A Waterborne Commerce Inventory Integrating Economic, Transportation, and Emissions Data

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ABSTRACT

Recent inventory efforts have focused on developing non-road inventories for emissions modeling and policy insights. Characterizing these inventories geographically, and explicitly treating the uncertainties that result from limited emissions testing, incomplete activity and usage data, and other important input parameters currently pose the largest methodological challenges. This paper presents an commercial marine vessel inventory that uses detailed statistics regarding fuel consumption, vessel movements, and cargo volumes in the Columbia and Snake river systems in Washington and Oregon. This inventory was prepared for inclusion in regional haze modeling conducted by the Western Regional Air Partnership (WRAP). The objective of this current extension to the inventory is to provide modelers with bounded parametric inputs for sensitivity analysis in pollution modeling. The ability to parametrically model the uncertainty in commercial marine vessel inventories will help policy makers determine whether better policy decisions can be enabled through further vessel testing and improved inventory resolution.

This analysis estimates that annual NOx emissions from marine transportation in the Columbia and Snake River systems in Washington and Oregon equal 6,909 tonnes NOx per year. This base case estimate is 2.6 times greater than previous NOx inventories for this region. By relying on fuel consumption estimates modeled in a “bottom-up” calculation that includes vessel characteristics and transit information, this inventory is considered to be more accurate than previous estimates. Specific insights from the characterization of uncertainty are presented, particularly the need for focused research to characterize air emissions from marine engines on the most heavily traveled water routes.

INTRODUCTION

Recent inventory efforts have focused on developing non-road inventories for emissions modeling and policy insights[1]. Characterizing these inventories geographically, and explicitly treating the uncertainties that result from limited emissions testing, incomplete activity and usage data, and other important input parameters currently pose the largest methodological challenges. Since directly monitored data for non-road emissions, fuel-consumption, and activity level generally are not available, the development of non-road inventories must rely on a number of assumptions that introduce significant uncertainty. To date, most non-road inventories have applied national or regional average values that suffer from two important weaknesses. First, these assumptions often are generated through engineering modeling or manufacturer test data, rather than in-service sampling. This means that certain assumptions may not apply to actual non-road vehicle operations. Second, emissions factors, fuel-consumption data, and activity-level information typically represent national averages (or regional averages at best), and therefore cannot capture the potential variability of non-road operations at the local level.

Nonetheless, these inventories are demonstrating that non-road emissions are more important than previously considered. One important example is non-road emissions from water transportation. This mode includes freight transportation by inland river towboats pushing barges, tugboats and other working harbor craft, deep-draft oceangoing vessels, passenger ferries, and fishing vessels. Commercial marine vessels represent one of the least-studied non-road transportation modes in terms of emissions inventories. However, recent research has begun to evaluate these emissions internationally and domestically[2-4].

In previous work, waterborne commerce emissions were estimated for various U.S regions and types of traffic, including oceangoing (international), coastwise (domestic), inland-river system, and Great Lakes[4]. This inventory only estimated emissions from cargo movements reported publicly by the U.S. Army Corps of Engineers (USACE)[5], and did not attempt to characterize emissions from all commercial vessel movements (such as vessel-assist tugboats). That work showed that more than 90% of all emissions in U.S. waters occur in shipping channels outside of port regions, either on rivers or within 200 miles of shore. NOx emissions from river commerce in the top 20 states with waterborne trade account for 65% of total waterborne commerce emissions in those states. In contrast, 72% of SOx emissions in these states occurs along coastal (Ocean or Great Lake) areas, where high-sulfur fuels are more commonly used. On a national basis, that study suggested that NOx emissions from waterborne commerce equaled 4% of all U.S. transportation emissions, more than double previous nationwide inventories of vessel emissions. This national inventory produced a geographically resolved depiction of emissions, using a geographic database of navigable waterways.

However, at least four sources of uncertainty were identified in that study. They include: 1) the use of average emission factors based on limited measurement of in-use marine engines; 2) simplified duty cycle assumptions; 3) uncertainties about the actual distance of cargo movements; and 4) the use of "average vessel" assumptions, particularly in inland rivers. It was shown that these errors could contribute to an underestimate of as much as 300% in some river systems, when the "top-down" fuel consumption was compared to a "bottom-up" estimate provided by the Tennessee Valley Authority (TVA) Barge Costing Model[6,7].

