has an unusually large vertical drop, which should increase its energy efficiency. Banks estimates that energy requirements for a level line would be about 35 percent greater.

The other estimates in Table A-7 (those by the Office of Technology Assessment, IBI Group, and one of those by Banks) are all based on engineering studies for proposed slurry pipelines. In general, they appear lower than those for the Black Mesa line--perhaps for several reasons. Most important, the proposed pipelines are longer so that the energy for preparation and dewatering is spread over many more miles. For example, Banks has estimated that if the proposed 1,600-mile ETSI line were as short as the Black Mesa line, its energy consumption would be over 50 percent higher, or 970 BTUs per ton-mile of load. Also, lines with larger capacity may generate greater economies of scale. On the other hand, these estimates are based on engineering studies, and the history of most new forms of transportation shows that performance in practice is often not as good as suggested by the first engineering estimates.

Other forms of slurry pipeline are being explored, including some that appear to be more energy-efficient than the coal/water slurry pipeline. Of these, the proposed coal/methanol slurry appears promising. One advantage is that methanol avoids the expensive dewatering of traditional slurries, and is a valuable source of energy itself.

Coal slurry pipelines have many advantages and disadvantages aside from their relatively low energy intensity, and these are likely to be much more important in deciding the future of slurry pipelines.

Summary of Propulsion Energy Requirements

Table A-8 summarizes the estimates of propulsion energy presented in Tables A-1 through A-8 for each of the modes. In addition, a typical or best estimate is selected for each mode. The estimate chosen does not represent an average, but rather reflects assessment of the quality of the data and the analysis contained in each estimate. The estimates for those modes that use petroleum energy are also adjusted for energy used during refining--about 5 percent. These adjusted estimates are used in Chapter III.

The estimates selected as typical for rail TOFC (950 BTUs) and unit coal train (350 BTUs) are based on the field measurements reported in Tables A-1 and A-2. The estimate for intercity truck (2,000 BTUs) is slightly lower than Rose's estimate in order to reflect the continuing

TABLE A-7. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR COAL SLURRY PIPELINES

Source a/	BTUs per Ton-Mile b/	Comments
Southern Pacific	312	Actual 1978 for Black Mesa line, 2,600 foot net drop over 273 miles
	1,042	Assuming 30 percent efficiency for electric generation
W. F. Banks	4,800	For Black Mesa line, includes water supply, pumping, preparation, and dewatering
	680	For Black Mesa line, pumping energy alone assuming 22 percent efficiency for electric generation (500 BTUs with 30 percent efficiency
	624	For proposed ETSI pipeline, 1,000 miles, 25 million tons per year
CACI	2,588	1975, estimated for Black Mesa line
Zucchetto	601	Direct fuel consumption for Black Mesa line
	673	Direct fuel plus water distribution for Black Mesa line

(Continued)

needed to prepare the slurry and then to dewater it. In this regard, the study by Banks appears to have been the most thorough. 15/ It also results in the highest estimate, 4,800 BTUs per net ton-mile, although the estimate of 680 BTUs for pumping alone is in line with that of other estimates.

15/ William F. Banks, Energy Consumption in the Pipeline Industry, prepared for U.S. Department of Energy (December 1977).

TABLE A-7. (Continued)

Source a/	BTUs per Ton-Mile b/	Comments
Office of Technology Assessment	610	Average for four case studies
	410	Proposed Wyoming-Texas line, 1,170 miles, 35 million tons per year
	710	Proposed Montana-Wisconsin line, 921 miles, 13.5 million tons per year
	920	Proposed Tennessee-Florida line, 803 miles, 16 million tons per year
	1,150	Proposed Utah-California line, 522 miles, 10 million tons per year
IBI Group	329	1,000-mile line
	1,097	1,000-mile line assuming 30 percent efficiency for electric generation
	522	200-mile line
	1,740	200-mile line assuming 30 percent efficiency for electric generation

a/ See Appendix B for full citation of each source.

b/ Per ton-mile of cargo unless stated otherwise.

At various times the Black Mesa line has been forced to operate at less than peak efficiency, either because of pipeline operating problems or because the power plant was not able to accept all the coal the pipeline could deliver. Thus, measured efficiency might vary considerably from one time to another. On average, its performance is probably inferior to what would be likely from a new pipeline. On the other hand, the Black Mesa line

TABLE A-8. SUMMARY ESTIMATES OF PROPULSION ENERGY REQUIREMENTS (In BTUs per ton-mile of cargo)

Mode	Range of Estimates	Typical Estimate	Estimate Adjusted for Energy Losses in Refining
Rail - Overall	550 - 690	630	660
TOFC	730 - 1,370	950	1,000
Unit coal train	220 - 410	350	370
Truck			
Average intercity	1,400 - 2,530	2,000	2,100
Barge - Overall	250 - 500	400	420
Upstream	---	550	580
Downstream	---	210	220
Air			
All-cargo plane	23,310 - 28,630	25,000	26,250
Belly freight a/	3,300 - 29,950	3,400	3,570
Oil Pipeline	160 - 540	325	325
Coal Slurry Pipeline b/	410 - 4,800	1,000	1,000

a/ The wide range of estimates results from the use of two different methods.

