Operation of a sail freighter on the Hudson River: Schooner Apollonia in 2021

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Abstract: In the discussion of sail freight worldwide, little analysis exists to illuminate the effects of sail freight vessels engaged in shipping along rivers. Even less of the literature provides meaningful, in-depth insight into the operations of such vessels. The 64-ft (19.5 m) schooner *Apollonia*, a small general cargo vessel and the only active, operational sail freighter in the United States, operates on the Hudson River and in New York Harbor. The ship's logs and other data from 2021, the *Apollonia's* first sail freight season, are examined here to gauge the performance of small sail freighters on river trade routes. The available data shows sail freight has a strong advantage over comparable trucking in fuel use per Ton-Mile.

INTRODUCTION

In the last half century, Wind Propulsion has been widely acknowledged since the Oil Crisis of the 1970s as a means of reducing fuel use in maritime transportation, and research started in that era has been resumed as climate and economic concerns force change in the maritime industry. Small sail freighters engaged in coastal or inland waterway trading with break bulk general cargo have been ignored in this discussion of working sail's revival, however. These vessels are neither bulkers carrying loose cargo such as iron ore or grain, nor do they use intermodal shipping containers. The cargo is instead loaded directly into the hold in smaller packaging, such as sacks, crates, boxes, coolers, and barrels. Analysis of logs, cargo, and fuel-use data from the schooner *Apollonia* operating on the Hudson River and New York Harbor allows for a comparison of these vessels to other methods of cargo transportation.

Sail freight is defined as "The maritime movement of cargo under primarily wind power."[1] As can be seen in the figure below, this includes sail and motor-sailing vessels which rely on their engines for less than half of their propulsive power.[2] Sail-Assist and conventional motor ships are excluded from this definition, but are by far the most-discussed in journals at this time.

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[1] Woods, Steven. "Sail Freight Revival: Methods of calculating fleet, labor, and cargo needs for supplying cities by sail." Master's Thesis. Prescott College, 2021. Pp 6. www.Researchgate.net

[2] Wind Ship Development Corporation, *Wind Propulsion For Ships Of The American Merchant Marine* Norwell, MA: WSDC, 1981. Pp II-5

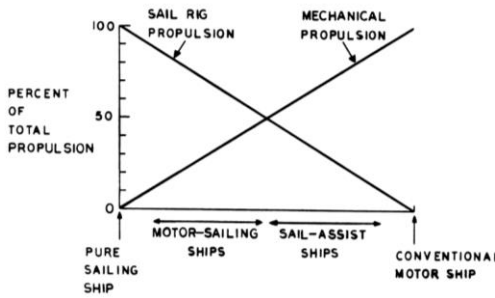

Figure 1: "Motor Sailing Propulsion Spectrum" in: Wind Ship Development Corporation, *Wind Propulsion For Ships Of The American Merchant Marine* Norwell, MA: WSDC, 1981. Pp II-5.

While there is considerable space within the sail freight continuum for high levels of engine use, the majority of coastal and inland trading under sail at this time is in small general cargo vessels which are either engineless, as with the ketch *Nordlys*,[3] or use engines only when docking or for safety reasons in crowded harbors, like the schooner *Apollonia*.

The tonnages involved in most studies of wind-assisted ship propulsion allow for comparison with conventional merchant ships. There are multiple studies which show the fuel saved from sail retrofits to existing vessels, compared to the ship's previous performance.[4] However, these are based on places where maritime shipping is the rule, such as small island states and archipelagoes, or transoceanic shipping. This is not the case when looking at inland and coastal vessels which displace rail and road transport instead of other ships.

Another element worth noting in this study is the *Apollonia*'s goals. The ship and her crew are not looking solely to reduce carbon emissions, though this is a significant part of their mission. Their goal overall is to have an environmental, economic, and social impact, the "Triple Bottom Line." This entails an extra educational bottom line, changing the way people think about the Hudson River, waterways, transportation, and supply chains. The economic mission involves paying more in labor than on fossil fuels. There is significant interaction between goals: Ecological improvements have a social impact by reducing pollution, while economic changes have social impacts on jobs and livelihoods. This multifaceted impact is outside the scope of this paper, which will be limited to assessing the comparative CO2 intensity of sail freight vessels and fossil fueled trucks.

