PROCEEDINGS—

Twenty-fifth Annual Meeting

Volume XXV • Number 1 1984

TRF

TRANSPORTATION RESEARCH FORUM

PROCEEDINGS–

Twenty-fifth Annual Meeting

Theme:

"Beyond Deregulation: Let Freedom Ring!"

October 22-24, 1984
Parker House
Boston, MA

Volume XXV • Number 1 1984

TRF

TRANSPORTATION RESEARCH FORUM
in conjunction with

CTRF CANADIAN TRANSPORTATION RESEARCH FORUM

Fuel Consumption and Fuel Costs in Exporting Grain to Japan and Europe

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ABSTRACT

Fuel efficiency in cargo ton-miles per gallon and total fuel consumption in gallons per short ton of grain were determined for grain shipments from Iowa origins to Japan and Europe. Estimates were made from data on truck, rail, barge, and ocean vessel movements. Rail and truck consumption was obtained from physical measurements; barge and ocean fuel consumption was obtained from company records or contracts. Minimum fuel consumption and minimum fuel cost routings and modal combinations were obtained for selected Iowa origins to Yokohama and Rotterdam.

Given the types of trucks, railroad equipment, barge tows, and ocean vessels evaluated in this analysis, the most fuel-efficient routing of Iowa grain to Japan is via unit-grain-strains to the West Coast and ocean vessel to Japan. Using 50,000 deadweight ton (WT) ocean vessels, this route holds a 1.2 to 2.9 gallon per short ton of grain fuel advantage over the next best combination of unit-grain-trains to New Orleans (NOLA) and ocean vessel to Japan. The West Coast fuel advantage was 7.0 gallons per short ton over the least fuel-efficient NOLA routing. At mid-1984 fuel prices, the West Coast route had $0.95 to $5.86 per short ton fuel cost advantage from western Iowa and a $0.20 to $4.08 per short ton fuel cost advantage from central Iowa.

Mississippi River barge movements fed by unit-grain-train shipments from interior elevators become fuel equivalent to unit-grain-trains direct to NOLA if a 100 percent loaded return is achieved by the barges. Our sample of barge tows had 35 percent loaded return. Therefore, if Europe-bound grain is loaded out of NOLA, the most fuel-efficient routing is unit-grain-trains direct.

INTRODUCTION

During the decade from 1971 to 1981, imported crude oil prices increased from $2 per barrel to an all-time high of almost $39 per barrel, a sevenfold increase even after adjusting for inflation [10, 11]. The higher fuel prices increased grain transportation costs at a time when world grain trade was increasing rapidly.

Most of the United States grain is produced in the Midwest. Export grain from the Midwest must move 1,000-2,000 miles to the Gulf of Mexico, West Coast, or East Coast export ports and then be transported several thousand miles in ocean vessels. The modes and routes used to move grain to importing countries are major determinates of transportation fuel consumption. Table 1 shows the distances for alternative routes from central Iowa to Yokohama, Japan. The distance from Iowa to Japan is 71 to 75 percent further via New Orleans (NOLA) than via Pacific Northwest (PNW) ports.

The large difference in distances between NOLA and PNW export ports suggests that routing Midwest grain to Japan through PNW ports could reduce fuel consumption. However, little information is available on the fuel consumption of the alternative routings. Previous research based on aggregate fuel consumption of an entire industry has produced conflicting estimates of rail, barge, and truck fuel consumptions.

REVIEW OF THE LITERATURE

Numerous fuel consumption studies were conducted in the 1970s. A 1975 U.S. Department of

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TABLE 1

DISTANCE FROM CENTRAL IOWA TO YOKOHAMA, JAPAN IN STATUTE MILES

	Export Port		
		NOLA	
Portion of trip	PNW Rail	Rail	Truck-barge
To export port	2,000	1,310	1,530
Ocean to Japan	4,900	10,500	10,500
Total	6,900	11,810	12,030

Source: [2,13]