b/ The wide variation results from different degrees of comprehensiveness (pumping energy alone as against coal preparation and dewatering as well), and also from the differences between engineering studies of large--as yet unbuilt--pipelines and the smaller-scale line now in operation.

improvements in truck fuel economy. The barge estimate (400 BTUs) is slightly higher than the 350 BTUs average reported by American Waterways Operators, but less than that estimated by most other analysts. The upstream-downstream split is based on Howe's formula for still-water speed as used by Leilich and others. The air cargo numbers (25,000 BTUs for all cargo planes and 3,400 BTUs for belly freight) follow Rose while the oil pipeline estimate (325 BTUs) is based largely on Hooker and others and on W. F. Banks. The estimate for coal slurry pipeline (1,000 BTUs) is based on less evidence than those for the other modes. It is near the high end of the engineering studies reported, while discounting some of the optimism likely from proponents of a new, relatively untested technology. It is substantially less than the Black Mesa estimate of W.F. Banks (4,800 BTUs) on the assumption that economies of scale and greater operating experience should result in improved efficiency for any new coal slurry pipeline.

VEHICLE MANUFACTURING ENERGY

Significant quantities of energy are used to manufacture transportation vehicles. Distributed over the expected life of the vehicle, however, on a ton-mile basis, manufacturing energy is considerably smaller than propulsion energy.

Table A-9 presents estimates of the energy used in the manufacture of several typical freight vehicles. With the exception of the estimate by Fels, they are based on input-output analysis, a technique that permits one to trace the energy used both directly and indirectly in any particular manufacturing operation. Unfortunately, the coefficients of input-output tables tend to be out-of-date; the most recent data available for energy analysis were collected in the 1960s, and manufacturing techniques and materials have changed somewhat since then.

One of the estimates is based on process analysis. This method identifies all the basic materials used in manufacturing and calculates the energy required to produce each one. In theory, process analysis and input-output analysis should result in identical answers. In fact, they differ. For smaller vehicles such as automobiles the differences are not large, but for larger vehicles such as airplanes process analysis shows considerably smaller energy requirements than does the input-output technique.

Not surprisingly, Table A-9 shows that the amount of energy required in vehicle manufacture increases with the size and complexity of the vehicle. The typical locomotive, for example, requires about eight times the energy needed for the typical freight car, but less than one-tenth that needed for a large jet airplane. For purposes of comparison it is necessary to distribute the energy required in manufacture over the ton-miles carried in the vehicle's lifetime. For example, if 1,500 million BTUs are required to

TABLE A-9. ESTIMATES OF VEHICLE MANUFACTURING ENERGY

Mode and Source	Vehicle	Millions of BTUs
Railroad		
Pollard	RR Locomotive (1967)	15,500
Pollard	RR Locomotive (1977)	12,988
IBI Group	RR Locomotive (1974)	14,726
Pollard	RR Freight Car (1967)	1,810
Pollard	RR Freight Car (1977)	1,659-1,752
IBI Group	Aluminum Hopper Car (1974)	1,731
IBI Group	50-Foot Box Car (1974)	1,491
Truck		
Pollard	Truck Tractor (1977)	1,920
IBI Group	Truck Tractor (Ford)	884
Pollard	45-Foot Truck Trailer (1977)	644
IBI Group	Truck Trailer (Fruehauf)	353
Water		
IBI Group	Ship (Self-Unloading Bulk Laker)	609,426
Air		
IBI Group	Airplane (Boeing 707-320B)	170,161
IBI Group	Airplane (Boeing 707-320C Freighter)	162,396
Fels	Airplane (Boeing 707-passenger)	20,130 a/

SOURCES: IBI Group, Indirect Energy in Transportation (March 1978); J. K. Pollard, Indirect Energy Consumption in Truck and Rail Freight Transportation, U.S. Department of Transportation, Transportation Systems Center (January 1980); Margaret Fels.

a/ Estimated using process analysis.

manufacture a railroad freight car, which then lasts for 35 years carrying an average of 657,000 ton-miles of cargo a year, 16/ the manufacturing energy

16/ Association of American Railroads, Yearbook of Railroad Facts, 1979 edition, p. 44.

is reduced to the equivalent of only 65 BTUs per ton-mile, or about 10 percent of the propulsion energy alone.