THE SCHOONER *APOLLONIA*

The *Apollonia* is a steel J Murray Watts design from 1946, built in Baltimore, MD. Acquired in 2016, she spent 4 years in repair and retrofit before launching for a first season of relationship building and experimentation in 2020, including one circuit from Hudson, New York to New York City with a small number of cargos. 2021 was the first season of regular operations. *Apollonia* has a sail area of 122 square meters, and is equipped with a Detroit diesel engine of approximately 125 Horsepower.

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[3] "Nordlys" https://fairtransport.eu/nordlys/ Accessed 27 November 2021.

[4] R.G. MacAlister "The retrofitting of sail to two existing motor ships of the Fiji Government fleet." *Proceedings of Regional Conference on Sail-Motor Propulsion* (Manila: Asian Development Bank, 1985)

Schooner *Apollonia* Critical Data:
Length: 64 ft/19.5m Beam: 15 ft/4.5m
Rig: 2 Masted Bald-Headed Gaff Schooner.
Sail Area: 122 sq m/1320 sq ft.
Cargo Deadweight: 10 Short Tons/9.07 tonnes.
Cargo Volume: 600 Cu ft/17 Cu M/½ TEU.
Displacement: 36 tons. Draft: 7 ft
Engine: 125 HP/92 KW Detroit Diesel.
Fuel Capacity: 250 Gal/946 Liters.
Crew: 4

Fig 1: Schooner *Apollonia* under sail off Rondout Lighthouse, 24 July 2022. Courtesy, Steven Woods.

***APOLLONIA*'S 2021 OPERATIONS**

The *Apollonia* made five circuits from Hudson, NY to New York City on the Hudson River: one per month from May through October, excepting June. Cargo was generally transported first- and last-mile by means of an electric-assist cargo bike and trailer powered by solar panels mounted on the wheelhouse of the vessel, minimizing the emissions of first- and last-mile transportation. This use of low energy intensity land transportation proves the viability of a sustainable cargo system, as well as allowing the ship to carry her own shoreside delivery capabilities. In addition, the use of a cargo bike avoids heavily congested roads. Handling of all break bulk cargo was by the "Armstrong Method" aided by ship's gear such as block and tackle.

The typical crew of four consisted of Master, Mate, Bosun, and Deckhand. All crew served as dockers as no longshore or stevedore crews were available or hired. Sailing was by both night and day depending on wind, tide, and current conditions, which dictated the watch rotation. Due to the small crew size, there was little real differentiation of roles.

Figure 2: Map of *Apollonia*'s Port Calls.[5]

APOLLONIA'S CARGO

The *Apollonia*'s main cargo was Malted Grains moving from the Germantown, NY area to several breweries down the Hudson River and around New York Harbor. These were exclusively embarked at Hudson, NY, packed in 50 pound sacks. Many other cargos were included in the season, including solar panels, a printing press, coffee, beer, tea, mead wine, salt, a cargo of wine and chocolate cross-loaded from the French Sail Freighter *Grain de Sail* in New York Harbor, 1 ton of peppers from Milton to Hudson, hot sauce, maple syrup, yarn, honey, jam, condiments, rope, CBD, pepper flakes, soap, skincare products, and other goods. A barrel of Rye Whiskey, aging on the ship since 2020, was carried until the October run. Another cargo was 11,500 pounds of Red Oak logs from Kingston to Brooklyn for an urban mushroom farm.

