A Comparative Analysis of Air Emissions from Alternative Fuel Transport via the SS Badger v. Trucks to Transport Cargo along the Great Lakes
Sustainable Intermodal Freight Transport Research Program

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1 Introduction

The *SS Badger* is an historic car ferry, the last remaining one operating under coal power, that transports passengers and cargo across Lake Michigan. Its operators are considering fuel-switching the *SS Badger* from coal to an alternative fuel. Therefore, this report examines in Phase I the emissions profiles assuming that the *SS Badger's* engines were fueled by a variety of other fuels, including: Intermediate Fuel Oil (IFO); Marine Diesel Oil (MDO); Compressed Natural Gas (CNG); Liquefied Natural Gas (LNG); and BD20, a blend of 80% diesel and 20% biodiesel. The results from the study will help decision makers understand the emissions implications associated with such a fuel switch in the context of alternative land-based routes.

Additionally, efficient and effective transportation in the Great Lakes region is a critical component of the U.S. economy. The Great Lakes region serves as an important gateway for many goods moving within the U.S. and into/out of Canada. This transportation can occur by truck, train, and/or ship using various routes that incorporate highways, railways, and waterways, respectively. Each of these modes has its advantages and disadvantages, which can be measured using criteria such as economics, time of delivery, reliability, energy use, safety, and environmental performance.

In Phase II, this study compares the *environmental performance* of alternative routes for moving goods from Green Bay, WI to Detroit, MI. The first route consists of an all-truck route using the highway system which encircles the southern portion of Lake Michigan, through Chicago, IL. The second route consists of an intermodal route that includes not only trucking, but also a car ferry that operates between Manitowoc, WI and Ludington, MI. The car ferry is the *SS Badger*, and it represents the last coal-fired ship in the United States. The primary purpose of this study is to evaluate the emissions of greenhouse gases (including carbon dioxide [CO_2] and methane (CH_4)) and criteria pollutants (sulfur oxides [SOx], nitrogen oxides [NOx], carbon monoxide [CO], and particulate matter [PM_{10}]) generated using these alternatives routes under existing conditions.

2 Background

The SS Badger is a historic ferry that currently carries both tourist passengers and cargo vehicles. The *SS Badger* started service in 1953 as a railcar-ferry, transporting railroad freight cars across Lake Michigan to various ports in Wisconsin. During the 1970s a change in economics made it less profitable for railroads to transport their freight by ship, and the railcar-ferries of the Great Lakes slowly ended operations, with the *SS Badger* last sailing in 1990. However, in 1991 an entrepreneur invested in the *SS Badger* to continue the tradition of ferrying passengers and road vehicles across the lake by ship. Since then the *SS Badger's* engines have been declared a mechanical engineering landmark by the American Society for Mechanical Engineers, and the ship itself was placed on the National Register of Historic Places [1]. While in recent years the vessel's main business revenue may derive from tourist passengers, the goods movement purpose is also gaining renewed attention; for example, in 2012, the SS Badger moved more than 300 loads of wind-turbine parts across Lake Michigan [2].

Currently the Lake Michigan Carferry Service (LMCS) operates the *SS Badger* across Lake Michigan, traveling between Manitowoc, WI and Ludington, MI, avoiding the alternative, land-based route through Chicago. The 4-hour, 62-mile cruise carries passengers, autos, RVs, tour buses, motorcycles, bicycles, and commercial trucks. In its current configuration, the *SS Badger* typically reserves space for 12 heavy-duty vehicles (HDVs) with 53' trailers, with space for additional vehicles (typically passenger cars). The full capacity of the *SS Badger* is 180 "vehicle units," a proprietary measure developed by LMCS. For comparison, one tractor trailer is equal to 4 vehicle units [3]. For our baseline analysis, we assume the *SS Badger* could carry a full load of 45 tractor trailers, which corresponds to 180 vehicle units; we consider more typical (e.g., smaller) cargo volumes in a sensitivity analysis.

The *SS Badger* propulsion system is powered by two Skinner Unaflow four-cylinder steam engines each rated at 3,500 horsepower (hp). The engines use high-pressure steam generated by coal-burning watertube boilers. Documents in support of a petition under section 5.3 of the EPA's *2008 National Pollutant Discharge Elimination System Vessel General Permit*, in effect until 19 December 2012, have been filed on behalf of LMCS in a public docket; these documents include much of the fuel consumption and engine-boiler plant details needed for this work [4]

3 Methodology

3.1 Emissions Calculations

In order to calculate the total emissions of a pollutant for a given route or route segment the following general equation is used:

$$\boldsymbol{P_{ij} = E_j \cdot EF_{ij}}$$

where P_{ij} represents pollutant of type *i* for mode *j* in kg/segment; E_j represents energy consumption for mode *j* in BTU/segment; and EF_{ij} represents an emissions factor for pollutant *i* for mode *j* in mass/energy unit (e.g., g/BTU or g/hp-hr).[1]

The *SS Badger's* propeller is powered by a reciprocating steam-engine using high-pressure steam produced by a water tube boiler [5]. Steam-boiler combustion properties differ substantially in an open-chamber furnace from internal combustion engines, resulting in lower thermal efficiencies for energy recovery and lower fuel efficiency. E_j for the *SS Badger* was calculated based on the amount of coal burned per trip, as discussed in Section 3.2. The emissions factors were compiled from various sources, as discussed in Section 3.3. Some factors were reported directly in terms of energy output, so no further calculations were needed. Others were reported in terms of fuel consumed, so an additional conversion was necessary. For CO_2, emissions are related to the carbon content of the particular fuel, and were also calculated according to Comer et al (2008). Emissions were then converted to a standard unit for comparison, in this case kg/TEU-mile. The emissions per TEU-mile were then multiplied by the number of miles in the route segment in order to calculate the total emissions per TEU-trip.

3.2 *SS Badger* Fuel Consumption

To estimate the current coal-fired emissions by the *SS Badger*, we used information provided by LMCS to perform a calculation using fuel-based emissions methods. However, to develop emissions estimates under alternative fuels, we needed to make energy conversions from coal to each of the fuel alternatives and consider whether other systems changes may also be made. The project scope specified that alternative fuels would be used to fire the boiler-steam-

[1] Often, emissions factors are provided in different units and conversions are required; for example, as demonstrated later, emissions factors for the *SS Badger* using coal are given in terms of pounds of emissions per ton of fuel burned. These types of emissions values then imply that the energy consumption is provided in tons of fuel burned.

engine system – as opposed to a retrofit scenario replacing the steam engine(s) with internal combustion or diesel engines. This is important for two reasons affecting this case study.

1. By converting the boiler-steam-engine system from coal to alternative fuels, the emissions under each fuel alternative are derived from watertube steam boiler combustion factors rather than emissions from high-pressure/high-temperature internal combustion power plants.

2. By applying the conversion to the boiler combustion, the amount of energy consumed represents the total energy delivered to service the vessel (i.e., including auxiliary servicers) rather than the energy associated with the propulsion steam engines alone. Truck fuel consumption also powers auxiliaries, and while the proportion may be insignificant compared to propulsion, this is included in the fuel consumption rates for trucking; importantly, almost 50% of consumption goes to auxiliaries on the Badger. Most analyses of marine propulsion emissions consider the main engines (dedicated to propeller thrust) separate from auxiliary engines (powered by independent internal combustion generators). For the SS Badger and some other older vessel designs, the use of boiler steam to power all main and auxiliary power needs required a more holistic calculus, similar to trucking.

To determine energy consumed by the *SS Badger* engines, we first determined how much fuel the engines currently consume per trip. We then converted fuel consumption to BTUs based on fuel energy content. The current consumption of coal is based on the reported fuel consumption in a year and normalized by the number of trips taken in a year.

For example, in 2011 the *SS Badger* burned 8,120 tons of coal ([6], page 51). In consuming that much coal, the vessel operated for 140 days, making two round trips 59% of those days and one round trip the rest, for a total of 445 trips ([6], page 4). This yields a total of 18.24 tons of coal per one way trip. Further examination revealed that this was a typical amount of consumption for this type of ship. Table 1 shows basic information for these types of engines and the bituminous coal being burned.

Table 1 Information related to energy calculations for the *SS Badger*.

Variable	Value	Source
Average speed	18 mph	[5, 7]
Total Engine HP	7,000 (2 @ 3,500) at 125 RPM	Skinner Unaflow 4-cylinder steam engines, [5]
Average Engine Load factor per trip	73%	Calculated from estimated vessel speed and design speed [5]
Engine Efficiency	17%	Typical steam-plant efficiency for D-type boilers and reciprocating steam engine [8]
Carbon Content of Coal Used	75%	Typical content for Bituminous coal[4]
Ship Capacity (assumed full of trucks)	45 53' trailers	[3]
Ship Capacity (assumed full of trucks)	117 TEUs	53' trailer = 2.6 TEU

3.3 Emissions Factors

3.3.1 SS Badger Using Coal

For coal, SO_x and CO_2 emissions were based on sulfur and carbon content. Emission calculations for NO_x, CH_4, CO and PM_{10} utilized emission factors from the EPA *AP42 Compilation of Emissions Factors (AP42)* document [9]. The *SS Badger's* boiler currently uses a spreader stoker in order to feed the coal into the boiler, so AP-42 numbers for a spreader stoker were used as a best value. In order to obtain the full range of potential values for a sensitivity analysis, the emissions for a hand-fed boiler were also considered. Emissions factors used for this analysis are shown in Table 2.

Table 2 Coal emissions factors used in the *SS Badger* analysis.

Coal Emissions Factors (lb/ton)	AP 42 Source	Low	Best	High
SOx	Based on sulfur content ranges*	0.19	0.43	2.05
NOx	Table 1.1-3, page 1.1-18	9.1	11	
PM_{10}	Table 1.1-4, page 1.1-21	6.2	13.2	
CH_4	Table 1.1-19, page 1.1-40		0.06	5
CO	Table 1.1-3 ,page 1.1-18		5	275

* Coal-sulfur ranges: 0.60% Low, 1.13% Best, 5.40% High

3.3.2 SS Badger Using IFO (No. 6 Fuel)

SO_x and CO_2 emissions were based on sulfur and carbon content, as mentioned previously. Emission calculations for NO_x, CH_4, CO and PM_{10} utilized emission factors from the EPA *AP42* document. IFO is considered similar to No. 6 Fuel, and the boiler on the Badger is less than 100 MMBTUs. Both sulfur and PM emissions are dependent on the amount of sulfur in the fuel. The low and high are from Appendix A in the AP42 while the best value is the global average of IFO fuel. Table 3 shows the values used in the analysis.