This paper compares two methodologies for estimating emissions for commercial marine transportation. The first inventory uses detailed statistics regarding fuel consumption, vessel movements, and cargo volumes in the Columbia and Snake river systems in Washington and Oregon. This inventory was prepared for inclusion in regional haze modeling conducted by the Western Regional Air Partnership (WRAP). This inventory is compared to a national inventory of waterborne commerce NOx emissions (i.e., emissions directly resulting from cargo movements) from vessels operating in U.S. waterways[4]. The potential for inventory methodologies that integrate engineering, economic, and environmental data in a GIS framework is discussed. Specific insights from the characterization of uncertainty are presented, particularly the need for focused research to characterize air emissions from marine engines on the most heavily traveled water routes.

METHODOLOGY AND CALCULATIONS

This analysis begins with the "bottom-up" fuel consumption estimates for 1999 from the TVA Barge Costing Model[6] to estimate NOx emissions for the Columbia and Snake river systems. The methodology presented here relies on government statistics about waterborne commerce movements, and applies an engineering approach to calculate vessel emissions. Like the "top-down" approach of earlier work, this methodology has certain advantages in that the statistics are geographically resolved, thus enabling a locally detailed inventory with less effort than traditional bottom-up approaches. As with all modeled inventories, this "bottom-up" approach also poses a potential for significant uncertainty. However, a carefully constructed analysis can describe this uncertainty sufficiently to provide a robust inventory for policy decision making at local, regional, national, and even international scales. Moreover, the techniques of uncertainty analysis can provide focused attention on those aspects of the inventory that require additional research attention.

The TVA model was developed to evaluate fuel usage by Inland River segment for fuel tax purposes. It combines statistics about vessel characteristics and cargo movements to estimate fuel consumption for each inland waterway segment. Rather than estimating fuel consumption based on cargo ton-miles (as the previous study did), this model is based on actual miles transited by vessels on inland rivers. A comparison of fuel consumption using cargo ton-miles and actual vessel miles for the Columbia, Snake, and Willamette rivers showed that using cargo ton-miles as the basis for fuel consumption underestimated fuel usage by more than 50%. Moreover, the TVA model has very good accuracy in estimating national fuel consumption from commercial marine vessels operating on inland rivers. Comparing model output with the Inland Waterways Trust Fund's fuel tax receipts for 1999 show that, on a national scale, TVA's Barge Costing Model is accurate to 0.8%; since 1996, the model errors have not exceeded 2.1%[8].

Table 1 presents the fuel consumption data from the Barge Costing Model for the Columbia and Snake river systems. This represents the output of the model using the best-estimate input parameters in the TVA model. Specifically, the base case scenario assumes that the vessel power at full throttle is 80% of maximum-rated horsepower and that a maneuvering vessel in the inland river (i.e., during transit through locks) operates at 20% of rated horsepower. However, it is possible that some vessels operate under different conditions. Therefore, the model was re-run using both upper and lower bound scenarios. The lower bound scenario uses a full-throttle of load 75% of rated power and a maneuvering load of 15% of rated power (which is the lowest power expected to provide adequate rudder control). The upper bound scenario uses the same 20% of rated power for maneuvering but increases full-throttle operations to 95% of rated horsepower. Fuel consumption estimates using these parameters are shown in Tables 2 and 3.

Table 1. 1999 WCSC Fuel Use for Columbia and Snake Rivers (Base Case Scenario)[a]

	Fuel Use (gallons)		
River Name	**Towboats**	**All others**	**Totals**
Snake River	1,562,009	570,566	2,132,576
Columbia River Entrance	112,583	1,185,218	1,297,801
Willamette above Portland and Yamhill	66,792	12,095	78,887
Columbia at Bakers Bay	68	466	534
Lower Willamette	1,447,151	728,418	2,175,568
Columbia & Lower Willamette below Vancouver	4,172,132	19,873,673	24,045,805
Columbia between Vancouver and the Dalles	3,418,962	268,554	3,687,516
Columbia above the Dalles Dam to McNary Lock & Dam	3,192,746	266,279	3,459,026
Columbia above McNary Lock & Dam to Kennewick	1,134,310	101,283	1,235,594
Columbia between Wenatchee & Kettle Falls	2,792	3,770	6,562
Totals	**15,109,545**	**23,010,323**	**38,119,868**

a. Base case assumes 80% of max-rated horsepower at full throttle and 20% of rated horsepower during maneuvering through locks. Data provided by Chris Dager, Tennessee Valley Authority, 16 March 2001.

