ENERGY USE IN FREIGHT TRANSPORTATION

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The Congress of the United States
Congressional Budget Office

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U.S. CONGRESS
WASHINGTON, D.C. 20515

Alice M. Rivlin
Director

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PREFACE

The use of energy by the major modes of freight transportation has become of increasing concern in setting transportation policy. This report complements previous Congressional Budget Office (CBO) studies of the relative energy efficiency of the major modes of urban passenger transport and of intercity passenger transport. It was prepared at the request of the Commerce, Transportation and Tourism Subcommittee of the House Committee on Energy and Commerce. In keeping with CBO's mandate to provide objective and impartial analysis, the study offers no recommendations.

Richard R. Mudge of CBO's Natural Resources and Commerce Division prepared the study under the supervision of Damian J. Kulash and David L. Bodde. Valuable comments were received from representatives of the Association of American Railroads, the American Trucking Association, the Coal Slurry Pipeline Association, and the National Waterways Conference, and from the following individuals: Axel Rose of Oak Ridge National Laboratory, Edward Gregory of the Department of Energy, John Pollard of the Transportation Systems Center, and Samuel E. Eastman. Other suggestions came from Peter Tarpgaard, Allen Kraus, and Richard Weissbrod of CBO. Francis Pierce edited the manuscript and Kathryn Quattrone prepared the paper for publication with help from Paula Mills.

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SUMMARY

This report examines the relative energy efficiency of the different modes of freight transportation. It finds that in terms of energy per ton-mile, oil pipelines are easily the most efficient of the modes of transportation considered. Inland barges rank second, although for some uses railroads are of comparable efficiency. Trucks use more energy than railroads, and cargo planes are at the bottom of the efficiency range (see Summary Table). But these simplified comparisons must be modified in several ways.

Modifying Factors

Oil pipelines use only 500 BTUs (British Thermal Units) per ton-mile (280 ton-miles per gallon of diesel fuel), but they are limited by their very specialized function. The efficiency of inland barges (990 BTUs per ton-mile or 140 ton-miles per gallon on average), is likewise offset by the roundaboutness or circuity of most rivers. Also, significant amounts of energy may be required to bring cargo to a waterway system: grain and other farm products are sometimes trucked 200 miles to a river, increasing energy use per ton-mile by 50 percent or more.

The efficiency of rail transportation varies considerably depending on the commodity and the level of service provided; at one extreme, unit trains designed to carry only coal typically require less than 900 BTUs per ton-mile of cargo (155 ton-miles per gallon), while at the other extreme high-speed short trailer-on-flat-car (TOFC) trains use about 2,000 BTUs per ton-mile of cargo (68 ton-miles per gallon).

Intercity trucks require on average about 3,400 BTUs per ton-mile of cargo (41 ton-miles per gallon), twice the rail average and 1.7 times that for rail TOFC. It is not surprising that trucks require more energy since they provide a generally higher level of service than rail.

An even higher level of service, and hence greater energy need, is characteristic of air freight. In planes devoted to air freight, over 28,000 BTUs per ton-mile of cargo may be required (5 ton-miles per gallon), although freight carried in the belly of a passenger plane may require only 3,900 BTUs per ton-mile of cargo (35 ton-miles per gallon).

A specialized new mode of freight transportation is the coal slurry pipeline; this appears to require about 1,270 BTUs per ton-mile of coal--although this conclusion is based largely on engineering studies.

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SUMMARY TABLE 1. ESTIMATES OF TYPICAL FREIGHT ENERGY EFFICIENCY (In BTUs per ton-mile of cargo)

Mode	Modal Energy a/
Rail - Overall	1,720
TOFC b/	2,040
Unit coal train	890
Truck	
Average intercity	3,420
Barge - Overall	990
Upstream	1,280
Downstream	620
Air	
All-cargo plane	28,610
Belly freight	3,900
Oil Pipeline	500
Coal Slurry Pipeline	1,270

a/ Combines propulsion energy, maintenance energy, vehicle manufacturing energy, construction energy, and the effect of circuity, as well as refinery losses and the energy used for empty movements and for the non-cargo weight of vehicles. One gallon of diesel fuel contains on the average 138,700 BTUs (British Thermal Units) of energy, and a gallon of gasoline 125,000 BTUs. A ton-mile represents the movement of one ton a distance of one mile.

b/ Trailer on flat car.

Components of Energy Use

These energy estimates include all of the energy consumed in transportation--that is, not only the energy used in propelling a vehicle but also the energy used in manufacturing and maintaining it, and in building the guideway over which it moves. In addition, they make allowance for "circuity"--the extent to which a vehicle's route departs from a straight line. The amounts of energy used for propulsion and for circuity are by far the most important, accounting between them for more than 70 percent of the energy used by most modes of transportation.