TABLE 2

SUMMARY OF TRANSPORTATION FUEL EFFICIENCY RESEARCH

		Fuel efficiency in net ton-miles per gallon		
		Rail		
Reference	Data years	Aggregate	Unit-train	Barge
U.S. Department of Transportation [12] average of 19 studies	1960-1974	290.1	460.2	305.5
Eldridge and Van Gorp [3]	1979	198.1	462.3	277.4
Lambert and Hougland [7]	1974	204.0	---	417.0
Baumel et al. [1]	1980-1981	---	---	502.5a/ 528.4b/
Paxson [8]	1979-1980	207.0	350.0	277.0
Hudson [6]	1979	---	247.7-495.4	432.1-502.5
Overall average		277.0	433.2	349.5
Coefficient of variation, %		51.7	14.8	38.3
Number of studies reporting data		20	5	19

a/ Upper Mississippi River
b/ Lower Missippi River

Transportation report to the U.S. Senate Commerce Committee [12] summarized 19 pre-1975 transportation energy studies. The fuel-efficiency estimates from these studies, along with those from several more recent investigations, are shown in table 2. Some of the individual studies did not clearly indicate whether the estimates were in gross or net ton-miles per gallon; by implication, net ton-miles per gallon were assumed. Since no barge backhaul information was given, data are assumed to be based on industrywide backhaul averages before 1975.

Among the recent works, the Eldridge and Van Gorp [3], Lambert and Hougland [7] and Paxson [8] analyses were based on aggregate modal data for all commodities over all routes. The Paxson trucks analysis reported 64 net ton-miles per gallon for a 25-ton truck with zero backhaul. The Baumel et al. study [1] estimated barge fuel efficiency by river system and for a 40 percent backhaul. The Hudson report [6] is unique in that it was route-specific in estimating fuel requirements for all modes.

The literature obviously provides a wide range of fuel-efficiency estimates. Conflicting estimates based on aggregate modal fuel consumption and aggregate gross or net ton-miles are of limited value in predicting either fuel consumption or fuel costs for individual grain shipments.

OBJECTIVES

The objectives of this research were to:

1. Measure fuel consumption in transporting grain from Iowa to export markets by route and mode.
2. Construct equations for estimating total fuel consumption from Iowa to export grain destinations.
3. Estimate total fuel consumption and fuel cost in transporting grain from selected Iowa origins to selected export destinations by route and modal combinations.

Definitions and Mathematical Relationships in Fuel Consumption

Fuel consumption is most easily measured by gross ton-miles per gallon. Adjustment factors can account for the ratio of net tons to gross tons (load factor), the ratio of loaded distance traveled and empty distance traveled (utilization factor), and the percentage of load on return trips (backhaul factor). The adjustment factors convert gross ton-miles per gallon into net ton-miles per gallon. Table 3 presents a summary of the notation used in the analysis to describe gross and net ton-miles per gallon.

Assume that there are two load conditions, fully loaded and a less-than-loaded return trip. The defining equations for G_i and G_r can be combined with the adjustment factors to yield:

$$G_i = \frac{W_i k_u M_t}{f_i} \quad (1)$$

and

$$G_r = \frac{W_i}{f_r}\,[1 - k_i(1 - k_h)]\,(1 - k_u)\,M_t \quad (2)$$

Net ton-miles per gallon for loaded (N_i) and return trips (N_r) are given by:

$$N_i = k_i G_i = \frac{k_i k_u W_i M_t}{f_i} \quad (3)$$

and

$$N_r = \frac{k_h k_i\,(1 - k_u)\,W_i M_t}{f_r} \quad (4)$$

Equations (1), (2), (3), and (4) can be combined to calculate average gross ($\bar{G}$) and net ($\bar{N}$) round-trip fuel efficiency as:

$$\bar{G} = \frac{G_i G_r[1 - (1 - k_h - k_u + k_h k_u)k_i]}{k_u G_r + [(1 - k_i) + (k_h k_i)](1 - k_u)G_i} \quad (5)$$

and

$$\bar{N} = \frac{G_i G_r(k_u + k_h - k_u k_h)k_i}{k_u G_r + (1 - k_i + k_i k_h)(1 - k_u)G_i} \quad (6)$$

Equations (5) and (6) will apply to any situation for which there are estimates of G_r and G_i.

METHOD OF ANALYSIS

Trucks

Data on truck fuel consumption were obtained from two sources, a metered truck hauling grain in Iowa, and 1983 company records for seven similar trucks.

A Helda fuel and mileage meter was installed on a 1980 White Freightliner tractor pulling a hopper-bottom grain trailer. The accuracy of this meter was verified to be in excess of 99 percent. The metered tractor-trailer hauled three loads of corn from a north central Iowa elevator to a grain processor at Muscatine, Iowa. Only one metered truck was available for the metered runs.

Because the fuel meter was installed under the engine cover, it could be read only when the truck was stopped. Therefore, the truck data provided only the average relationships among fuel consumption, gross and net weight, and miles for each of the three trips. Fuel consumption could not be related to speed or road characteristics.