Table 2. Fuel Use for Columbia and Snake Rivers (Lower Bound Scenario)[b]

	Fuel Use (gallons)		
River Name	**Towboats**	**All others**	**Totals**
Snake River	1,456,781	522,354	1,979,135
Columbia River Entrance	106,314	1,131,587	1,237,901
Willamette above Portland and Yamhill	60,994	10,903	71,897
Columbia at Bakers Bay	64	438	502
Lower Willamette	1,334,181	697,650	2,031,831
Columbia & Lower Willamette below Vancouver	3,894,854	18,934,844	22,829,698
Columbia between Vancouver and the Dalles	3,180,205	248,668	3,428,874
Columbia above the Dalles Dam to McNary Lock & Dam	2,983,265	247,212	3,230,477
Columbia above McNary Lock & Dam to Kennewick	1,062,997	94,037	1,157,034
Columbia between Wenatchee & Kettle Falls	2,537	3,396	5,934
Totals	**14,082,193**	**21,891,090**	**35,973,283**

b. Lower bound assumes 75% of max-rated horsepower at full throttle and 15% of rated horsepower during maneuvering through locks. Data provided by Chris Dager, Tennessee Valley Authority, 16 March 2001.

Table 3. Fuel Use for Columbia and Snake Rivers (Upper Bound Scenario)[c]

	Fuel Use (gallons)		
River Name	**Towboats**	**All others**	**Totals**
Snake River	1,862,101	665,532	2,527,632
Columbia River Entrance	135,428	1,440,914	1,576,342
Willamette above Portland and Yamhill	77,353	13,811	91,164
Columbia at Bakers Bay	82	558	640
Lower Willamette	1,695,797	886,914	2,582,711
Columbia & Lower Willamette below Vancouver	4,955,249	24,102,855	29,058,104
Columbia between Vancouver and the Dalles	4,065,444	317,589	4,383,033
Columbia above the Dalles Dam to McNary Lock & Dam	3,799,742	314,532	4,114,274
Columbia above McNary Lock & Dam to Kennewick	1,359,096	120,110	1,479,206
Columbia between Wenatchee & Kettle Falls	3,218	4,302	7,520
Totals	**17,953,511**	**27,867,116**	**45,820,627**

c. Upper bound assumes 95% of max-rated horsepower at full throttle and 20% of rated horsepower during maneuvering through locks. Data provided by Chris Dager, Tennessee Valley Authority, 16 March 2001.

Using the bottom-up fuel consumption estimated by the Barge Costing Model, one can apply fuel-based emission factors to construct an emissions inventory. First, a conversion is made from volume of fuel (in gallons) to mass of fuel (in metric tons or tonnes). This requires an assumption of the fuel density, which can vary within specifications[9-11]. Second, the mass of fuel consumed annually is multiplied by a fuel-based emissions factor to estimate the annual NOx emissions. This emission factor also can vary, and is based on limited sampling of in-use marine engines. Table 4 presents best estimates, lower and upper bound estimates for fuel density and fuel-based NOx emissions factors. Towboats are assumed to be more homogenous in both fuel selection and engine type, so they have narrower bounds on fuel density and NOx factors than other vessels (which include deep-draft self-propelled vessels, harbor tugboats, etc.). Tables 5 through 7 present the base case, lower bound, and upper bound estimates, respectively, of NOx emissions for the Columbia and Snake river systems.

Table 4. Fuel Density and NOx Emissions Parameters Used in Calculations

Fuel Density and Emissions Factors	**Best Estimate**	**Lower Bound**	**Upper Bound**
	kg/l	**kg/l**	**kg/l**
Fuel Density for Towboats[11]	.8401	0.8401	0.94
Fuel Density for All Other Vessels[10]	.8401	0.8401	0.987
	kg NOx/tonne fuel	**kg NOx/tonne fuel**	**kg NOx/tonne fuel**
NOx Emissions Factor for Towboats[12,13]	57	56	63
NOx Emissions Factor for All Other Vessels[11-13]	59	56	96

Table 5. 1999 NOx Emissions for Columbia and Snake Rivers (Base Case Estimates)

	Annual NOx Emissions (tonnes)		
River Name	**Towboats**	**All others**	**Totals**
Snake River	283	107	387
Columbia River Entrance	20	222	235
Willamette above Portland and Yamhill	12	2	14
Columbia at Bakers Bay	0.01	0.09	0.10
Lower Willamette	262	136	394
Columbia & Lower Willamette below Vancouver	756	3,716	4,358
Columbia between Vancouver and the Dalles	620	50	668
Columbia above the Dalles Dam to McNary Lock & Dam	579	50	627
Columbia above McNary Lock & Dam to Kennewick	206	19	224
Columbia between Wenatchee & Kettle Falls	0.50	0.71	1.19
Totals	**2,739**	**4,303**	**6,909**

NORTHWEST RIVER INVENTORY

Most mobile source inventories consider the emissions on a per vehicle basis. However, with defined waterway routes (like highways) these estimates can be represented as line sources on a per waterway mile basis. Calculating annual NOx emissions using these “stationary” units and representing them geographically provides a representation of the emissions intensity from commercial marine activity. Emissions are assigned to specific waterways geographically by multiplying the weighted-average of each waterway link by the total NOx estimated for that river segment. For example, the Columbia & lower Willamette river segments below Vancouver contain 18 links in the USACE waterway network. The largest link account for 17% of the total length of this river segment, so the annual NOx emissions estimated for that link would equal 17% times the total NOx estimated for the waterway segment. Using a geo-referenced data set, such as the USACE waterway network [5], this can be represented in a GIS platform.