Table 3 IFO emissions factors used in the *SS Badger* analysis.

IFO Emissions Factors (lb/ton)	AP 42 Source	Low	Best	High
SOx	Based on sulfur content ranges*	79.5	429	636
NOx	Table 1.3-1, page 1.3-12		55	
PM_{10}	Table 1.3-1, page 1.3-12	7.82	28.03	39.98
CH_4	Table 1.3-3, page 1.3-14		1	
CO	Table 1.3-1, page 1.3-12		5	

* 0.5% Low, 2.7% Best, 4% High

3.3.3 SS Badger Using MDO (No. 2 Distillate Fuel)

Again, SO_x and CO_2 emissions were based on sulfur and carbon content. Emission calculations for NO_x, CH_4, CO and PM_{10} utilized emission factors from the EPA *AP42* document. MDO was considered similar to distillate fuel. The sulfur low and high values are from the ranges of the fuel, with the best value being the average of the two. Emissions factors used for MDO are shown in Table 4.

Table 4 MDO emissions factors used in the *SS Badger* analysis.

MDO Emissions Factors (lb/ton)	AP 42 Source	Low	Best	High
SOx	Based on sulfur content ranges*	28.8	86.4	144
NOx	Table 1.3-1, page 1.3-12		18	
PM_{10}	Table 1.3-1, page 1.3-12		2	
CH_4	Table 1.3-3, page 1.3-14		0.05	
CO	Table 1.3-1, page 1.3-12		5	

* 0.2% Low, 1% High

3.3.4 SS Badger Using LNG

Emissions factors for each pollutant were determined from the EPA *AP42* document. According to this document the emissions factors are the same for all forms of natural gas, so for this analysis the same values appear for both liquefied and compressed natural gas. We examined literature for natural gas emissions factors that indicated the life-cycle analysis (LCA) for LNG would increase these emissions slightly [10]. However, while an LCA-based reanalysis may be merited in the future, this was beyond the scope of this study; moreover, comparison of these LCA ranges for EFs with other inputs in Section 5 sensitivity analysis were determined to be less important than other input parameters in this study design. Table 5 shows the values used in this analysis.

Table 5 LNG emissions factors used in the *SS Badger* analysis.

LNG Emissions Factors (lb/MMBtu)	Best
SOx	0.001
NOx	0.098
PM_{10}	0.007
CH_4	0.002
CO	0.082

3.3.5 SS Badger Using CNG

Similar to LNG, emissions factors were determined from *AP42* with potential ranges determined from Jaramillo [10] and also Farrell et al [11]. Table 6 shows the values used in this analysis.

Table 6 CNG Emissions Factors

CNG Emissions Factors (lb/MMBtu)	Best
SOx	0.001
NOx	0.098
PM_{10}	0.007
CH_4	0.002
CO	0.082

3.3.6 SS Badger Using BD20

Calculating emissions factors for BD20 was slightly more complicated. BD20 is a mixture of biodiesel (BD) and standard diesel, so the resulting emissions are a combination of decreasing the emissions by burning less diesel fuel and increasing the emissions by the amount produced by consuming the biodiesel. For this analysis diesel emissions were obtained from the AP42 document. In boilers, NOx generally decreases by 1% for every percent of biodiesel added, up to a 20% mixture, so for this analysis NOx was decreased by 20% from diesel emissions. Sulfur dioxides are also decreased by 20%. For hydrocarbons, PM_{10}, and CO, emissions reductions in a boiler were not reported, so emissions from a compression ignition engine were used. With a 20% mixture of biodiesel hydrocarbons are decreased by 20% while PM_{10} and CO are decreased by 10% [12]. These reductions are approximations, however, so for the full sensitivity analysis a 10% range was examined around the best estimate. These parameters are shown in Table 7.

Table 7 BD20 emissions factors used in the *SS Badger* analysis.

BD20 Emissions factors (kg/MMBTU)	Low	Best	High
SOx	2.47	2.74	3.01
NOx	0.86	0.95	1.05
PM_{10}	0.10	0.11	0.12
CH_4	0.01	0.01	0.01
CO	0.24	0.27	0.29

3.4 Phase II Case Route Determination

While comparing the emissions for alternative fuels on the Badger is useful from the perspective of the passengers, considering a cargo shipment journey from origin to destination offers a more complete comparison of freight performance among intermodal options. For this comparative analysis, we applied the Geospatial Intermodal Freight Transport (GIFT) model ([13, 14]. Using GIFT, we solved two alternate routes each involving the transport of cargo from Green Bay, WI to Detroit, MI (see Figure 1Figure 1). The details of the routes are as follows:

- Route 1: A highway route from Green Bay, WI, to Manitowoc, WI (45 miles), followed by a ferry (*SS Badger*) route to Ludington, MI (62 miles), and then a highway from Ludington, MI, to Detroit, MI (260 miles).
- Route 2: An alternative all-highway route (Scenario A) from Green Bay, WI to Detroit, MI (620 miles). All-truck Scenarios A and B are considered along with a longer 650-mile route in the Sensitivity Analysis in Section 5. Note that this route is designed to avoid potential Chicago-area congestion.

3.5 The GIFT Model

The GIFT model combines networks for roadways, railroads and the waterways of the U.S. and Canada, along with the intermodal facilities in the North American continent on the ArcGIS™ Network Analyst platform. The model uses a generic "shortest path algorithm" provided in the platform to determine optimal routes to ship goods from one location to another. The transportation network data and the facilities data were sourced from the National Transportation Atlas Database (NTAD) maintained by the US Department of Transportation's Bureau of Transportation Statistics (BTS); GeoGratis, maintained by Natural Resources Canada; and STEEM (an international shipping database describing the ocean shipping lanes), developed by University of Delaware.

The key to building the intermodal network is to create nodes (modal transfer points) to model real world locations where the independent modal networks (road, rail, and waterway) intersect at an intermodal facility. In GIFT, this is achieved by establishing virtual segments of zero distance to link (1) road-to-transfer facility connections; (2) water-to-transfer facility connections; and (3) rail-to-transfer facility connections. This "hub and spoke" construct models freight transfer among freight modes through facilities such as ports, railyards, and truck terminals (see Figure 2).

In estimating the operational costs, time-of-delivery, energy use, and emissions from freight transport, the main concept is to associate 'penalties' or ' impedance factors' with traversing each segment of the transportation network, and to provide multiple routing solutions that aggregate the impedances for time, distance, environmental, and energy criteria. These impedances are primarily temporal, economic, and environmental attributes associated with each segment of the transportation networks. They can vary based on vehicle type, fuel choice, operational and governmental policy in force, and other scenario attributes. The shortest path algorithm searches and selects routes that minimize the defined 'penalties' and reports the accumulated totals of other impedances to provide for tradeoff comparison. This means that GIFT not only solves for typical objectives such as least-cost and time-of-delivery, but also for energy and environmental objectives, including emissions of CO_2, carbon monoxide (CO), NO_x, SO_x, PM_{10}, and volatile organic compounds (VOCs). In this case, the model was solved for the shortest time routes between Green Bay and Detroit, with the *SS Badger* route forcing the water segment to be utilized. Details on how GIFT was constructed and programmed can be found in previously published literature [14-18].

Figure 1. Alternative Cargo Routes between Green Bay, WI, and Detroit, MI.