For rail and barge transportation, propulsion consumes between 35 and 50 percent of all energy used. For intercity trucks, propulsion accounts for about 60 percent, and for airlines about 90 percent, of total energy use. Circuity requires about 45 percent of barge energy, 35 percent of rail energy, and 20 percent of intercity truck energy, the differences corresponding largely to the extent of each mode's transport network. On the other hand, circuity accounts for less than 10 percent of energy use by airlines and pipelines. With a few exceptions, none of the other components of energy use--vehicle manufacture, guideway construction, and maintenance--accounts for more than 10 percent of total energy use.

Other Factors

Factors such as speed, terrain, and type of cargo have a major influence on energy use. For example, a train carrying only coal is much more efficient per ton-mile cargo moved than a mixed train carrying various manufactured goods in boxcars, many of them empty. Similarly, upstream barge traffic requires more energy than barges moving downstream.

Finally, energy is only one of the concerns that enter into the setting of transportation policy. Of more importance, usually, are the total costs of each mode of transportation, the service qualities it possesses, the effects it may be expected to have on regional development, and the way in which it is financed.

CHAPTER I. INTRODUCTION

Increasingly, debate in the Congress is shaped by concern over energy. This is particularly true for transportation, which accounts for a quarter of the nation's energy use and half of its petroleum use. The potential for energy savings has played a part in the debate over truck and rail deregulation, user fees on the inland waterway system, and federal aid to railroads, among other examples.

There is much disagreement as to the relative energy efficiency of different modes of transportation. Some spokesmen maintain that railroads offer the most energy-efficient means of transporting freight, and that in this they are four times as efficient as trucks. Others reply that barges on the inland waterways far exceed railroads in efficiency. Still others point to the recent improvements in motor vehicle economy and also argue that trucks provide a higher level of service than other modes. The debate is difficult to resolve because the parties use conflicting data and different analytical approaches.

This paper examines the available evidence as to energy efficiency for each mode of transportation in a systematic way in an effort to provide a basis for informed discussion. The comparisons are limited to the energy requirements of intercity freight transportation. 1/ (Local freight movement is not considered because Congressional actions focus on interstate commerce, and also because reliable data are lacking.) Of necessity, the emphasis is on average or typical conditions, and the results will have to be modified to fit differing circumstances. For example, in special geographical conditions, such as mountainous terrain, energy requirements may differ considerably from the average. Also, some of the longer-term considerations such as the amount of energy used in vehicle manufacture or guideway construction will not apply to analyses concerned with the short term.

1/ Freight transportation uses 10 percent of total energy and over 20 percent of the nation's petroleum. In the future these fractions are likely to increase as improvements in automobile fuel economy outstrip foreseeable improvements in the various modes of freight transportation.

It is hardly necessary to add that energy is not the only criterion to be considered in setting transportation policy. In most circumstances it is probably not even the most important criterion. Others include cost and quality of service, equity, the needs of regional development, and the concern for environmental pollution.

Chapter II of the report describes the three measures of energy use that form the basic analytical framework. Chapter III presents the results of the analysis and discusses some of the policy implications. Appendix A provides a detailed description of the data. Appendix B lists the major sources.

CHAPTER II. ANALYTICAL APPROACH

The energy efficiency of different modes of freight transportation may be compared on the basis of energy used per ton-mile of cargo carried. This is done by estimating the energy used (measured in British Thermal Units--BTUs) 1/ and dividing it by the tonnage carried times the route miles covered.

$$\text{Energy Efficiency} = \frac{\text{Total Energy Used (BTUs)}}{\text{Tons x Miles}}$$

The principal problem is that of estimating the total amounts of energy used. In comparing the long-term energy efficiency of, say, railroads and trucks, it is necessary to include not only the energy used in propelling the vehicles but that consumed in manufacturing them and in building the guideways (tracks and highways) on which they run, as well as in maintaining each system. The same holds for other modes of transportation such as canals, pipelines, and airlines.

In this paper the estimation of energy efficiency is carried out in three steps. First, operating energy is calculated--the energy required for vehicle propulsion divided by the average load. Estimates of average load must be adjusted for the amount of travel with no load (called empty backhauls). Energy losses during the refining process are incorporated as well.

The second step is to estimate line-haul energy. This adds to operating energy the energy used to maintain vehicles and guideways, the energy required to construct the guideways, and the energy used in vehicle manufacture. Estimates must also be made of the length of life of vehicles and guideways in order to allocate construction and manufacturing energy over their effective lives.

