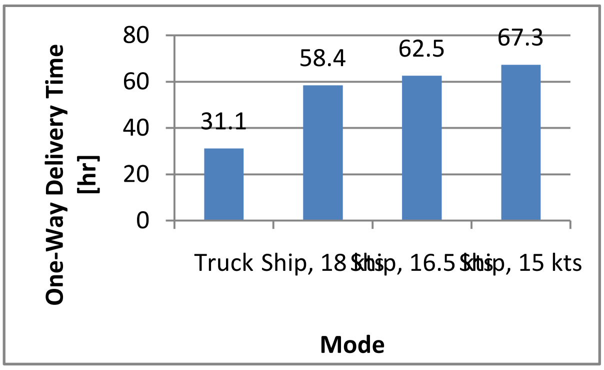


Figure 9: Time of Delivery, Per Trailer

By increasing the vessel's speed by 3 knots from 15 to 18 knots, an S3 operator sees a reduction in time of roughly 9 hours. However, even for a ship traveling 18 knots, the trucking operation is still significantly faster than the S3 option. Additionally, a speed increase of 3 knots contributes significantly to fuel cost and vessel cost. With that point made, it is unrealistic for this S3 route to carry any time-sensitive cargo. For instance, a shipment of electronics that must be delivered to Boston from Charleston in less than two days must be transported by a truck. Therefore, this sea shipping route is reserved for less time-sensitive cargo.

7.2 Cost

Having identified the various capital and operational costs associated with both trucking and shipping, a comparison can now be made to find the least expensive mode.

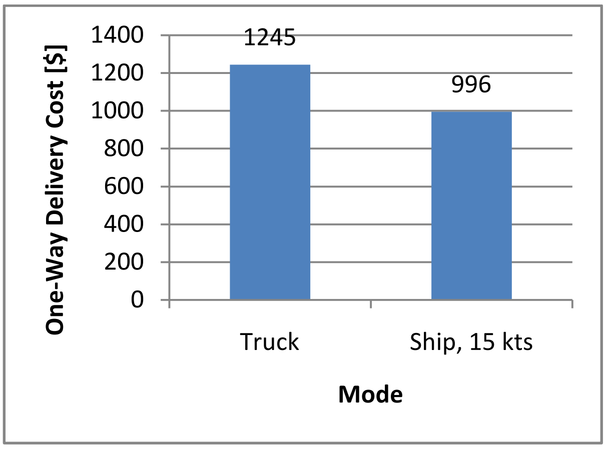


Figure 10. Cost of Delivery, Per Trailer

Note that in both cost estimates, only fixed and operating costs were tabulated. All effects of tax, including depreciation, were neglected, since it was very difficult to estimate hypothetical taxable profits.

As it stands, the shipping route is about 20% less expensive than the trucking route. However, it is interesting to look at these results and see how they may change as some of the original assumptions are varied.

One of the most fluctuating variables in the cost analysis is the fuel cost. Using current fuel prices, fuel cost accounts for roughly 28% of the total cost of the trucking route, and roughly 9% of the S3 cost. However, as of May 2009, fuel prices were at an annual low and expected to rise again in the future. The US Department of Energy publishes projected fuel prices from now until 2030; these prices, though highly uncertain, are still a good barometer of expected fuel costs in the future. Table 10 shows this data for ULSD and LNG for 5-year increments over the next twenty years.

Table 10: Projected Fuel Prices

	Cost ($/gal)	
Year	LNG	ULSD
2014	1.36	3.44
2019	1.46	3.57
2024	1.55	3.68
2029	1.74	3.91

Effectively, LNG prices will rise significantly soon, driving up the cost of S3. If these predictions hold true, by 2014, the fuel cost will become a much larger portion of the total S3 cost.

Truckers are likewise affected by the same cost fluctuations. In 2014, the price of ULSD will also increase, driving fuel costs to $538, 43% of the total trucking cost of $1245. Figure 11 shows updated trucking and S3 costs with rising fuel costs, *ceteris paribus*. The graph represents cost difference between the two routes over time.

Table 11. Projected Trucking and S3 Costs with Increasing Fuel Price

	Operation Cost ($)		
Year	Truck	Ship	Diff (%)
2009	1245	996	20.0
2014	1439	1135	21.1
2019	1460	1145	21.5
2024	1477	1154	21.9
2029	1513	1173	22.5

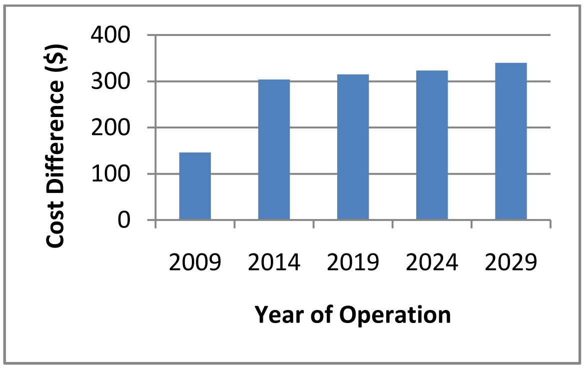


Figure 11. Projected Cost Differences with Increasing Fuel Price

The relatively low difference in overall cost (20.0% versus future projections greater than 21%) is due to the current low price of ULSD. Assuming that LNG and ULSD both reach these expected price increases, S3 will become even more competitive, since fuel is a larger percentage of the trucking cost. It should be noted that fuel prices are subject to high volatility, and the EPA's projections may be far off for both LNG and ULSD.