Each trip required one full day. At the end of each trip, the truck returned to company headquarters. The next morning, the empty truck was driven to the elevator for another load. Since empty miles exceeded loaded miles, equation (5) and (6) were applies to adjust gross and net ton-miles per gallon to $k_h = 0$ and $k_u = 0.5$.

The company owning the metered truck provided records on 1983 fuel consumption for seven tractors with exactly the same specifications as the metered truck. These seven tractors were driven 669,179 miles in 1983. However, the unmetered tractors pulled flat trailers rather than hopper-bottom grain trailers.

Railroads

Five railroad companies participated in the rail fuel consumption tests. Railroad Company One installed 3/4" x 1" Red Seal, Low Flow Neptune meters on three two-year-old SD-40-2 locomotives pulling 54-car unit-grain-trains from Sioux City, Iowa. Three trains were monitored; two were unloaded at Tacoma, Washington, and the third was unloaded at Kalama, Washington.

Railroad Company Two used a Pulse recorder to measure fuel consumption on three 75-car unit-grain-trains from Council Bluffs, Iowa to Los Angeles, California. A Pulse recorder records the time that the locomotive throttle is in each of its 10 positions. The cumulative time for each position is then multiplied by a standard fuel flow rate to calculate fuel consumption for the trip. The Company Two trains were powered by three two-year-old SD-40-2 locomotives. At Salt Lake City, Utah, two additional locomotives, also with Pulse recorders,

TABLE 3

NOTATION AND RELATIONSHIPS USED IN FUEL CONSUMPTION CALCULATIONS

Measurement	Notation	Defining equation
Fuel consumption in gallons: loaded, return, round-trip	f_i, f_r, f_t	
Distance in miles: loaded, return, round-trip	M_i, M_r, M_t	
Weights in tons		
Gross: loaded, empty, partial load	W_i, W_e, W_r	
Net	W_n	$W_i - W_e$
Fuel efficiency in ton-miles per gallon		
Gross: loaded	G_i	$\frac{W_i M_i}{f_i}$
return	G_r	$\frac{W_r M_r}{f_r}$
round-trip	$\overline{G}$	Equation (5)
Net: loaded	N_i	$k_i G_i$
return	N_r	$k_u k_i G_r$
round-trip	$\overline{N}$	Equation (6)
Adjustment factors		
Load factor: ratio of net to gross tons	k_i	W_n/W_i
Utilization factor: ratio of fully loaded miles to total miles	k_u	M_i/M_t
Backhaul factor: fraction of maximum load on return trip	k_h	$(W_r - W_e)/W_n$

were added to cross the Sierra Nevada mountains. A recorder malfunction eliminated the data from the entire empty return of the first trip, leaving two metered empty return trips by Company Two.

Railroad Company Three installed 3/4″ x 1″ Red Seal, Low Flow Neptune meters on three seven-year-old SD-40-2 locomotives. These units pulled a 120-car unit-grain-train from Fort Dodge, Iowa to Reserve, Louisiana. As is the usual operating practice for railroad Company Three, this train moved in two 60-car units from Fort Dodge to Freeport, Illinois, where the two 60-car trains were combined. Only one of the 60-car trains was metered from Fort Dodge to Freeport. Therefore, the Fort Dodge-to-Freeport fuel consumption and ton-miles were doubled to calculate the fuel required to move the 120-car train from Fort Dodge into position at Freeport. The 120-car train was then pulled to Reserve, Louisiana, where it was unloaded. This was the last train railroad Company Three pulled from Iowa to New Orleans during the study period; the empty train did not return to Iowa. The empty return fuel consumption was estimated from metered 120-car trains returning empty to Tuscola, Illinois, from Reserve, Louisiana. Fuel consumption data were recorded manually by railroad Company Three personnel.

Railroad Company Four installed new 3/4″ x 1″ Red Seal, Low Flow Neptune fuel flow meters on three two-year-old SD-40-2 locomotives. Three 75-car unit-grain-trains were pulled from Boone, Iowa to Ama, Louisiana, interlining with Company Five at Dupo, Illinois. The grain was unloaded at Ama, and the trains returned empty to Boone.