Third, the estimate of line-haul energy is modified to take account of the additional energy used in circuity or roundaboutness, and the energy used in access. Circuity is the amount of excess or unproductive travel used to move goods from one point to another, as compared with the theoretical

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1/ One gallon of diesel fuel contains 138,700 BTUs, and a gallon of gasoline 125,000 BTUs.

minimum distance or great-circle route. Access energy is the amount of energy required to move the cargo to and from the system. The resulting measure (line-haul energy adjusted for circuity and access) is termed "modal energy." It is the most comprehensive measure of energy use in transportation. 2/ The analytical framework may be depicted as follows:

Basic Energy Components	Measures of Energy Use		
Propulsion energy per ton-mile	Operating energy	Line-haul energy	Modal energy
Terminal and maintenance energy			
Guideway construction energy			
Vehicle manufacturing energy			
Energy used in access			
Circuity			

Many analyses of transportation energy efficiency consider only operating energy and fail to include the energy used in manufacture, construction, maintenance, circuity, and access. 3/

2/ A fuller description of this approach can be found in the Congressional Budget Office Background Paper, Urban Transportation and Energy: The Potential Savings of Different Modes (December 1977), Chapter II.

3/ For example, see Transportation Research Board, National Cooperative Highway Research Program, Energy Effects, Efficiencies, and Prospects for Various Modes of Transportation (1977).

GENERAL MEASUREMENT PROBLEMS

Freight transportation modes cannot all be analyzed in exactly the same way. One reason is that there are differences in their typical cargos. One of the more significant variables is cargo density--a ton of television sets requires five to six times as much space as a ton of coal, for example. 4/ Many manufactured goods fill the space available before reaching the weight limit for the vehicle. This is particularly common with trucks, which often fill up before reaching their maximum allowable weight.

Further, different commodities have different handling requirements. Manufactured goods must be handled with greater care than bulk commodities such as coal or grain. Consequently, specialized equipment and operating procedures are used for some cargos, and this is reflected in energy requirements. Coal is often delivered directly to its final destination with the aid of highly automated rail or barge equipment. Many manufactured goods, in contrast, are handled through warehouses and delivered by local delivery trucks, a service that is less energy-efficient than full truckload service directly to the consignee. Further, high-value goods, such as most manufactured items, often require fast and particularly reliable service, resulting in greater energy use than would otherwise be the case. For example, railroads operate TOFC (trailer-on-flat-car) trains at much higher speeds than normal, with much greater use of energy per ton of cargo. The importance attached to speed also figures in the greater energy requirements for air transport as compared with other modes.

The analysis of freight energy requirements is also hindered by limitations of data. Virtually all freight service is provided by the private sector, and large segments of it are relatively unregulated. The number of operating companies is quite large, except for the airlines, thus greatly complicating data collection and making it difficult to reach a representative estimate of energy efficiency.

Given the wide variation in the characteristics of different freight modes, the requirements of particular commodities, and the influence of geography, there is no single, perfect summary measure of energy efficiency. Although cargo ton-miles (also called net ton-miles) make by far

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4/ Edward K. Morlok, "An Engineering Analysis and Comparison of Railroad and Truck Line-Haul Work (Energy) Requirements," presented at the Transportation Research Board Fifty-Fifth Annual Meeting, January 1976.

the most useful measure of the output of freight transportation, they give greater than average weight to dense, bulk commodities and to longer hauls. Some analysts have argued for the use of a space-related measure, such as trailer miles. 5/ This might be particularly useful for comparing truck energy use with that of rail TOFC (trailers on flat cars) or COFC (containers on frame cars). It would avoid comparing the energy efficiency of all rail service including bulk goods with the energy efficiency of trucks, which carry predominantly manufactured goods. Of course, net ton-miles could still be used to compare similar services, such as rail TOFC versus truck.

Some analysts argue that any energy measure based on tonnage is biased since it does not reflect the different levels of service provided by each mode. Some have suggested as an alternative the amount of energy used per dollar of transportation expenditure or per dollar value of cargo. 6/ Again, their objection can be met by disaggregating total energy into the energy needed for bulk commodities and that needed for manufactured goods, together with an overall modal average. Such disaggregation is particularly important for railroads, since they carry both bulk and manufactured goods.

A similar suggestion is that the analysis be limited to movements of comparable commodities over comparable distances. 7/ The difficulty in this is that some modes cannot be compared in this way. Clearly, transcontinental rail movements cannot be compared with transcontinental barge movements.

Caution must therefore be used in interpreting the results of any study of average or overall energy efficiency. The results may be quite useful for debate over national policy, but may also be quite misleading if applied to particular circumstances.

5/ American Trucking Association, Inc., "Debunking the Rail Energy Efficiency Myth" (January 1978).