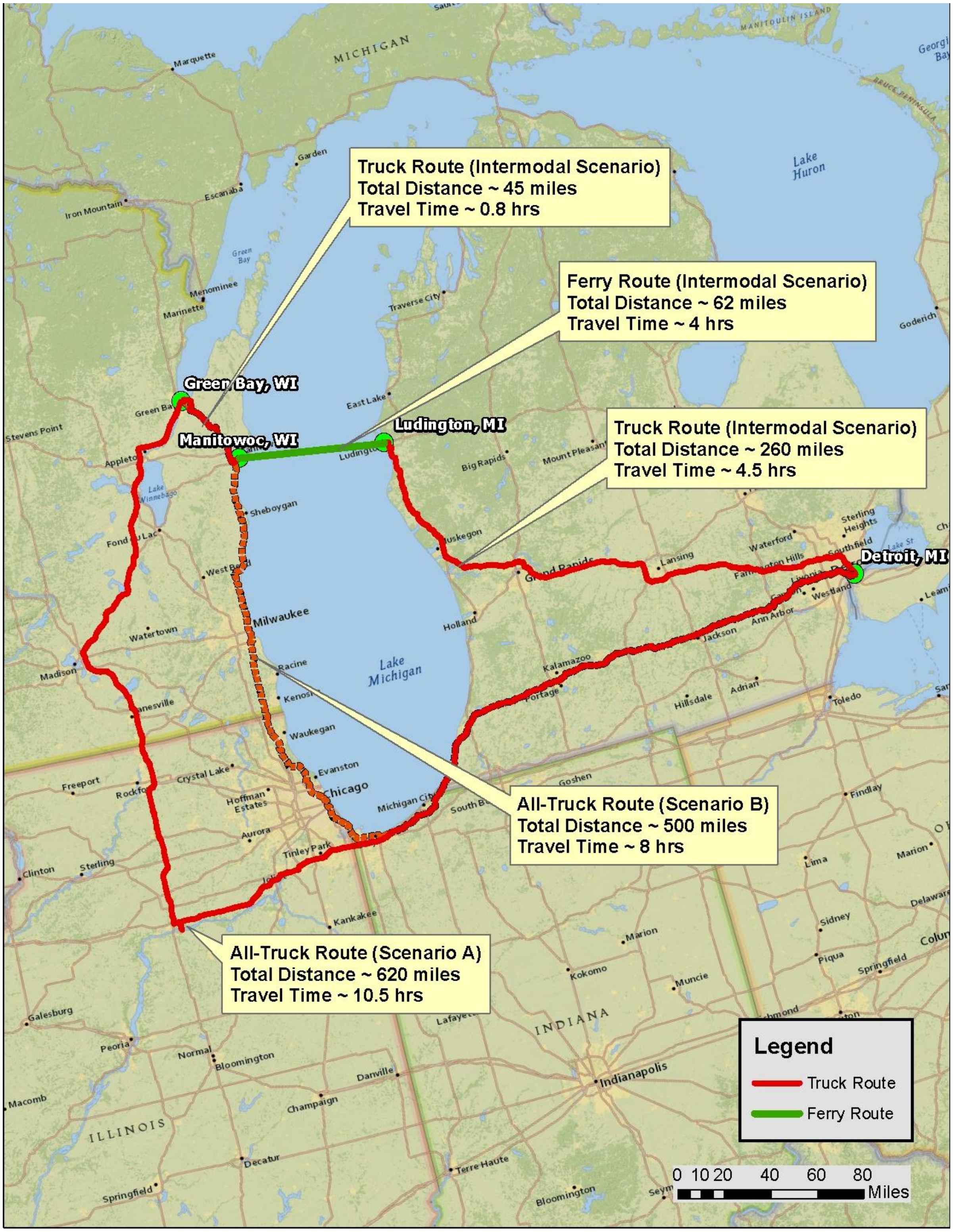
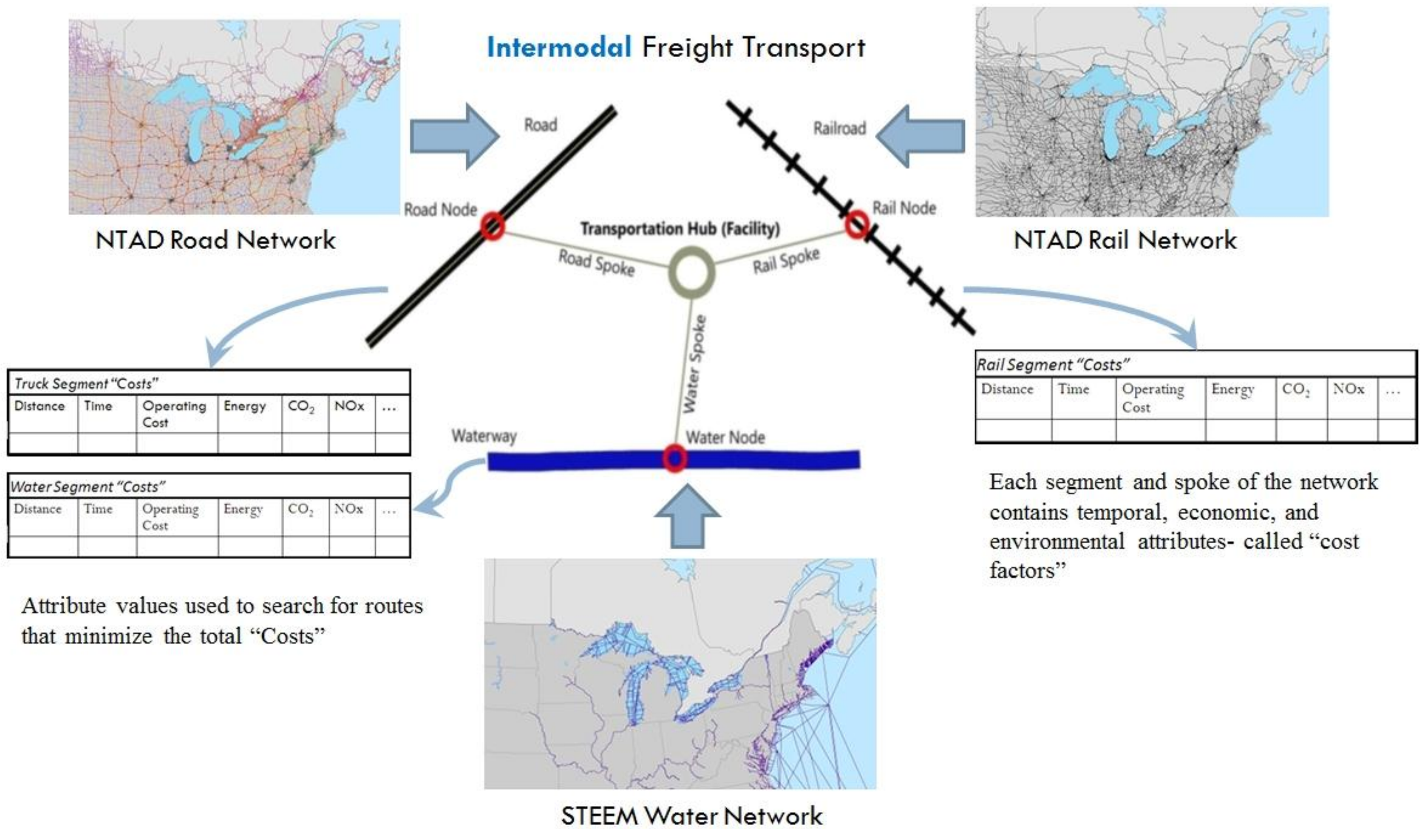


Figure 2. The GIFT model depicting how different modal networks are linked through intermodal facilities using a 'hub-and-spoke' approach.



3.6 Truck Emissions Factors

We estimated the energy consumption of the truck mode according to the methodology developed in the GIFT Model, which is based upon the efficiency of typical HDV engines. The assumptions made for truck engines are shown in Table 8. The fuel economy value of 6 mpg was based on the average fuel economy of diesel heavy duty trucks, estimated from figures obtained from the EIA Annual Energy outlook 2012 (Table 49)[19]. The assumed fuel for this case is on-road diesel fuel with an energy content of 128,450 Btu/gal, a mass density of 3170 g/gal, and a carbon fraction of 86%. The fuel parameters are based on our past studies using the GIFT Model [15]. A Class 8 HDVs meeting model year (MY) 2007 and later emissions standards were assumed to be carrying 2.6 TEUs (typical for a ~53 foot chassis). The fuel economy of the vehicle and the typical fuel parameters for this study are listed in Table 8 Assumptions for Class 8 HDVs used in this analysis.

Variable	Estimates of Current Conditions
Fuel Economy (mpg)	6
Energy content of fuel (BTU/gal)	128,450
Mass density of fuel (g/gal)	3,167
Sulfur content (ppm)	15
Carbon content (%)	86
Truck Capacity (TEU)*	2.6

* TEU = twenty foot equivalent unit

Table 9, as discussed previously in Section 3.1. The emission factor values for NOx and PM_{10} are based on the assumption that the truck operates at the maximum allowable emissions standards for NOx [0.2 grams per brake horsepower-hour (g/bhp-hr)] and PM_{10} (0.01 g/bhp-hr) according to the Code of Federal Regulations (CFR) 40 CFR 86.007–11[15]. The emissions factor for CH_4 was sourced from the EPA Climate Leaders Greenhouse Gas Inventory

Protocol document under section 3, Table 2[20]. The emissions factor for CO came from the Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET v.1.8b) model, and reference in past studies [21]. Truck emissions factors are summarized in Table 9. Some sources reported units in power-based units, and others in distance-based averages as shown; we made conversions to comparable unit-transforms for calculations in this study. For this analysis we use the "Best" values reported as they represent our best judgment for the typical value from the literature sources we reviewed. The "Low" and "High" values were obtained where available, and are included in the sensitivity analyses in Section 5.

Table 8 Assumptions for Class 8 HDVs used in this analysis.

Variable	Estimates of Current Conditions
Fuel Economy (mpg)	6
Energy content of fuel (BTU/gal)	128,450
Mass density of fuel (g/gal)	3,167
Sulfur content (ppm)	15
Carbon content (%)	86
Truck Capacity (TEU)*	2.6

* TEU = twenty foot equivalent unit

Table 9 Truck emissions factors used in this analysis.

Truck Emissions Factors	Best	High
NOx (g/hp-hr)	0.2	0.3
PM_{10} (g/hp-hr)	0.01	
CH_4 (g/mile)	0.0051	
CO (g/TEU mile)	1.6	

4 Results

4.1 Phase I Emissions results

Emissions were calculated for each pollutant on a TEU basis for each main segment of the trip, using the best estimate values in the tables in Section 3.5. Table 10 reports total emissions for each pollutant to transport one TEU from Ludington to Manitowoc.

Table 10 Total voyage emissions for the SS Badger route using conventional and alternative fuels. Emissions values are measured on a per TEU basis for the entire voyage.

	Total Voyage Emissions (kg/TEU)					
	CO2	SOx	NOx	PM	CH4	CO
Carferry route using Coal	389	4	91	109	0.5	41
Carferry route using IFO	334	634	81	41	1	7
Carferry route using MDO	322	128	27	3.0	0.1	7.4
Carferry route using LNG	216	0.001	0.2	0.01	0.004	0.2
Carferry route using CNG	216	0.001	0.2	0.01	0.004	0.2
Carferry route using BD20	312	11	3.9	0.4	0.0	1.1

Figure 3 through Figure 8 indicate that natural gas is the only fuel switch that will reduce all emissions from coal-fired boiler operation, and this applies to either liquefied or compressed natural gas. Coal produces the highest emissions for most pollutants, performing better than other fuels only in the emission of sulfur oxides from petroleum fuels (IFO and MDO), and methane produced from burning IFO. Note the log scale on all graphs other than for CO_2.

Figure 3. CO_2 emissions for all fuel scenarios.