Normally, railroad companies Four and Five use only two SD-40-2 locomotives to power 75 car unit-grain-trains from Boone to Ama. The third locomotive was included as a backup to avoid invalidating the fuel test for an entire trip in the event of a locomotive failure. The third locomotive was on fuel saver during 98 percent of the moving time. The fuel consumption of the third locomotive while on fuel saver status or while idling was deducted from the total fuel consumed. The fuel added to the three locomotive tanks during the trips was measured by off-board meters. The on-board and off-board measurements agreed within 1 percent.

The fuel consumption data were converted to gross and net ton-miles per gallon by using equations (1) to (6). Only one load condition, k_h = 0.0 and k_u = 0.5, was represented by these tests. This is typical of unit-grain-train hauls. Therefore, generalizations to other types of rail movements are inappropriate.

All unit-grain-trains were powered by 2 to 8 year-old SD-40-2 locomotives. The 3,000-hp SD-40-2 model makes up 19.3 percent of the total road locomotive fleet of the 10 largest U.S. railroad companies. These railroad companies have no other model as numerous as the SD-40. However, it may not be the most fuel-efficient locomotive. Railroad company executives point out that newer model locomotives such as the 3,000 hp B30-7A and the 3,500 hp GP-50 may, under certain operating circumstances, be as much as 15 percent more fuel efficient than the SD-40-2 locomotives.

Barges

Three barge companies operating towboats on both the Upper and Lower Mississippi rivers provided data on towboat fuel consumption. Vibrations created when one or both propellers are in reverse make on-board metering impossible. Daily fuel tank measurements obtained from calibrated steel tape measures were the only available method of obtaining towboat fuel consumption. Fuel measurements are taken daily and recorded on either the daily engine room or the daily deck and radio log. The logs are also used to record number of empty and loaded barges, daily distances traveled according to river mileposts, explanation of delays and other mechanical information.

Two of the three companies provided copies of the daily logs. The third company provided a summary of fuel consumption prepared from the daily logs. Fuel consumption data were obtained for 18 different tow-boats pushing 22 tows on the Upper Mississippi River and 35 tows on the Lower Mississippi River. The tows were split nearly evenly among northbound and southbound movements. Fuel consumed by switch boats moving barges in and out of tows was not included.

The tow boat data were analyzed by river segment and by direction of travel. River segment was the only factor influencing fuel efficiency on the fully loaded southbound move. On the northbound moves, percentage backhaul on both river segments ranged from 0 percent to 100 percent. Least-squares regression was used to relate gross ton-miles per gallon to backhaul factor and number of barges per tow.

Ocean Vessels

Fuel consumption data for bulk carrier ocean vessels were taken from *The Journal of Commerce and Commercial* [9] ship fixture breakdown on bulk carrier time charters. The *Journal of Commerce* time charter data include DWT, grain capacity in cubic feet, average daily speed for the negotiated time charter rate, average daily fuel consumption of the main engines for the specified speed, average daily generator fuel consumption, and the year built.

The Bulk Carrier Register [5] reports similar information plus draft and bunker fuel capacity. The *Bulk Carrier Register* fuel-consumption data, however, are for maximum vessel speeds whereas *The Journal of Commerce and Commercial* reports fuel consumption as specified in negotiated contract rates. Ship brokers consider *The Journal of Commerce and Commercial* fuel consumption as a more reliable estimate of actual fuel consumption. Therefore, the fuel consumption data for the 254 time-charters in this analysis were taken from *The Journal of Commerce and Commercial,* February 1 to July 31, 1983. The vessels were grouped by size in increments of 15,000 DWT, starting at 10,000 DWT. Fuel consumed by electric generators was included in the fuel consumption.

The actual grain-carrying capacity of a vessel is less than its listed DWT because DWT includes fuel, stores and cargo. Because grain is less dense than commodities such as coal or ore, full-holds of grain will not load a vessel to its maximum weight. Gross weights for vessels were based on full-hold grain weights and a grain density of 56 pounds per bushel (1 bushel = 1.245 ft^3).

To maintain immersion of propellers, empty vessels are filled with ballast (water) to about 60 percent of their fully-loaded gross weight. Shipping company executives stated that a ship under ballast will require about 90 percent of fully-loaded fuel consumption at the same speed. This assumption was used to calculate empty-return fuel consumption.

Gross and net ton-miles per gallon, and load factor both increase with ship size. Least-squares regression equations were used to relate fuel efficiency and load factor with vessel size in DWT.