TABLE 1: MALT CARGO DATA			
DESTINATION	**DIST from Hudson NY**	**WEIGHT (Lb)**	**TON-MILES**
Poughkeepsie	41.4	2,505	51.85
Beacon	56.35	3,900	109.88
Peekskill	73.6	3,600	132.48
Ossining	85.1	6,550	278.7
Yonkers	98.9	2,950	145.88
LIC, Queens	130	4,750	308.75
GBX	138	9,700	669.3
	TOTALS:	33,955lb/16.98 tons	1,696.84 ton-miles

[5] Esri *Light Gray Canvas Reference* [Basemap] Scale Not Given. February 2022. https://basemaps.arcgis.com/arcgis/rest/services/World_Basemap_v2/VectorTileServer (Accessed 1 March 2022)

TABLE 2: ADDITIONAL CARGO DATA					
Origin	**Destination**	**Cargo**	**Weight (Lb)**	**Distance**	**Ton-Miles**
Milton	Hudson	Peppers	2,000	78.2	78.2
Poughkeepsie	South St	Flour	1,500	91.1	68.32
Kingston	GBX	Mushroom Logs	11,500	97.75	562
GBX	Ossining	Coffee	440	55.2	12.15
GBX	Kingston	Coffee	120	97.75	5.87
Hudson	Newburgh	Whiskey, Barrel	150 (est)	56.35	4.23
GBX	Kingston	Whiskey, 2 cases	50 (est)	97.75	2.44
Milton	South Street	Pumpkins	2,900	85.35	123.76
Milton	GBX	Pumpkins	500	87.4	21.85
Milton	Ossining	Pumpkins	100	39.1	1.96
Milton	South Street	Apples, 8 boxes	160(est)	85.35	6.83
Milton	South Street	Squash, Assorted	200	85.35	8.54
Milton	South Street	Grapes, 3 flats	30 (est)	85.35	1.28
Milton	South Street	Cider, 2 cases	30 (est)	85.35	1.28
GBX	Kingston	Printing Press	500 (est)	97.75	24.44
				Additional Ton Miles:	923.15
				TOTAL TON MILES:	2,619.99

ABBREVIATIONS: GBX=Gowanus Bay Terminal. **South St**= South Street Seaport Museum, Manhattan. All locations are in New York State. All distances in Statute Miles for comparison to trucking.

Small cargos included ceramic plates, books, apparel, and postcards. The ship also carried what were essentially classical "Tramping" cargos, purchased by the ship and sold on her own account.[6] This makes tracking the ton-miles involved with these cargos difficult, and these small and tramping goods have been excluded from the study. We will focus only on major cargos here, understanding the figures produced are a minimum impact.

The principal cargos and destinations for malt remained the same over the course of the season, and have been consolidated in Table 1 above. Other cargos are given in more detail in Table 2. Official river miles between ports, converted to statute miles, are used to give a uniform comparison, but the total miles covered by *Apollonia* were much greater due to tacking, jybing, and other maneuvers.[7]

FUEL USE DATA

Fuel Use for *Apollonia* over the season is estimated at 37 gallons over 38 hours of engine use.[8] Not all engine hours were recorded prior to July 2021 due to recordkeeping changes aboard ship, and

[6] Thomas F. Tartaron, *Maritime Networks in the Mycenaean World* (New York: Cambridge University Press, 2013). Pp 30-32

[7] United States Department of Commerce, *Distances between United States Ports,* 13th ed. (Washington DC: US Department of Commerce, 2019).

[8] The *Apollonia*'s fuel tank was not full at the season's start, and fuel purchase records from 2020 have been lost. The tank does not have a gauge, and was not "sticked" before the season began. About 40 gallons were added in 2021 and visual inspection at the end of the season shows the fuel level slightly above where it was in May. There was no plan of making these studies when the 2021 season began.

engine hours are only noted in full hours, limiting the precision of these figures. Approximately 18 hours of engine time was spent on educational programming out of Hudson, NY separate from the vessel's cargo runs. This gives an average rate of about 0.97 gallons per hour, which is reasonable for rarely exceeding clutch speed on the engine. Fuel use per voyage was calculated by the total hours of engine operation noted in the log for each voyage; total fuel used for cargo transport was about 19.47 gallons for the season.

Without the installation of costly and complicated differential fuel gauges on the ship the collection of more precise fuel use data is impossible. Such approximations are generally in line with methods used in other studies where this equipment was not available, and the data is considered sufficient for the purpose of this paper.[9] The Schooner *Apollonia* has an estimated efficiency of 134.6 Ton-Miles per gallon of diesel fuel.

