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Estimates of Total Fuel Consumption in Transporting Grain from Iowa to Major Grain-Importing Countries by Alternative Modes and Routes

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Contents

Summary and Conclusions

Previous fuel consumption studies for rail, truck, and barge freight transport are based on industry averages over all commodities. The conflicting results from these studies are of limited usefulness in predicting total fuel consumption and fuel costs for individual grain shipments.

This study measured fuel consumption in transporting grain from Iowa origins to Japan and Amsterdam by alternative routes and modes of transport and applied these data to construct equations for fuel consumption from Iowa origins to alternative final destinations.

Barge fuel consumption data were taken from daily towboat logs for 11 tows on the Upper Mississippi River, and 16 southbound and 19 northbound tows on the Lower Mississippi River. Ocean vessel fuel consumption was estimated from data for 254 ocean vessels obtained from *The Journal of Commerce and Commercial* and *The Bulk Carrier Register, 1982*. The unit-train data were taken from six metered trips to West Coast ports and four metered trips to New Orleans (NOLA). The truck data were taken from three metered trips to Muscatine, Iowa. In addition, the company owning the metered truck provided records on 1983 fuel consumption for seven trucks with the same specifications as the metered truck but pulling flat trailers rather than hopper-bottom trailers.

Regression analyses related total fuel consumption to various vehicle and operating characteristics. The results of the fuel tests and regression equations were used to predict fuel consumption from Iowa origins to Yokohama, Japan, and Amsterdam, Netherlands, via alternative routes and modes. The results are as follows:

1. The metered tractor-trailer truck averaged 186.6 gross ton-miles per gallon and 90.5 net ton-miles per gallon when loaded 50 percent of total miles. The truck averaged 249.6 gross ton-miles per gallon when loaded and 108.8 gross ton-miles per gallon when empty. The 90.5 net ton-miles per gallon is 41.4 percent higher than the 64 net ton-mile estimate from a 1977 study of 25-ton trucks with 50 percent loaded miles.

2. The 1983 fuel consumption of the seven trucks taken from company records was 82.4 net ton-miles per gallon at 67.5 percent loaded miles and 68.6 net ton-miles per gallon at 50 percent loaded miles. Net ton-miles per gallon increased sharply with higher backhauls. The trucking company executives believe that the difference between the metered and the company record net ton-miles per gallon was largely due to driver performance.

3. Unit grain trains from Iowa to West Coast ports averaged 437.0 net ton-miles per gallon whereas unit grain trains from Iowa to New

Orleans averaged 640.1 net ton-miles per gallon—a 46 percent advantage for the NOLA move. All trains returned empty.

4. Average barge fuel consumption on the Mississippi River from Iowa to NOLA export grain elevators was 544.5 net ton-miles per gallon, with a 35 percent backhaul rate.
   - On the Upper Mississippi River, southbound tows achieved 953 net ton-miles per gallon with all barges loaded while the northbound tows achieved only 243 net ton-miles per gallon with a 37.7 percent backhaul.
   - On the Lower Mississippi River, southbound tows achieved 1,290 net ton-miles per gallon with all barges loaded while northbound tows averaged only 185 net ton-miles per gallon with a 31.5 percent backhaul.
   - Barge net ton-miles per gallon are highly related to the percentage of backhaul. As backhaul increases from zero to 35 percent, net ton-miles per gallon increase 37 and 22 percent on the Upper and Lower Mississippi rivers, respectively.

5. Ocean vessel net ton-miles per gallon varies widely by size of ship and backhaul percentage. With no backhaul, the average net ton-miles per gallon were as follows:

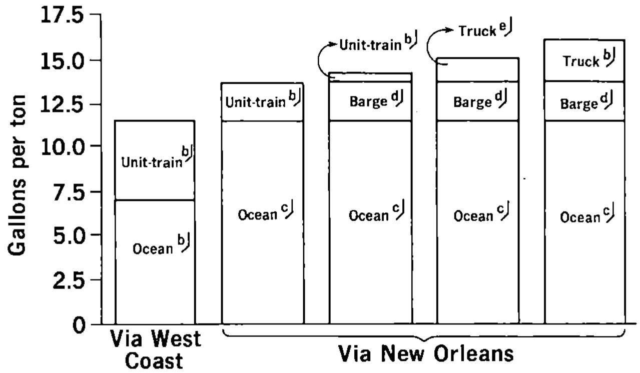
Size of ship	Net ton-miles per gallon
30,000 dwt	574.8
50,000 dwt	701.9
70,000 dwt	835.1
100,000 dwt	1,043.4

6. The most fuel efficient route and modal combination to transport grain from Iowa to Japan depends on the size of ocean vessel, the percentage of backhaul, and the origin of the grain. Alternative routes and modal combinations in shipping grain to Japan are ranked in descending order of fuel efficiencies as follows when similar-sized ocean vessels and typical ocean vessel routes are used.

I. Unit trains direct to West Coast ports.
II. Unit trains direct to NOLA and the unit-train-barge combination with 100 percent barge backhaul.
III. Unit-train-barge combinations with less than 100 percent backhaul. The barge movements in this analysis had an average of 35 percent backhaul.
IV. Truck-barge combination with 100 percent truck backhaul.
V. Truck-barge combination with zero percent truck backhaul.

Figure 1 shows the total gallons of fuel consumed per short ton (2,000 pounds) of grain transported from central Iowa to Japan for the alternative modes and routes using a 50,000 dwt ocean vessel. Fuel consumption data from the metered truck were used in all estimates of total fuel consumption in Figure 1. If truck consumption estimates based on the company records had been used in place of the metered truck data, the impact would have varied by location; from Burlington, the impact would have been zero, whereas from Boone, the metered trucks would have added 0.3 gallon of fuel per ton of grain.

Figure 1. Estimated gallons of fuel to transport one ton of grain from Boone, Iowa, to Yokohama, Japan, by alternative routes and modes [a]



[a] Assumes a 50,000 dwt ocean vessel
[b] Loaded 50 percent of total miles
[c] Loaded 65 percent of total miles
[d] Loaded 67 percent of total miles
[e] Loaded 100 percent of total miles

7. There is little difference in total fuel consumption among the following three modal combinations in shipping grain from Iowa to Japan.
   a. Unit grain trains to West Coast ports and 50,000 dwt vessels with 50 percent loaded miles.
   b. Unit grain trains direct to NOLA and 30,000 dwt ship with 100 percent loaded miles.
   c. Unit grain trains to barge-loading elevators on the Mississippi River, barges to NOLA with 100 percent backhaul, and 30,000 dwt ship with 100 percent loaded miles.

8. A 50,000 dwt vessel consumes almost one more gallon of fuel to haul one short ton of grain from Tacoma to Japan than does a 70,000 dwt vessel. A 50,000 dwt ship uses about 1.7 more gallons of fuel per short ton than a 100,000 dwt vessel. It is not possible, however, to move 70,000 to 100,000 dwt vessels through the Panama Canal.

9. Under most scenarios, the most fuel efficient route for shipping Iowa grain to Japan is through West Coast ports for all Iowa origins. For a variety of reasons, however, this has

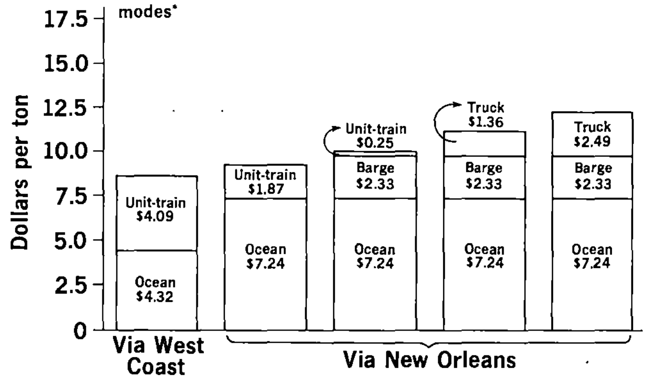
historically not always been the most cost efficient route.

10. Larger ocean vessels also reduce the fuel consumption in shipping grain from NOLA to Amsterdam. On the NOLA-Amsterdam route, 70,000 and 100,000 dwt vessels use 1.2 and 2.3 fewer gallons of fuel per ton than 50,000 dwt vessels. The ports of Amsterdam, Rotterdam, and Antwerp can take fully loaded 100,000 dwt ships. The 40-foot draft at NOLA ports, however, will not permit a 100,000 dwt ship to be fully loaded there [5].

11. Figure 2 shows the fuel cost, at mid-1984 fuel prices, to transport one ton of grain to Japan for most modal combinations.

    - For 30,000 dwt ocean vessels, the West Coast option had the lowest fuel cost for all Iowa origins.
    - For 50,000 dwt ocean vessels, the West Coast option had the lowest fuel cost per ton of grain for all Iowa origins in the analysis except Burlington. From Burlington, unit trains direct to NOLA had a slight fuel cost advantage over the West Coast option.
    - The lowest fuel cost options from Burlington to Japan with 70,000 dwt ocean vessels are unit train direct to NOLA and unit-train-barge with a 100 percent backhaul. From Cedar Rapids to Japan, NOLA had the lowest fuel cost with unit trains direct to NOLA and with the unit-train-barge combination with a 100 percent barge backhaul.

Figure 2. Estimated fuel costs to transport one ton of grain from Boone, Iowa, to Yokohama, Japan, by alternative routes and modes*



* Assumes a 50,000 dwt ocean vessel and 35 percent barge backhaul

    - Figure 2 shows the estimated fuel cost to transport one short ton of grain from central Iowa to Japan for the alternative routes and modes by using a 50,000 dwt ocean vessel.

12. The West Coast fuel cost advantage decreases if the cost of diesel fuel used by railroads and barges increases relative to the less refined fuels used by ocean vessels, and conversely, the West Coast fuel cost advantage will increase if the cost of railroad diesel fuel declines relative to the cost of less refined ocean vessel fuel.

The analysis deals only with limited samples of truck, barge, and rail grain shipments, each using somewhat different methods of measuring fuel consumption. These results should not be used for other commodities, vehicles, vessels, or routes.

Estimates of Total Fuel Consumption in Transporting Grain from Iowa to Major Grain-Importing Countries by Alternative Modes and Routes[1]

by C. Phillip Baumel, Charles R. Hurburgh, and Tenpao Lee[2]

Introduction

During the decade from 1971 to 1981, imported crude petroleum prices increased from approximately $2 per barrel to an all-time high of almost $39 per barrel. As shown in table 1, real imported crude prices, when corrected for inflation, increased more than 7-fold between 1971 and 1981. Although crude prices declined to $29 per barrel by early 1983, real prices in 1983 were still almost 5.5 times greater than 1971 levels. These significantly higher fuel prices have had major impacts on the costs of world grain trade and transportation.

World feed grain, soybean, and wheat trade increased 81, 128, and 154 percent, respectively, during the past decade. In 1971-72, the United States originated 49 percent of world grain trade. By 1981-82, the U.S. share had grown to 60 percent [13, 14, 15, 16, 17, 18].

In 1971-72, the European Economic Community (EEC) was the largest buyer of U.S. grain exports, followed by Asian Pacific Rim countries, the USSR and other Eastern European countries, and finally the rest of the world. By 1981-82, Pacific Rim countries purchased one-third of all U.S. grain exports and were, by far, the largest customers for U.S. grain exports.

Japan has become the largest customer for U.S. grains in the Pacific Rim and in the world. In 1981-82, Japan purchased 4.3 million metric tons of soybeans, over 11 million metric tons of corn, and 5.5 million metric tons of wheat. It is also among the world's top five users of grain sorghum and is an important purchaser of barley.

Exports to the Pacific Rim countries are expected to grow inasmuch as these countries have more than 33 percent of the world population and a weighted annual population growth rate of 1.7 percent. The major Pacific Rim purchasers of U.S. grains have also experienced rapid economic growth. As other Pacific Rim countries share in economic growth, the share of total U.S. grain exports going to this part of the world is likely to increase [3].

Most of the U.S. grain is produced in the Midwest. A large share of Midwest grain is exported to Pacific Rim and EEC countries. Grain moving to Pacific Rim countries from the Midwest must move 1,000 to 2,000 miles to export ports on the Gulf of Mexico or on the West Coast. Much of the grain moving to EEC countries is exported through Gulf ports. From export ports, grain is transported several thousand miles on ocean vessels. The modes and routes used to transport this grain to importing countries are the major determinants of fuel consumption.

Table 2 shows the distances for alternative routes

Table 1. Prices of imported crude petroleum at U.S. ports, 1971-1983.

Year	Average market price	Wholesale price index	Deflated price
1971	$2.00	113.1	$1.77
1972	2.25	119.1	1.89
1973	2.50	135.5	1.84
1974	12.52	160.1	7.82
1975	13.93	174.9	7.96
1976	13.48	183.0	7.36
1977	14.53	194.2	7.48
1978	14.57	209.3	6.96
1979	21.67	235.6	9.20
1980	33.89	268.8	12.60
1981	37.05	293.4	12.62
1982	33.55	299.3	11.19
1983	29.00	303.1	9.57

Source: [19 and 20]

Table 2. Distances from Boone, Iowa, to Yokohama, Japan, in statute miles.

	Export Port		
	Pacific	New Orleans	
Portion of trip	Northwest rail	Rail	Truck-barge combination
To export port	2,000	1,310	1,563
Ocean to Japan	4,888	10,482	10,482
Total	6,888	11,792	12,045

Source: [4 and 22]

[1]Project No. 2439 of the Iowa Agriculture and Home Economics Experiment Station.

[2]Charles F. Curtiss Distinguished Professor of Agriculture and Extension Economist, Assistant Professor of Agricultural Engineering, and former Research Assistant, respectively.