Total fuel consumption and costs

The modal fuel consumption data and equations were combined to predict fuel requirements, in gallons per short ton, for grain shipments from several Iowa origins to both Japan and Europe. Equations (5) and (6) were used to determine average gross and net ton-miles per gallon for a particular mode. Various routings and backhaul assumptions were evaluated to determine the minimum fuel consumption alternative. Mid-1984 fuel costs were used to convert the estimated fuel consumption to fuel costs.

RESULTS

Fuel consumption data by mode

Table 4 presents fuel efficiency and other characteristics by mode. Where noted, the values in table 4 originate from regression equations as described

TABLE 4

FUEL CONSUMPTION CHARACTERISTICS BY MODE

	Fully loaded				Empty or partially loaded return trip				Round-trip	
Mode	Load factor (k_i)	Gross ton-miles per gallon (G_i)	Net ton-miles per gallon (N_i)	Percent[a] CV of G_i	Backhaul factor (k_h)	Gross ton-miles per gallon (G_r)	Net ton-miles per gallon (N_r)	Percent[a] CV of G_r	Gross ton-miles per gallon[f] ($\bar{G}$)	Net ton-miles per gallon[g] ($\bar{N}$)
Truck:										
Metered	0.652	249.6	162.8	3.8	0.00	108.8	0.0	3.0	186.6	90.5
Company records	0.616	212.1	130.7	12.2	0.00	90.1	0.0	11.8	154.2	68.6
	—	—	—	—	0.35	113.3	49.8	11.8	158.6	82.4
Unit-train:										
West coast	0.712	937.0	667.0	9.4	0.00	514.0	0.0	3.7	791.0	437.0
NOLA	0.733	1,379.5	1,009.8	10.0	0.00	640.2	0.0	5.5	1,108.8	640.1
Barge:										
Upper Mississippi	0.815	1,169.7	952.7	17.0	0.00	171.0[c]	0.0	13.7	611.0	420.2
	—	—	—	—	0.35[b]	380.6[c]	230.8	13.7	702.9	526.0
	—	—	—	—	1.00	768.4[c]	627.1	13.7	928.2	756.5
Lower Mississippi	0.818	1,577.5	1289.9	12.1	0.00	167.7[d]	0.0	10.4	697.5	482.7
	—	—	—	—	0.35[b]	328.7[d]	200.9	10.4	729.0	548.3
	—	—	—	—	1.00	630.9[d]	516.1	10.4	901.3	737.3
Ocean vessel:[e]										
30,000 DWT	0.677	1,613.2	1,092.1	13.0	0.00	1,098.6	0.0	16.6	1,123.3	574.8
50,000 DWT	0.692	1,927.2	1,333.6	13.0	0.00	1,312.4	0.0	16.6	1,326.7	701.9
70,000 DWT	0.708	2,241.1	1,586.7	13.0	0.00	1,526.2	0.0	16.6	1,523.9	835.1
100,000 DWT	0.731	2,712.0	1,982.5	13.0	0.00	1,846.9	0.0	16.6	1,811.3	1,043.4

a/ Coefficients of variation of data or where used, regression equations.

b/ Average backhaul factor of northbound tows on both river segments was 0.35

c/ From regression equation (7), with an average tow size of 15.

d/ From regression equation (8), with an average tow size of 24.

e/ From regression equations (9), (10), and (11).

f/ From equation (5).

g/ From equation (6).

in the "Method of Analysis." The remaining values are averages of observed data points.

The metered tractor-trailer truck, at 90.5 net ton-miles per gallon, achieved 40 percent higher fuel efficiency than the Paxson [8] estimate of 64 net ton-miles per gallon and approximately the same fuel efficiency as estimated by Hudson [6]. This truck averaged 6.4 and 8.0 miles per gallon on loaded and empty moves, respectively—clearly an above-average showing, but indicative of the improved equipment being sold today. The seven trucks represented by company records obtained 82.4 net ton-miles per gallon with an average backhaul of 35 percent. On a zero backhaul basis, the seven trucks obtained 68.6 net ton-miles per gallon. Although these trucks pulled flatbed trailers rather than hopper-bottom trailers, the trucking company executives believe the difference between the metered truck and company records was largely due to driver performance.

The unit-grain-trains, on average, outperformed estimates from previous studies. The West Coast trains were comparable to the aggregate estimates shown in table 4, but the NOLA trains obtained about 50 percent higher fuel efficiency than the estimates in the earlier studies. The difference between the West Coast and the NOLA trains was largely the result of the terrain of the two routes.