Examining a single voyage with better records shows the October run moved 397.37 ton-miles with three engine hours, giving 136.55 ton-miles per gallon, or 51.77 tonne-kilometers per liter. Other voyages at higher percentages of the schooner's maximum load, or lower engine use will score differently, but are less well documented.

ENGINE USE STRATEGY

Apollonia's engine use strategy is quite simple: The engine is only used for safety purposes and docking where necessary. If the tide is against the vessel's course, she drops anchor or ties up in port, instead of employing the engines. If there was no wind, she would occasionally use only the tide for propulsion. This is substantially the same engine use strategy as 17th and 18th century Hudson River sloop masters,[10] and was adopted due to ecological as opposed to economic imperatives. This leads to a very low engine use figure, averaging less than 4.5% of hours under way over the season. 60% of voyages show less than 3.75% of hours underway involved engine use. As previously mentioned, the engine was rarely, if ever, brought above idle RPMs.

TABLE 3: *Apollonia* Engine Use and Sailing Data

Month	Sailing Days	Hours Sailing	Hours at Anchor	Hours at Port	Average VMC	Engine Hours	% Engine Hours
May	11	89.25	67.5	113.75	2.48	4 (est)	4.48
July	14	108.25	58.25	139.5	2.13	4	3.70
August	13	95	77.75	85.25	2.74	6	6.32
September	12	86.5	48.75	100	2.83	3	3.47
October	10	80	48.1	102.95	2.85	3	3.75

[9] R.G. MacAlister "The retrofitting of sail to two existing motor ships of the Fiji Government fleet."
[10] Paul E Fontenoy. *The Sloops of the Hudson River: A Historical and Design Survey* (Mystic: Mystic Seaport Museum, 1994)

Apollonia used her engine less than 4.5% of the time, making her a near-pure-sail vessel. The hope for future seasons is to reduce this engine use intensity as much as possible, though with the docks available it is likely that some level of engine use will be unavoidable.

Speed and distance actually traveled by *Apollonia* is a complex calculation. Due to the inland and tidal nature of the Hudson River, it is frequently necessary to drop anchor when the tide or current is against the intended course when sailing. Due to a longer ebb than flood tide, it is easier to go South. The winds on the Hudson do not lend themselves to consistent sailing, which requires frequent tacking and gybing. There were a total of 62 days of operations over the season, with 459 hours sailing and 300.35 at Anchor. *Apollonia* made an average Velocity Made good on Course (VMC) ranging from 2.35 to 2.85 Knots while under way, with speed being higher, but unrecorded. A trend of increasing VMC through the season is noted in the logs, likely reflecting increased crew skill. Overall VMC once hours at anchor are included amounts to a seasonal average of 1.578 knots.

While the tide cycle on the Hudson River is approximately 6 hours, favorable winds cannot be scheduled so regularly. Whether the vessel's next stop would be at anchor or at dock depended on a multitude of factors and could not be reliably predicted far in advance.

When examining coastal Sail Freight, there will be different sailing characteristics in open waters, which may impact average VMC. *Apollonia* makes frequent stops, using her engine when docking frequently in comparison to a longer coastal route. As was found by Perez *et al* studying large ships, the advantages of Sail Freight are greatest on long routes with low engine use.[11] This confirms historic trends noted by Riesenberg[12] and Erikson.[13] The fewer stops or maneuvers a motor-sailer makes on their route the better expected fuel efficiency will be.

COMPARISONS TO TERRESTRIAL TRANSPORTATION

Apollonia is involved in inland waterway trading, which means she should not be compared to oceangoing cargo vessels due to the tonnages, cargos, and routes involved. The average freight-ton efficiency in the US for trucking is not a good comparison as this average is skewed by the relatively high efficiency of very large trucks moving cargo very long distances.[14]

A few other concerns arise for making a valid comparison: *Apollonia* is not capable of moving containerized cargo, making her a general cargo ship. As rail lines are not generally loaded with break bulk cargo, this means rail should also be excluded. In the case of other sail freighter designs using containerized cargo, such as those by Derek Ellard, the comparison would rightly be with large trucks or rail. In the case of his Electric Clipper 180, carrying 36 TEUs, the appropriate comparison would be rail.