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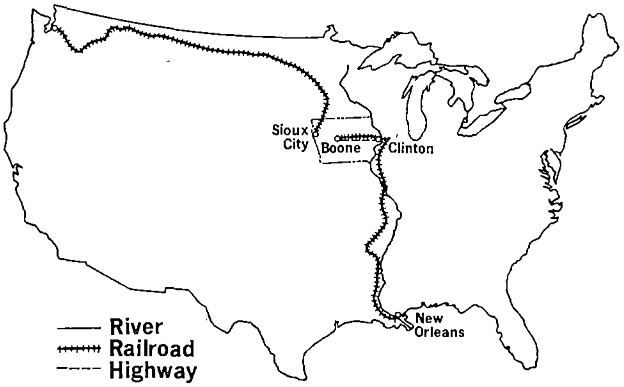
The authors wish to express their appreciation to Mr. M. S. Reid, President, Rail Maintenance and Planning, Inc., Glen Ellyn, Illinois, for his assistance in organizing the railroad fuel consumption runs and to Mr. William Nibel, Des Moines, Iowa, for spending many uncomfortable hours riding railroad locomotives to monitor fuel readings.

Figure 3. One rail-barge and one truck-barge route to New Orleans and one rail route to Seattle and New Orleans

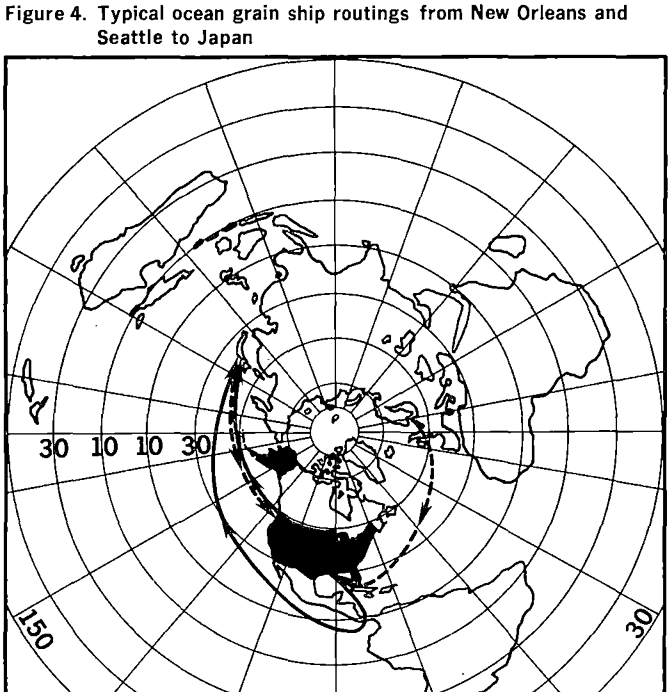


and modes from central Iowa to Yokohama, Japan. The distance to Japan via New Orleans (NOLA) by rail-ocean is almost 69 percent farther than via Pacific Northwest (PNW) ports. The ocean distance to Japan from PNW ports is less than half as far as from NOLA via the Panama Canal, but the rail distance to PNW ports is about 75 percent farther than to NOLA. The main difference between the rail and truck-barge distances to NOLA is the meandering of the Mississippi River.

Figure 3 shows one rail and one truck-barge routing from central Iowa to NOLA and one rail routing to Seattle. Figure 4 shows ocean routings from Seattle and NOLA to Japan. A typical 50,000 deadweight ton (dwt) vessel routing from Seattle—or other West Coast ports—is loaded with grain to Japan and returns under ballast (empty) to Seattle. A typical 50,000 dwt vessel routing from NOLA to Japan starts with a loaded vessel arriving in Holland where it is unloaded. It then steams under ballast from Amsterdam to NOLA where it is loaded with grain destined for Japan [1]. Grain company executives estimate that at least 75 percent of the bulk carrier vessels entering the port of NOLA from Europe are under ballast.

The large difference in distances to Japan via the NOLA and PNW export ports suggests that routing Midwest grain exports through PNW ports could reduce fuel consumption. Little information, however, is available on the combined fuel consumption of the alternative routings. Furthermore, although fuel consumption savings are obvious on the ocean distance from the PNW to Japan, little is known of the relative rail fuel consumption between the rail trip over the Rocky Mountains and the rail movement "down the river" from Iowa to NOLA. Previous research has produced conflicting estimates of rail, barge, and truck fuel consumption. Most of this research is based on aggregate fuel consumption of the entire rail, barge, and truck industries. Barge traffic generally consists of long distance hauls of bulk products. The rail and truck industries move thousands of commodities of differing weight, bulk, size, type of shipment, and distance hauled. Therefore, reliable data are not available to estimate the total fuel consumption to transport grain from Iowa to importing countries.

Figure 4. Typical ocean grain ship routings from New Orleans and Seattle to Japan



Objectives

The objectives of this research are to:

1. Determine total fuel consumption to transport grain from Iowa to major export markets, by route and mode of transport.
2. Construct equations to estimate fuel consumption by mode and route used to ship grain.

Although this information will be useful in forecasting transport rates and routes under alternative fuel prices or public policy scenarios, fuel is only one of many variables that determine modal and route decisions.

Review of Literature

The rapidly rising fuel prices of the 1970s stimulated considerable research on fuel efficiency of alternative transport modes. Methods ranged from use of aggregated data to theoretical engineering microanalyses. A 1975 U.S. Department of Transportation report to the U.S. Senate Commerce Committee summarized the results of 19 energy studies conducted before 1975 [21]. This summary, with all measurements converted to net ton-miles per gallon, is presented in table 3. Although some of the studies did not state whether the estimates are in gross or net ton-miles per gallon, the tone of the narrative implied net ton-miles per gallon.

Table 3. Summary of fuel efficiency studies of rail and inland waterway transportation.

Author	Source	Data years	Fuel consumption in net ton-miles per gallon: Rail, aggregate	Unit train	Barge
Hirst, Eric	Energy Consumption for Transportation in the United States. March 1972, Oak Ridge National Laboratory, ORNL-NSF-EP-15.	Mid-1960s	204.1	---	256.9
Hirst, Eric	Intensiveness of Passenger and Freight Transportation Modes: 1950-1970. April 1973, Oak Ridge National Laboratory. ORNL-NSF-EP44.	1960-70	243.3-256.9	---	338.3-630.5
Rice, Richard A.	Energy Efficiencies of the Transport System. Transportation Research Institute, Carnegie Mellon University. Doc. No. 730066.	1967-70	693.5	---	577.9
Rice, Richard A.	System Energy and Future Transportation MIT Technology Review, January 1972.	1967-70	330.2-577.9	---	577.9-630.5
Mooz, William E.	The Effect of Fuel Price Increases on Energy Intensiveness of Freight Transportation. December 1971, Rand, R-804-NSF.	1960-68	138.8-196.5	---	243.3-358.4
Peat, Marwick; and Jack Faucett Associates	Industrial Energy Studies of Ground Freight Transportation, SIC Codes 4011, 4013, 4041, 4212, 4213, 4214, 4231. July 1974.	1973	198.1	420.3	277.4
Sebald, Anthony V.	Energy Intensity of Barge and Rail Freight Hauling. May 1974, Center for Advanced Computation, University of Illinois at Urbana-Champaign. CAC Technical Memo No. 20.	1971	195.1-217.1	386.4-613.7	176.7
Tihansky, Dennis P.	Methods for Estimating the Volume and Energy Demand of Freight Transport. December 1972, Rand, R-988-NSF.	1965-67	184.9	---	277.4
Batelle Memorial Institute	Energy Required for Movement of Intercity Freight.	---	204.0-292	---	---
Reebie Associates	Referenced in Peat, Marwick, Mitchell/ Faucett study	---	255.0	---	---
Mascy, A.C. & Paullin, R.L.	Transportation Vehicle Energy Intensities. June 1974, NASA/DOT.	1974	252.2-420.3	---	---
National Petroleum Council	Transportation Task Group Interim Report Phase I.	1973	---	---	272.0
Brinegar, Claude S.	Statement before the House Appropriations Subcommittee on Transportation, March 5, 1974.	1973	179.9	---	300.2
Cook, Harry N.	Letter to DOT Secretary C.S. Brinegar from National Waterways Conference, Inc., February 4, 1974.	1961-68	---	---	334.2-639.2
A "Major" Railroad	Report to U.S. Transportation Systems Center	---	275.2-441.7	---	---
Upper Mississippi Waterway Association	The Economic Impact of Waterborne Transportation on the Upper Mississippi River Basin, June 1975.	1972	204.3	---	331.0
Barloon, Marvin	Reported in Upper Mississippi Waterway Association study.	1970	213.4	---	333.4
Southern Pacific Railroad	Reported in Upper Mississippi Waterway Association study.	1973	582.8	---	---
U.S. Army Engineer District, St. Louis Missouri	Locks and Dam No. 26 (Replacement) Design Memorandum No. II Formulation Evaluation Report, Volume 2, Appendix F. April 1975.	1971	195.1	---	213.7

Source: [21]. Fuel is assumed to contain 138,700 Btu per gallon [9].

The estimated rail fuel efficiency ranges from 138.8 to 693.5 net ton-miles per gallon. By using the midpoint of the range of estimates, the average efficiency for railroads is 241.2 net ton-miles per gallon.

Only two studies presented fuel efficiency estimates for unit trains. The average fuel efficiency for unit trains from these two studies is 438.9 net ton-miles per gallon.

Barge fuel efficiency ranged from 243.3 to 639.2 net ton-miles per gallon with an average of 305.5 net ton-miles per gallon. The summary report did not state the barge backhaul percentages, so one must assume that these data are industry averages based on whatever backhaul factors existed at the time.

Except for the unit-train estimates, all the studies are aggregated estimates over all shipments. Eldridge and Van Gorp [6] developed rail fuel efficiency estimates by type of rail operations, as shown in table 4. By their estimates, unit-train operations are 2.33 times as efficient as overall rail operations. Similar analyses of different types of barge and truck operations were not reported.

Lambert and Hougland examined the fuel consumption of 149 towboats operating on the Mississippi river system under a variety of conditions [10]. Operations varied from dry bulk carriers with a mixture of one-way and backhaul movements to oil and chemical tows with entirely one-way loaded hauls. Some companies engaged in short-haul or harbor switching activities. Lambert and Hougland calculated a barge industry fuel efficiency of 419 net ton-miles per gallon. Using railroad industrywide data, Lambert and Hougland estimated overall rail fuel consumption at 204 net ton-miles per gallon.

Using records provided by four barge companies and data from the U.S. Army Corps of Engineers, Baumel, Hauser, and Beaulieu estimated barge fuel consumption for moving grain to New Orleans from several origins on the Mississippi river system [2]. As presented in table 5, barge fuel efficiency varied widely among river segments and backhaul percentages. At 50 percent backhaul, barges on the Lower Mississippi and Ohio rivers achieved over 600 net ton-miles per gallon. Barges are least fuel efficient on the Upper Missouri and Arkansas rivers, with 324 and 289 net ton-miles per gallon respectively at 50 percent backhaul. Net ton-miles per gallon increased about 40 percent as the backhaul percentage increased from 0 to 50 percent. The northbound trip used about two-thirds of the round-trip fuel consumption on the Lower Mississippi River and about 55 percent on the Upper Mississippi River.

Paxson reported fuel consumption estimates for barge, rail, and alternative truck sizes and backhaul levels [11]. The Paxson estimates, presented in table 6, show a wide range of fuel efficiencies of different sizes and types of rail and truck shipments.

In an unpublished report, Hudson estimated total fuel consumption required to ship grain from Toledo, Ohio, to Rotterdam [8]. This is the only analysis known to the authors that combines fuel consumption to transport grain from a given origin to a given destination. The Hudson analysis, presented in table

Table 4. Eldridge and Van Gorp transportion energy estimates.

Mode	Fuel consumption, in net ton-miles per gallon
Rail, unit train	462.3
Rail, main line haul	277.4
Overall rail, including branch lines	198.1
Barge	277.4
Slurry pipeline, including coal preparation and dewatering	184.9
Truck	69.4

Source: [6]

Table 5. Estimated barge fuel consumption in net ton-miles per gallon, by river segment for selected origins and percent backhaul.

River	Origin	Percent backhaul 0	25	40	50
Upper Mississippi	Minneapolis	358.8	436.0	480.3	509.0
	Davenport	376.1	456.5	502.5	532.4
Lower Mississippi	Cairo	435.7	526.7	578.4	611.8
Missouri	Sioux City	229.3	278.2	306.2	324.3
	Kansas City	294.6	356.6	293.0	414.9
Illinois	Seneca	376.0	456.4	502.4	532.2
	Peoria	383.1	464.7	511.5	541.7
Ohio	Cincinnati	449.3	545.7	601.0	636.8
Arkansas	Catoosa	202.9	247.3	272.8	289.4

Source: [2]

Table 6. Paxson estimates of rail, barge, and truck fuel consumption.

Type of service	Percent loaded miles	Fuel consumption, in net ton-miles per gallon
Rail		
Unit train	50	350
Carload	60	198
Local	55	40
All types of service	57	207
Barge	--	277
Truck		
25-ton size	100	114
25-ton size	50	64
15-ton size	100	75
15-ton size	50	41

Source: [11]

Table 7. Hudson estimates of fuel consumption by mode and route.

Mode	Route	Shipment size	Fuel consumption, in net ton-miles per gallon
Rail	Toledo to Norfolk	Unit train	247.7
	Toledo to New Orleans	Unit train	396.3
	Toledo to Cincinnati	Unit train	495.4
	Champaign to St. Louis	Unit train	495.4
Truck	Toledo to Cincinnati	20 tons	99.1
Barge	Cincinnati to New Orleans	a/	432.1
	St. Louis to New Orleans	a/	502.5
Ocean Vessel	Toledo to Rotterdam	25,000 dwt	447.4
	Norfolk to Rotterdam	48,000 dwt	792.6
	New Orleans to Rotterdam	59,000 dwt	866.9

a/ The backhaul assumptions and the size of the barge tows are undefined.