The barges included in this analysis were about 75 percent more fuel efficient than earlier barge study estimates. The Mississippi River barge tows were much more fuel efficient on the southbound movements with the river current than on the northbound movements against the current. The average round-trip gross and net ton-miles per gallon were almost identical on the Upper and Lower Mississippi rivers. However, the tows on the Upper Mississippi achieve fewer gross and net ton-miles per gallon on the southbound trips and more gross and net ton-miles on the northbound trips than did tows on the Lower Mississippi. These differences are probably caused by the slower speed of the current on the pooled Upper Mississippi River.

Regression analyses were used to relate gross ton-miles per gallon to two barge tow characteristics. No significant regression equations were obtained for southbound movements, but the linear regression for northbound tows were of the general form

$$G_r = a + b\,(k_h N_B) + c N_B \qquad (7)$$

where

N_B = number of barges per tow

The $k_h N_B$ term is a substitute for W_r and includes the 300 ton empty weight of a barge, and the 1520-tons of grain in a loaded weight barge. The estimated regression equations were:

$$G_r = 216.0 + 39.92\,(k_h N_B) - 3{,}927\, N_B \qquad (8)$$

$$R^2 = 0.96$$
$$CV = 13.6\%$$

TABLE 5

ESTIMATED TOTAL FUEL CONSUMPTION AND FUEL COST REQUIRED TO TRANSPORT ONE SHORT TON OF GRAIN FROM SELECTED IOWA ORIGINS TO YOKOHAMA, JAPAN VIA ALTERNATIVE SURFACE MODES AND 50,000 DWT OCEAN VESSELS

	Unit trains direct to		Unit train-barge to NOLA, by percent barge backhaul [b]			Truck-barge to NOLA: 0% truck backhaul, by percent barge backhaul [b]			Truck-barge to NOLA: 100% truck backhaul, by percent barge backhaul [b]		
Iowa Origins	Tacoma, WA[a]	NOLA[b]	0	35	100	0	35	100	0	35	100
Western											
Sioux City											
gallons	11.4	14.0	15.4	14.9	14.1	16.9	16.4	15.6	18.4	17.9	17.2
dollars	$8.27	$9.22	$10.55	$10.09	$9.42	$12.33	$11.87	$11.20	$14.13	$13.68	$13.01
Council Bluffs											
gallons	11.2	14.1	15.3	14.8	14.1	16.7	16.2	15.5	18.3	17.8	17.1
dollars	$8.10	$9.32	$10.48	$10.05	$9.42	$12.19	$11.77	$11.13	$14.00	$13.57	$12.94
Central											
Boone											
gallons	11.6	13.8	15.0	14.6	13.9	16.0	15.5	14.8	17.0	16.5	15.8
dollars	$8.41	$9.11	$10.24	$9.82	$9.18	$11.35	$10.93	$10.29	$12.49	$12.06	$11.43
Eastern											
Cedar Rapids											
gallons	11.8	13.6	14.9	14.4	13.7	15.3	14.8	14.1	15.7	15.2	14.5
dollars	$8.64	$8.95	$10.06	$9.63	$9.00	$10.53	$10.10	$9.47	$11.00	$10.57	$9.94
Burlington											
gallons	12.2	13.4	14.5	14.1	13.4	14.5	14.1	13.4	14.5	14.1	13.4
dollars	$9.02	$8.75	$9.69	$9.31	$8.75	$9.69	$9.31	$8.74	$9.69	$9.31	$8.74

[a] Ship steams loaded from Tacoma to Yokohama and returns empty to Tacoma

[b] Ship steams empty from Amsterdam to NOLA and loaded with grain from NOLA to Yokohama. Truck fuel consumption is based on the metered truck fuel consumption.

[c] The coefficient of variation of the gallon estimates is approximately 13 percent.

for the Upper Mississippi River and

$$G_r = 150.9 + 19.17\,(k_h N_B) + 0.827\,N_B \quad (9)$$

$$R^2 = 0.91$$
$$CV = 10.4\%$$

for the Lower Mississippi River. The average weight of towboats, 617.7 and 896.4 tons for the Upper and Lower Mississippi rivers respectively, were included as part of the empty weight. The round-trip fuel efficiencies, at the average 35 percent backhaul, are at the upper end of the estimates in previous studies. The 13.7 percent coefficient of variation (CV) indicates that there was more variation in fuel consumption among tows on the Upper Mississippi River than on the Lower Mississippi River.