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11 Perez, S; Guan, C; Mesaros, A; Talay, A, "Economic Viability of bulk cargo merchant sailing vessels", *Journal of Merchant Ship Wind Energy*, 17 August 2021. (Accessed 3 December 2021) https://www.jmwe.org/uploads/1/0/6/4/106473271/jmwe_17_august_2021.pdf

12 Felix Riesenberg, *Standard Seamanship For The Merchant Service* 2nd ed. (New York: D. Van Norstrand, 1936) pp 11.

13 See: Georg Kahre, *The Last Tall Ships: Gustaf Erikson and the Aland Island Sailing Fleets, 1872-1947* Basil Greenhill, Ed. (London: Conway Maritime Press, 1990)

14 In 2018 trucks moved 2,033,921 million ton-miles, using 28,987 million gallons of fuel, averaging 70 ton-miles per gallon. SEE: Bureau of Transportation Statistics *National Transportation Statistics* www.bts.gov/us-tonne-kilometers-freight AND www.bts.gov/content/combination-truck-fuel-consumption-and-travel (Accessed 15 Nov 2021)

Something like the Electric Clipper 100 carrying 4 TEUs would be more accurately compared to a class 8 truck.[15]

As with the 1920s when Walter Hedden studied *How Great Cities Are Fed*, it is small trucks which move most food and goods within 100 miles of major cities.[16] The cargo taken on *Apollonia* moved to its destination principally in 2½ ton box trucks before transitioning to Sail Freight in 2021. Apollonia has a similar cubic capacity to a 12 foot box truck, at about 600 cubic feet, which would be in the same class as a 2½ to three ton truck. A 2½ ton truck at 12 miles per gallon gives a maximal theoretical efficiency of 30 ton-miles per gallon, which is similar to figures given by the National Highway Safety Administration in 2006.[17] This holds for essentially all the cargos involved with *Apollonia*, excepting those likely moved by less efficient pickup trucks, and is the appropriate comparison.

COMPARISON TO BOX TRUCKS

Apollonia's Ton Miles of transport avoided the use of around 67.9 Gallons of fuel, and she has an advantage of 104.6 ton-miles per gallon against the theoretical optimum for 2½ ton trucks.[18] The *Apollonia* requires only 22.3% of comparable ideal trucking fuel use values. If account is taken of empty miles back to the malthouse or point of origin for these trucks, the advantage is immediately doubled. In this case, fuel use is less than 12% of trucking.

It should be noted this comparison contrasts real-world results aboard *Apollonia* with theoretical best-case conditions for the trucks. If the trucks are less than fully loaded, the ton-mile efficiency of the truck declines. Further, the New York Metro Area is a maze of congested roads with dozens of over-capacity *Passages Obligés* such as bridges and major intersections, leading to 335.9 million gallons of wasted fuel[19] and an economic cost of 18.26 billion dollars in 2019.[20] These figures alone bring the 30 ton mile per gallon figure for trucks into question when looking at the New York Metro Area, giving *Apollonia* a further advantage, though the effects of road congestion on truck fuel efficiency are not considered here. If there are any other disadvantages for the truck, such as steep climbs or sub-optimal maintenance, its efficiency declines. In terms of carbon impacts, the consumption of tires, lubricants, spare parts, and road wear should be included in the calculation for trucks,[21] while *Apollonia*'s inputs are essentially fuel, one tenth of a set of sails annually, and a small amount of paint.

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[15] Derek Ellard "The Electric Clippers" gosailcargo.com (accessed 1 December 2021)

[16] Walter P Hedden, *How Great Cities are Fed* (New York: D.C. Heath, 1929).

[17] NHTSA *Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles* (Washington, DC: NHTSA, 2010) https://www.nhtsa.gov/sites/nhtsa.gov/files/nhtsa_study_trucks.pdf (Accessed 28 November 2021) Pp 12-13. The figure given for typical ton-miles for vehicles in this study is quite clearly a multiplication of the load capacity by the average miles per gallon, not accounting for deadheading or partial loads.

[18] It is worth noting that even when compared to the optimal efficiency of 10 ton trucks, *Apollonia* retains an advantage of 22.6 tm/gal using her observed real-world efficiency. When comparing her maximum efficiency to the same 10 ton trucks, she is over 5.5 times more efficient.