Table A-10 presents summary estimates of vehicle manufacturing energy per ton-mile of cargo and as a fraction of propulsion energy per ton-mile (see Table A-8). The estimates used here are somewhat less than those of IBI (a Canadian consulting firm), since input-output analysis appears to

TABLE A-10. SUMMARY ESTIMATES OF VEHICLE MANUFACTURING ENERGY

Mode	BTUs per Ton-Mile of Cargo	As Percent of Propulsion Energy
Rail - Overall	90	13.6
TOFC	80	8.0
Unit coal trains	60	16.2
Truck		
Average intercity	100	4.8
Barge - Overall	40	9.5
Upstream	40	6.4
Downstream	40	18.2
Air		
All-cargo plane	150	0.6
Belly freight	20	0.6
Oil Pipeline	0	0.0
Coal Slurry Pipeline	0	0.0

give estimates at the high end of the range. 17/ While the summary estimates in Table A-10 are less definitive than those for propulsion energy in Table A-8, they appear intuitively plausible. All-cargo planes require the most energy per ton-mile of cargo, followed by truck, rail, barge, and finally, as a special case, belly freight.

GUIDEWAY CONSTRUCTION ENERGY

Constructing the guideway for any transportation mode requires very large amounts of energy. The long economic life of the typical guideway, however, makes it a small factor per ton-mile. As a result, when calculated on a per ton-mile basis, construction energy is roughly comparable to vehicle manufacturing energy in importance, and small relative to propulsion energy. Trucks require more construction energy than any other mode (see Table A-12), yet this equals only 14 percent of truck propulsion energy.

Table A-11 presents estimates of the total energy required to construct transport guideways in terms of billions of BTUs per lane-mile or track-mile (except for noncontinuous facilities such as terminals or airport runways). Most of the estimates are based on input-output analysis. Those by Fels and DeLeuw Cather use process analysis. While in theory the two techniques should yield identical results, in practice input-output analysis gives substantially higher estimates of construction energy--two to three

---

17/ The estimates of railroad manufacturing energy use the lowest estimates shown in Table 9: 12,988 million BTUs for a locomotive (from Pollard), 1,491 million BTUs for a boxcar, and 1,731 million BTUs for a hopper car. In general, IBI's assumptions about vehicle life are used: 25 years for a locomotive and 30-35 years for hopper cars and boxcars respectively. On average, one locomotive is assumed to be required for each 30 boxcars and each 15 hopper cars. Truck manufacturing energy requirements represent an average of the results of Pollard and IBI, combined with IBI's assumption of a 15-year life, 80,000 miles per year, and a 16-ton average load. Manufacturing energy for barges is estimated at 10 percent of propulsion energy--somewhat less than that used by IBI. Airplane manufacturing energy is an average of the results for process analysis and input-output analysis as a simple way to adjust for the wide differences between these two methods. Cargo planes are assumed to have a life of 20 years and fly an average of one million miles a year with an average load of 31 tons (based on IBI). Manufacturing energy for belly freight is assumed to bear the same relationship to propulsion energy--0.6 percent--as for all-cargo planes.

TABLE A-11. ESTIMATES OF GUIDEWAY CONSTRUCTION ENERGY

Mode	Source	Per Lane-Mile or Track-Mile (In billions of BTUs)
Rail		
Rail line	IBI a/	82.0
Urban rail (at grade)	Fels b/ f/	17.1-19.1
Urban rail (at grade)	DeLeuw Cather c/ e/	
Freight yard	IBI a/	2,060.0 d/
Truck		
Rural arterial	IBI a/	17.8
Rural freeway	IBI a/	23.9
Urban arterial	IBI a/	24.6
Urban freeway	IBI a/	55.4
Urban freeway	Fels b/	15.7
Urban freeway	DeLeuw Cather (road only) c/	17.1 d/
Bridge	DeLeuw Cather c/	130.4 d/
Urban freeway	Bezdek and Hannon c/	41.6
Terminal and garage	IBI a/	52.0 d/
Water		
Bulk materials dock	IBI a/	797.0 d/
Canal	Simpson f/	100.0
Air		
Runway system	IBI a/	6,312.0 d/
Cargo terminal	IBI a/	78.0 d/

(Continued)

times as high in the case of highways and four to six times as high for railroads. The two methodologies do provide upper and lower bounds. In general, the results of process analysis are probably more realistic, since they are based on a more detailed analysis of each construction activity. The input-output approach (in addition to using data about 15 years old) has a considerable amount of aggregation in nonmanufacturing areas such as

TABLE A-11. (Continued)

Mode	Source	Per Lane-Mile or Track-Mile (In billions of BTUs)
Coal Slurry		
Pipeline	IBI a/	32.0 d/
Terminal	IBI a/	2,611.0 d/

a/ Based on 1966 input-output analysis. IBI Group, Indirect Energy in Transportation, prepared for Strategic Studies Branch of Transport Canada (March 1978).

b/ Based on process analysis. Margaret F. Fels, "Comparative Energy Costs of Urban Transportation Systems," Transportation Research, vol. 9 (1975), pp. 197-208.

c/ Based on process analysis. DeLeuw, Cather and Company, Indirect Energy Consumption for Transportation Projects, prepared for California Department of Transportation (October 1976).