Source: [8]

7, suggests that fuel consumption varies by mode, size of shipment, and route.

In summary, the existing literature on modal fuel consumption provides a range of estimates depending on the method of analysis as well as the size, type, and routing of the shipment. Conflicting estimates based on aggregate modal fuel consumption and aggregate gross or net ton-miles are not useful to predict fuel consumption or fuel costs for individual grain shipments.

Definitions and Mathematical Relationships in Fuel Consumption

Fuel consumption is most easily measured by gross ton-miles per gallon, where the empty weight of the vehicle is included. Adjustment factors 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 (if any) on return trips (backhaul factor). The adjustment factors convert gross ton-miles per gallon to net ton-miles per gallon. Table 8 presents a summary of the notation used to describe gross and net ton-miles per gallon.

Assume that there are two load conditions, namely, 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 and return trips can be estimated 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 round-trip fuel efficiency as:

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

and

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

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

For shipment involving several modes, the total fuel required can be calculated by summing the fuel requirements of the modes as in equation (7).

Table 8. Notation and relationships used in fuel consumption calculations

Measurement	Notation	Defining equation
Fuel consumption, gallons: loaded, return, round trip	f_i, f_r, f_t	
Distance, miles: loaded, return, round-trip	M_i, M_r, M_t	
Weights, tons		
Gross: loaded, empty, partial load	W_i, W_e, W_r	
Net	W_n	$W_i - W_e$
Fuel efficiency, 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	$k_r k_i G_r$
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	$(W_r - W_e)/W_n$

$$f_t = f_{i1} + f_{r1} + f_{i2} + f_{r2} \ldots\ldots + f_{in} + f_{rn} \quad (7)$$

Each component can be calculated by rearranging equations (1) and (2) with the appropriate modal data as:

$$f_i = \frac{W_i k_u M_t}{G_i} \quad (8)$$

and

$$f_r = \frac{W_i [1 - k_i(1 - k_h)](1 - k_u) M_t}{G_r} \quad (9)$$

Method of Analysis

Several methods were used to obtain modal fuel consumption data. Data on barge fuel consumption were taken from daily towboat logs. Ocean vessel fuel consumption was estimated from data obtained from *The Journal of Commerce and Commercial* [12] and *The Bulk Carrier Register, 1982* [7]. Fuel meters were installed on one tractor-trailer truck and on four sets of railroad locomotives to measure fuel consumption of these two modes of transport. In addition, data from company records were obtained on seven tractor-trailer trucks. Although direct measurement was the preferred method, it was not possible for either ocean or barge. Where appropriate, regression equations were used to relate fuel consumption to vehicle and operation characteristics. The fuel tests and regression equations were then combined to estimate total fuel consumption from Iowa origins to Japan and Amsterdam via alternative routes.

Trucks

A Helda fuel meter was installed on a 1980 truck tractor and hopper bottom grain trailer with the specifications shown in table 9. The metered tractor-trailer hauled three loads of corn from a north-central Iowa elevator to a grain processor at Muscatine, Iowa. The same driver made all three trips. An Iowa State University representative monitored each trip to record mileage, gross and net weights, and fuel meter readings.

Table 9. Specifications of the tractor-trailer used in the fuel consumption test.

	Tractor	Trailer
Make and year	White Freightliner, 1980	Wilson, 1980
Tare weight(lbs)	17,220	9,330
Tires	11 R-22.5 steel belted radials	11 R-22.5 steel belted radials
Engine	Cummins NTC 300F 300 hp @ 1800 rpm	---
Transmission	Spicer 1107-2A (7-speed manual with 1:1 direct in 7th gear)	---
Fan clutch	Switzer viscous	---
Front axle	Rockwell FE-971 with centerpoint steering	---
Rear axle	Rockwell SQHD full tandem	---
Rear axle ratio	3.7	---
Capacity	---	1,455 cubic feet

Because the fuel meter was installed under the engine cover, readings were possible only while the truck was stopped. Therefore, it was impossible to develop relationships among fuel consumption, speed, and road characteristics. To supplement the metered-truck data, the 1983 fuel consumption records were obtained for seven similar trucks owned and operated by the same company.

Railroads

Five railroad companies participated in the rail fuel consumption tests. Railroad companies 1 and 2 operate grain trains from Iowa to West Coast ports; railroad company 3 serves NOLA directly; and company 4 interlines with company 5 at St. Louis, Missouri, to reach NOLA.

Railroad company 1 installed ¾" × 1" Red Seal, Low Flow Neptune meters on three SD-40-2 locomotives pulling 54-car unit trains from Sioux City, Iowa, to the Pacific Northwest. The meters were calibrated to a maximum of 2 percent error by using a fuel-weight test. The meters were first used for a series of test runs and then were transferred to the grain-train locomotives. Two of the three unit grain trains were unloaded at Tacoma, Washington, and the third at Kalama, Washington. On one Tacoma trip, manual readings were taken by an Iowa State University representative to verify the on-board computer monitoring the fuel meters. On this trip, the meter on the third locomotive indicated consistently low readings when compared with the other locomotive readings. Therefore, the average readings of locomotives one and two were substituted for the third locomotive meter readings. All three locomotives were "on line"—delivering power to the train—at all times.

Railroad company 2 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 amount of time each locomotive throttle is in a particular throttle position during the trip. The recorded time for each position is then multiplied by a predetermined fuel-flow rate, and the totals for the throttle positions are summed. These trains were powered by three SD-40-2 locomotives from Council Bluffs to Salt Lake City, Utah. An additional locomotive was added from Salt Lake City to Yermo, California. Two helper SD-40-2's were needed to cross the Sierra Nevada west of Yermo. Helper locomotive fuel consumption is included in the loaded train fuel consumption data. Three SD-40-2 locomotives were used to power the empty return trip. Fuel consumption data were not recorded for 161 miles of the loaded portion of the second trip because of failure in the pulse recorder. The quantity of fuel consumed on the same segment of the third trip was added to the fuel consumption of the second trip. No fuel consumption data were recorded on the entire empty return of the first trip. As a result, fuel consumption data are available for only five empty return trips from West Coast ports.

Railroad company 3 also used ¾" × 1" Red Seal, Low Flow Neptune meters on three 7-year-old SD-40-2 locomotives pulling a 120-car unit grain train from Fort Dodge, Iowa, to Reserve, Louisiana (NOLA). As is the usual operating practice for railroad company 3, this train moved in two 60-car units from Fort Dodge to Freeport, Illinois, where they were combined. Only one 60-car unit was metered; the fuel consumption and ton-miles were doubled to reflect the movement of 120 cars from Fort Dodge to Freeport. This was the last train that railroad company 3 pulled from Iowa to NOLA during the study period, and 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 3 personnel.

Railroad company 4 also installed Neptune fuel-flow meters on three SD-40-2 locomotives. The three locomotives also were equipped with a Barco speed and throttle recording device and a manually operated fuel-saver system. Three 75-car unit grain trains were pulled from Boone, Iowa, to Dupo, Illinois. From Dupo, company 5 operated the trains to Ama, Louisiana. The empty trains returned by the same route to Boone, Iowa.

Normally, railroad companies 4 and 5 use only two 3,000-hp locomotives to power 75-car unit grain trains from Boone, Iowa, to Ama, Louisiana via St. Louis (Dupo). The third locomotive was included as a backup against a locomotive failure. The third locomotive was in a nonworking, fuel-saver status during most of the time on all three trips. The fuel-saver status restricts the locomotive to its first two throttle positions, which provide only enough tractive effort to propel itself. Consequently, when in fuel-saver status, it contributed nothing to moving the train, and its fuel consumption, when in fuel saver, was subtracted from the total fuel consumption. The metered fuel consumption was recorded by Iowa State University representatives on two trips, and by railroad personnel on the remaining trip.

All metered unit grain trains were powered by SD-40-2 locomotives that were 2 to 8 years old. According to data of the 10 largest railroad companies in the United States, the SD-40-2 model locomotive makes up 19.3 percent of the total road locomotive fleet. These railroad companies have no other model as numerous as the SD-40. The next most numerous models are the older GP-7 and GP-9 models, which make up 14.3 percent of the road locomotive fleet. These older models are being phased out. The third most numerous models are the GP-28 and GP-38, which constitute 11.8 percent of the road fleet. The SD-40, however, 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 and SD-40-2 locomotives.

The routes used in these fuel consumption tests are the usual routes used by these railroad companies to reach the West Coast and NOLA. In some instances, these routes may be the most fuel efficient routes; in others, alternative routes may be more fuel efficient.

Clearly, the fuel measurement methods in this analysis varied among the railroads involved. Actual fuel metering was the preferred method, but was not possible in one instance. Therefore, the data should be viewed as the best obtainable given the operating conditions at the time of the measurements. The time-in-throttle or pulse measurement does involve assumptions that render it potentially, although not necessarily, less accurate than actual, temperature-compensated flow metering.

Barges

Three Mississippi River barge companies provided data on towboat fuel consumption, representing various numbers of loaded and empty barges. Executives from all three companies explained that it was not possible to meter fuel consumption of towboats, given current fuel meter technology. Large vibrations are created when one or more towboat propellers are in reverse. Therefore, daily fuel tank measurements were the only available method of obtaining towboat fuel consumption. These measurements were obtained from a calibrated steel tape measure inserted periodically into the fuel tanks. Fuel consumption was calculated by subtracting the current measurement from the previous measurement, then adding any fuel taken on board since the last measurement. Fuel measurements are recorded on the daily engine-room or deck-and-radio logs. The daily logs also contain the number of empty and loaded barges, distance traveled as measured by river mileposts, explanation of delays, and other mechanical information.

Table 10. Size distribution of towboats.

	Number of towboats			
	Upper Mississippi		Lower Mississippi	
Horsepower	Southbound	Northbound	Southbound	Northbound
2,000 - 3,999	3	3	0	0
4,000 - 5,999	6	8	4	4
6,000 - 7,999	2	0	11	11
8,000 and above	0	0	1	4

Two of the three companies provided copies of their daily logs. The third company provided a summary of fuel consumption taken from the daily logs. The size distribution of the towboats from which fuel consumption data were provided is presented in table 10. No fuel consumption data were obtained for switching barges in and out of tows.

Ocean Vessels

Fuel consumption data for bulk carrier vessels were taken from *The Journal of Commerce and Commercial* ship fixture breakdown on bulk carrier time charters [12]. The Journal of Commerce data include deadweight tons, grain cubic feet, average daily speed for the negotiated rate, daily fuel consumption of the main engines for the specified speed, average daily generator fuel consumption, and the year built. *The Bulk Carrier Register* reports similar data as well as draft and bunker (fuel) capacity for individual vessels [7]. However, the *Bulk Carrier Register* fuel data are for maximum vessel speeds. *The Journal of Commerce and Commercial* fuel data are part of the negotiated rates and are considered by ship brokers to be more reliable estimates of actual fuel consumption. The fuel consumption data used in this analysis are taken from all time charters listed in *The Journal of Commerce and Commercial* from February 1, 1983, to July 31, 1983. Data on draft and bunker capacity for the vessels were obtained from *The Bulk Carrier Register-1982*. Regression equations were used to relate gross and net ton-miles per gallon to vessel size.

Limitations of the Method of Analysis

The truck and rail data were obtained from small samples of one particular type of movement. The barge data were obtained from tows operating only on the Upper and Lower Mississippi River. These data should not be applied to other types of traffic. Moreover, only the direct fuel consumption of each mode was measured. Indirect fuel consumption such as switching barges in and out of barge tows, lock and dam construction, river dredging, rail line or highway construction, or positioning of railroad locomotives in the event of locomotive failure are not included. Uncontrolled variables such as operating practices, delays, weather, diesel-engine efficiency, and wind may result in a greater variation in the fuel consumption within all modes than would be predicted by our data. This study is a starting point rather than a comprehensive description of all possibilities. Therefore, the results must not be taken beyond the specific types of movements they are intended to portray.

Results

Trucks

The data for the three metered truck trips are presented in table 11. The metered truck averaged 6.35 miles per gallon on the loaded portion of the trips and 7.96 miles per gallon on the empty portion. Each trip required one full day. At the end of the trip, the truck returned to the truck company headquarters, not to the elevator. Thus, empty miles exceeded loaded miles by 24.6 percent. Equations (5) and (6) (with $k_h = 0$ and $k_u = 0.5$) were applied to adjust the data to a 50-percent-loaded-mile basis.

The adjusted fuel consumption, overall gross, and net ton-miles per gallon are presented in table 12. The three round trips averaged 186.6 gross ton-miles per gallon and 90.5 net ton-miles per gallon. The 90.5 net ton-miles per gallon average is 41.4 percent

Table 11. Fuel consumption data for three metered tractor-trailer truck shipments from central Iowa to Muscatine, Iowa.

Load status	Trip	Miles	Gallons of fuel consumed	Miles per gallon	Gross tons	Net tons	Percent load factor	Gross ton-miles per gallon	Net ton-miles per gallon
Loaded	1	225.4	34.4	6.6	39.2	25.56	65.3	256.7	167.5
	2	214.9	33.3	6.4	39.2	25.58	65.2	253.3	165.1
	3	214.9	35.4	6.1	39.3	25.67	65.3	238.8	155.8
Average loaded		218.4	34.37	6.4	39.2	25.60	65.2	249.7	162.8
Coefficient of variation[a]		(2.8)	(3.1)	(4.0)	(0.2)	(0.2)	(0.0)	(3.8)	(3.8)
Empty	1	270.3	32.8	8.2	13.6	---	---	112.2	---
	2	270.1	34.1	7.9	13.7	---	---	108.3	---
	3	275.9	35.7	7.7	13.7	---	---	105.6	---
Average empty		272.1	34.2	8.0	13.6	---	---	108.8	---
Coefficient of variation		(1.2)	(4.2)	(3.3)	(0.2)	---	---	(3.0)	---

[a] The coefficient of variation is the standard deviation as a percent of the mean.