Table 6. NOx Emissions for Columbia and Snake Rivers (Lower Bound Estimates)

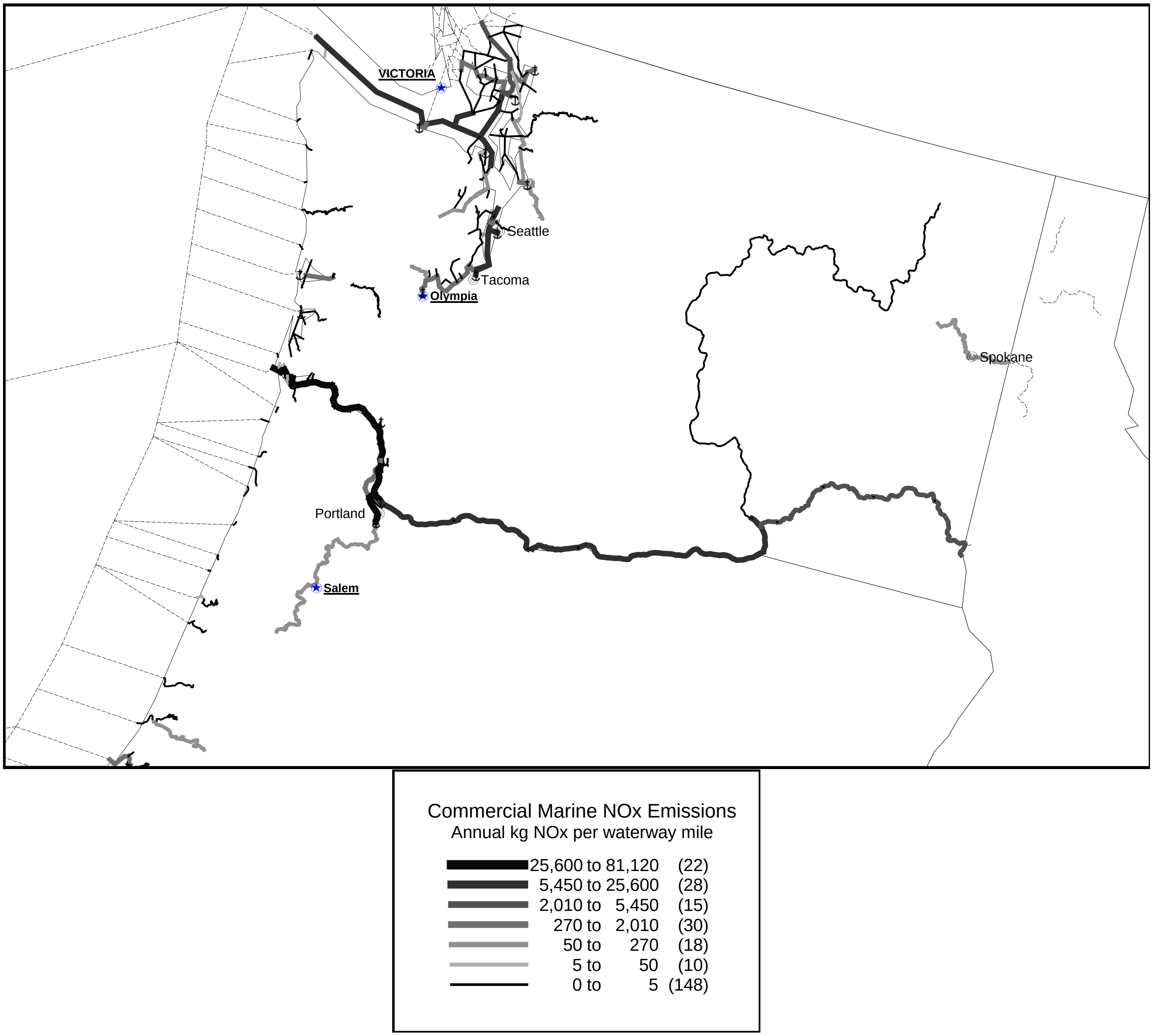
	Annual NOx Emissions (tonnes)		
River Name	**Towboats**	**All others**	**Totals**
Snake River	264	95	359
Columbia River Entrance	19	205	224
Willamette above Portland and Yamhill	11	2	13
Columbia at Bakers Bay	0.01	0.08	0.09
Lower Willamette	242	126	368
Columbia & Lower Willamette below Vancouver	706	3,432	4,138
Columbia between Vancouver and the Dalles	576	45	621
Columbia above the Dalles Dam to McNary Lock & Dam	541	45	586
Columbia above McNary Lock & Dam to Kennewick	193	17	210
Columbia between Wenatchee & Kettle Falls	0.46	0.62	1.08
Totals	**2,552**	**3,968**	**6,520**