d/ For full facility.

e/ For urban rail transit at grade. The Fels estimate is based on BART.

f/ Based on input-output analysis for the Tennessee-Tombigbee Waterway. David Simpson, Energy and Labor Requirements for the Construction and Annual Operations of the Tennessee-Tombigbee Waterway Project, Technical Memo No. 21, Energy Research Group, Center for Advanced Computation, University of Illinois at Urbana (July 1974).

construction. Typically, most construction activity is lumped together in a single energy coefficient. One detailed comparison of input-output analysis and process analysis in rail transit construction found that excavation accounted for the bulk of this difference. 18/

18/ G. P. Williams, "Energy Costs of Heavy Rail Transit Construction," Masters Thesis, School of Engineering and Applied Sciences, Princeton University, June 1978.

The summary construction energy estimates shown in Table A-12 also use the IBI report as a starting point, again because it is the only comprehensive report to give such detail. The data are adjusted to compensate roughly for the higher estimates given by input-output techniques yielding estimates that are about half those made by IBI. An important exception is that for trucks, where the high end of the range is

TABLE A-12. SUMMARY ESTIMATES OF CONSTRUCTION ENERGY

Mode	BTUs per Ton-Mile of Cargo	As Percent of Propulsion Energy
Rail - Overall	200	30.3
TOFC	200	20.0
Unit coal train	100	27.0
Truck		
Average intercity	300	14.3
Barge - Overall	50	11.9
Upstream	50	8.6
Downstream	50	22.7
Air		
All-cargo plane	100	0.4
Belly freight	25	0.7
Oil Pipeline	25	7.7
Coal Slurry Pipeline	50	5.0

used. IBI allocated highway construction energy on the basis of the amount of space used by each vehicle (passenger-car equivalents). Pavement, a major component of highway construction, is known to wear in proportion to a measure of weight per axle called axle-load equivalent. Using this measure, heavy trucks are accountable for most of the energy used in the pavement part of highway construction.

MAINTENANCE ENERGY

Table A-13 displays estimates of the energy needed to maintain both vehicles and infrastructure, based on input-output analysis. As before, these estimates should be treated as upper bounds. They show vehicle maintenance energy at about 10 percent of truck propulsion energy, 5 percent of rail propulsion energy, and only 1 percent of air freight propulsion energy. On this basis, one may estimate vehicle maintenance energy for barges (including tugs) at 5 percent or less of propulsion requirements.

For most fixed facilities, the annual maintenance energy is about 0.5 percent of the total construction energy estimated using input-output techniques. (Air cargo terminals, truck terminals, and urban arterial roads are the major exceptions, with much higher maintenance energy requirements). If most infrastructure investments are assumed to have an economic life of 20 years, this translates into maintenance energy requirements equal to about 10 percent of construction energy. Again, these results should be treated as rules of thumb at best. In any case, maintenance energy is clearly less important than construction energy.

Table A-14 presents summary estimates of total maintenance energy per ton-mile of cargo and as a percentage of propulsion energy. These estimates combine maintenance energy for both the vehicle and for the infrastructure and are based on the estimates made by IBI.

ACCESS ENERGY

The energy required to move freight to and from the transportation system--termed "access energy"--can have a major influence on the system's relative energy efficiency. Typically, the mode of transportation used for local pick-up and delivery is less energy-efficient per ton-mile of cargo than the long-distance mode.

No reliable data are available on access energy requirements, and this energy factor will have to be discussed in largely qualitative terms. 19/ Access energy can play a major role in waterborne transportation, since commodities must often be moved a considerable distance to or from a port

---

19/ Reebie Associates' studies of rail TOFC/COFC movements and truck freight are the only analyses of freight energy intensity that have included access energy. Unfortunately, not enough detail was presented to enable one to split the access portion from the line-haul requirements.

TABLE A-13. ESTIMATES OF VEHICLE AND INFRASTRUCTURE MAINTENANCE ENERGY

Mode	Vehicle Maintenance Energy (In BTUs per vehicle-mile)	Infrastructure Maintenance Energy (In millions of BTUs per lane-mile or track-mile)
Rail		
Locomotive	16,625	---
Boxcar	1,313	---
Hopper car	1,225	---
Railway line	---	240
Freight yard	---	12,000 a/
Truck		
Tractor trailer	3,150	---
Rural arterial road	---	75
Rural freeway	---	118
Urban arterial road	---	378
Urban freeway	---	396
Truck terminal	---	800 a/
Water		
Self-unloading bulk laker	70,000	---
Bulk materials dock	---	4,000 a/
Canal (inland waterway)	---	900
Air		
Boeing 707 freighter	13,300	---
Runway system	---	53,000 a/
Cargo terminal	---	17,500 a/
Coal Slurry		
Line and terminal	---	960,000 a/

SOURCE: IBI Group, Indirect Energy in Transportation, except for canal (inland waterway) operating energy which is from David Simpson, Energy and Labor Requirements for the Construction and Annual Operations of the Tennessee-Tombigbee Waterway Project.

a/ For full facility.