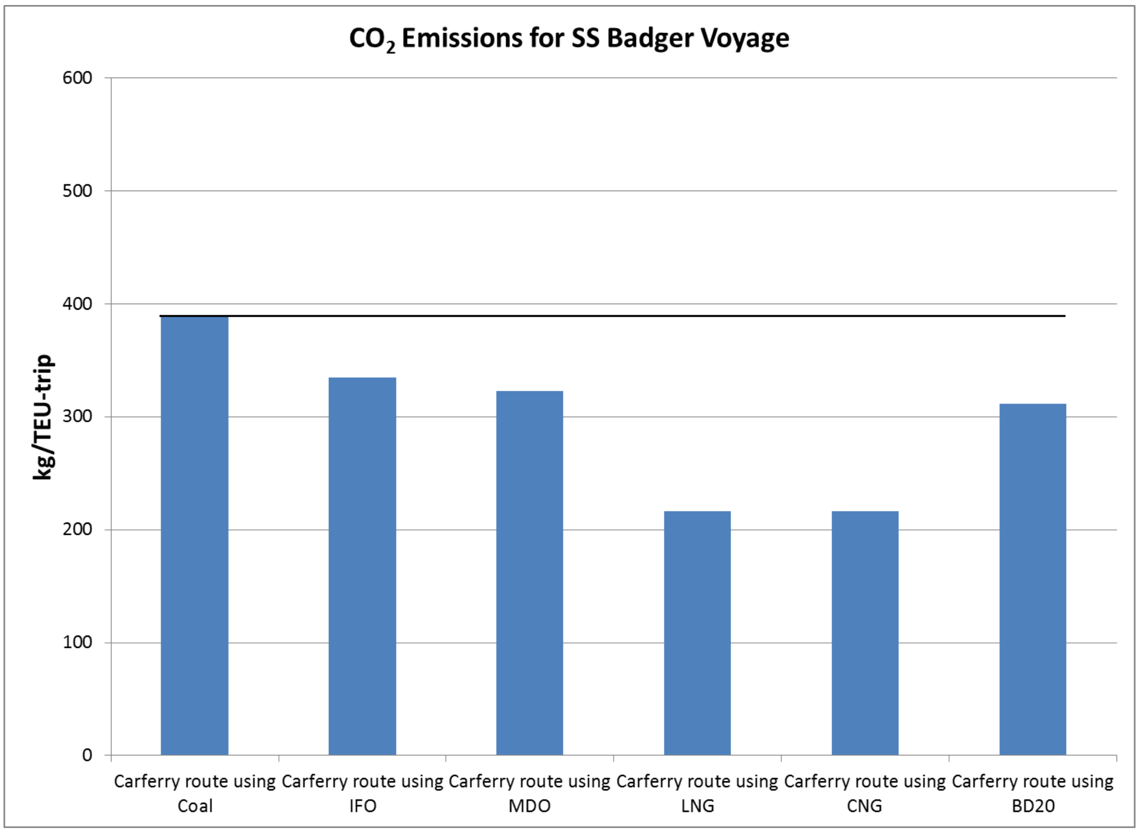
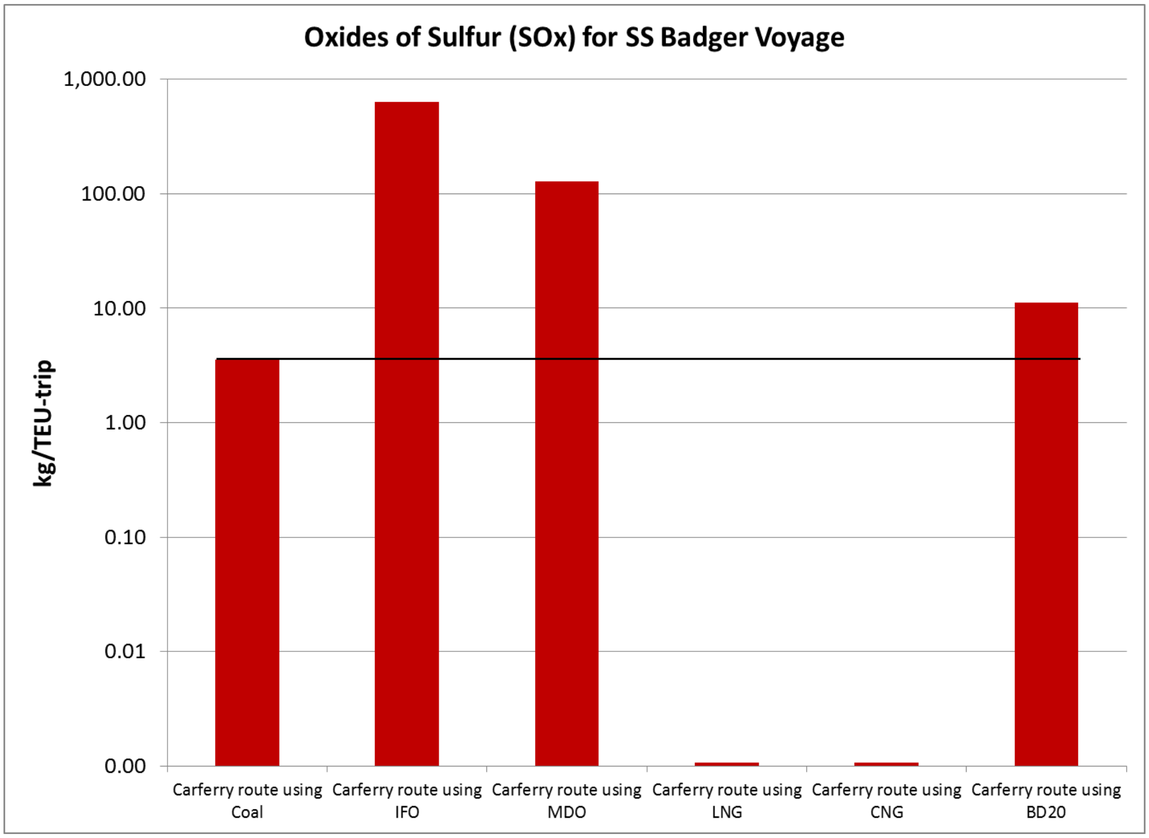


Figure 4. SOx emissions for all fuel scenarios.



Oxides of Sulfur (SOx) for SS Badger Voyage
kg/TEU-trip
1,000.00
100.00
10.00
1.00
0.10
0.01
0.00
Carferry route using Coal
Carferry route using IFO
Carferry route using MDO
Carferry route using LNG
Carferry route using CNG
Carferry route using BD20

Figure 5. NOx emissions for all fuel scenarios.

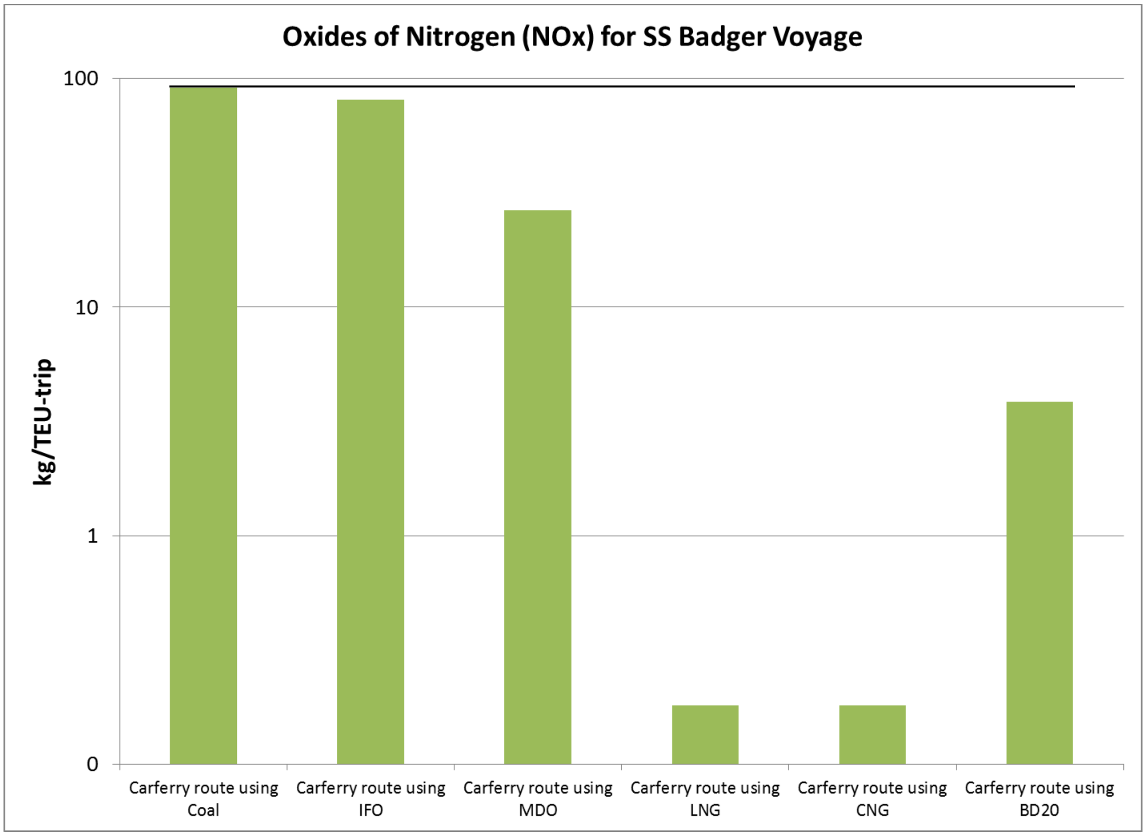


Figure 6. PM_{10} emissions for all fuel scenarios.

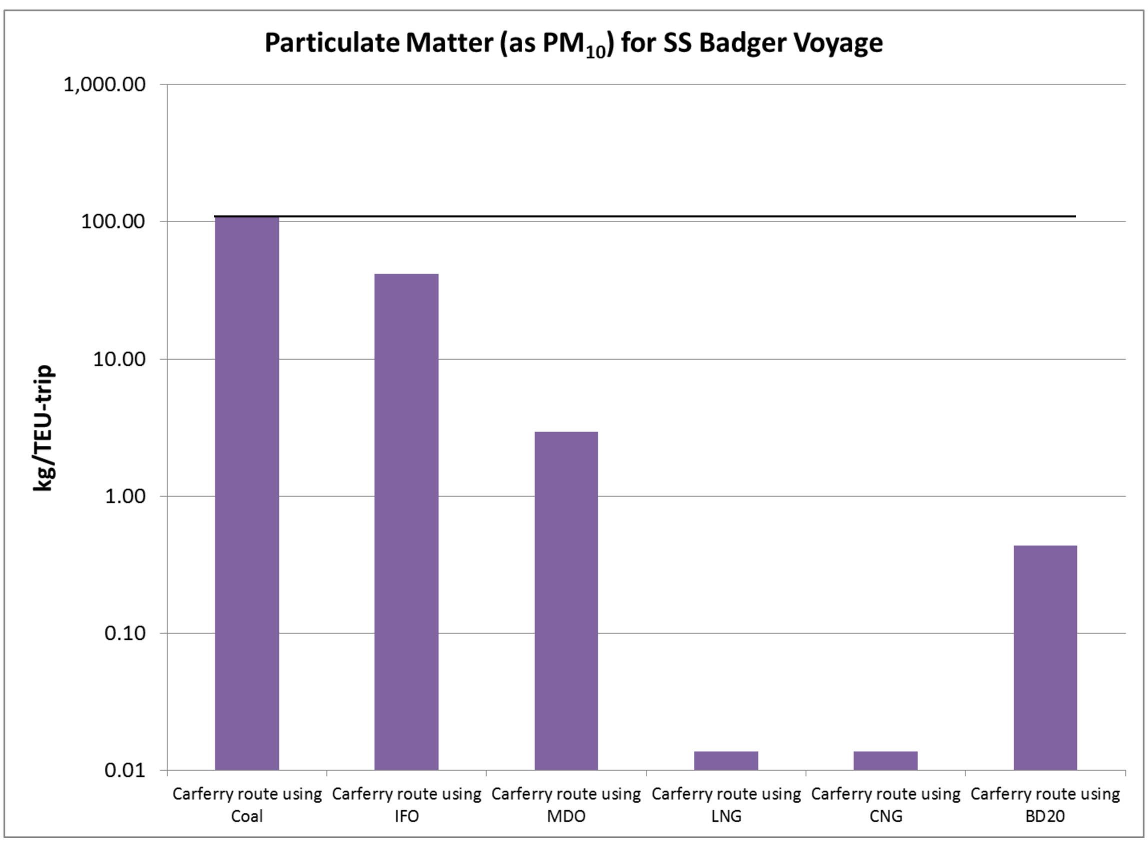


Figure 7. CH_4 emissions for all fuel scenarios.