Table 7. NOx Emissions for Columbia and Snake Rivers (Upper Bound Estimates)

	Annual NOx Emissions (tonnes)		
River Name	**Towboats**	**All others**	**Totals**
Snake River	338	121	458
Columbia River Entrance	25	261	286
Willamette above Portland and Yamhill	14	3	17
Columbia at Bakers Bay	0.01	0.10	0.12
Lower Willamette	307	161	468
Columbia & Lower Willamette below Vancouver	898	4,369	5,267
Columbia between Vancouver and the Dalles	737	58	794
Columbia above the Dalles Dam to McNary Lock & Dam	689	57	746
Columbia above McNary Lock & Dam to Kennewick	246	22	268
Columbia between Wenatchee & Kettle Falls	0.58	0.78	1.36
Totals	**3,254**	**5,051**	**8,305**

A map of emissions intensity by waterway is shown for the base case data in Figure 1. Please note that the scale presented is non-linear, and was calculated automatically by the software according to “natural breaks” in the data, which highlights waterway segments of greater and lesser emissions intensity. Clearly, the Columbia and Lower Willamette rivers below Vancouver, WA (near Portland, OR) to the mouth of the Columbia River have the greatest highest NOx emissions per waterway mile. This is expected because this river segment can accept deepwater oceangoing ships in addition to towboats and other river craft. It is worth observing that annual NOx emissions from most (55%) of the waterway links in the Columbia and Snake river system are below 5 kg NOx per waterway mile; the numbers in parentheses represent the number of waterway links at each scale category.

Figure 1. Commercial marine vessel NOx emissions (1999), base case scenario



Uncertainty analysis

The parametric analysis developed above provides three scenario estimates that can be used in air pollution models and by policy makers. However, it does not directly provide adequate information about which input parameters are most uncertain. To evaluate this, the input parameters are varied under a Monte Carlo simulation by sampling from distributions for each of the input parameters. For simplicity, triangular distributions were defined for the best estimates, lower bounds, and upper bounds for each input parameter (fuel consumption, fuel density, and emissions factor). Figures 2 and 3 show results of 10,000 iterations under Monte Carlo simulation, with results ranging from 6,818 tonnes NOx per year to 9,119 tonnes NOx per year.

The uncertainty analysis shows that the base-case estimate of 6,909 tonnes NOx per year would fall at the bottom of the uncertainty distributions. This is a result of more conservative assumptions in the base case scenario than in the uncertainty analysis. The upper bound estimate of 8,305 tonnes NOx per year shown in Table 7 – calculated parametrically by varying only the throttle power assumptions in the Barge Costing Model – falls at the 92nd percentile in the uncertainty analysis, showing consistency between the parametric analysis and Monte Carlo simulation.

Figure 2. Monte Carlo simulation frequency chart of annual NOx totals for Columbia and Snake river systems.