TABLE A-14. SUMMARY ESTIMATES OF VEHICLE AND INFRASTRUCTURE MAINTENANCE ENERGY

Mode	BTUs per Ton-Mile of Cargo	As Percent of Propulsion Energy
Rail - Overall	180	27.3
TOFC	140	14.0
Unit coal train	60	16.2
Truck		
Average intercity	300	14.3
Barge - Overall	30	7.1
Upstream	30	5.2
Downstream	30	13.6
Air		
All-cargo plane	750	2.9
Belly freight	100	2.8
Oil Pipeline	100	30.8
Coal Slurry Pipeline	100	10.0

or inland waterway. Indeed, under some circumstances, access energy may be even greater than the energy required for the primary mode. Grain bound for New Orleans or other Gulf ports by barge is often first trucked to the Mississippi River, sometimes over a distance of 200 miles. Since the propulsion energy for trucks is about five times that of barges and about ten times that of downstream barges, relatively few truck miles are enough to offset the energy advantage that barges have over railroads.

Access energy is also likely to be significant where there are a limited number of terminals compared with the number of ultimate origins or destinations. Examples include intercity trucks in large, congested urban areas, railroad TOFC/COFC yards, and air freight.

CIRCUITY

It is impossible to travel directly as the crow flies. Even airplane flights involve extra distance because of landing patterns near airports, circling, storm avoidance, and intermediate stops. 20/ The ratio between actual miles traveled and the theoretical minimum as measured by the great-circle distance is called circuity. A circuity of two, for example, means that twice the great-circle distance was traveled.

Circuity is the most important single factor after propulsion in determining the relative energy needs of freight transportation. Its importance has long been recognized, and a number of researchers have studied the circuity of particular modes. Table A-15 summarizes some recent estimates.

Circuity may be divided into two components: network circuity, or the circuity inherent in the transportation network itself; and route circuity, or that of the particular route selected. Total circuity is a combination of these two effects.

Network Circuity

Network circuity is dictated by geography and by the extent or size of the transportation network. For example, water transport modes should have the highest circuity since, except for a few canals, they must follow natural waterways. At the other extreme, air transport should have the lowest circuity since it is restricted by very few natural barriers. Because the highway network is much more extensive than that for rail, direct routes between given pairs of cities are more likely. Thus, truck transport should have somewhat lower network circuity than railroads. Specialized modes such as pipelines and electric transmission lines are less constrained by either geography or the need to serve intermediate points, and thus should have quite low circuity. Of course, they may require extensive feeder networks for access.

20/ An extreme example of this is the operation of Federal Air Express, which carries small packages among the nation's major cities. All shipments, regardless of origin or destination, move by way of Memphis, Tennessee, where they are consolidated.

TABLE A-15. ESTIMATES OF CIRCUITY FOR INTERCITY FREIGHT TRANSPORTATION

Source	Rail	Truck	Inland Water	Air a/
Network Circuity				
Rose	1.321 b/	1.148	1.828	1.00
Mays and others (Boeing) c/	1.240	1.150		1.00
Hannon d/	1.240	1.210	1.710	
Eastman e/	1.320	1.030	1.740	1.00
Eastman f/	1.736		1.991	
Iowa DOT g/	1.200	1.250	1.380	1.05
Western RR Association			1.780 h/	
Reebie i/	1.180			
Office of Technology Assessment j/	1.340			
Nebraska Energy Office k/	1.440		1.950	
Route Circuity				
Interstate Commerce Commission l/	1.150 m/	1.060		

NOTE: These are estimates of network circuity except for the ICC estimate, which is for the circuity of the routes actually used. The estimates by the Western Railroad Association, Reebie, and the Office of Technology Assessment are circuities relative to other transportation modes; see footnotes h, i, and j.

a/ In fact, air circuity is quite large, but the Civil Aeronautics Board reports flight data in such a way that circuity is already taken into account.

(Continued)

TABLE A-15. (Continued)

---

b/ Lower bound. Rose also estimates coastal circuity at 1.298 and Great Lake circuity at 1.063.

c/ Estimates in original included ICC route circuity of 1.15 for rail and 1.06 for truck, for total circuities of 1.425 for rail and 1.22 for truck.

d/ From Sebald. Rail and water for region served by Gulf Intracoastal Waterway and Mississippi River. Rail circuity "a balance of minimum distance and minimum number of carriers" (p. 3).

e/ Uses Rose's estimate for rail circuity, Water Transport Association survey for inland water.

f/ For sample of TVA coal traffic, typical distance = 100-150 miles.

g/ 1,000-mile trip.

h/ Circuity is 1.35 relative to rail; range is 1.20-1.55. High estimate based on study by Missouri Pacific Railroad. Using 1.32 for rail circuity results in 1.78 for water, and a range of 1.52-2.05.

i/ Carload service relative to truck on Interstate highway--1.02 under optimal conditions. 1.11 for TOFC, relative to truck--1.10 under optimum conditions. Use of 1.15 for truck results in 1.36 for rail, 1.28 for TOFC.

j/ For four coal unit train routes relative to four proposed coal slurry routes. Coal slurry circuity = 1.03-1.10. Using 1.05 for coal slurry results in 1.41 for rail, and a range of 1.38-1.47.

k/ For grain traffic from South Sioux City, Neb., to New Orleans.

l/ Average difference between actual route and short-line distance over rail or highway network.

m/ Range is 1.08-1.18, depending on type of car. Data are for 1964.