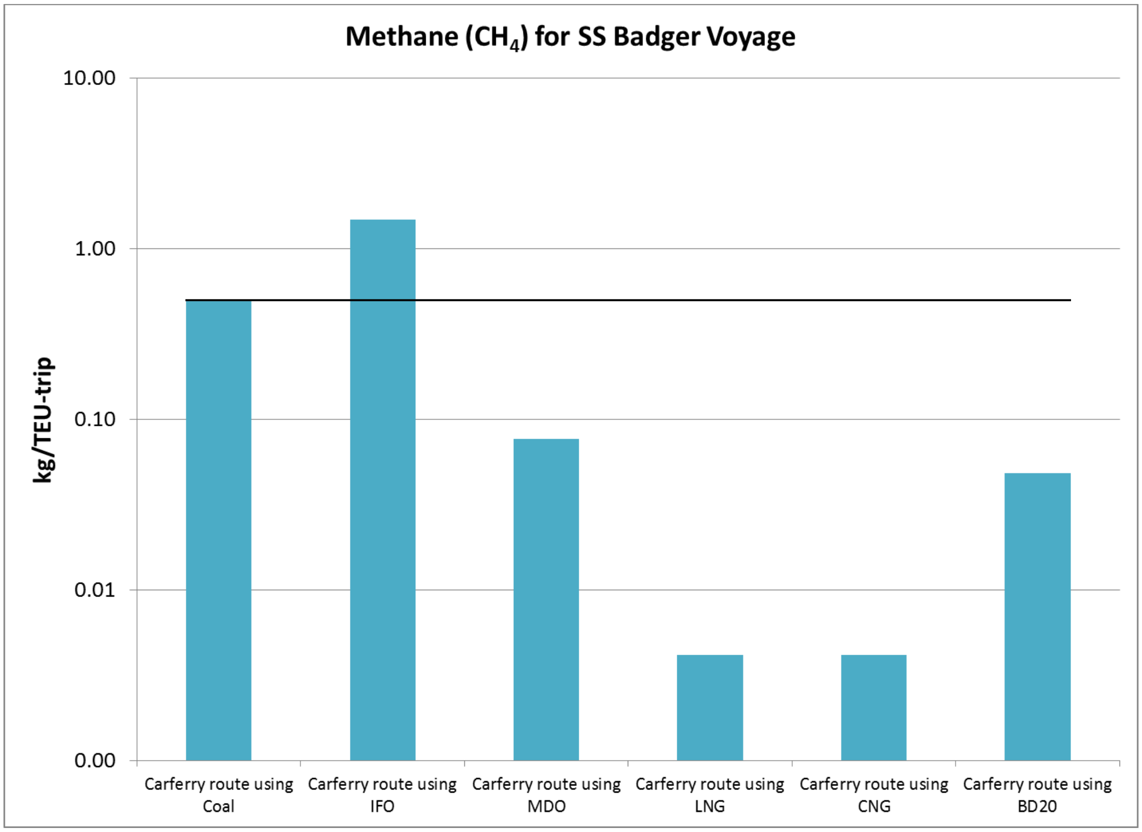
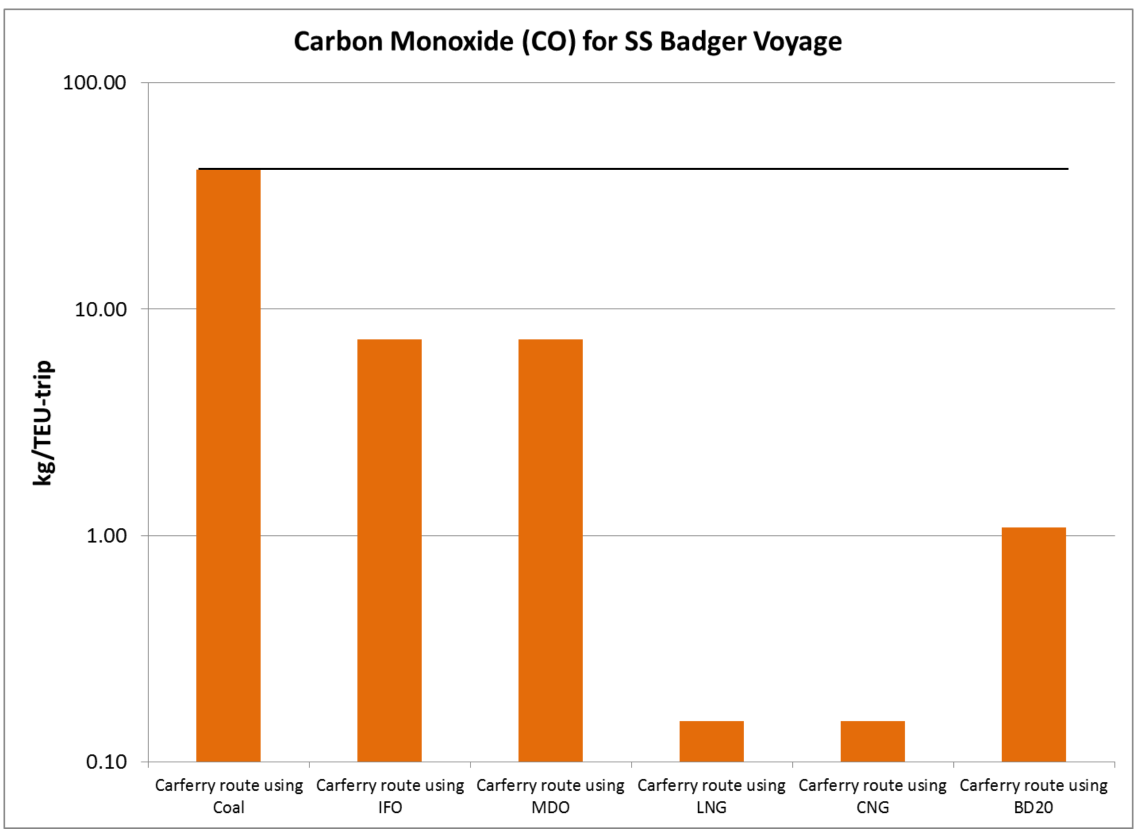


Figure 8. CO emissions for all fuel scenarios.



4.2 Phase II Emissions Results

Phase II modifies the calculation context to consider emissions for a freight trip from Green Bay to Detroit, utilizing either exclusively trucks or and intermodal route using both trucks and the SS Badger, under the alternative fuel scenarios described above. Emissions were calculated for each pollutant on a TEU basis for each main segment of the trip, using the best estimate values in the tables in Section 3.5. Table 10 reports total emissions for each pollutant to transport one TEU from Green Bay to Detroit.

Table 11 Total trip emissions for the two alternative routes using conventional and alternative fuels. Emissions values are measured on a per TEU basis for the entire trip.

	Total Trip Emissions (kg per TEU-trip)					
	CO_2	SOx	NOx	PM_{10}	CH_4	CO
All Truck Route (Full)	400	0.004	0.17	0.0084	0.0012	1.0
Carferry route using Coal	590	3.6	91	110	0.50	42
Carferry route using IFO	530	630	81	41	1.5	7.9
Carferry route using MDO	520	130	27	3.0	0.081	7.9
Carferry route using LNG	410	0.003	0.26	0.018	0.0081	0.65
Carferry route using CNG	410	0.003	0.26	0.018	0.0081	0.65
Carferry route using Bio-Diesel	500	11	3.9	0.44	0.053	1.6

Figure 3 shows the total CO_2 emissions for the two alternative routes and for each of the *SS Badger* fuel scenarios. It can be seen that transporting goods by truck – although a longer distance compared to the *SS Badger* route – produces the lowest amount of CO_2 emissions. Using the coal in the *SS Badger* emits almost *50% more* CO_2 compared to an all-truck route. Switching from coal to other fuels helps somewhat, but only a switch from coal to natural gas competes well with the all-truck alternative; CO_2 emissions are only 3% higher using natural gas compared to trucks. Figure 4 Figure 10 through Figure 14 present the results for the remaining pollutants. Note the log scale on the Y-axis for each of these figures. For nearly all pollutants, using coal produces the largest amount of emissions. In addition, the car ferry (with its existing engine system) does not compete well with an all-truck route in almost all cases, though natural gas does lower emissions for some pollutants.

Figure 9. CO_2 emissions for all fuel scenarios.

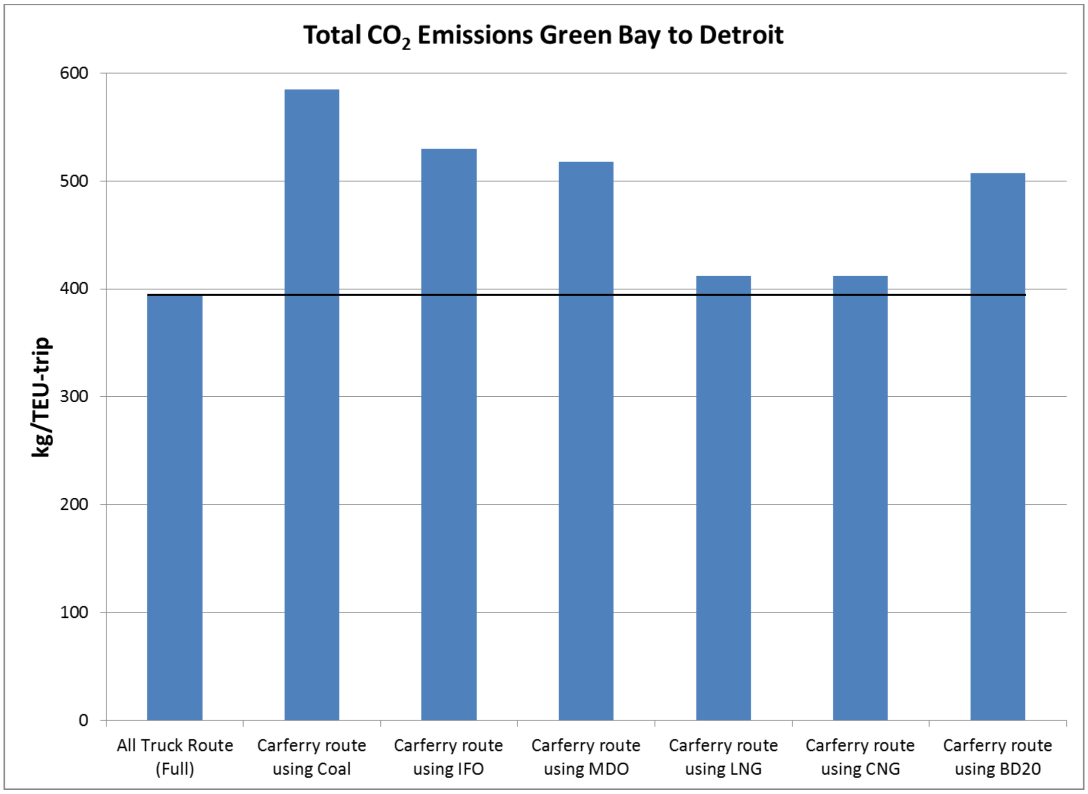


Figure 10. SOx emissions for all fuel scenarios.