Table 12. Adjusted[a] round trip gross and net ton-miles per gallon for a tractor-trailer truck hauling grain from central Iowa to Muscatine, Iowa.

Load status	Trip	Adjusted miles	Adjusted fuel consumption, in gallons	Gross tons	Net tons	Gross ton-miles per gallon	Net ton-miles per gallon
Loaded	1	225.4	34.4	39.17	25.56	256.7	167.5
	2	214.9	33.3	39.25	25.58	253.3	165.1
	3	214.9	35.4	39.33	25.67	238.8	155.8
Average loaded		218.4	34.4	39.25	25.60	249.7	162.8
Empty	1	225.4	27.3	13.61	---	112.2	---
	2	214.9	27.2	13.67	---	108.3	---
	3	214.9	27.8	13.66	---	105.6	---
Average, empty		218.4	27.4	13.65	---	108.8	---
Round-trip average		218.4	30.9	26.4	12.8	186.6	90.5

[a] Adjusted to $k_h = 0.0$, $k_u = 0.5$.

Table 13. Fuel consumption data from company records for seven tractor-trailer trucks, 1983

Tractor	Fuel consumed, gallons	Total miles	Average load factor, k_i	Average utilization factor, k_u	Gross ton-miles per gallon			Net ton-miles per gallon		
					Loaded trip	Return trip	Round-trip	Loaded trip	Return trip	Round-trip
1	12,909	65,790	0.616	0.661	199.7	106.6	149.3	122.0	45.8	76.9
2	20,708	109,295	0.616	0.585	196.3	104.9	146.8	112.8	24.3	71.1
3	18,670	104,573	0.616	0.732	231.6	123.7	173.2	148.3	66.2	93.5
4	12,433	67,543	0.616	0.555	197.3	105.4	147.0	110.1	15.5	69.4
5	20,765	110,960	0.616	0.586	199.4	106.5	149.1	114.7	24.6	72.3
6	19,393	103,545	0.616	0.789	232.0	124.0	173.5	153.9	82.2	97.0
7	21,159	107,473	0.616	0.776	219.6	117.3	164.2	144.5	78.5	91.1
Weighted average	18,005	95,597	0.616	0.675	212.1	113.3	158.6	130.7	49.8	82.4
Coefficient of variation	20.8	20.9	0	14.5	6.1	7.8	7.8	14.4	57.5	14.5
Averages adjusted to k_u = 0.5	---	---	0.616	0.500	212.1	90.1	154.2	130.7	0.0	68.6

higher than the Paxson estimate of 64 net ton-miles per gallon for a 25-ton truck with 50 percent loaded miles.

Total 1983 fuel consumption data were also obtained for seven 1980 White Freightliner trucks owned and operated by the same trucking company. The seven tractors had the same specifications as the metered truck except the seven trucks pulled flat trailers rather than covered hopper trailers. These trucks logged a total of 669,179 miles during 1983 with an average backhaul of 35 percent. The fuel consumption data for these seven trucks are presented in table 13. These seven trucks averaged 158.6 gross ton-miles per gallon and 82.4 net ton-miles per gallon.

The seven trucks averaged 154.2 gross ton-miles per gallon and 68.6 net ton-miles per gallon when adjusted to zero backhaul. Thus, net ton-miles per gallon increase sharply as the percentage of backhaul increases. The trucking company executives stated that the difference in fuel consumption between the seven trucks and the metered truck was largely caused by driver performance. However, the flat trailers could also have affected the fuel consumption.

Railroads

The fuel data for the six West Coast unit-train shipments are shown in table 14. The highest loaded gross ton-miles per gallon (1,088) was achieved on a route that has significantly less grade than the other routes. The variance in the fuel consumption among the loaded trips was about three times as large as among the empty trips.

Table 15 presents the gross and net ton-miles for the four NOLA unit-train shipments. The loaded gross ton-miles per gallon to NOLA, at 1,379.5 gross ton-miles per gallon, was 47 percent higher than on the West Coast trips. The empty return, at 640.2, was

Table 14. Fuel consumption for metered unit-grain-train shipments from Iowa to West Coast ports.

Load status	Load factor k_i	Gross ton-miles per gallon	Net ton-miles per gallon
Loaded	0.693	950	658
Loaded	0.735	1088	780
Loaded[a]	0.720	1012	687
Loaded	0.713	818	583
Loaded	0.707	883	624
Loaded	0.705	870	613
Average	0.712	937	667
Coefficient of variation	2.0	9.4	10.5
Empty	---	547	---
Empty	---	499	---
Empty[a]	---	513	---
Empty	---	505	---
Empty	---	506	---
Average empty	---	514	---
Coefficient of variation	---	3.7	---
Round-trip[b] average with k_h = 0.0, k_u = 0.5	---	791	437

[a]An Iowa State University representative rode this train to verify data.
[b]Calculated from equations (5) and (6) with k_h = 0, k_u = 0.5.

Table 15. Fuel consumption for metered unit-grain-train shipments from Iowa to New Orleans ports.

Trip status	Load factor (k_u)	Gross ton-miles per gallon	Net ton-miles per gallon
Loaded	0.723	1,222.8	883.9
Loaded[a]	0.738	1,535.6	1,133.3
Loaded[a]	0.738	1,509.6	1,114.1
Loaded[a]	0.735	1,315.5	948.1
Average[a]	0.732	1,379.5	1,009.8
Coefficient of variation	1.0	10.0	10.9
Empty	---	682.4	---
Empty[a]	---	636.1	---
Empty[a]	---	624.4	---
Empty[a]	---	598.6	---
Average[a]	---	640.2	---
Coefficient of variation	---	5.5	---
Round-trip average[a]		1,108.8	640.1

[a]Calculated from equations (5) and (6) with k_h = 0.0 and k_u = 0.5 after deducting fuel consumed by the nonworking locomotive.

18.5 percent more efficient than the West Coast empty return. Variability was also lower among the NOLA trains than the West Coast trains.

As described before, an extra locomotive was included in the train on the NOLA trips as protection against breakdowns. A breakdown did in fact occur on trip 2 when a fuel filter became clogged on one locomotive. There were short intervals when all three locomotives were in working throttle positions. This was the preference of the train crews to use the additional power available, rather than a necessity. The third unit was working less than 1 percent of the total travel time. Table 16 shows the amount of fuel deducted for the nonworking locomotive.

About the same amount of fuel was deducted from both the empty and loaded trips. This is logical because the third locomotive consumed approximately the same amount of fuel both ways to pull itself. More gallons of fuel were deducted from the first trip than for trips two and three because the third locomotive was used in a working status for a slightly longer time on the first trip than on the other two trips.

Unit grain trains from Iowa to NOLA achieve 48 percent more net ton-miles per gallon than the unit grain trains from Iowa to West Coast ports. This is almost certainly the result of the differences in the terrain of the two basic routes. The routes to NOLA are largely over level terrain and generally follow the route of the Mississippi River. The route used by railroad companies 4 and 5 had an average uphill elevation of only 3.8 feet per mile, an average downhill fall of 4.7 feet per mile, and an average curvature of 1,164.7 degree-feet per mile. One degree-foot is 1 foot of track at a one degree of central angle curvature per mile. The routes to West Coast ports must cross one or more mountain ranges to reach some West Coast ports. For example, one of the routes taken by a company 1 train has an average uphill elevation of 8.7 feet per mile, an average downhill fall of 8.8 feet per mile, and an average curvature of 1,745.4 degree-feet per mile. On the return trips, uphill elevation and downhill fall are reversed.

The fuel efficiency of the unit trains in this analysis exceeds the published estimates based on 1960-1970 data [21]. With the exception of the Rice studies and the two railroad company estimates, all "rail" estimates are significantly below the estimates of unit grain train gross and net ton-miles per gallon obtained in this analysis. The Peat, Marwick, and Faucett unit-train data approximate our West Coast results, and the Sebald unit-train estimates include our West Coast data, but both are lower than the NOLA unit-train results in this analysis.

Table 16. Total gallons of fuel consumed and gallons of fuel deducted from the nonworking locomotive on three unit-grain-train shipments to New Orleans.

Trip	Total gallons consumed	Gallons deducted from the nonworking locomotive: Loaded	Empty	Total
1	15,879.1	933.8	905.6	1,839.4
2	16,162.3	809.0	826.9	1,635.9
3	16,576.5	794.2	798.5	1,592.7

Barges

Summarized data for the barge grain movements are presented in table 17. Barge tows are three to four times more fuel efficient on southbound movements with the river current than on the northbound movements against the current. There are also major differences in the fuel efficiency of barge tows between the Upper and Lower Mississippi rivers. For the tows

Table 17. Estimated barge fuel consumption on the Upper and Lower Mississippi rivers.

River	Direction	Number of tows	Number of barges per tow	Miles travelled per tow	Gross tons per tow	Net tons per tow	Load factor	Backhaul factor	Total gross ton-miles	Total net ton-miles	Total fuel consumed	Gross ton-miles per gallon	Net ton-miles per gallon
Upper Mississippi	Southbound	11	14.3	469.5	26,671.6	21,734.0	0.815	—	137,275,290	111,814,240	117,363	1,169.7	952.7
			(7.2)[a]	(26.5)	(7.1)	(7.2)	(0.8)	—				(17.0)	(17.1)
	Northbound	11	14.7	428.5	13,568.6	8,553.0	0.630	0.377	58,112,159	35,888,720	147,527	393.9	243.3
			(20.5)	(42.7)	(66.5)	(105.2)	(81.6)	(105.2)				(59.8)	(102.8)
	Round-trip		—	—	—	—	—	—	195,387,449	147,702,960	264,890	737.6[b]	557.6[b]
Lower Mississippi	Southbound	16	21.8	999.2	40,594.1	33,193.0	0.818	—	649,503,858	531,083,440	411,722	1,577.5	1,289.9
			(10.2)	(5.8)	(10.1)	(10.2)	(0.3)	—				(12.1)	(12.2)
	Northbound	19	24.3	862.1	19,863.3	11,676.2	0.588	0.315	316,362,240	181,846,720	985,422	321.0	184.5
			(22.2)	(27.4)	(41.5)	(64.5)	(40.1)	(70.2)				(32.0)	(57.8)
	Round-trip		—	—	—	—	—	—	—	—	—	718.5[b]	536.5[b]
Round-trip weighted average			—	—	—	—	—	—	—	—	—	725.7[b]	544.5[b]

[a] Bracketed numbers are coefficients of variation

[b] Calculated from equations (5) and (6) with k_h = 0.377 for the Upper Mississippi River, 0.315 for the Lower Mississippi River and 0.35 for the combined rivers.

included in this analysis, the average round trip gross and net ton-miles per gallon were almost identical on the two rivers. The tows on the Upper Mississippi River, however, achieved 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 River. These differences are undoubtedly related to the slower current speed on the pooled Upper Mississippi River.

The coefficients of variation show that there is much greater variation among northbound tows on both rivers than among southbound tows. Most of this variance is related to the backhaul factor. Although all southbound barges were loaded, the percentage backhaul and gross and net ton-miles per gallon were highly variable on the northbound trip. The average backhaul for all tows was 31.5 percent on the Lower Mississippi River and 37.7 percent on the Upper Mississippi.

Regression equations were used to relate gross ton-miles per gallon to barge tow characteristics. The linear regressions were of the general form

$$G_r = a + b\,W_r + c\,N_b \qquad (10)$$

where

N_b = number of barges per tow.

No significant regression equations were obtained for southbound movements; rather the average gross ton-miles per gallon was the best indicator of fuel consumption for southbound tows when all barges are loaded. The estimated regression equations for the northbound tows are:

for the Upper Mississippi River

$$G_r = 199.8 + 0.02626\,W_r - 10.9063\,N_b$$
$$R^2 = 0.96;\ CV = 13.7 \qquad (11)$$

and for the Lower Mississippi River

$$G_r = 139.6 + 0.01261\,W_r - 2.9557\,N_b$$
$$R^2 = 0.91;\ CV = 10.4 \qquad (12)$$

These equations can be simplified by substitution from the following identity:

$$W_r = N_b\,(W_n k_h + W_b) + T \qquad (13)$$

where

W_n = weight of cargo in a loaded barge, 1520 tons,
W_b = empty weight of a barge, 300 tons,
T = weight of towboats, 617.7 tons or 896.4 tons.

The average towboat weights were 617.7 and 896.4 tons on the Upper and Lower Mississippi, respectively. The towboats contributed about 2 percent of the total tonnage when the barges were fully loaded and about 12 percent when the tows were completely empty. Substituting equation (13) into equations (11) and (12) gives:

$$G_r = 216.0 + 39.92\,k_h\,N_b - 3.028\,N_b \qquad (14)$$

for northbound tows on the Upper Mississippi River and

$$G_r = 150.9 + 19.17\,k_h N_b + 0.827\,N_b \qquad (15)$$

for northbound tows on the Lower Mississippi River.[3]

Equations (5), (6), (14), (15), the average gross ton-miles per gallon on the southbound trips, and the average tow sizes were combined to estimate the round-trip net ton-miles per gallon on the Upper and Lower Mississippi River rivers as presented in table 18. Barges on the Lower Mississippi River are more fuel efficient than barges on the Upper Mississippi for backhauls of 50 percent or less. At 100 percent backhaul, there is little difference between river segments.

Table 18. Estimated barge round trip net ton-miles per gallon by Mississippi River segment and percent backhaul.

Percent backhaul	Net ton-miles per gallon	
	Upper Mississippi	Lower Mississippi
0	420.2	482.7
20	476.3	509.6
35	526.0	548.3
40	543.1	562.5
50	577.8	592.4
100	756.5	753.7

The estimated round-trip net ton-miles per gallon are generally higher than those reported in other studies. However, the Rice data and the upper range of the Hirst and the Cook data fall within our 50-100 percent backhaul range.