Most of the results reported in Table A-14 are network circuities. Rose 21/ has made extensive calculations of the great-circle distance or theoretical minimum distance between most major cities as well as the minimum distance by rail, truck, and water. If information were also available on ton-miles moved by each mode between each city pair combination, a properly weighted estimate of network circuity could be calculated. Rose was able to do this only for truck transport, resulting in an estimate of 1.148. His estimate of rail circuity used a network of railroad mainlines that carried about two-thirds of railroad gross ton-miles. He argues that the resulting circuity, 1.321, is a lower bound 22/ since mileage on branch lines as well as to and from interchange points is not included. Rose's estimates of waterway circuities are weighted by ton-miles, but only for individual waterways. The estimate of 1.828 for all inland waterways he considers an "absolute lower bound," 23/ since it does not allow for the more circuitous interwaterway movements. Like most others, Rose assumes air transport to have no circuity since the Civil Aeronautics Board shows total fuel consumption but reports distance in terms of great-circle miles rather than actual miles flown. (Thus, the effect of air circuity is already included in the data on propulsion energy. This explains the misleadingly low estimates of air circuity shown in Table A-15.)

The other estimates of overall modal circuity are less comprehensive, with only a few indicating in detail how the calculations were made. Some of the more extreme results come from regional studies. For example, Eastman's estimates of 1.736 for rail and 1.991 for inland water--the highest estimates for both modes--while based on a detailed shipment-by-shipment analysis, is for relatively short hauls in the mountainous area served by the Tennessee Valley Authority. The results probably overstate the circuity typical of rail traffic and thus narrow the difference between rail and barge circuity.

The estimates by the Western Railroad Association, Reebie Associates, and the Office of Technology Assessment compare the circuity of one mode with another, rather than with a common standard such as great-circle distance. Thus, they must be adjusted upward for the circuity of the base mode. Of these studies, the results found by the Office of Technology

---

21/ Op. cit. Rose calculated great-circle distances and network circuities for truck, rail, and water for up to 2,450 city pairs.

22/ Op. cit., pp. 5-6.

23/ Op. cit., pp. 4-5. Rose's published study reported a water circuity of 1.914; the number used here is an updated estimate provided in a private communication.

Assessment are of interest since they compare several proposed coal slurry pipelines with competitive unit train coal movements. The routes for coal slurry lines, like other pipelines, are less constrained by geographical or historical factors than other surface transportation modes. Their circuity appears to average about 1.05, and is less than 1.10 in any case.

Route Circuity

Route circuity is a function of several factors: the extent to which different transportation companies have exclusive territories; the minimum size of load required for economic movement; and the complexity of the transportation network. If there is relatively little interaction among the networks of different companies (as is typical for railroads), additional movement may be required to coordinate interchanges. Further, as the size of the minimum economic movement increases, greater efforts are justified to assemble goods at central locations, such as railroad yards or port terminals. On the other hand, the sparser the network--with coal slurry representing one extreme--the closer route circuity will be to zero, as there may be no alternative routes between places.

The Interstate Commerce Commission results are the only estimates of route circuity. They result from detailed surveys of both rail and truck movements. For railroads, the ICC found an average route circuity of 1.15 with a range of 1.08 to 1.18 depending on the type of car. 24/ The importance of interchanges can be seen from the fact that local or one-railroad movements had a circuity of 1.10 while interline movements averaged 1.16. While these data are for 1964, they seem applicable today since there is no evidence of dramatic changes in circuity. A more recent ICC survey indicated that route circuity for the trucking industry averaged 1.06. 25/ Although no surveys have been made for the inland waterway industry, its route circuity is probably negligible since there is rarely any choice about which route to select. Air transport, on the other hand, may have some route circuity since many flights make intermediate stops, but no data are available on the amount of circuity involved.

24/ Interstate Commerce Commission, Bureau of Economics, Circuity of Rail Carload Freight, Statement No. 68-1 (April 1968). For earlier years, the Commission reports circuity of 1.11 in 1933, 1.12 in 1938, 1.13 in 1942, 1.14 in 1944 and 1947, and 1.13 in 1950.

25/ Interstate Commerce Commission, Empty/Loaded Truck Miles on Interstate Highways During 1976 (April 1977).