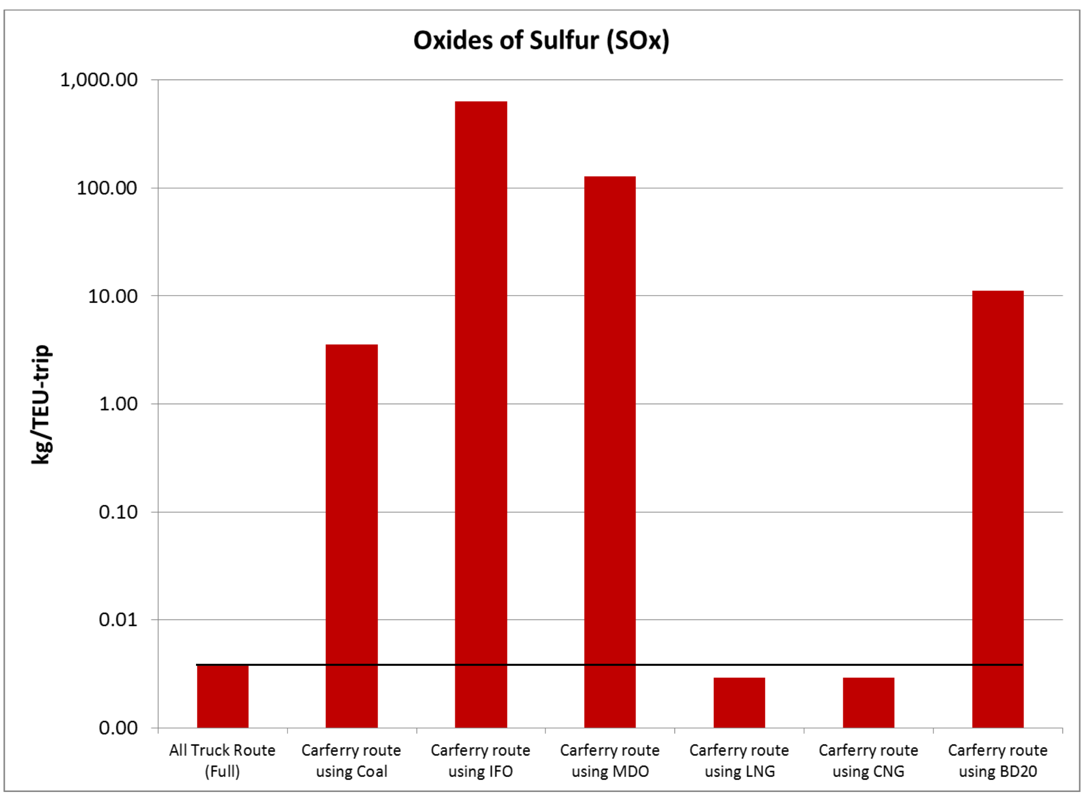


Figure 11. NOx emissions for all fuel scenarios.

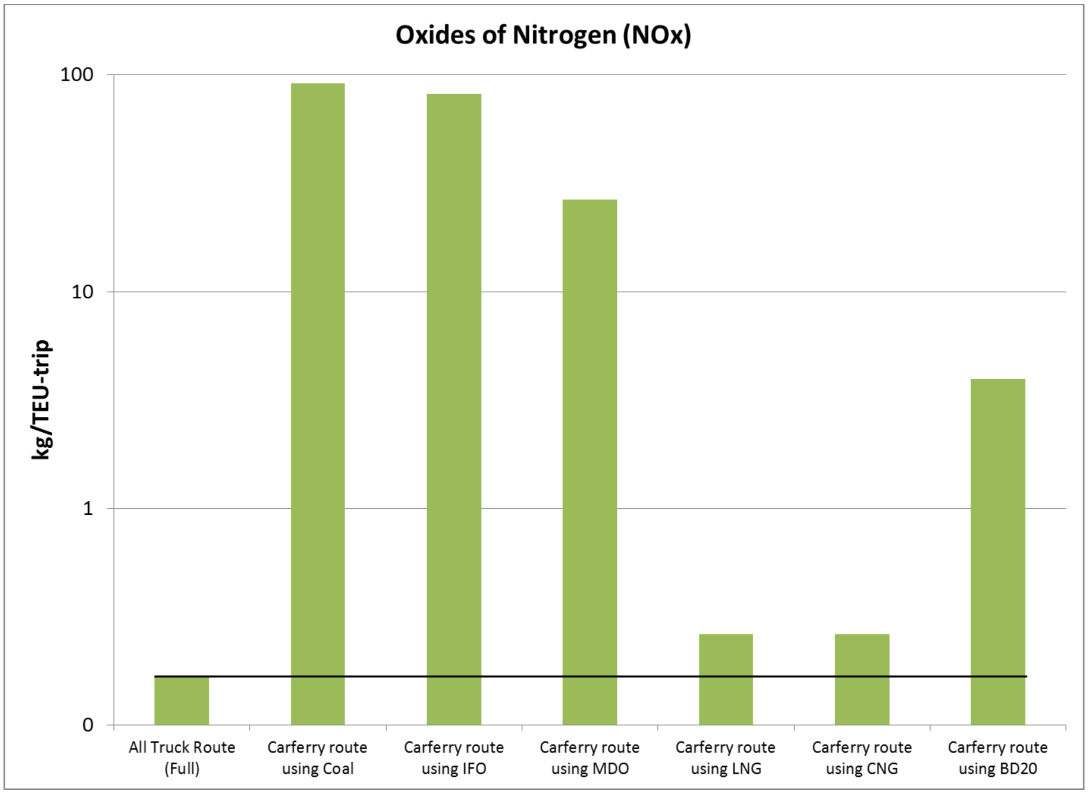


Figure 12. PM_{10} emissions for all fuel scenarios.

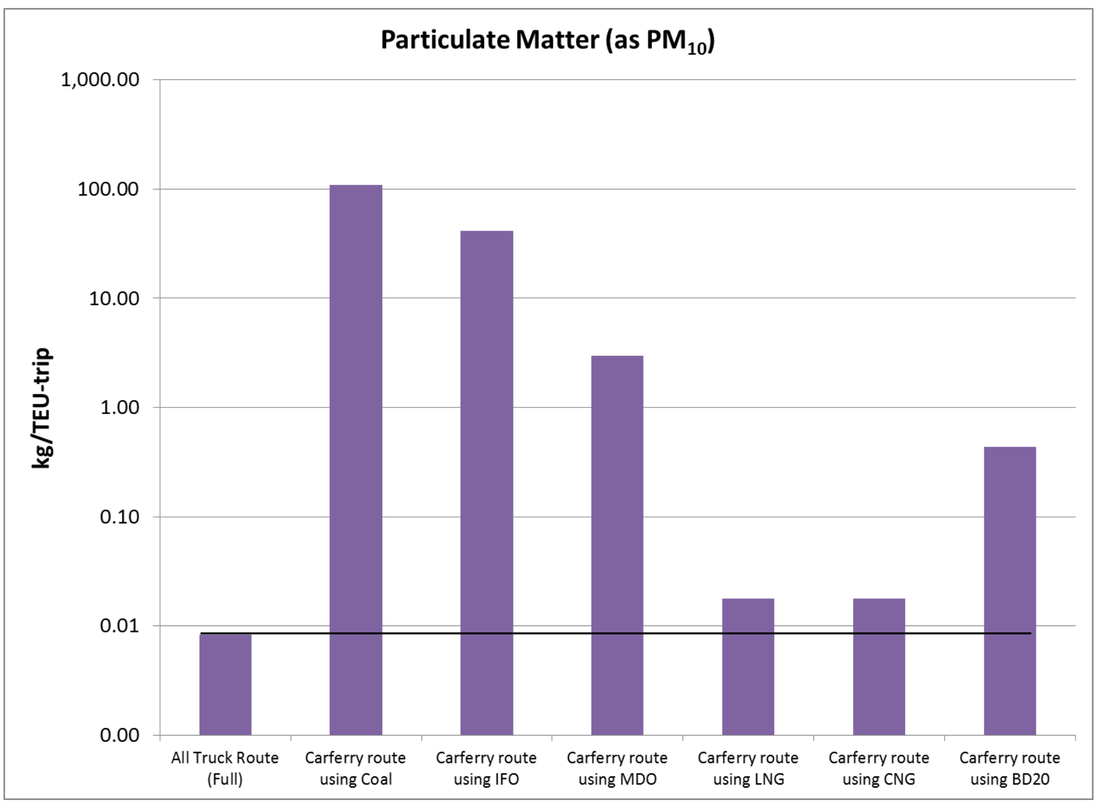


Figure 13. CH_4 emissions for all fuel scenarios.