[19] Bureau of Transportation Statistics "Annual Wasted Fuel Due To Congestion" *National Transportation Statistics* https://www.bts.gov/content/annual-wasted-fuel-due-congestion (Accessed 18 January 2022)

[20] Bureau of Transportation Statistics "Annual Highway Congestion Cost" *National Transportation Statistics* https://www.bts.gov/content/annual-highway-congestion-cost (Accessed 18 January 2022)

[21] David Austin, *Pricing Freight Transport to Account for External Costs* (Washington DC: Congressional Budget Office, 2015). https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/workingpaper/50049-Freight_Transport_Working_Paper-2.pdf. Pp 2 Summary.

Given better freight ton efficiency data for small trucks and historical data for the same cargo movements, a more accurate calculation of *Apollonia*'s impact could be made. This data is not readily available, and the above are the likely floor for efficiency gains from small Sail Freighters on inland routes using an auxiliary diesel engine.

Intensity as a percentage of maximum load weight for *Apollonia* is worth considering. The maximum a 10 CDWT capacity could have carried per circuit would be 2,346 ton miles. This assumes a two-way voyage from Hudson to New York City, each leg of which is 117.3 miles long, with a full hold. For five trips, this would be a maximum of 11,730 ton-miles. *Apollonia* only moved slightly over 21.5% of this maximum in 2021, as some runs were not made with a completely full hold, while others, such as a 2,000 load of peppers from Milton to Hudson, were affected by cargo density. *Apollonia*'s maximum theoretical fuel efficiency would be some 626 ton-miles per gallon of fuel (266 tkm/l), at the crew's current skill level and engine use patterns.

This maximum figure is over twenty times that of comparable trucking, nearly 9 times the average for trucking in the US, and 25% better than rail figures of around 500 ton-miles per gallon. With the time allowed by the season on the Hudson, a total of 12 voyages could be undertaken, which may result in higher realized efficiency through higher average cargo intensity or less engine use per ton-mile across the season.

The issue of cargo density as mentioned above is important for both trucks and sail freighters: It would be impossible to fit 10 tons of fresh peppers into the hold of the ship or onto most trucks, and cubic space should play into this calculation. As Malt is generally between .3-.7 tons per cubic meter in density (load factor), this is a serious concern for *Apollonia*'s main trade reaching full tonnage loads due to cargo density and the limits of storage space, meaning neither will likely reach their theoretical efficiencies in service. If fuel were allocated to vehicles based solely on their maximum theoretical fuel efficiency, no cargo moved by fossil fuels or electrified transport would ever arrive on target. This lack of clear information on average or real-world relative energy and carbon intensity for various vehicle types is a significant problem for sustainable transportation planning and research. By contrast, over 5,000 years of precedent has shown a lack of fuel does not fundamentally affect sail freighters' ability to reach their destination, though it may affect port-to-port time and scheduling.

Turning to Carbon Emissions, at 22.48 pounds of CO2 per gallon of diesel[22] *Apollonia* emitted about 437.68 pounds of CO2 in the course of her operations. A 2.5 ton truck would emit 1,963.25 pounds (890.5 kg) of CO2, assuming no deadheading and maximum efficiency loads. In the worst-case scenario, *Apollonia* avoided over 1,530 pounds (694 kg) of carbon emissions in 2021. Her impacts on particulates, SOx, NOx, and other pollutants will be proportionate, and the issue of noise pollution is not covered here.