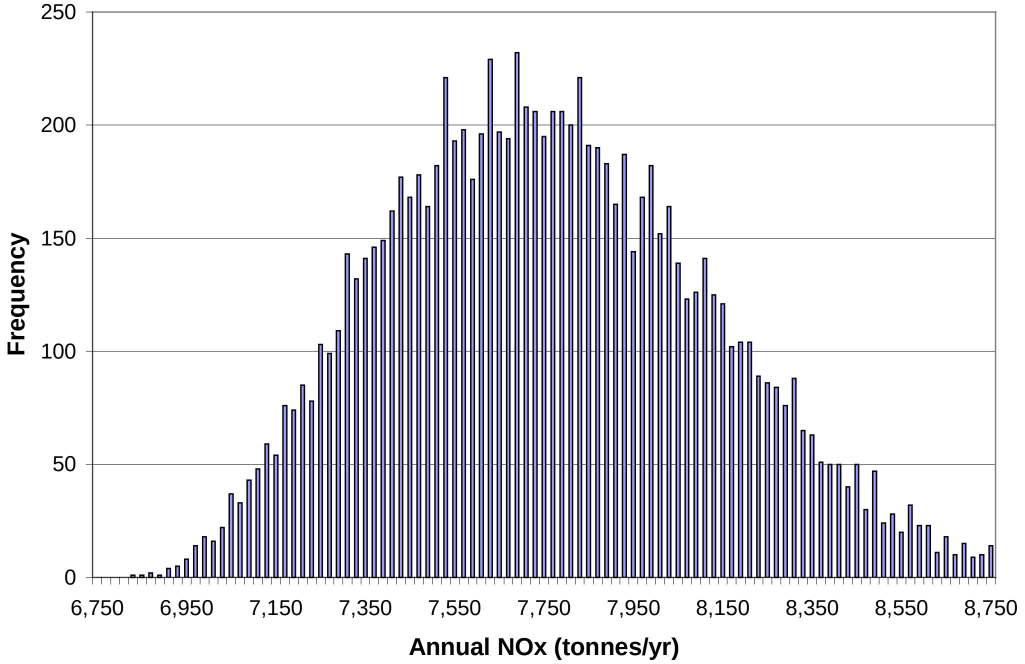
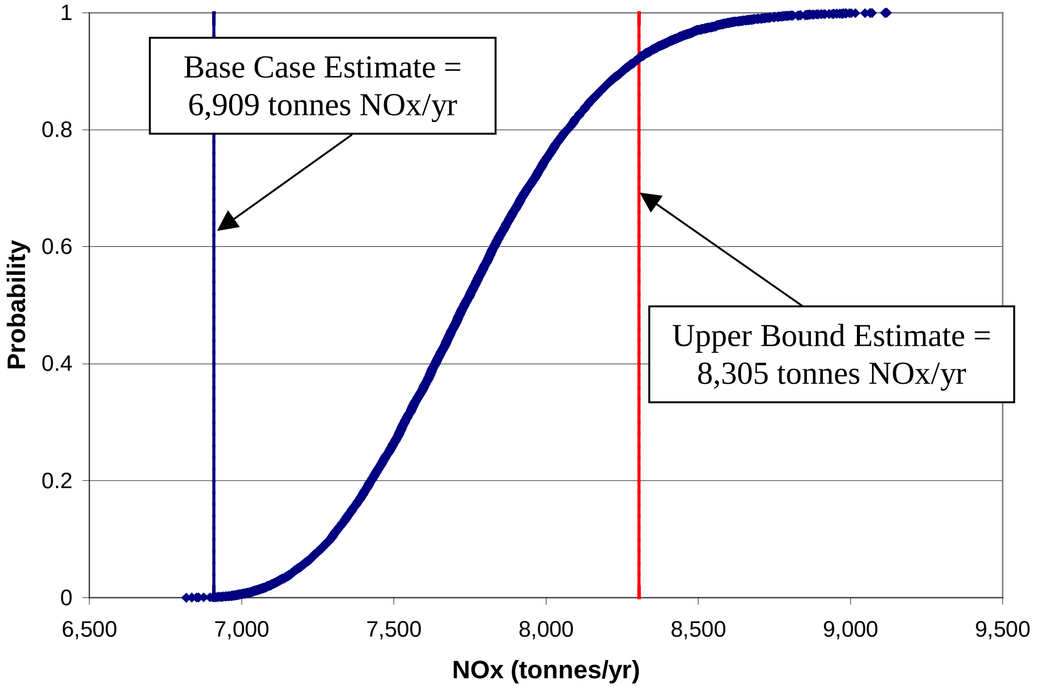
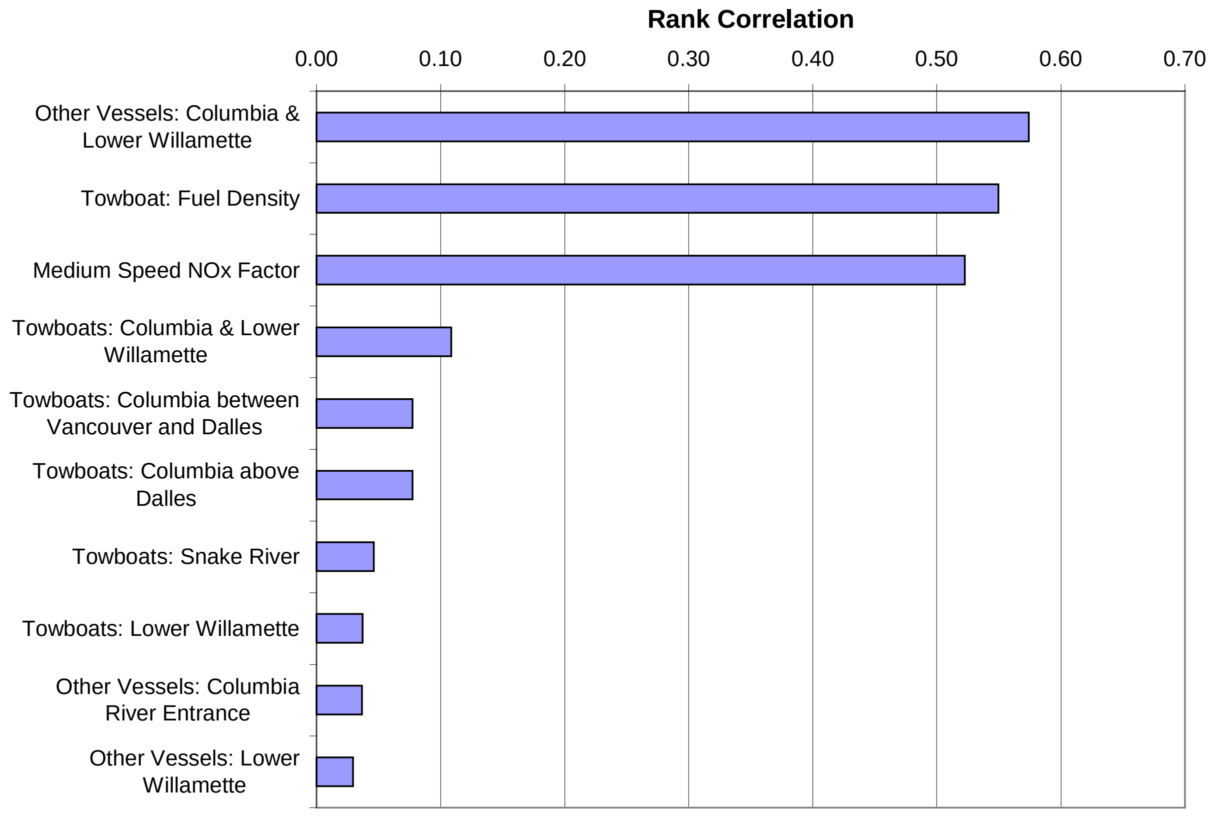