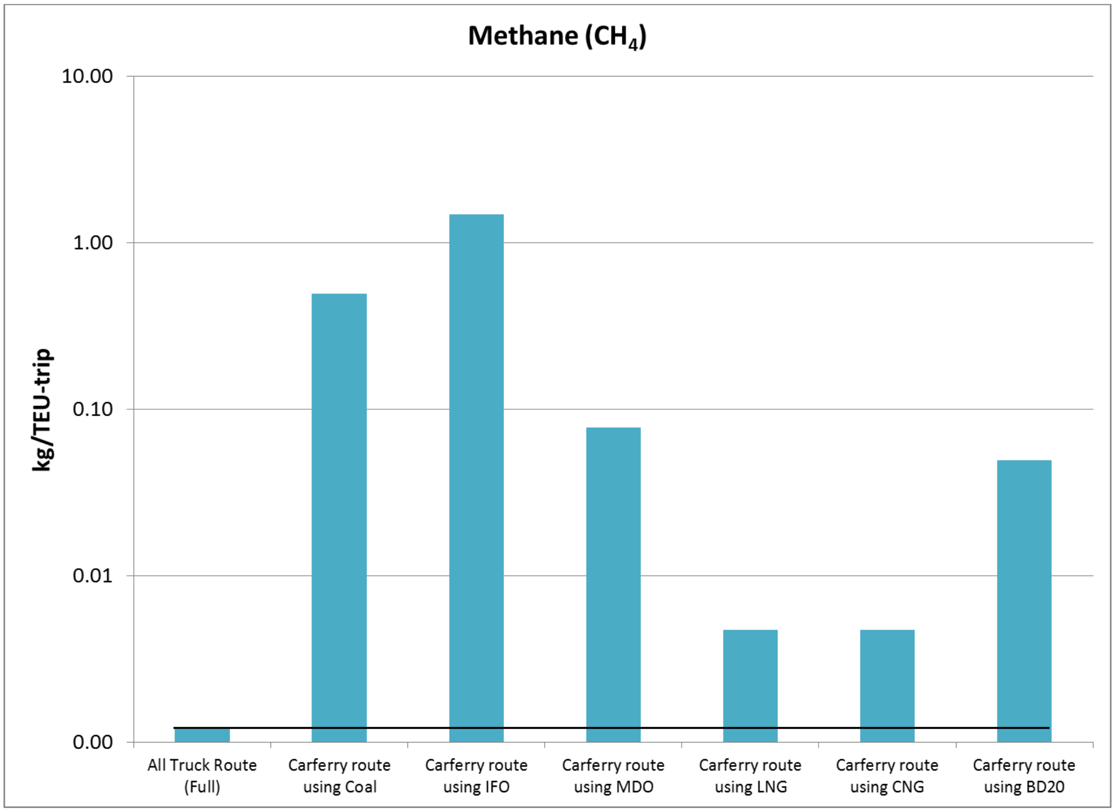
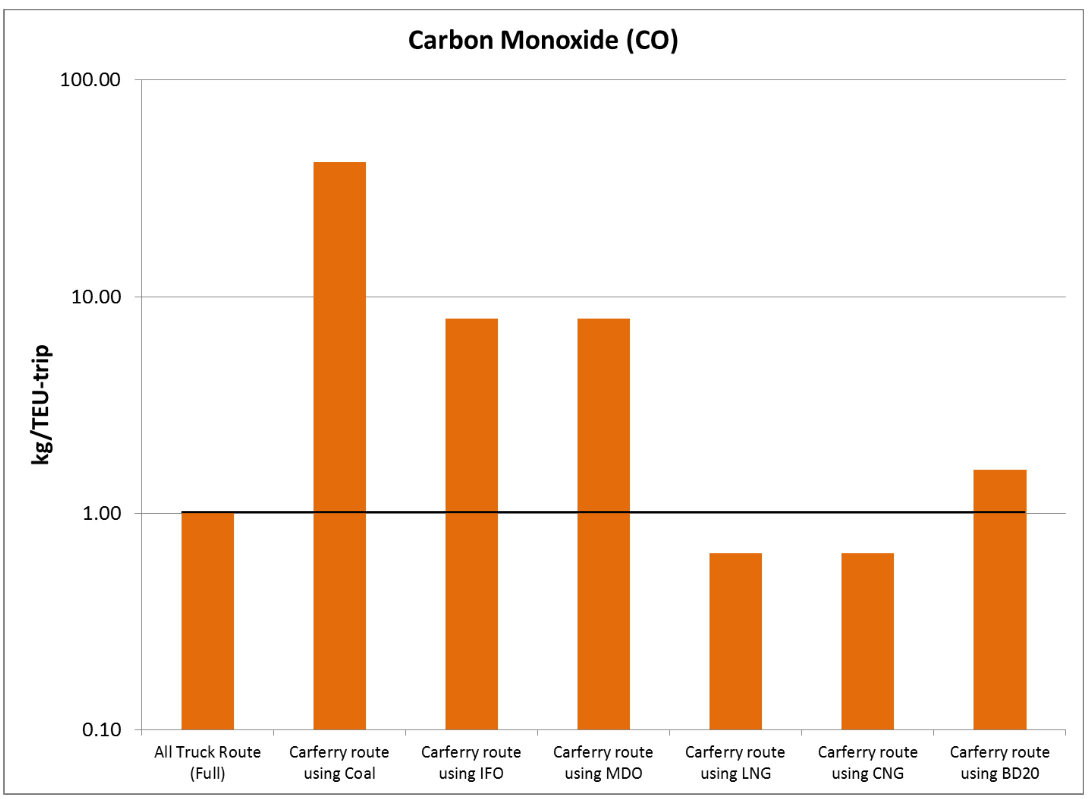


Figure 14. CO emissions for all fuel scenarios.



5 Discussion

Switching from coal to natural gas reduces emissions from the SS Badger, under currently-installed boiler-generated reciprocating steam technology. Three key messages are made clear from these results:

1. **Natural gas is a promising marine fuel for Great Lakes vessels in terms of intermodal emissions comparisons.** Natural gas fuel, if used by the water-tube boiler, reciprocating steam-engine power plant on the *SS Badger*, provides the greatest improvement in environmental performance with respect to other fuels. Natural gas (LNG or CNG in-use emissions) can perform similarly or better for SOx, and CO. However, natural gas performance cannot achieve parity with the all-truck land route for all other pollutants.
2. **Generally, emissions performance of the older (1930s) vessel design does not compete with technologies decades more advanced.** The all-truck route using a modern, emission-controlled heavy-duty diesel can move goods using less energy and producing fewer emissions than the *SS Badger* (as currently configured); this result was repeated across all fuels considered in this study, for nearly all pollutants. Additionally, as HDV engines become cleaner due to new EPA regulations on fuel efficiency, we would expect emissions to decrease over time using the all-truck route, *ceteris paribus*.
3. **Technology modernization could enhance a fuel-transition for Great Lakes integration with internal combustion gas engine propulsion.** With a movement towards a new propulsion system (i.e., away from steam and towards a more efficient internal combustion engines or other highly efficient plant designs), the case-study route using the *SS Badger* car ferry could become much more competitive with the all-truck route from an environmental performance basis.

Although these findings appear robust, spanning orders of magnitude in difference for some pollutants, we also recognize they are based on case-study inputs that are "best estimates" from a range of real-world values. This is especially true for fuel efficiency and emissions rates. Moreover, the case study conditions are specific to the *SS Badger*, and may motivate consideration of intermodal routes with greater payload efficiencies for the vessel, more favorable distance savings through water crossings, and more modern power plant designs, etc. For example, the typical thermal efficiency of internal combustion propulsion is more than twice that of historic reciprocating steam engines powered by older marine boiler systems (currently as much as ~2.7 times better). Therefore, we performed the following additional analyses: (a) a sensitivity analysis of the inputs to this study of boiler-steam engine power for the *SS Badger*, of vessel payload, and of trucking fuel economy; and (b) an initial scoping analysis of the impact of steam versus internal combustion plant efficiencies on CO_2 emissions. In addition to the ranges for fuel-related vessel emissions rates (in Section 3.5), the ranges used for other parameters are shown in Table 11.

Table 12. Sensitivity ranges for vessel and vehicle characteristics

Parameter	Low	Best	High
Annual Vessel Trips	445	445	460
Vessel Engine Load Factor (%)	50	73	80
Vessel Boiler-Engine Efficiency (%)	17	22	45
Vessel Payload Capacity (TEU)	31.2	117	117
Ship Speed (mph)	15.9	18.0	18.6
Truck efficiency (mpg)	5.5	6	7.2
Truck Payload Capacity (TEU)	1	2.6	2.6
All-truck route distance (miles)*	500	620	650

* Distances reflect the alternate Scenarios A and B in Figure 1 (with a longer 650-mile distance not illustrated).

5.1 Phase II *SS Badger* Boiler-Steam Engine Sensitivity Analysis

Figure 15 shows the difference between the truck route and the car ferry route using the different fuels investigated, for multiple combinations of the input parameters' ranges. Sensitivity-range bars indicate the range of emissions that occur based on modifications of our input parameters within the ranges presented above. It demonstrates that powering the *SS Badger* with natural gas is the best alternative to the all truck route. While an intermodal route using the *SS Badger* operating on natural gas may be able only to reach parity with an all-truck route in terms of CO_2 emissions, it might prove favorable for other pollutants.

Figure 15. Difference between the all-truck route and the car ferry route using a variety of fuels. Range bars represent results from sensitivity analysis.

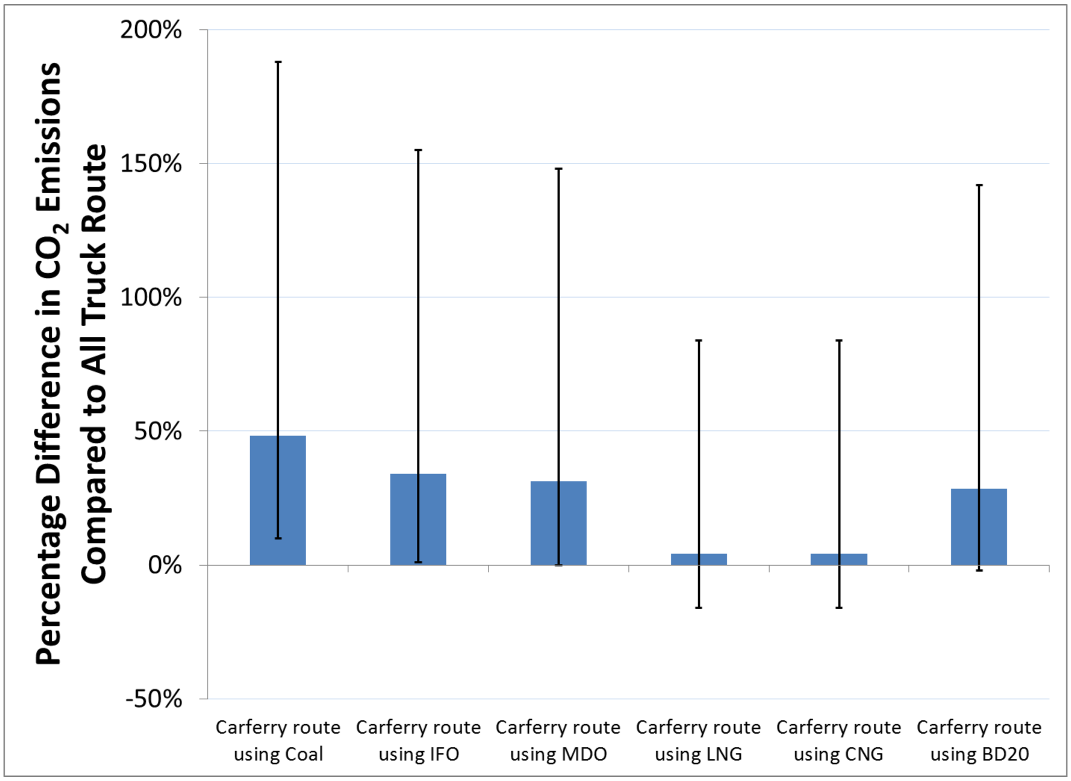


Table 13. Sensitivity Analysis Results for CO_2 emissions, in percent difference of intermodal route from all-truck route.