Another interesting point of comparison is the capacity of the *CLR*. Her actual capacity is about 943 - 53 foot trailers, and it was assumed that most of these slots are filled on every trip (roughly 95% capacity). Fully loading the ship, while ideal economically, is not always possible, given demand along the route.

To consider the range of loading amounts, the *CLR* was loaded from 32% full (300 trailers) to fully loaded (943 trailers). Figure 12 shows the diminishing cost of S3 as the RO/RO carries more trailers.

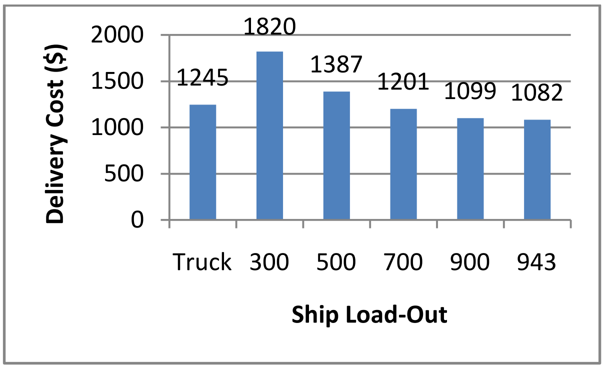


Figure 12: Shipping Costs with Varying RO/RO Loads

Figure 12 shows the obvious, that the S3 operator will benefit most with a fully loaded ship. Using the economic estimate model, it was found that a load of 640 trailers per trip would level the S3 and trucking routes pricewise.

Finally, two other sources of cost in the S3 operation are from drayage and stevedoring. Not only do shorter drayage moves reduce the time of the S3 operation, but can significantly reduce cost. In a study of drayage distance versus cost in southern California, it was estimated that a dray of 100 miles costs $300, while a dray of 400 miles costs $650 (Tioga Group). For the S3 route to stay competitive, its clients must be located as close to Charleston and Boston. For customers outside of the 100-mile range of either port city, it is economically beneficial to eschew the water route and put their cargo on a truck.

8. Emissions Comparison

Having established emissions profiles for both of the modes of transportation, it is now possible to compare trucking to shipping, head-to-head. Comparisons are made between trucks and the *CLR* for CO_2, NO_X, and SO_X. Each emitted pollutant will be compared individually and an overall analysis will follow.

8.1 Carbon Dioxide

As long as the US government continues its current hands-off policy on CO_2 emissions, a truck traveling from Charleston to Boston will continue to emit the same amount of carbon dioxide in the upcoming years. The amount of CO_2 produced by the shipping operation depends on the speed. Figure 13 below compares the amount of pollutants directly if CO_2 extraction is not used for the exhaust stream.

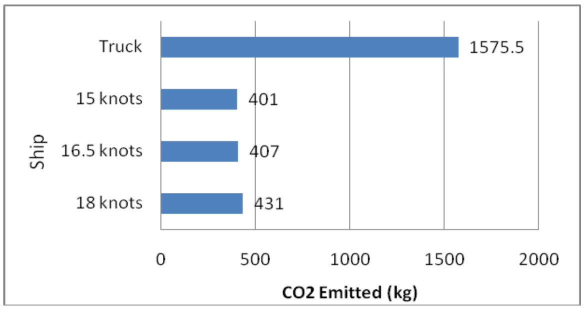


Figure 13: CO_2 Comparison, Per Trailer

Figure 13 shows that ships hold the upper hand over trucks with CO_2 emissions. It is significant that the ship emits minimal CO_2 and that even this amount of would still meet current EPA regulations.

8.2 Nitrous Oxides

Figure 14 shows the comparison between trucks and the *CLR*'s NO_X emissions.

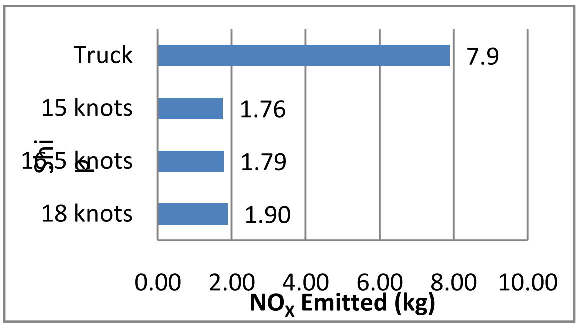


Figure 14: NO_X Comparison, Per Trailer

In regards to NO_X it is apparent that once again the *CLR* has the upper hand, especially with the Bergen engines. By burning LNG the ship is able to dramatically reduce its NO_X production. The truck produces more than 4 times the NO_X of the ship.

Again, as in Figure 13, the difference in nitrous oxides emitted varies very little amongst the three speeds of the ship.