Ocean Vessels

Table 19 describes the 254 grain-carrying ocean ships included in this analysis. Over half (55 percent) of the ships are less than 35,000 deadweight tons, and 32 percent are 35,000-64,999 deadweight tons. A deadweight ton (dwt) is the total weight of cargo, bunkers, dunnage, provisions, stores, and spare parts, expressed in tons of 2,240 pounds. Age and size of the ships are highly correlated because the new vessels are increasingly heavier. Speeds are expressed in knots (1 knot equals 1.15 miles per hour).

Daily fuel consumption of the main engines and generators increases with ship size. The coefficient of

[3]It may seem counterintuitive that the sign of the coefficient of the N_b term is different between the two rivers. The original regressions (11) and (12) are consistent in sign. However, on the slower current of the Upper Mississippi River, G_r was more sensitive to both an increase in gross weight and the number of barges. More gross weight clearly increases fuel efficiency. Spreading the weight over more barges, however, results in more drag area and a negative sign for the N_b term. When equation (13) is substituted into (12), the gross weight advantage added by more barges is increasing faster than the drag reduction of those barges, causing a net shift in sign for the N_b term for the Lower Mississippi only.

Table 19. Estimated fuel consumption for ocean vessels.

Deadweight tons in (000)	Number of vessels	Gross weight tons	Average age, years from 1983	Steaming speed, knots	Ballast weight as percent of gross weight	Load factor	Draft, feet	Fuel consumed, tons per day: Main engines	Fuel consumed, tons per day: Generator	Gross ton-miles per gallon: 100 percent loaded miles	Gross ton-miles per gallon: 50 percent loaded miles	Net ton-miles per gallon: 100 percent loaded miles	Net ton-miles per gallon: 50 percent loaded miles
< 25.0	47	28,755	10.6	14.2	60.8	0.662	31.7	27.8	1.8	1,455.6	1,025.0	966.5	508.7
		(14.7)[a]	(0.2)	(5.9)	(12.0)	(5.0)	(5.4)	(15.5)	(19.4)	(14.3)	(14.3)	(16.6)	(16.6)
25.0-34.9	92	38,100	9.2	14.8	65.1	0.672	34.5	36.0	2.1	1,547.6	1,081.7	1,040.6	547.7
		(9.2)	(0.2)	(5.1)	(12.3)	(4.1)	(3.5)	(11.5)	(17.5)	(9.7)	(9.7)	(11.1)	(11.1)
35.0-44.9	40	49,648	10.9	14.7	64.7	0.690	37.6	40.7	2.1	1,769.3	1,219.9	1,219.6	641.9
		(8.1)	(0.3)	(4.5)	(11.7)	(4.5)	(3.9)	(9.2)	(14.7)	(8.1)	(8.1)	(8.2)	(8.2)
45.0-54.9	13	64,049	12.6	14.4	67.4	0.716	40.3	43.9	2.5	2,077.4	1,403.9	1,486.0	782.1
		(9.8)	(0.2)	(5.4)	(9.6)	(4.4)	(4.9)	(8.1)	(14.1)	(11.8)	(11.8)	(11.5)	(11.5)
55.0-64.9	29	74,726	7.0	14.7	69.7	0.716	41.7	48.7	2.3	2,263.6	1,529.7	1,621.0	853.2
		(3.5)	(0.2)	(4.5)	(5.9)	(1.9)	(3.1)	(15.8)	(27.3)	(12.1)	(12.1)	(12.0)	(12.0)
65.0-74.9	17	81,622	8.2	14.5	69.6	0.718	45.3	52.0	2.4	2,290.4	1,547.8	1,647.7	867.2
		(6.0)	(0.1)	(7.1)	(8.1)	(1.5)	(3.4)	(17.5)	(15.6)	(11.8)	(11.8)	(11.6)	(11.6)
75.0+	16	123,583	8.1	14.7	74.0	0.714	52.1	68.4	3.6	2,675.8	1,811.1	1,921.7	1,011.4
		(20.9)	(0.2)	(5.7)	(16.0)	(3.8)	(8.2)	(19.7)	(16.6)	(25.6)	(25.6)	(28.4)	(28.4)
TOTAL	254	51,997	9.5	14.6	65.8	0.686	37.4	40.2	2.1	1,795.4	1,241.7	1,240.3	652.8
		(50.0)	(0.2)	(5.5)	(12.4)	(5.0)	(15.2)	(29.3)	(22.9)	(25.0)	(25.0)	(28.5)	(28.5)

[a] Numbers in brackets are coefficients of variation.

variation of fuel consumption within a category was reasonably uniform (10-15) across size categories of vessels.

Typically, an empty ship carrying ballast will weigh about 60 percent of the loaded vessel. It is not appropriate, however, to estimate empty fuel consumption from the size category corresponding to 60 percent of loaded gross tons. Executives of shipping companies stated that ships under ballast use about 90 percent of the fuel used by a fully loaded ship at the same speed. This estimate was used to calculate ship fuel consumption under ballast. Note that until the cargo weight exceeds 60 percent of fully loaded, fuel consumption will be the same as if completely empty.

On the average, the 254 ships obtained 1,240 net ton-miles per gallon when loaded 100 percent of the distance and 653 net ton-miles per gallon when loaded 50 percent of the distance. Therefore, the ocean mode is the most fuel efficient of all grain transport modes. However, net ton-miles also varies with size. The smallest ships obtain only 509 net ton-miles per gallon whereas the largest size ships achieve 1,011 net ton-miles per gallon when loaded 50 percent of the distance. The smallest ships are roughly comparable to newer barges at 35 percent backhaul.

Four regression equations were estimated for ocean vessels:

$$G_i = 1{,}142.3 + 0.015696\, W_d \qquad R^2 = 0.73;\ CV = 13.0 \tag{16}$$

$$k_i = 0.654 + 7.766030 \times 10^{-7} W_d \qquad R^2 = 0.36;\ CV = 4.2 \tag{17}$$

and

$$N_i = 543.8 + 0.0199\, W_d - 5.6381 \times 10^{-8} (W_d)^2 \qquad R^2 = 0.36;\ CV = 13.8 \tag{18}$$

$$G_c = 202.4 + 0.0398\, W_d \qquad R^2 = 0.97;\ CV = 9.6 \tag{19}$$

where

G_c = grain-carrying capacity in thousands of cubic feet,
W_d = deadweight tons.

Figure 5 shows the scatter of net ton-miles per gallon of dwt and the shape of equation (18).

Engineering mechanics dictate that speed will be a significant variable in determining fuel consumption. Because available speed data are steaming speeds for different ships, it would not be reasonable to draw conclusions about the effects of steaming speed on a particular vessel. Ship company executives indicate that, on average, fuel consumption declines about 20 percent for each 10 percent reduction in speed. This relationship can be used to approximate ocean fuel consumption under slower than normal speeds.

There is a strong relationship between dwt and ship draft. This relationship was estimated by the following regression equation:

$$DR = 28.0 + 2.2575 \times 10.0\, W_d \qquad R^2 = 0.94;\ CV = 3.8 \tag{20}$$

where

DR = draft, feet.

By substituting equation (20) into equation (16), G_i can be related to draft as follows:

$$G_i = 1{,}194 + 70.8695\,(DR - 27.65) \qquad (21)$$

This equation can be used to estimate fuel consumption to ports with restricted depths [5]. If the port depth is known, equation (20) can be used to estimate the fuel consumption to that port for a vessel drawing the maximum draft at that port.

The actual grain-carrying capacity of an ocean vessel is less than its deadweight tons. This is because grain takes up more cubic feet per long ton (2,240 pounds) than heavier bulk commodities like coal and ore. Corn requires 50 cubic feet per long ton, and wheat and soybeans require 48 cubic feet per long ton. Nevertheless, the grain-carrying capacity of a vessel is positively related to its dwt as specified in equation (19).

By using equation (19), a 50,000 dwt vessel has a grain-carrying capacity of 2,192,400 cubic feet and can load 43,848 long tons of corn. All ocean vessel fuel consumption estimates in this study are based on actual grain-carrying capacity rather than on dwt.

The amount of fuel required to move one short ton (2,000 pounds) of grain from both NOLA and the West Coast to Japan is given in table 20. For the West Coast-Japan route, ships are assumed to be loaded to Japan and empty (ballast) on return to the West Coast, as outlined in figure 4. Two alternative assumptions were made for the NOLA-Japan route: first, the ship would steam from Amsterdam to NOLA under ballast, then steam loaded with grain from NOLA to Japan; or second, the ship would enter NOLA loaded, unload, then reload with grain destined to Japan. The assumed levels of daily generator fuel consumption are 1.5 long tons for a 30,000 dwt ship, 2.0 long tons for a 50,000 dwt ship, 2.5 long tons for a 70,000 dwt ship, and 3.0 long tons for a 100,000 dwt ship.

Table 20. Estimated gallons of fuel required to move one short ton of grain from NOLA and West Coast ports to Japan and from NOLA to Amsterdam by ocean vessel.

Deadweight tons	Tacoma-Japan-Tacoma route	Amsterdam-NOLA-Japan route	One-way NOLA-Japan route	Amsterdam-NOLA-Amsterdam route
30,000	7.8	13.0	8.7	8.9
50,000	6.1	10.2	6.8	7.0
70,000	5.1	8.6	5.7	5.9
100,000	4.4	a/	a/	5.2

a/ Ships over approximately 70,000 dwt cannot traverse the Panama Canal.

Only 60 percent as much fuel is required to move one ton of grain from the West Coast to Japan as is required for the Amsterdam-NOLA-Japan route. About 13 percent more fuel is required for a one-way trip NOLA-Japan than for the West Coast-Japan and return route.

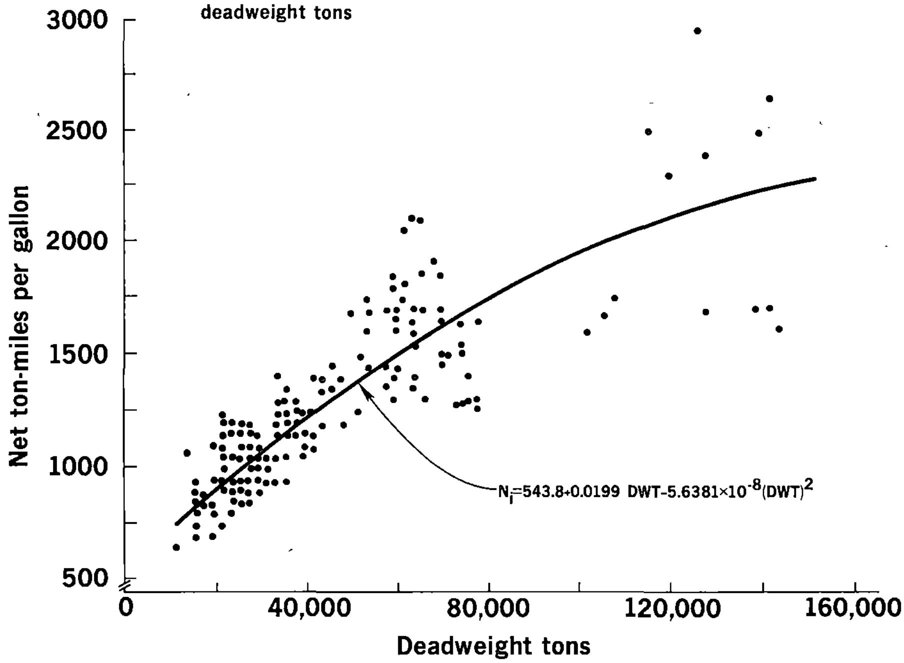
Major fuel savings occur if the grain moves in larger ships. About 70 percent as much fuel is required to move grain in 70,000 dwt vessels as is required for a 30,000 dwt vessel.

Summary of Modal Results

A summary of the fuel usage characteristics by mode is presented in table 21. The ocean and barge regression equations were used to generate values in this table.

In energy terms, fuel consumption in gallons is not directly comparable across modes. Trucks, railroad locomotives, and towboats use number 2 diesel fuel, which is normally assumed to contain 140,000

Figure 5. Net ton-miles per gallon of fuel for a sample of ocean grain ships by deadweight tons



Source: The Journal of Commerce and Commercial, February 1-July 31, 1982 and The Bulk Carrier Register-1982.

Table 21. 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)	Coefficient of variation of G_i[a]	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 (14), with an average tow size of 15.

[d] From regression equation (15), with an average tow size of 24.

[e] From regression equations (16), (17), (18), and (19).

[f] From equation (5).

[g] From equation (6).

Btu per gallon. Ocean vessels use number 2 to number 6 fuel oil. The heavier, less refined fuels contain increasingly more energy; i.e., 160,000 Btu per gallon for number 6 fuel oil. We recognize that aggregating gallons across modes is not precisely accurate from an energy standpoint. The key measure in an economic sense, however, is fuel cost. This intermodal fuel analysis is based on gallons because a fuel-cost comparison of routings can be developed from gallons consumed and fuel prices.

Combined Fuel Consumption from Iowa to Japan

An important use of the modal fuel consumption data is to estimate the direct fuel requirements and fuel costs to transport grain from origins to destinations under several routing alternatives. Tables 22, 23, and 24 show the estimated gallons of fuel required to transport a 2,000-pound ton of grain from Iowa origins to Yokohama, Japan. The alternative modal combinations include unit trains direct to Tacoma and NOLA; unit-train-barge and truck-barge combinations to NOLA with 30,000, 50,000, and 70,000 dwt ocean vessels to Japan. The truck movements included trips with 50 and 100 percent loaded miles. The metered truck fuel consumption data were used in all estimates of total fuel consumption in tables 22 to 29. The ocean vessels leaving Tacoma are assumed to steam loaded to Japan and return under ballast to Tacoma; the vessels leaving NOLA steam under ballast from Amsterdam to NOLA where they are loaded with grain destined for Yokohama. Gallons of fuel were calculated from equations (8) and (9), then combined into aggregate estimates with equation (7).