Figure 3. Cumulative distribution of NOx uncertainty for Columbia and Snake river systems.



A sensitivity analysis of the simulation identifies three primary inputs that could most improve the robustness of the inventory calculations. These inputs are: 1) the fuel consumption for non-towboat vessels (mostly deepwater draft vessels with tug assist) on the busiest river segment; 2) the fuel density factor for towboats; and 3) the NOx emission factor. As seen in Figure 4, uncertainty in each of these input assumptions are positively correlated with the total annual NOx estimates; in other words, varying these assumptions from the base case tends to increase the NOx inventory estimates for the Columbia and Snake river systems.

Figure 4. Results of sensitivity analysis showing top ten inputs by rank correlation.



COMPARISON WITH PREVIOUS INVENTORY WORK

These estimates are significantly higher than previous estimates for the Columbia and Snake river systems, which relied on cargo ton-miles to derive emissions[4]. In fact the 6,909 tonnes NOx per year estimated in this work for these river systems exceeds the total emissions for all waterborne commerce in Washington and Oregon estimated previously (4,890 tonnes NOx/yr). This is expected because the current method uses actual vessel transits and miles traveled to estimate fuel consumption for all vessel traffic, where the previous analysis assumed towboats were the dominant commercial vessel type on all river segments.

Comparing only the NOx from towboats in the current work (2,739 tonnes NOx/yr) with the previous study (which estimated 1,919 tonnes NOx/yr for the same river segments) provides much better agreement, although the earlier work still underestimates emissions by 43%. In other words, the previous inventory analysis appears to have defined a ***lowest*** bound case. This can be explained by summarizing the main differences between the methodologies. The methodology developed here captures both empty and full vessel movements, includes tug assist of deepwater vessels in the Columbia and Lower Willamette Rivers below Vancouver, and accounts for other vessels with higher horsepower (such as self-propelled bulk and tanker vessels).

Tables 8 and 9 provide further detail of the numbers and types of commercial marine vessels in on these waterway segments. In the Columbia and Lower Willamette Rivers below Vancouver, most of the vessel transits are by vessels other than towboats. This insight reinforces the results of the sensitivity analysis in Figure 4 that showed other vessels contributing significantly to the uncertainty in the NOx inventory. While other river segments have lower percentages of towboat traffic, these tend to be shorter in distance and therefore have less impact on the overall uncertainty. However, improvements in vessel characterization for the Columbia and Lower Willamette Rivers would presumably improve the characterization of traffic on connected segments of the river system.