	Boiler-Steam Plant		
	Difference using Best Estimate Parameters	**Lower Bound Minimum Difference**	**Upper Bound Maximum Difference**
Carferry route using Coal	48%	10%	188%
Carferry route using IFO	34%	1%	155%
Carferry route using MDO	31%	0%	148%
Carferry route using LNG	4%	-16%	84%
Carferry route using CNG	4%	-16%	84%
Carferry route using Bio-Diesel	28%	-2%	142%

The primary inputs that affect the relative CO_2 comparison between the all-truck route and intermodal route using a natural-gas-fueled vessel are these (in descending order of importance): a) Vessel payload capacity; b) Truck payload capacity; c) Route distance for the all-truck comparison; and d) Truck efficiency mpg. (These are the same dominant inputs affecting the ranges for the MDO scenario, the IFO scenario, and the BD20 scenario, using the boiler-steam engine design.) In other words, if re-configuration of the cargo-carrying spaces could accommodate (and economically attract) more goods transport (i.e., if the SS Badger were to retrofit cargo spaces independent from or coupled with power plant upgrades), then resulting larger payload efficiencies could improve the vessel performance in this comparison.

5.2 "First Look" Potential for Improving Power Plant Efficiency

As a final component of this study, we examined the impacts of varying the thermal efficiency by looking at the CO_2 emissions that would result if the existing *SS Badger* engine was switched over from a steam boiler to an internal combustion engine. For this initial comparison, we focus only on CO_2 emissions, and recognize that the primary difference affecting CO_2 emissions from combustion (boiler or reciprocating engine) is the thermal efficiency of the combustion-power system. The existing steam system on the *SS Badger* has a thermal efficiency of ~17% per Table 1, whereas a steam turbine thermal efficiency may be in the range of 20-25%, and modern marine diesels have a thermal efficiency in the range of 32-45%.

Running the model under this assumption still shows only natural gas as having potential to compete on an emissions basis against and all-truck land route. The primary inputs that affect the relative CO_2 comparison between the all-truck route and intermodal route using an internal combustion engine-powered vessel remain similar to the results discussed in Section 5.1, except that the relative power plant efficiencies rank second; the primary inputs are (again, in descending order of importance): a) Vessel payload capacity; b) *SS Badger* steam-boiler plant efficiency; c) Truck payload capacity; and d) Truck efficiency (mpg).

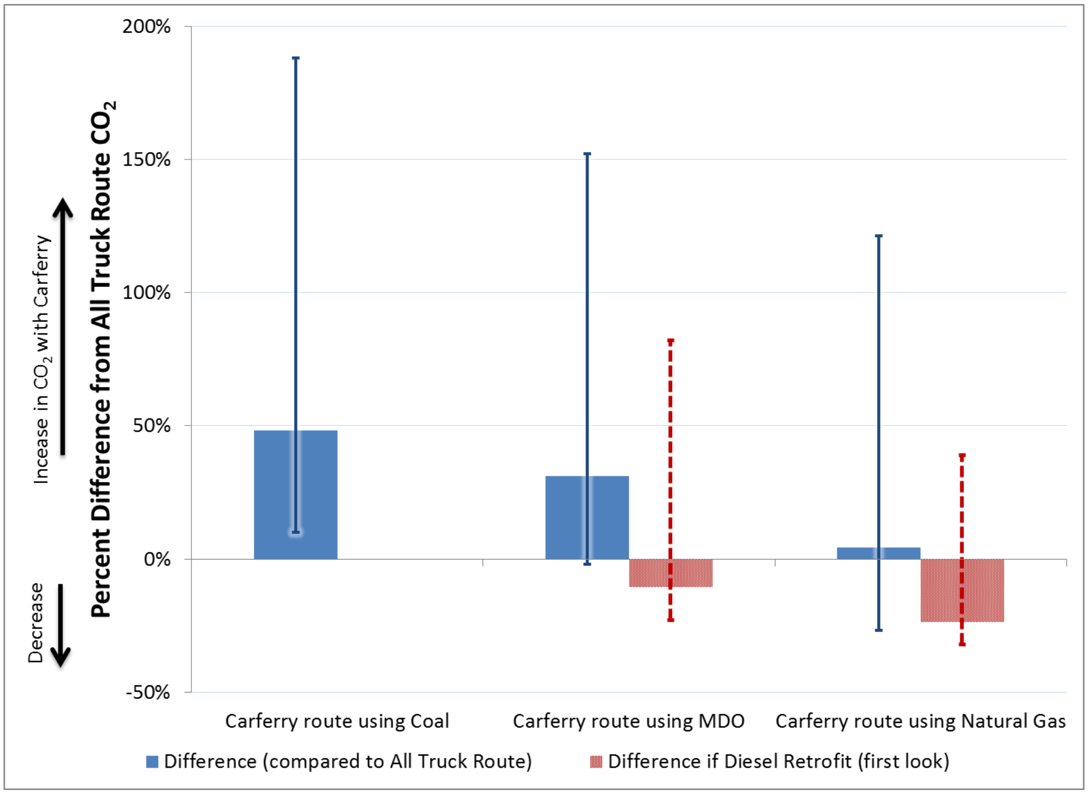
A modern vessel using natural gas fuels coupled with internal-combustion engine propulsion could perform at lower CO_2 emissions than the all-truck route. This is shown in Table 14 and Figure 16 for MDO and natural gas scenarios, where the red bar-graph results depict best-estimate inputs. With sensitivity analysis ranges applied, natural gas fuel appears to be a robust contender for reducing CO_2 in the intermodal route, and MDO has some potential to achieve parity. Not shown, BD20 and IFO fuels compare better under diesel engine efficiencies and may perform similarly to MDO for CO_2. Further study would be needed to evaluate other pollutants. However, some results can be expected, such as a higher sulfur residual fuel would not be competitive for PM_{10} or SOx with the all-truck route without aftertreatment. In addition, conversion to internal combustion engines is not the only method to improve emissions, other technology improvements also deserve further study.

Table 14. Sensitivity analysis results for CO_2 emissions for MDO and natural gas fuels, exploring potential internal combustion engine plant, in percent difference of intermodal route from all-truck route.

	Boiler Steam Plant			Internal Combustion Engine Plant		
	Difference using Best Estimate Parameters	Lower Bound Minimum Difference	Upper Bound Maximum Difference	Difference using Best Estimate Parameters	Lower Bound Minimum Difference	Upper Bound Maximum Difference
Carferry route using Coal	48%	10%	188%	NA	NA	NA
Carferry route using MDO	31%	0%	148%	-11%	-0.23	0.82
Carferry route using Natural Gas	4%	-16%	84%	-24%	-0.32	0.39

Note: The diesel plant results are based on the same total energy consumption as the current boiler-steam plant; additional analyses would be recommended to account for alternate engine room designs that include diesel propulsion (@ 3500 Hp), and potentially more innovative technologies for delivering ferry hotel and auxiliary power.

Figure 16. Difference between Phase II truck and intermodal routes using coal, MDO, and Natural Gas. Blue bars represent steam-boiler system and red bars represent an internal combustion engine, albeit made to accept and burn alternative fuels. Range bars represent the results from sensitivity analysis.



6 Conclusions and Recommendations

This analysis represents the inaugural case study using the GIFT Model specifically applied to a Great Lakes Maritime Research Institute (GLMRI) study. Because the *SS Badger* is a coal-fired vessel, this study also is groundbreaking because of the range of alternative fuels considered for marine modes. The study presents three primary conclusions, two directly resulting from the case study and one resulting from including internal combustion engine parameters in the sensitivity analysis for CO_2 emissions. These are:

1. **Natural gas is a promising marine fuel for Great Lakes vessels in terms of intermodal emissions comparisons.**

2. **Generally, emissions performance of the older (1930s) vessel design does not compete with technologies decades more advanced.**

3. **Technology modernization can accompany a fuel-transition for Great Lakes integration with internal combustion gas engine propulsion.**

4. **A Great Lakes shipping transition to natural gas fuels will need to be strategic, and analyses like this study can serve as important decision support role for GLMRI and industry partners.**

This analysis represents a replicable analytical design that can be applied to virtually any Great Lakes vessel type; in fact, it can be applied to any intermodal comparison of short-sea shipping with other uni-mode routes. We recommend that

GLMRI consider whether natural gas as an alternative fuel for Great Lakes shipping may serve other vessel types and/or other routes with clearer benefits. This suggestion follows from the promising “first look” results obtained from parametrically changing the vessel power plant efficiency to approximate an internal combustion engine design. Practically, this kind of analysis can be used to explore and prepare applications for clean diesel funding or fleet modernization funding mechanisms. For example, the National Clean Diesel Campaign (NCDC) is one of the strategies made available by the federal government to make existing diesel engines operate more cleanly, as well as funding to help build diesel emission reduction programs; funding similar to the NCDC may need to be identified for a retrofit to the *SS Badger* because the U.S. EPA program may only apply to existing diesel vessels and cannot be used to improve other engine types.

Depending on feasibility considerations and flexibility to retrofit the *SS Badger*, this study may be leveraged to consider an internal combustion powered system in more detail for this or another car ferry design. In this regard, we can also expand the study to consider other dimensions related to fuel switching, including economic and operational impacts from fuel costs, retrofit capital, and modified engine crew responsibilities (if any). The study team looks forward to working with GLMRI on next-phase studies for the *SS Badger*, and on extensions of this work to provide full-spectrum decision support analyses for the Great Lakes.

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