Under these assumptions, the West Coast option uses the smallest amount of fuel per ton of grain for all Iowa locations and all ships. Even though unit trains to the West Coast consume more fuel per ton of grain than unit trains to NOLA, the shorter distance from the West Coast to Japan gives it a consistent fuel advantage.

With 30,000 dwt ships, the West Coast requires 2.5 to 4.2 fewer gallons of fuel per ton of grain than the best NOLA-Japan option. The West Coast advantage is greatest for western Iowa origins and least for eastern Iowa origins. If similar sized ships are used, the West Coast route requires less fuel even for origins on the Mississippi River, where no truck or rail fuel would be needed.

The West Coast fuel advantage declines as ship size increases. With 50,000 dwt vessels, the West Coast represents a 1.2 to 2.6 gallon fuel savings over the best NOLA-Japan option. Again, the West Coast fuel advantage is greatest for western Iowa origins and smallest for eastern Iowa origins.

As illustrated in table 25, the fuel savings of West Coast grain shipments disappear for eastern Iowa origins when 50,000 dwt ships out of Tacoma are compared with 30,000 dwt ships that enter NOLA loaded with cargo, unload, and reload with grain for Japan. In this instance, the 30,000 dwt vessel has no ballast distance to charge to the grain shipment. An

Table 22. Estimated total fuel consumption in gallons per short ton, and fuel cost in dollars per short ton, to transport grain from Iowa origins to Yokohama, Japan via alternative surface modes and 30,000 dwt ocean vessels.

	Unit trains direct to		Unit-train-barge to NOLA by percent barge backhaul[b/]			Truck-barge to NOLA: 100 percent truck backhaul by percent barge backhaul[b/]			Truck-barge to NOLA: Zero truck backhaul by percent barge backhaul[b/]		
Iowa origins	Tacoma,[a/] WA	NOLA[b/]	0	35	100	0	35	100	0	35	100
Sioux City											
gallons	13.4	17.3	18.7	18.2	17.4	20.2	19.7	18.9	21.7	21.2	20.5
standard error	(1.7)	(2.1)	(2.5)	(2.4)	(2.3)	(2.6)	(2.5)	(2.4)	(2.7)	(2.6)	(2.6)
fuel cost	$9.49	$11.26	$12.58	$12.13	$11.46	$14.36	$13.91	$13.24	$16.17	$15.72	$15.05
Council Bluffs											
gallons	13.2	17.4	18.6	18.1	17.4	20.0	19.5	18.8	21.6	21.1	20.4
standard error	(1.7)	(2.1)	(2.5)	(2.4)	(2.3)	(2.6)	(2.5)	(2.4)	(2.7)	(2.6)	(2.5)
fuel cost	$9.31	$11.36	$12.51	$12.09	$11.45	$14.23	$13.80	$13.17	$16.04	$15.61	$14.97
Algona											
gallons	13.4	17.3	18.6	18.0	17.3	19.4	18.8	18.1	20.2	19.6	18.9
standard error	(1.7)	(2.1)	(2.5)	(2.4)	(2.3)	(2.6)	(2.5)	(2.4)	(2.6)	(2.5)	(2.5)
fuel cost	$9.53	$11.27	$12.47	$11.99	$11.30	$13.41	$12.92	$12.24	$14.36	$13.88	$13.19
Boone											
gallons	13.5	17.1	18.4	17.9	17.2	19.3	18.8	18.1	20.3	19.8	19.1
standard error	(1.7)	(2.1)	(2.5)	(2.4)	(2.3)	(2.5)	(2.5)	(2.4)	(2.6)	(2.5)	(2.5)
fuel cost	$9.62	$11.15	$12.28	$11.85	$11.22	$13.39	$12.96	$12.33	$14.52	$14.10	$13.46
Cedar Rapids											
gallons	13.8	17.0	18.2	17.7	17.0	18.6	18.1	17.4	19.0	18.5	17.8
standard error	(1.7)	(2.1)	(2.5)	(2.4)	(2.3)	(2.5)	(2.4)	(2.3)	(2.5)	(2.5)	(2.4)
fuel cost	$9.86	$10.98	$12.10	$11.67	$11.03	$12.56	$12.14	$11.50	$13.04	$12.61	$11.97
Burlington											
gallons	14.2	16.7	17.8	17.4	16.7	17.8	17.4	16.7	17.8	17.4	16.7
standard error	(1.8)	(2.1)	(2.4)	(2.4)	(2.3)	(2.4)	(2.4)	(2.3)	(2.4)	(2.4)	(2.3)
fuel cost	$10.23	$10.78	$11.73	$11.35	$10.77	$11.73	$11.35	$10.77	$11.73	$11.35	$10.77

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.

Table 23. Estimated total fuel consumption in gallons per short ton, and fuel cost in dollars per short ton, to transport grain from 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: 100 percent truck backhaul by percent barge backhaul[b/]			Truck-barge to NOLA: Zero truck backhaul by percent barge backhaul[b/]		
Iowa origins	Tacoma,[a/] WA	NOLA[b/]	0	35	100	0	35	100	0	35	100
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
standard error	(1.4)	(1.8)	(2.0)	(2.0)	(1.9)	(2.1)	(2.1)	(2.0)	(2.3)	(2.2)	(2.1)
fuel cost	$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
standard error	(1.4)	(1.9)	(2.0)	(1.9)	(1.9)	(2.1)	(2.1)	(2.0)	(2.2)	(2.2)	(2.1)
fuel cost	$8.10	$9.32	$10.48	$10.05	$9.42	$12.19	$11.77	$11.13	$14.00	$13.57	$12.94
Algona											
gallons	11.5	14.0	15.3	14.7	14.0	16.0	15.5	14.7	16.9	16.3	15.6
standard error	(1.4)	(1.8)	(2.0)	(2.0)	(1.9)	(2.1)	(2.0)	(1.9)	(2.2)	(2.1)	(2.0)
fuel cost	$8.31	$9.24	$10.44	$9.95	$9.27	$11.37	$10.89	$10.20	$12.32	$11.84	$11.15
Boone											
gallons	11.6	13.8	15.0	14.6	13.9	16.0	15.5	14.8	17.0	16.5	15.8
standard error	(1.4)	(1.8)	(2.0)	(1.9)	(1.9)	(2.1)	(2.0)	(1.9)	(2.1)	(2.1)	(2.0)
fuel cost	$8.41	$9.11	$10.24	$9.82	$9.18	$11.35	$10.93	$10.29	$12.49	$12.06	$11.43
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
standard error	(1.5)	(1.8)	(2.0)	(1.9)	(1.9)	(2.0)	(2.0)	(1.9)	(2.1)	(2.0)	(1.9)
fuel cost	$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
standard error	(1.5)	(1.8)	(2.0)	(1.9)	(1.8)	(2.0)	(1.9)	(1.8)	(2.0)	(1.9)	(1.8)
fuel cost	$9.02	$8.75	$9.69	$9.31	$8.74	$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.

Table 24. Estimated total fuel consumption in gallons per short ton, and fuel cost in dollars per short ton, to transport grain from Iowa origins to Yokohama, Japan via alternative surface modes and 70,000 dwt ocean vessels.

	Unit trains direct to		Unit-train-barge to NOLA by percent barge backhaul[b/]			Truck-barge to NOLA: 100 percent truck backhaul by percent barge backhaul[b/]			Truck-barge to NOLA: Zero truck backhaul by percent barge backhaul[b/]		
Iowa origins	Tacoma,[a/] WA	NOLA[b/]	0	35	100	0	35	100	0	35	100
Sioux City											
gallons	10.3	12.0	13.4	12.9	12.2	14.9	14.4	13.7	16.5	16.0	15.2
standard error	(1.3)	(1.6)	(1.8)	(1.7)	(1.6)	(1.9)	(1.8)	(1.7)	(2.0)	(1.9)	(1.8)
fuel cost	$7.55	$8.00	$9.33	$8.87	$8.20	$11.11	$10.66	$9.99	$12.92	$12.46	$11.79
Council Bluffs											
gallons	10.1	12.1	13.3	12.9	12.2	14.8	14.3	13.6	16.3	15.9	15.2
standard error	(1.3)	(1.6)	(1.7)	(1.7)	(1.6)	(1.9)	(1.8)	(1.7)	(2.0)	(1.9)	(1.8)
fuel cost	$7.37	$8.10	$9.26	$8.83	$8.20	$10.98	$10.55	$9.91	$12.78	$12.35	$11.72
Algona											
gallons	10.3	12.0	13.3	12.8	12.0	14.1	13.6	12.8	14.9	14.4	13.6
standard error	(1.3)	(1.6)	(1.8)	(1.7)	(1.6)	(1.8)	(1.8)	(1.7)	(1.9)	(1.8)	(1.7)
fuel cost	$7.59	$8.02	$9.22	$8.73	$8.05	$10.15	$9.67	$8.98	$11.11	$10.62	$9.94
Boone											
gallons	10.4	11.9	13.1	12.6	11.9	14.0	13.6	12.9	15.0	14.5	13.8
standard error	(1.3)	(1.6)	(1.7)	(1.7)	(1.6)	(1.8)	(1.8)	(1.7)	(1.9)	(1.8)	(1.7)
fuel cost	$7.68	$7.89	$9.02	$8.60	$7.96	$10.13	$9.71	$9.07	$11.27	$10.84	$10.21
Cedar Rapids											
gallons	10.7	11.7	12.9	12.5	11.7	13.3	12.8	12.1	13.7	13.3	12.5
standard error	(1.3)	(1.5)	(1.7)	(1.7)	(1.6)	(1.8)	(1.7)	(1.6)	(1.8)	(1.7)	(1.6)
fuel cost	$7.92	$7.73	$8.84	$8.41	$7.78	$9.31	$8.88	$8.25	$9.78	$9.36	$8.72
Burlington											
gallons	11.1	11.5	12.5	12.1	11.5	12.5	12.1	11.5	12.5	12.1	11.5
standard error	(1.4)	(1.5)	(1.7)	(1.6)	(1.6)	(1.7)	(1.6)	(1.6)	(1.7)	(1.6)	(1.6)
fuel cost	$8.29	$7.53	$8.47	$8.09	$7.52	$8.47	$8.09	$7.52	$8.47	$8.09	$7.52

[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.

Table 25. Estimated total fuel consumption in gallons per short ton, and fuel cost in dollars per short ton to transport grain from Iowa origins to Yokohama, Japan using a 50,000 dwt ocean vessel from Tacoma and a 30,000 dwt ocean vessel from NOLA with no empty miles.

	Unit trains direct to		Unit-train-barge to NOLA by percent barge backhaul[b/]			Truck-barge to NOLA: 100 percent truck backhaul by percent barge backhaul[b/]			Truck-barge to NOLA: Zero truck backhaul by percent barge backhaul[b/]		
Iowa origins	Tacoma,[a/] WA	NOLA[b/]	0	35	100	0	35	100	0	35	100
Sioux City											
gallons	11.4	12.4	13.8	13.3	12.5	15.3	14.8	14.0	16.8	16.3	15.6
standard error	(1.4)	(1.6)	(1.8)	(1.7)	(1.6)	(1.9)	(1.9)	(1.8)	(2.0)	(2.0)	(1.9)
fuel cost	$8.27	$8.24	$9.56	$9.11	$8.44	$11.34	$10.89	$10.22	$13.15	$12.70	$12.03
Council Bluffs											
gallons	11.2	12.5	13.7	13.2	12.5	15.1	14.6	13.9	16.7	16.2	15.5
standard error	(1.4)	(1.6)	(1.8)	(1.7)	(1.6)	(1.9)	(1.9)	(1.8)	(2.0)	(2.0)	(1.9)
fuel cost	$8.10	$8.34	$9.49	$9.07	$8.43	$11.21	$10.78	$10.15	$13.02	$12.59	$11.95
Algona											
gallons	11.6	12.4	13.7	13.1	12.4	14.5	13.9	13.2	15.3	14.7	14.0
standard error	(1.4)	(1.6)	(1.8)	(1.7)	(1.7)	(1.9)	(1.8)	(1.7)	(1.9)	(1.9)	(1.8)
fuel cost	$8.31	$8.25	$9.45	$8.97	$8.28	$10.39	$9.90	$9.22	$11.34	$10.86	$10.17
Boone											
gallons	11.5	12.2	13.5	13.0	12.3	14.4	13.9	13.2	15.4	14.9	14.2
standard error	(1.4)	(1.6)	(1.8)	(1.7)	(1.6)	(1.9)	(1.8)	(1.7)	(1.9)	(1.9)	(1.8)
fuel cost	$8.41	$8.13	$9.26	$8.83	$8.20	$10.37	$9.94	$9.31	$11.50	$11.08	$10.44
Cedar Rapids											
gallons	11.8	12.1	13.3	12.8	12.1	13.7	13.2	12.5	14.1	13.6	12.9
standard error	(1.5)	(1.6)	(1.8)	(1.7)	(1.6)	(1.8)	(1.8)	(1.7)	(1.8)	(1.8)	(1.7)
fuel cost	$8.64	$7.96	$9.08	$8.65	$8.01	$9.54	$9.12	$8.48	$10.02	$9.59	$8.95
Burlington											
gallons	12.2	11.8	12.9	12.5	11.8	12.9	12.5	11.8	12.9	12.5	11.8
standard error	(1.5)	(1.6)	(1.7)	(1.7)	(1.6)	(1.7)	(1.7)	(1.6)	(1.7)	(1.7)	(1.6)
fuel cost	$9.02	$7.76	$8.71	$8.33	$7.75	$8.71	$8.33	$7.75	$8.71	$8.33	$7.75

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

[b/] Ship steams loaded to NOLA where it is unloaded and reloaded with grain to Yokohama.

example would be a ship hauling cars from Japan to NOLA and returning to Japan loaded with grain. Under this assumption, the best NOLA route option is about as fuel efficient as the West Coast option from as far west as Cedar Rapids, Iowa. West of Cedar Rapids, however, Tacoma was the most fuel efficient port under any scenario.