Table 8. Number of Vessel Transits by Vessel Type and River Segment

River Segment	Self-Propelled Dry	Tanker	Towboat
Snake River	1,127	0	2,342
Columbia River Entrance	7,337	898	815
Willamette above Portland and Yamhill	596	0	4,403
Columbia at Bakers Bay	9	0	3
Lower Willamette	3,599	773	20,547
Columbia & Lower Willamette below Vancouver	20,304	908	18,754
Columbia between Vancouver and the Dalles	1,488	4	3,015
Columbia above the Dalles Dam to McNary Lock & Dam	193	0	1,927
Columbia above McNary Lock & Dam to Kennewick	195	0	2,118
Columbia between Wenatchee & Kettle Falls	23,768	0	14
Totals	**58,616**	**2,583**	**53,938**

Table 9. Distribution of Vessel Transits by River Segment

River Segment	Self-Propelled Dry	Tanker	Towboat
Snake River	32.5%	0.0%	67.5%
Columbia River Entrance	81.1%	9.9%	9.0%
Willamette above Portland and Yamhill	11.9%	0.0%	88.1%
Columbia at Bakers Bay	75.0%	0.0%	25.0%
Lower Willamette	14.4%	3.1%	82.5%
Columbia & Lower Willamette below Vancouver	50.8%	2.3%	46.9%
Columbia between Vancouver and the Dalles	33.0%	0.1%	66.9%
Columbia above the Dalles Dam to McNary Lock & Dam	9.1%	0.0%	90.9%
Columbia above McNary Lock & Dam to Kennewick	8.4%	0.0%	91.6%
Columbia between Wenatchee & Kettle Falls	99.9%	0.0%	0.1%

CONCLUSIONS

This analysis estimates that annual NOx emissions from marine transportation in the Columbia and Snake River systems in Washington and Oregon equal 6,909 tonnes NOx per year. This base case estimate is 2.6 times greater than previous NOx inventories for this region. By relying on fuel consumption estimates modeled in a "bottom-up" calculation that includes vessel characteristics and transit information, this inventory is considered to be more accurate than previous estimates.

Estimating the emissions intensity on a per waterway mile basis shows that the Columbia and Lower Willamette river systems have the greatest NOx emissions density. This is expected, since this segment accounts for the greatest amount of vessel traffic (60% more than the next busiest segment). The NOx emissions per mile of waterway can be compared to on-road emissions per mile of highway by using an average automobile emission rate of 1 gram NOx per mile. (This reflects a rough fleet-average factor for automobiles built since the 1980s[11], but ignores NOx emissions from other onroad light- and heavy-duty truck traffic.) This inventory estimates that some 42 tonnes NOx/yr are emitted from vessel traffic along the Columbia and Lower Willamette river segments; this would be roughly equivalent to freeway traffic of 116,000 automobiles per day. For comparison, this would be nearly equal to the 126,000 vehicles that crossed the Columbia River on Interstate 5 or to the 132,000 vehicles that crossed the Columbia river on Interstate 205 in 1999 during an average weekday[14].

Using a parametric analysis, lower and upper bounds were modeled by changing the input parameters to the fuel consumption model from the validated base case scenario. These three scenarios are geographically resolved to be used as input data sets for pollution and regional haze modeling. By evaluating the impact of these inventories in a regional haze model, pollution impacts attributable to commercial marine transportation can be evaluated. For example, if the upper bound inventory does not show significant contribution to regional haze, that would provide strong evidence that commercial marine vessels do not contribute to the problem in this region. However, if the lower bound inventory shows significant impact in the regional haze model, then initial policy action to reduce emissions may be warranted.

The third possibility is that either one or both of the lower-bound and base-case inventories show little impact on regional haze while significant impacts may result from modeling the upper bound inventory. This would provide support for additional research efforts that reduce the uncertainty in these inventories. In this case, the uncertainty analysis presented here could provide guidance. The uncertainty analysis shows greatest improvement in inventory for the Columbia and Snake river systems could result from three activities. First, there is a need for improved understanding of the vessel, engine, and duty-cycle characteristics of non-towboat vessels (primarily deep-draft vessels and tugboats). Second, towboat fuel characteristics (specifically fuel density) should be reviewed. Third, emissions testing should include more towboats to better characterize the fuel-based emissions factors with greater accuracy.

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KEY WORDS

NOx emissions, non-road, inventory, commercial marine vessels, Northwest, inland river, Columbia and Snake Rivers.