8.3 Sulfurous Oxides

Truck SO_X emissions are scheduled to remain constant in the near future, but the pending creation of a SECA zone on the East Coast has created interest in using a low sulfur fuel such as LNG for ships. Both modes of transportation are incredibly low in emissions, as far as SOx is concerned. By burning LNG in Bergen engines, absolutely no SOx is created, which is a large deviation from the sulfur emissions of a ship burning HFO.

Trucks burning ultra-low sulfur diesel produce miniscule amounts of SO_X. Estimates on trucking show roughly 10 grams per trailer (compared to the 7.9 *kilo*grams from NOx; but by burning LNG, the *CLR* is able to keep its competitive edge.

8.4 Overall

With the upcoming push for "green," environmentally-friendly technologies, short sea shippers must try to keep their ships' noxious emissions near or below the low level of truck emissions. One of the biggest decisions for the shipper is ship speed; throughout the analysis, emissions estimates have been run at three different speeds. Ultimately, a speed must be selected that will deliver cargo on time while still consuming a reasonable amount of fuel. From Figures 13 and 14, it is evident that ship speed does not greatly affect emission levels (and for the Bergen engines, no sulfurous oxides are created at *any* speed).

Another important variable is ship capacity. Ship capacity is not only key to S3's economic success, but also to its environmental success. Each estimate assumed that the RO/RO was loaded at 900 53-foot trailers. If the *CLR* were loaded with fewer trailers, the emissions per trailer (for all forms of noxious emissions) would thereby be higher. Conversely, a fully-loaded vessel minimizes the emissions per trailer. Therefore, it is in the best interest of the shipper to keep his ship as fully loaded as possible.

Table 12 below shows the potential bottom line for comparing trucking to shipping, using the *CLR* with CO2 exhaust gas extraction. The table shows the percent difference of each emission in comparison to a truck's emissions.

Table 12. Potential Shipping Emissions (as a Percent of Trucking)

Operating Speed	15 Knots
CO2	0%
NOX	0%
SOX	0%

The biggest issue preventing shippers from going "green", and realizing all of these emissions reductions, is a common concern for investors: cost. For NOX and SOX emissions, the suggested changes represent significant costs. Using the LNG-powered Bergen engines would constitute a substantial capital cost with potentially high repair costs inherent in new technology, especially compared to cheaper, already-proven HFO-burning engines.

The best way to enact environmental reform in ships is for the US government to begin regulating NOX, SOX, and CO2 much more stringently. Trucking emissions were regulated beginning in the early 1970s; only recently, since the 1990s, have ships begun to follow suit. The shipping industry has lagged behind the trucking industry in environmental regulation over the last 25 years; consequently, shipping still has much ground left to make up. Ships must not only catch up with trucks in NOX and SOX emissions, but also must retain their advantage in terms of low CO2 production.

Shipping advocates have often boasted that ships are far more efficient than trucks; certainly, this is true in terms of fuel efficiency. As a result, ships produce less CO2 than trucks over the same route. In the past, ships have chosen to burn a lower quality of fuel and have had less-advanced exhaust conditioning; they have lost their advantage when it comes to NOX and SOX emissions. Taking the extra step and using an LNG-fueled vessel such as the *CLR* will allow ships to truly declare that they are the more environmentally friendly mode of transportation.

9. Conclusions

Having examined the time, cost, and environmental impact of S3, reasonable conclusions can be made about its overall viability on the East Coast. Taking a snapshot of both transportation modes today, it is clear that trucking presently holds the upper hand for time. Short Sea shipping could marginally cost less, and could emit less NOX, SOX, and CO2 than trucking. Short Sea shipping could also produces less external, "intangible" costs.

The authors admit that an ideal comparison has been made where it is assumed that there are nearly full ship loads of cargo available, in both directions; where both the technology and practicality of 100% removal of CO2 from the exhaust stream is possible and where the minor amounts of NOX introduced into the cooling water will meet future regulations.

On an East Coast route, a RO/RO will never be as competitive as a heavy-duty truck in terms of time. The time "in route" may be comparable, but the required drayage and port times put the Short Sea shipping operation at a disadvantage.

The US East Coast does not have the typical qualities which make for a good short sea shipping route. There is no geographical advantage to move the cargo by sea, as the ships are competing with a very complete and advanced highway system, however, that highway system shows signs of being stressed by increasing truck traffic. For both the reasons of reduced highway infrastructure stress and cleaner air, the Short Sea shipping option offers significant gains.

Even though S3 produces less highway infrastructure stress and could produce fewer emissions, there is no compensation for the Short Sea shipping option to recognize those savings. Thus, as Short Sea shipping is not competitive against the clock, even with a comparable transport cost, S3 investors will probably not support it on the East Coast. It is improbable that carbon offsets will be enough to change the equation. It would seem that government support in the form of additional truck taxing, or reduced taxing on ocean shipping, would be necessary to recognize the intangible benefits of S3.

By using a vessel such as the *CLR* presented here, not only are hundreds of thousands of trucks removed from the east corridor highways physically, but an emissions free vessel puts nothing into the atmosphere, compared to considerable emissions from trucks, even under future truck fuel regulations.

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