Of all the reasonable possibilities for NOLA routing to Japan, the largest fuel savings can be achieved by shifting to larger ocean vessels. The data in tables 22, 23, and 24 indicate that shifting from 30,000 dwt ships to 50,000 dwt ships will save about 3.0 gallons of fuel per ton. Shifting to 70,000 dwt vessels will save an additional 2.0 gallons of fuel per ton of grain. Alternatively, with a 30,000 dwt ship and no ballast miles, about the same amount of fuel is used per ton of grain as with a 70,000 dwt ship steaming under ballast from Rotterdam to NOLA and loaded with grain from NOLA to Japan.

There is little difference between the total fuel consumption of unit trains direct to NOLA and of the unit-train-barge combination to NOLA with 100 percent loaded barge backhaul. Therefore, the next largest savings in fuel consumption in the NOLA-Japan alternatives can be achieved by shifting to unit trains direct to Gulf ports or to unit-train-barge combinations with 100 percent barge backhaul. As the percentage of barge backhaul declines, however, direct unit trains become more fuel efficient. At a 35 percent barge backhaul, the unit-train-barge combination consumes from 0.7 to 0.9 more gallons of fuel per ton of grain than the unit train direct to NOLA ports. At zero barge backhaul, the unit-train-barge combination consumes 1.1 to 1.4 more gallons of fuel per ton of grain than the unit train direct to NOLA ports. One reason unit trains direct to NOLA consume less fuel per ton of grain than the unit-train-barge combination with less than 100 percent barge backhaul is that unit trains direct to NOLA travel fewer total miles than the unit-train-barge combination. For example, the one-way, unit-train distance from Boone, Iowa, to NOLA over the combined route used by railroad companies 4 and 5 through Dupo, Illinois, is 1,310 miles. The one-way train miles from Boone to Clinton, Iowa, is 197 miles, and the one-way barge distance from Clinton to New Orleans is 1,366 miles. Thus, the direct unit-train route is 253 miles shorter than the unit-train-barge combination route. The longer barge distance is due to the meandering of the Mississippi River. A second reason unit trains direct to NOLA consume less fuel than the unit-train-barge combination is that the largest share of total barge fuel consumption is required to return northbound against the current of the Mississippi River. The data in table 17 indicate that the barges included in this analysis achieved 953 net ton-miles per gallon southbound and only 243 net ton-miles per gallon northbound on the Upper Mississippi River. On the Lower Mississippi, the sample barges achieved 1,290 net ton-miles per gallon on the southbound trip and only 184 net ton-miles per gallon on the northbound trip. Barge fuel efficiency, however, measured in net ton-miles per gallon, climbs dramatically as the percentage of backhaul increases.

The next most fuel efficient modal combination to transport grain to Japan through NOLA is the truck-barge combination where the truck is loaded to the Mississippi River, unloads at a barge elevator and picks up a load to haul elsewhere or returns to the original elevator loaded with products from the river. Except for origins located on the Mississippi River, the truck-barge combination to NOLA with 100 percent truck backhaul consumes 1.1 to 2.8 more gallons of fuel per ton of grain than unit trains direct to NOLA and 0.4 to 1.5 more gallons of fuel per ton of grain than the unit-train-barge combination. The truck-barge combination to NOLA with no truck backhaul consumes more fuel per ton of grain than all the other combinations examined in this study. Depending on the origin of the grain, the truck-barge combination with no truck backhaul uses 1.9 to 4.3 more gallons of fuel per ton of grain than the unit train direct and 0.8 to 3.0 more gallons of fuel per ton of grain than the unit-train-barge combination. The truck-barge combination with no truck backhaul uses 0.4 to 1.5 more gallons of fuel per ton of grain than the truck-barge combination with 100 percent truck backhaul; all this additional fuel is required for the empty truck to return to the originating elevator.

If the fuel consumption estimates based on company records had been used in place of the metered truck estimates, the impact would have varied by the mode of shipment and the origin and destination of the grain; the impact would have been zero for shipments to the West Coast, for all rail-barge shipments to NOLA, and for truck-barge shipments from Burlington to NOLA. The company record truck estimates would have added 0.3 gallon of fuel per ton of grain shipped by truck-barge from Boone to NOLA.

The standard error of the fuel consumption estimates is about 12.5 percent of total fuel consumption per ton of grain for the West Coast option and about 13 percent of total fuel consumption for the NOLA options. In absolute values, the standard error is about 1.5 gallons per short ton for West Coast to Japan shipments, 1.5 to 2.1 gallons per short ton for unit trains direct to NOLA and then ocean vessel to Japan shipments, and 1.6 to 2.6 for barge combinations through NOLA to Japan. The procedure for calculating the standard errors is presented in the Appendix.

Combined Fuel Cost from Iowa to Japan

Tables 22, 23, 24, and 25 also show the estimated total fuel cost in shipping one short ton of grain from Iowa origins to Japan via alternative modes and routes. Truck fuel was priced at $1.15 per gallon; ocean vessel generator fuel and rail and barge fuel were priced at $0.90 per gallon; and ocean vessel propulsion fuel was priced at $0.60 per gallon [20].

Using 30,000 dwt ocean vessels, the total fuel cost of the West Coast option is lower than all NOLA model options. The fuel cost of the West Coast option is about $0.55 per short ton of grain less than the best NOLA option out of Burlington in eastern Iowa and

$1.77 cheaper than the best NOLA option out of Council Bluffs in western Iowa.

The West Coast fuel cost advantage declines as ocean vessel size increases. With 50,000 dwt ocean vessels, the NOLA options of unit trains direct and barges with 100 percent backhaul originating at Burlington have a slight fuel cost advantage, but the West Coast option retains the fuel cost advantage for all other Iowa origins.

With 70,000 dwt ocean vessels, the NOLA option has a fuel cost advantage out of Burlington with unit trains direct and barges with 35 and 100 percent backhaul. The NOLA option also has a slight fuel cost advantage out of Cedar Rapids with the unit trains direct and unit-train-barges with 100 percent barge backhaul.

By comparing a 50,000 dwt vessel out of Tacoma and a 30,000 dwt vessel with no ballast distance out of NOLA, the NOLA option has a fuel cost advantage for all modal combinations out of Burlington; out of Cedar Rapids, the NOLA option had a fuel cost advantage over the West Coast for unit trains direct to NOLA, unit-train-barges with 35 and 100 percent backhaul, and one-way truck-barge with 100 percent barge backhaul; out of Boone and Algona, unit trains direct to NOLA and unit-train-barges with 100 percent barge backhaul had a slight fuel cost advantage over the West Coast option.

When fuel costs in hauling grain to the Mississippi River are compared, truck cost ranges from $0.46 to $2.06 per short ton more than unit trains out of Cedar Rapids and $1.78 to $3.59 out of Sioux City. The higher costs are for zero truck backhaul.

Combined Fuel Consumption from Iowa to Europe

Tables 26, 27, 28, and 29 show the estimated gallons of fuel required to transport one short ton of grain from Iowa origins to Amsterdam via alternative modal combinations through the NOLA ports. The alternative modal combinations include unit trains direct to NOLA; unit-train-barge and truck-barge combinations to NOLA; and 30,000, 50,000, 70,000, and 100,000 dwt ocean vessels to Amsterdam. The truck movements include trips with 100 percent backhaul as well as trips with zero percent backhaul. The vessels leaving NOLA steam under ballast from Amsterdam to NOLA where they are loaded with grain destined for Amsterdam.

Of the alternatives examined in this analysis in shipping grain to Amsterdam via NOLA, the largest savings in total fuel consumption can be achieved by shifting to larger ocean vessels. The data in tables 26, 27, 28, and 29 indicate that shifting from 30,000 dwt ships to 50,000 dwt ships would save about 2.3 gallons of fuel per ton of grain; shifting to 70,000 dwt vessels would save an additional 1.2 gallons of fuel per ton of grain; and using a 100,000 dwt vessel would save an additional 1.1 gallon of fuel per short ton. Thus, a 100,000 dwt vessel will reduce fuel consumption 4.6 gallons per short ton from a 30,000 dwt vessel when shipping from NOLA to Amsterdam.

The next largest savings in fuel consumption can be achieved by shifting to unit trains direct to NOLA or to the unit-train-barge combination with a 100 percent barge backhaul. There is little difference between the total fuel consumption of unit trains direct to NOLA and unit-train-barges with 100 percent barge backhaul. Direct unit trains become more fuel efficient, however, as the percentage of barge backhaul declines. At a 35 percent barge backhaul—the approximate percentage backhaul of the barges in this analysis—the unit-train-barge combination consumes from 0.6 to 0.9 more gallons of fuel per ton of grain than unit trains direct. At zero barge backhaul, the unit-train-barge combination consumes 1.0 to 1.4 more gallons of fuel per ton of grain than do unit trains direct to NOLA.

The next most fuel efficient modal combination to transport grain to NOLA is truck-barge with 100 percent truck backhaul. Except for origins located on the Mississippi River, the truck-barge combination with 100 percent truck backhaul consumes 1.6 to 2.9 more gallons of fuel per ton of grain than do unit trains direct to New Orleans and 0.4 to 1.5 more gallons of fuel per ton of grain than the best unit-train-barge combination. The truck-barge combination with zero truck backhaul consumes more fuel per ton of grain than all the other combinations examined in this study. Depending on the origin of the grain, the truck-barge combination with no truck backhaul uses 2.0 to 4.5 more gallons of fuel per ton of grain than do unit trains direct and 0.8 to 3.5 more fuel per ton of grain than the unit-train-barge combination. The truck-barge combination with no backhaul uses 0.4 to 1.6 more gallons of fuel per ton of grain than the truck-barge combination with 100 percent truck backhaul.

The standard error of the fuel consumption estimates from Iowa origins to Amsterdam is about 12 percent of total fuel consumption for unit trains direct to NOLA and about 13 percent of total rail-barge and truck-barge fuel consumption. In absolute values, the standard errors range from 0.8 to 1.5 gallons of fuel for unit trains through NOLA to Rotterdam and 1.0 to 2.0 gallons of fuel for barge combinations through NOLA to Rotterdam. The largest standard errors are for small ships and for the truck-barge combination.

Combined Fuel Cost from Iowa to Europe

Tables 26, 27, 28, and 29 also show the estimated total fuel cost in shipping 1 ton of grain from Iowa origins to Amsterdam via alternative modal combinations. Fuel was priced at the same levels as in the fuel cost analysis to Japan.

Shifting from 30,000 dwt to 50,000 dwt ocean vessels would save $1.39 in fuel costs per ton of grain; shifting to 70,000 dwt vessels would save an additional $0.78 per ton of grain, and 100,000 dwt vessels would save an additional $0.66 per ton of grain. Fuel cost savings in shifting from 30,000 to 100,000 dwt vessels total $2.83 per ton of grain.

Table 26. Estimated total fuel consumption in gallons per short ton, and fuel cost in dollars per short ton, to transport grain from Iowa origins to Amsterdam, Netherlands via alternative surface modes and 30,000 dwt ocean vessels.

Iowa origins	Unit trains direct to NOLA[a]	Unit-train-barge to NOLA by percent barge backhaul[b]			Truck-barge to NOLA: 100 percent truck backhaul by percent barge backhaul[b]			Truck-barge to NOLA: Zero truck backhaul by percent barge backhaul[b]		
		0	35	100	0	35	100	0	35	100
Sioux City										
gallons	12.5	13.9	13.4	12.7	15.4	14.9	14.2	17.0	16.5	15.7
standard error	(1.5)	(1.8)	(1.8)	(1.7)	(2.0)	(1.9)	(1.8)	(2.1)	(2.0)	(1.9)
fuel cost	$8.33	$9.61	$9.15	$8.48	$11.44	$10.98	$10.31	$13.24	$12.79	$12.12
Council Bluff										
gallons	12.6	13.8	13.4	12.7	15.3	14.8	14.1	16.8	16.4	15.7
standard error	(1.5)	(1.8)	(1.7)	(1.7)	(1.9)	(1.9)	(1.8)	(2.0)	(2.0)	(1.9)
fuel cost	$8.43	$9.53	$9.10	$8.47	$11.30	$10.88	$10.24	$13.11	$12.68	$12.05
Algona										
gallons	12.5	13.8	13.3	12.5	14.6	14.1	13.3	15.4	14.9	14.1
standard error	(1.5)	(1.8)	(1.8)	(1.7)	(1.9)	(1.8)	(1.7)	(2.0)	(1.9)	(1.8)
fuel cost	$8.34	$9.52	$9.03	$8.35	$10.48	$9.99	$9.31	$11.43	$10.95	$10.26
Boone										
gallons	12.4	13.6	13.1	12.4	14.5	14.1	13.4	15.5	15.1	14.3
standard error	(1.4)	(1.8)	(1.7)	(1.7)	(1.9)	(1.8)	(1.7)	(1.9)	(1.9)	(1.8)
fuel cost	$8.22	$9.32	$8.89	$8.26	$10.46	$10.04	$9.40	$11.60	$11.17	$10.53
Cedar Rapids										
gallons	12.2	13.4	13.0	12.3	13.8	13.3	12.6	14.2	13.8	13.1
standard error	(1.4)	(1.8)	(1.7)	(1.7)	(1.8)	(1.8)	(1.7)	(1.9)	(1.8)	(1.7)
fuel cost	$8.06	$9.16	$8.73	$8.09	$9.63	$9.21	$8.57	$10.11	$9.68	$9.05
Burlington										
gallons	12.0	13.0	12.6	12.0	13.0	12.6	12.0	13.0	12.6	12.0
standard error	(1.4)	(1.8)	(1.7)	(1.6)	(1.8)	(1.7)	(1.6)	(1.8)	(1.7)	(1.6)
fuel cost	$7.85	$8.80	$8.42	$7.84	$8.80	$8.42	$7.84	$8.80	$8.42	$7.84

[a] Ship steams loaded from NOLA to Amsterdam and returns empty to NOLA.