There were 254 grain-carrying ships included in the ocean data. Daily fuel consumption of both main engines and generators, load factor and fuel efficiency were related to ship size. Four regression equations were developed for fully loaded grain ships:

$$G_i = 1{,}142.3 + 0.015696\ \text{DWT}) \quad (10)$$

$$R^2 = 0.73$$
$$CV = 13.0\%$$

$$k_i = 0.654 + 7.766030 \times 10^{-7}\,(\text{DWT}) \quad (11)$$

$$R^2 = 0.36$$
$$CV = 4.2\%$$

$$N_i = 543.8 + 0.0199\,(\text{DWT}) - 5.6381 \times 10^{-8}\,(\text{DWT})^2 \quad (12)$$

$$R^2 = 0.77$$
$$CV = 13.8\%$$

$$W_n = 4533.8 + 0.8915\,(\text{DWT}) \quad (13)$$

$$R^2 = 0.97$$
$$CV = 9.6\%$$

Speed is a significant variable in determining fuel consumption, but the speed data available for this study were steaming speeds for different ships. It would be inappropriate to draw conclusions about the effects of steaming speed on a particular vessel. Ship company executives stated that, on average, fuel consumption declines about 20 percent for a 10-percent reduction in speed. This relationship can be used to approximate ocean fuel consumption at slower-than-normal speeds.

Total fuel consumption from Iowa origins to Japan

Total fuel consumption from Iowa origins to Japan via alternative modes and routes can be calculated from the data in table 4; however, it is necessary to assume the size and route of the ocean vessel, the percentage backhaul of trucks and barges, and the modal combination. Table 5 presents the estimated combined fuel consumption in gallons per short ton to Japan via alternative routes and modes assuming a 50,000 DWT ocean vessel. Ocean vessels leaving Tacoma steam loaded to Japan and return under ballast. Vessels leaving NOLA arrived under ballast from Amsterdam before being loaded with grain destined for Japan. Grain industry executives estimate that at least 75 percent of all dry bulk ships entering NOLA ports from the Amsterdam area are under ballast. Barge fuel consumption was estimated for zero, 35 and 100 percent backhaul. Truck fuel consumption data were taken from the metered truck.

The option of unit-grain-trains direct to Tacoma and ocean vessels to Japan used the smallest amount of fuel for all Iowa locations, including those located on the Mississippi River. Depending on the Iowa origin, the West coast option used 1.2 to 2.9 fewer gallons of fuel per short ton of grain than the best NOLA-Japan option. The West Coast fuel advantage is greatest for western Iowa origins and least for eastern Iowa origins.

The minimum fuel consumption options in shipping grain through NOLA are unit-trains direct and the unit-train-barge combination with a 100 percent loaded barge backhaul. As the percentage of barge backhaul declines, however, direct unit-trains become more fuel efficient, for two reasons: 1) unit-trains direct to NOLA ports travel fewer total miles than the unit-train-barge combination; and 2) the largest share of the barge fuel consumption is required to return northbound against the current.

Using 30,000 DWT ocean vessels, the West Coast movement requires 2.5 to 4.1 fewer gallons per ton of grain than the best NOLA-Japan option; with 70,000 DWT vessels, the West Coast option uses 0.4 to 1.7 fewer gallons of fuel than the best NOLA-Japan option. Thus, the West Coast fuel consumption advantage declines as the size of ocean vessel increases.

Total fuel cost from Iowa origins to Japan

Total fuel costs as derived from the fuel consumption estimates are also presented in table 5. Truck diesel fuel was priced at $1.15 per gallon; ocean vessel generator, rail and barge (propulsion) fuel was priced at $0.90 per gallon; and ocean vessel bunker fuel was priced at $0.60 per gallon [4]. Fuel cost in shipping grain from Iowa to Japan through PNW ports was lower than through NOLA for all origins except Burlington (located on the Mississippi River). Total fuel costs in shipping grain from Burlington through NOLA by unit-train direct or barges with a 100 percent backhaul was $0.27 per short ton of grain less than via the West Coast route. However, the fuel cost for the unit-train-barge option is higher than the West Coast option at zero and 35 percent barge backhaul. One dollar per ton equals 2.8¢ per bushel.

From Boone (central Iowa), the West Coast fuel cost was $0.70 to $4.18 per short ton of grain lower than through NOLA. The smallest difference was for unit-trains direct to NOLA and unit-grain-train-barge with a 100 percent barge backhaul and the largest difference was for truck-barge to NOLA with no barge backhaul. From Sioux City, the West Coast fuel cost was $1.05 to $5.90 per short ton less than through NOLA with the smallest difference being for unit-trains direct to NOLA and unit-train-barge with 100 percent barge backhaul.