Total Circuity

Route circuities and network circuities should be combined to find total circuity. A study by Mays and others of the Boeing Corporation is perhaps the only previous analysis to do this. 26/ Their estimate of route circuity was taken from the ICC, and their estimate of network circuity (shown in Table A-15) from an analysis of distances between selected city pairs.

Table A-16 shows total circuity based on estimates of typical network circuity and route circuity. Rose's analysis, while limited by data in some cases, is the most comprehensive and consistent available. It includes only network circuity, however, and needs to be modified to include route circuity. The Interstate Commerce Commission estimates railroad route circuity at 1.15 and truck route circuity at 1.06 (see Table A-15). For railroads, route circuity should vary with the type of service. For example, while average circuity for all types of rail cars is 1.15, that for TOFC (trailers-on-flat-cars) is 1.09, reflecting the higher priority generally given this service. For coal unit trains, a route circuity of 1.145 is used, representing an average of the circuity found for gondola cars in special service (1.16) and hopper cars in special service (1.13). The total circuity for railroads in general is calculated as 1.52 (1.32 times 1.15); for TOFC service and coal unit trains it is 1.44 and 1.51 respectively. Combining the ICC's estimate of truck route circuity (1.06) with Rose's estimate of truck network circuity (1.15) results in an estimate of overall truck circuity of 1.22.

Rose's estimate of 1.828 for inland barge circuity is used, though it may be a conservative estimate. A circuity factor of 1.05 is used for air freight, as a rough estimate of the effect of indirect routing caused by intermediate stops. No network circuity is included for air because of the way fuel consumption data are reported. Both oil and coal slurry pipelines are given a circuity of 1.10. This estimate is at the upper end of the data range, but is probably justified since the estimates do not include the effect of feeder and distribution pipelines.

26/ R.A. Mays, M.P. Miller, and G. J. Schott, "Intercity Freight Fuel Utilization at Low Package Densities--Airplanes, Express Trains and Trucks," in Measuring Energy Efficiency in Freight Transportation, papers presented at the 55th Annual Meeting of the Transportation Research Board (January 1976).

TABLE A-16. SUMMARY ESTIMATES OF CIRCUITY FOR INTERCITY FREIGHT TRANSPORTATION

Mode	Network Circuity	Route Circuity	Total Circuity
Rail - Overall	1.32	1.15	1.52
TOFC	1.32	1.09	1.44
Unit coal train	1.32	1.145 a/	1.51
Truck	1.15	1.06	1.22
Barge	1.83	1.00	1.83
Air	1.00	1.05	1.05
Oil Pipeline	1.10	1.00	1.10
Coal Slurry Pipeline	1.10	1.00	1.10

SOURCES: Table A-15 and text.

a/ Average of circuity for gondola cars and hopper cars in special service.

APPENDIX B. MAJOR SOURCES

Alexander, J.D., J.B. Brackbill, and A.T. Curren, Time, Cost and Energy Factors for Intercity Transportation, Engineering Foundation Conference (July 1978).

American Trucking Association, Debunking the Rail Energy Efficiency Myth (January 1978).

Association of American Railroads, Yearbook of Railroad Facts, 1979, 1980 editions.

Banks, William F., An Energy Study of Pipeline Transportation Systems, U.S. Department of Energy, Division of Transportation Energy Conservation (December 1977).

Batts, Lana R., Intermodal Relative Energy Efficiencies Revisited, American Trucking Association (July 1980).

Bezdek, Roger, and Bruce Hannon, "Energy, Manpower, and the Highway Trust Fund," Science, vol. 185 (August 23, 1974).

Booz, Allen, Hamilton, Energy Use in the Marine Transportation Industry, prepared for Energy Research and Development Administration (January 1977).

CACI, Freight Transportation Energy Use, U. S. Department of Transportation, Research and Special Program Administration (July 1979).

Corsi, Thomas M., and Merrill J. Roberts, Consequences of Motor Carrier Deregulation on Fuel Efficiency, Interstate Commerce Commission, Office of Policy and Analysis (September 1979).

DelCan Ltd, A Comparison of Modal Energy Consumption in Intercity Freight, prepared for Transport Canada (1979).

DeLeuw, Cather and Company, Indirect Energy Consumption for Transportation Projects, prepared for California Department of Transportation (October 1976).

Eastman, Samuel, Energy Intensiveness of Intercity Motor Common Carriage of General Freight: Its Measurement and the Effect of Federal Regulations, in Proceedings of the Transportation Research Forum (1976), p. 17.

Eastman, Samuel, Circuity and the Energy Intensiveness of Inland Waterway and Rail Freight Transportation Systems: A Progress Report, paper presented to the Maritime Transportation Research Board (June 1978).

Eastman, Samuel, Fuel Efficiency in Freight Transportation, The American Waterways Operators, Inc. (June 1980).