Table 27. Estimated total fuel consumption in gallons per short ton, and fuel cost in dollars per short ton, to transport grain from Iowa origins to Amsterdam, Netherlands via alternative surface modes and 50,000 dwt ocean vessels.

Iowa origins	Unit trains direct to NOLA[a]	Unit-train-barge to NOLA by percent barge backhaul[b]			Truck-barge to NOLA: 100 percent truck backhaul by percent barge backhaul[b]			Truck-barge to NOLA: Zero truck backhaul by percent barge backhaul[b]		
		0	35	100	0	35	100	0	35	100
Sioux City										
gallons	10.3	11.7	11.2	10.4	13.2	12.7	11.9	14.7	14.2	13.5
standard error	(1.1)	(1.5)	(1.4)	(1.4)	(1.6)	(1.6)	(1.5)	(1.7)	(1.7)	(1.6)
fuel cost	$6.94	$8.21	$7.76	$7.09	$10.04	$9.59	$8.92	$11.85	$11.39	$10.72
Council Bluff										
gallons	10.4	11.6	11.1	10.4	13.0	12.5	11.8	14.6	14.1	13.4
standard error	(1.1)	(1.5)	(1.4)	(1.3)	(1.6)	(1.6)	(1.5)	(1.7)	(1.7)	(1.6)
fuel cost	$7.04	$8.14	$7.71	$7.08	$9.91	$9.48	$8.85	$11.71	$11.29	$10.65
Algona										
gallons	10.3	11.6	11.0	10.3	12.3	11.8	11.0	13.2	12.6	11.9
standard error	(1.1)	(1.5)	(1.5)	(1.4)	(1.6)	(1.5)	(1.4)	(1.6)	(1.6)	(1.5)
fuel cost	$6.95	$8.13	$7.64	$6.96	$9.08	$8.60	$7.91	$10.04	$9.55	$8.87
Boone										
gallons	10.1	11.3	10.9	10.2	12.3	11.8	11.1	13.3	12.8	12.1
standard error	(1.1)	(1.5)	(1.4)	(1.3)	(1.6)	(1.5)	(1.4)	(1.6)	(1.6)	(1.5)
fuel cost	$6.83	$7.93	$7.50	$6.86	$9.07	$8.64	$8.01	$10.20	$9.78	$9.14
Cedar Rapids										
gallons	9.9	11.2	10.7	10.0	11.6	11.1	10.4	12.0	11.5	10.8
standard error	(1.1)	(1.5)	(1.4)	(1.3)	(1.5)	(1.5)	(1.4)	(1.6)	(1.5)	(1.4)
fuel cost	$6.66	$7.76	$7.34	$6.70	$8.24	$7.82	$7.18	$8.72	$8.29	$7.65
Burlington										
gallons	9.7	10.8	10.3	9.7	10.8	10.3	9.7	10.8	10.3	9.7
standard error	(1.1)	(1.5)	(1.4)	(1.3)	(1.5)	(1.4)	(1.3)	(1.5)	(1.4)	(1.3)
fuel cost	$6.46	$7.41	$7.03	$6.45	$7.41	$7.03	$6.45	$7.41	$7.03	$6.45

[a] Ship steams loaded from NOLA to Amsterdam and returns empty to NOLA.

Table 28. Estimated total fuel consumption in gallons per short ton, and fuel cost in dollars per short ton, to transport grain from Iowa origins to Amsterdam, Netherlands via alternative surface modes and 70,000 dwt ocean vessels.

Iowa origins	Unit trains direct to NOLA[a]	Unit-train-barge to NOLA by percent barge backhaul[b]			Truck-barge to NOLA: 100 percent truck backhaul by percent barge backhaul[b]			Truck-barge to NOLA: Zero truck backhaul by percent barge backhaul[b]		
		0	35	100	0	35	100	0	35	100
Sioux City										
gallons	9.0	10.4	9.9	9.2	11.9	11.4	10.6	13.5	13.0	12.2
standard error	(1.0)	(1.3)	(1.3)	(1.2)	(1.5)	(1.4)	(1.3)	(1.6)	(1.5)	(1.4)
fuel cost	$6.16	$7.44	$6.98	$6.31	$9.27	$8.81	$8.14	$11.07	$10.62	$9.95
Council Bluff										
gallons	9.1	10.3	9.8	9.1	11.7	11.3	10.6	13.3	12.8	12.1
standard error	(1.0)	(1.3)	(1.3)	(1.2)	(1.4)	(1.4)	(1.3)	(1.5)	(1.5)	(1.4)
fuel cost	$6.26	$7.36	$6.93	$6.30	$9.13	$8.70	$8.07	$10.94	$10.51	$9.87
Algona										
gallons	9.0	10.3	9.8	9.0	11.1	10.5	9.8	11.9	11.4	10.6
standard error	(1.0)	(1.4)	(1.3)	(1.2)	(1.4)	(1.3)	(1.3)	(1.5)	(1.4)	(1.3)
fuel cost	$6.17	$7.35	$6.86	$6.18	$8.31	$7.82	$7.14	$9.26	$8.78	$8.09
Boone										
gallons	8.9	10.1	9.6	8.9	11.0	10.5	9.8	12.0	11.5	10.8
standard error	(1.0)	(1.3)	(1.3)	(1.2)	(1.4)	(1.3)	(1.2)	(1.5)	(1.4)	(1.3)
fuel cost	$6.05	$7.15	$6.72	$6.08	$8.29	$7.86	$7.23	$9.42	$9.00	$8.36
Cedar Rapids										
gallons	8.7	9.9	9.4	8.7	10.3	9.8	9.1	10.7	10.2	9.5
standard error	(1.0)	(1.3)	(1.3)	(1.2)	(1.3)	(1.3)	(1.2)	(1.4)	(1.3)	(1.2)
fuel cost	$5.89	$6.98	$6.56	$5.92	$7.46	$7.04	$6.40	$7.94	$7.51	$6.88
Burlington										
gallons	8.5	9.5	9.1	8.4	9.5	9.1	8.4	9.5	9.1	8.4
standard error	(1.0)	(1.3)	(1.2)	(1.1)	(1.3)	(1.2)	(1.1)	(1.3)	(1.2)	(1.1)
fuel cost	$5.68	$6.63	$6.25	$5.67	$6.63	$6.25	$5.67	$6.63	$6.25	$5.67

[a] Ship steams loaded from NOLA to Amsterdam and returns empty to NOLA.

Table 29. Estimated total fuel consumption in gallons per short ton, and fuel cost in dollars per short ton, to transport grain from Iowa origins to Amsterdam, Netherlands via alternative surface modes and 100,000 dwt ocean vessels.

Iowa origins	Unit trains direct to NOLA[a]	Unit-train-barge to NOLA by percent barge backhaul[b]			Truck-barge to NOLA: 100 percent truck backhaul by percent barge backhaul[b]			Truck-barge to NOLA: Zero truck backhaul by percent barge backhaul[b]		
		0	35	100	0	35	100	0	35	100
Sioux City										
gallons	7.9	9.3	8.8	8.1	10.8	10.3	9.6	12.4	11.9	11.1
standard error	(0.8)	(1.2)	(1.1)	(1.0)	(1.3)	(1.3)	(1.2)	(1.4)	(1.4)	(1.3)
fuel cost	$5.50	$6.77	$6.32	$5.65	$8.60	$8.15	$7.48	$10.41	$9.95	$9.28
Council Bluff										
gallons	8.0	9.2	8.8	8.1	10.7	10.2	9.5	12.2	11.8	11.1
standard error	(0.8)	(1.2)	(1.1)	(1.0)	(1.3)	(1.2)	(1.1)	(1.4)	(1.3)	(1.3)
fuel cost	$5.59	$6.69	$6.27	$5.63	$8.47	$8.04	$7.40	$10.27	$9.84	$9.21
Algona										
gallons	7.9	9.2	8.7	7.9	10.0	9.5	8.7	10.8	10.3	9.5
standard error	(0.8)	(1.2)	(1.1)	(1.0)	(1.3)	(1.2)	(1.1)	(1.3)	(1.3)	(1.2)
fuel cost	$5.51	$6.68	$6.20	$5.51	$7.64	$7.16	$7.47	$8.60	$8.11	$7.43
Boone										
gallons	7.8	9.0	8.5	7.8	9.9	9.5	8.8	10.9	10.4	9.7
standard error	(0.8)	(1.2)	(1.1)	(1.0)	(1.2)	(1.2)	(1.1)	(1.3)	(1.3)	(1.2)
fuel cost	$5.38	$6.48	$6.06	$5.42	$7.62	$7.20	$6.56	$8.76	$8.33	$7.70
Cedar Rapids										
gallons	7.6	8.8	8.4	7.6	9.2	8.7	8.0	9.6	9.2	8.4
standard error	(0.8)	(1.2)	(1.1)	(1.0)	(1.2)	(1.1)	(1.1)	(1.2)	(1.2)	(1.1)
fuel cost	$5.22	$6.32	$5.89	$5.26	$6.80	$6.37	$5.74	$7.27	$6.85	$6.21
Burlington										
gallons	7.4	8.4	8.0	7.4	8.4	8.0	7.4	8.4	8.0	7.4
standard error	(0.8)	(1.1)	(1.1)	(1.0)	(1.1)	(1.1)	(1.0)	(1.1)	(1.1)	(1.0)
fuel cost	$5.02	$5.96	$5.58	$5.01	$5.96	$5.58	$5.01	$5.96	$5.58	$5.01

[a] Ship steams loaded from NOLA to Amsterdam and returns empty to NOLA.

Unit trains direct to NOLA from Cedar Rapids would save $0.67 per ton of grain over the unit-train-barge combination with 35 percent backhaul. The unit-train-barge combination would save $0.48 per ton of grain over the truck-barge combination with a 100 percent truck backhaul and an additional $0.47 over the truck-barge with zero truck backhaul. Out of Sioux City, unit trains direct to NOLA would save $0.82 in fuel costs per ton of grain over the unit-train-barge combination with 35 percent barge backhaul. The unit-train-barge combination would save $1.83 per ton of grain over truck-barge with 100 percent truck backhaul and an additional $1.81 per ton of grain over the truck-barge combination with zero truck backhaul.

Limitations of the Results

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 it has become an increasingly large cost component.

The analysis deals only with limited samples of truck, barge, and rail grain shipments, each using somewhat different methods of fuel consumption measurements. These results should not be used for other commodities, vehicles, vessels, or routes.

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Appendix

Method of Estimating Standard Errors

The variances of G_i and G_r were calculated directly for each mode from primary data or regression results. The variances of f_i and f_r were then estimated based on the variances of G_i and G_r respectively. Since, however, both G_i and f_i, and G_r and f_r are inversely related as shown in equations (8) and (9), the estimation of the exact variances of f_i and f_r from the variances of G_i and G_r is based on Taylor's expansion theorem.

Taylor's expansion theorem states that it is possible to express any arbitrary function F(X) in a polynomial form as equation (A.1) provided that F(X) has finite, continuous derivatives up to the desired n degree at the expansion point X_o:

$$F(X) = F(X_o) + F'(X_o)(X-X_o) + \dots + F^{(n)}(X)(X-X)^n/_{n!} + R_n$$

where R_n denotes the remainder. (A.1)

Let $F(X) = \frac{1}{X}$, then $F'(X) = -\frac{1}{X^2}$ and $F''(X) = \frac{2}{X^3}$.

The expected value of F(X) is:

$$E[F(X)] = E[\frac{1}{X}] = E[F(X_o) + F'(X_o)(X-X_o) + F''(X_o)(X-X_o)^2/_{2!} + \dots].$$

If $X_o = \overline{X}$ and an approximation is made to the second-order level,

then,

$$E[F(X)] = E[\frac{1}{X}] = \frac{1}{\overline{X}} + \frac{V(X)}{\overline{X}^3} \qquad (A.2)$$

where V(X) is the variance of X.

Let $F(X) = \frac{1}{X^2}$, then $F'(X) = -\frac{2}{X^3}$ and $F''(X) = \frac{6}{X^4}$

The expected value of F(X) becomes:

$$E[F(X)] = E[\frac{1}{X^2}] = E[F(X_o) + F'(X_o)(X-X_o) + F''(X_o)(X-X_o)^2/_{2!} + \dots]$$

If $X_o = \overline{X}$ and an approximation is made to the second-order level,

then,

$$E[F(X)] = E[\frac{1}{X^2}] = \frac{1}{(\overline{X})^2} + \frac{3V(X)}{(\overline{X})^4} \qquad (A.3)$$

The variance of X can be defined as:

$$V(X) = E[X^2] - (E[X])^2$$

If the estimate is approximated at the second-order level, then

$$V(\frac{1}{X}) = E[\frac{1}{X^2}] - (E[\frac{1}{X}])^2 = \frac{1}{(\overline{X})^2} + \frac{3V(X)}{(\overline{X})^4} + \left[\frac{1}{\overline{X}} + \frac{V(X)}{\overline{X}^3}\right]^2 = \frac{V(X)}{(\overline{X})^4} - \frac{[V(X)]^2}{(\overline{X})^6} \qquad (A.4)$$

Inasmuch as W_i, k_u, k_i, k_h, and M_t are constant in equations (8) and (9), equation (A.4) can be used to estimate variances of f_i and f_r from variances of G_i and G_r that were calculated from the primary data or regression results.

The standard errors presented in tables 22 to 29 are square roots of variances of total fuel consumption required under each scenario. The variances of total fuel consumption are the summation of variances of each mode, i.e., variances of f_i and f_r of each mode.