CONCLUSIONS

The following conclusions can be drawn from the fuel consumption data and accompanying intermodal fuel analysis:

1. The metered tractor-trailer truck obtained 90.5 net ton-miles per gallon when loaded 50 percent of total miles—a fuel efficiency substantially higher than that reported in most of the previous studies. The 1983 fuel consumption of the seven trucks taken from company records was 82.4 net ton-miles per gallon at 35 percent backhaul and 68.6 net ton-miles per gallon at zero backhaul. Truck net ton-miles per gallon increase sharply with backhaul. The trucking company executives believe that the difference between the metered and company record net ton-miles per gallon at zero backhaul is due to driver performance.
2. Unit-grain-trains from Iowa to West Coast ports averaged 437.0 net ton-miles per gallon and 640.1 net ton-miles per gallon to New Orleans (NOLA)—a 46 percent advantage for the NOLA move. The NOLA fuel advantage is largely related to route terrain.
3. Southbound barge tows achieved 953 net ton-miles per gallon on the Upper Mississippi River and 1,290 net ton-miles per gallon on the Lower Mississippi River. With an average of 35 percent backhaul, northbound tows achieved 380.6 and 328.7 net ton-miles per gallon on the two river segments, respectively. At a 35 percent backhaul, the average round-trip barge fuel efficiency was 526 net ton-miles per gallon for the Upper Mississippi River and 548 net ton-miles per gallon on the Lower Mississippi River.
4. Ocean vessels are more fuel efficient than the other modes of grain transport. Ocean vessel net ton-miles per gallon increased rapidly with the ship size; 100,000 DWT vessels are approximately 80 percent more fuel efficient than 30,000 DWT vessels.
5. The most fuel-efficient route and modal combination from Iowa to Japan depends on the size of ocean vessel, percentage back-haul, and origin of the grain shipment. With similar size ocean vessels, and typical ocean vessel routes to and from both West Coast and NOLA ports, the most fuel-efficient route is unit-trains to the West Coast and ocean vessels to Japan. Under most reasonable future scenarios, the most fuel-efficient route to Japan will be through West Coast ports for all Iowa origins.

6. At mid-1984 fuel prices and 50,000 DWT ocean vessels, the West Coast fuel cost advantage over the NOLA option was $1.22 to $5.90 per short ton from Council Bluffs, Iowa, and $0.70 to $4.08 per short ton from Boone in central Iowa. The smallest West Coast cost advantage was with unit-trains direct to NOLA and the largest West Coast cost advantage was with truck-barge with no backhauls. From eastern Iowa, the West Coast option also had a fuel cost advantage over the NOLA options except from Burlington where NOLA bound unit-trains and unit-train-barges with 100 percent barge backhaul had a $0.27 per short-ton fuel cost advantage over the West coast option.
7. The West Coast fuel cost advantage will decrease if the cost of diesel fuel used by railroads and barges increases relative to the less refined fuels used by ocean vessels. Conversely, the West Coast fuel cost advantage will increase if the cost of rail and barge fuels declines relative to the cost of less refined fuel.
8. Larger ocean vessels, unit-grain-trains and higher barge backhauls also reduce the fuel consumption and fuel cost in shipping grain from NOLA to Amsterdam.

LIMITATIONS OF THE ANALYSIS

Most grain route and modal decisions are based on net revenue to the seller and total cost to the buyer. Fuel is only one of several variables that determine net revenue or total cost, but fuel has become an increasingly large component of total cost.

The analysis deals with limited samples of truck, barge, and rail grain shipments, each using different methods of fuel consumption measurements. The truck and rail data were obtained from small samples of one particular type of truck and one type of locomotive pulling unit-grain-trains. The railroad locomotives nd trucks included in this analysis are likely to represent the bulk of the near-term grain-hauling truck and locomotive fleets. Only direct fuel consumption of each mode is included in this analysis. Indirect fuel consumption, such as switching barges in and out of tows or positioning railroad locomotives in the event of malfunction, was not included. However, indirect fuel consumption is a relatively small percentage of direct fuel consumption. Uncontrolled variables such as operating practices, weather, and equipment mechanical condition will result in a larger variation in the fuel consumption among both trucks and unit-trains than would be predicted by the coefficients of variation in the data. Therefore, the results must not be taken beyond the specific types of vehicles and movements from which the results were derived.

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