IMPLICATIONS FOR INLAND AND COASTAL SAIL FREIGHT EFFICIENCY

There are lessons to be learned from the *Apollonia* for inland and coastal Sail Freight in small vessels. Internal Combustion Engine propulsion experiences economies of scale, and becomes more efficient the larger a vessel becomes.[23] As sail freight vessels grow in CDWT terms both important

[22] Energy Information Administration. *Carbon Dioxide Emissions Coefficients* https://www.eia.gov/environment/emissions/co2_vol_mass.php (Accessed 8 February 2022)

[23] WSDC, *Wind Propulsion For Ships Of The American Merchant Marine* Pp X-6

efficiency metrics, Ton-Mile Fuel Efficiency and Tons Per Sailor, increase so long as engine use patterns remain the same. The application of electric engines with underway battery recharging will give further advantages against all forms of terrestrial transport. Engineless coastal vessels will have a much higher fuel efficiency in the middle legs of their voyages, but must use tugs when entering certain ports, inducing some fuel use on the terminal ends of the voyage which will be difficult to measure accurately. This will give a significant incentive in climate adaptation planning to shift cargo to coastal and inland sail-motor freighters where possible, but will need to be tested once such vessels are in service and can give real-world comparisons.

How the overall distance traveled by *Apollonia* compares to trucking routes for the same cargo has not been examined, but may conceal other difficulties in measuring efficiency by changing the relative ton miles by river or road. From Hudson Valley Malt to Sing Sing Kill brewery is 78.2 miles by truck, but 85.1 river miles from Hudson to Ossining. This makes comprehensive comparison complex, but does not affect relative fuel efficiency.

OPPORTUNITIES FOR FURTHER RESEARCH

The *Apollonia* refined her routing over the course of 2021 to optimize her circuit. This involved stopping at ports only while headed in one direction, for example. This reduces the total number of dockings per circuit, which can have a significant effect on the amount of engine time used per voyage. Less engine use translates directly to less fuel use for the same number of ton-miles. The skill of the crew and their familiarity with both the ship and the waters they sail will only grow as the operation continues, which will be worth examining when data becomes available.

No economic analysis of the *Apollonia* has been undertaken, and is outside the scope of this study. Examining the economics of coastal and inland sail freighters will have to be made based on a vessel and route pairing to make the appropriate comparison. Fuel cost and trucking rates will also play a role in making such a comparison, both of which are quite volatile at this time.

Research with small sail freighters equipped with other engine types, such as electric motors powered by batteries, propeller regeneration, and solar charging systems is worth funding once such vessels are available for study. Their ecological footprint will be significantly different than *Apollonia*'s, and their engine use strategy could be far more intensive without increasing carbon emissions or other pollution. Vessel design is outside the scope of this paper, and these vessels have yet to be commissioned, making a comparison impossible at this time.

The complete effects of *Apollonia*'s operations are difficult to quantify, such as social impact. This could be measured in the lives prolonged by a lack of pollutants released in New York City, traditional skills learned, and educational moments which changed how people think of transportation, consumption, and waterways like the Hudson River and New York Harbor. These topics are outside the scope of this study.

CONCLUSION

Schooner *Apollonia*'s cargo and fuel use records from 2021 show that the ton-mile fuel efficiency of even a very small sail freighter is far higher than comparable trucking. Operational results show a fuel efficiency of 134.6 ton-miles per gallon of diesel fuel while operating at 21.5% tonnage intensity, as compared to an average of 70 tm/gal for US trucking overall. When compared to the 2½ ton box trucks she replaces, she has an advantage of 104.6 tm/gal at the same intensity against the truck at 100% intensity. If *Apollonia* were used at full CDWT capacity with current engine use patterns, she would give 626 tm/gal, 25% better than rail, nearly 21 times better than 2½ ton trucks, and just under 9 times more efficient than the US trucking average.

Due to the engine use strategy of the ship, considerable time was spent at anchor. Over 62 days of operations, 459 hours were spent underway, with 300.35 at anchor. Velocity Made good on Course (VMC) while under way ranged from 2.35-2.85 knots, while overall VMC including time at anchor was 1.578 knots.

The nature of navigation and winds on the Hudson River make these results applicable principally to this route and engine use pattern. Predominant winds force frequent tacking and jybing, and the slightly longer ebb tide makes southbound travel easier than northbound. It is clear that larger vessels will be more efficient, and other routes which require less docking and maneuvering under power will increase efficiency, making these figures a likely floor of fuel efficiency for inland and coastal sail freighters.

Acknowledgements: Thanks are due to *Apollonia*'s Bosun Tanya Van Renesse, and Supercargo Brad Vogel for their critical assistance in collecting information on cargo weights, destinations, and origins.

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