Jack Faucett and Associates, Truck Fleet Experience with Fuel Economy Improvement Measures, prepared for the Federal Energy Administration (April 1976).

Fels, Margaret F., Comparative Energy Costs of Urban Transportation Systems, Transportation Research, vol. 9 (1975).

Hooker, J.N., Oil Pipeline Energy Consumption and Efficiency, Oak Ridge National Laboratory, prepared for the U.S. Department of Energy.

Hooker, John, Axel Rose, and Kenneth M. Bertram, Comparison of Operational Energy Intensities and Consumption of Pipelines Versus Coastal Tankers: U. S. Gulf Coast to Northeast Coast Routes, Oak Ridge National Laboratory, prepared for U. S. Department of Energy, Office of Transportation Programs (January 1980).

Hopkins, John B. and A. T. Newfell, Railroads and the Environment: Estimation of Fuel Consumption in Rail Transportation, vol. II, Transportation Systems Center, prepared for Federal Railroad Administration (September 1977).

Hopkins, John B., Morrin E. Hazel, and Timothy McGrath, Railroad and the Environment: Estimation of Fuel Consumption in Rail Transportation, vol. III, Transportation Systems Center, prepared for Federal Railroad Administration (September 1978).

IBI Group, Indirect Energy in Transportation, prepared for Strategic Studies Branch of Transport Canada (March 1978).

Interstate Commerce Commission, Bureau of Economics, Circuity of Rail Carload Freight (April 1968).

Interstate Commerce Commission, Empty/Loaded Truck Miles on Interstate Highways During 1976 (April 1977).

Interstate Commerce Commission, Bureau of Accounts, Ratios of Empty to Loaded Freight Car-Miles by Type of Car and Performance Factors for Way, Through and All Trains Combined-1972 (December 1973).

Iowa Department of Transportation, Energy and Transportation for the Future (May 1977).

Leilich, R. H., and others (Peat Marwick Mitchell and Co.), Energy and Economic Impacts of Projected Freight Transportation Improvements, prepared for Transportation Systems Center (November 1976).

Maio, Domenic J., Freight Transportation Petroleum Conservation Opportunities--Viability Evaluation, Transportation Systems Center, U. S. Department of Transportation (March 1979).

Mays, R.A., Miller, M.P., and Schott, G.J., "Intercity Freight Fuel Utilization at Low Package Densities--Airplanes, Express Trains and Trucks," paper presented at the 55th Annual Meeting of the Transportation Research Board (January 1976).

Moon, Albert, Energy Study of Railroad Freight Transportation, SRI International, prepared for Energy Research and Development Administration (May 1977).

Morlak, Edward K., "An Engineering Analysis and Comparison of Railroad and Truck Line-Haul Work (Energy) Requirements," Transportation Research Board 55th Annual Meeting (January 1976).

National Highway Traffic Safety Administration, press release on Frederick Maryland road tests, 1980.

Office of Technology Assessment, A Technology Assessment of Coal Slurry Pipelines (March 1978).

Paxson, David S., "The Energy Crisis and Intermodal Competition," Transportation Research Record 758, Transportation Research Board, National Academy of Sciences (1980).

Pollard, John K., Changes in Transportation Energy Intensiveness, 1972-78, U.S. Department of Transportation, Transportation Systems Center (May 1980).

Pollard, John K., Indirect Energy Consumption in Truck and Rail Freight Transportation, U.S. Department of Transportation, Transportation Systems Center (January 1980).

Reebie Associates, An Improved Truck/Rail Operation: Evaluation of a Selected Corridor, prepared for the U.S. Department of Transportation, Federal Highway Administration (December 1975).

Reebie Associates, National Intermodal Network Feasibility Study, prepared for the U.S. Department of Transportation, Federal Railroad Administration (November 1975).

Rose, Axel, Energy Intensity and Related Parameters of Selected Transportation Modes: Freight Movements, Oak Ridge National Laboratories (June 1979).

Sebald, Anthony V., "Energy Intensity of Barge and Rail Freight Hauling," Center for Advanced Computation, University of Illinois at Urbana-Champaign (May 1974).

Simpson, David, "Energy and Labor Requirements for the Construction and Annual Operation of the Tennessee-Tombigbee Waterway Project," Center for Advanced Computation, University of Illinois at Urbana-Champaign.

Transportation Research Board, Energy Effects, Efficiencies, and Prospects for Various Modes of Transportation, National Cooperative Highway Research Program, National Research Council (1977).

United States Railway Association, personal communication from Larry Kaufer, Director of Operations Planning (1980).

Western Railroad Association, personal communication from Joseph Feeney, General Counsel (1979).

Zucchetto, James, S. Bayley, L. Shapiro, D. Man, and J. Nessel, "The Direct and Indirect Energy Costs of Coal Transport by Alternative Bulk Commodity Modes," International Journal of Resource Recovery and Conservation, vol. 5, pp. 161-177 (1980).