6/ Samual Eastman, "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 believes that this approach would show trucks as less energy-intensive than railroads.

7/ Samuel Eastman, "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.

CHAPTER III. ESTIMATED ENERGY EFFICIENCIES OF FREIGHT TRANSPORTATION MODES

Using the analytical framework from Chapter II, this chapter presents representative estimates for the principal components of energy use: propulsion energy, vehicle manufacturing energy, construction energy, maintenance energy, and circuity. 1/ Given the wide range of existing estimates for the energy use of each mode of transportation, it was necessary to use judgment in the selection of data. Rather than averaging various estimates together, typical or representative values were selected for each mode, taking into account the character of each source, including its apparent analytical quality. There is bound to be some disagreement over the estimates used. The analytical framework is straightforward, however, and readers can use their own judgment if they prefer to select different estimates.

CALCULATION OF ENERGY EFFICIENCY

Table 1 presents estimates of the basic components of energy use for each of the six major modes of freight transportation. These estimates are discussed in detail in Appendix A. Several estimates are provided for rail, water, and air transportation. The rail estimates include an overall modal average and separate estimates for TOFC service and coal unit trains. TOFC (trailers on flat cars) represents the highest quality rail service, and also the most energy-intensive, while coal unit trains represent probably the most energy-efficient form of rail service, at least on a BTU-per-net-ton-mile basis. The barge estimates include, in addition to a modal average, estimates for upstream and downstream traffic in order to reflect obvious differences. Since air freight energy use varies greatly depending on whether all-cargo planes or combined passenger-freight planes are used, estimates for both are given.

Table 2 compares the relative importance of each component of energy use. In general, maintenance energy and the energy used in vehicle manufacturing and guideway construction are small relative to propulsion energy and the effect of circuity. For most modes, propulsion energy and circuity together account for more than three times the sum of the other

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1/ No attempt was made to estimate access energy.

TABLE 1. ESTIMATES OF BASIC COMPONENTS OF ENERGY USE FOR SIX MODES OF FREIGHT TRANSPORTATION (In BTUs per net ton-mile)

Mode	Propulsion Energy	Vehicle Manufacturing Energy	Construction Energy	Maintenance Energy	Circuity
Rail - Overall	660	90	200	180	1.52
TOFC	1,000	80	200	140	1.44
Unit coal train	370	60	100	60	1.51
Truck					
Average intercity	2,100	100	300	300	1.22
Barge - Overall	420	40	50	30	1.83
Upstream	580	40	50	30	1.83
Downstream	220	40	50	30	1.83
Air					
All-cargo plane	26,250	150	100	750	1.05
Belly freight	3,570	20	20	100	1.05
Oil Pipeline	325	0	25	100	1.10
Coal Slurry Pipeline	1,000	0	50	100	1.10

SOURCE: Tables A-8, A-10, A-12, A-14, and A-16.

energy components. The fact that the others are relatively small helps to offset the much greater margin for error associated with estimating their magnitude.

Operating Energy

Table 3 combines the energy components into three summary measures of energy efficiency. The first, operating energy, is simply propulsion energy adjusted for refinery losses and corresponds to what is usually meant

TABLE 2. RELATIVE IMPORTANCE OF BASIC COMPONENTS OF ENERGY USE FOR SIX MODES OF FREIGHT TRANSPORTATION (In percent of total modal energy)

Mode	Propulsion Energy	Vehicle Manufacturing Energy	Construction Energy	Maintenance Energy	Circuity
Rail - Overall	38	5	12	10	34
TOFC	49	4	10	7	30
Unit coal train	42	7	11	7	34
Truck					
Average intercity	61	3	9	9	18
Barge - Overall	42	4	5	3	45
Upstream	45	3	4	2	45
Downstream	35	6	8	5	45
Air					
All-cargo plane	92	1	a/	3	5
Belly freight	92	1	1	3	5
Oil Pipeline	65	0	5	20	10
Coal Slurry Pipeline	79	0	4	8	9

NOTE: Totals may not add because of rounding.

a/ Less than 0.5 percent.

by the phrase "energy intensity." Measured by operating energy alone, the oil pipeline is the most efficient mode of freight transportation, followed by barge, rail, coal slurry pipeline, intercity truck, and airplane. Except perhaps for the coal slurry pipeline, where data are limited, this rank ordering of modes follows that of most other studies. It is notable that those modes with the greatest operating energy requirements (air and truck) also provide the highest speed and generally highest quality of service.

TABLE 3. SUMMARY MEASURES OF ENERGY EFFICIENCY FOR SIX MODES OF FREIGHT TRANSPORTATION (In BTUs per net ton-mile)

Mode	Operating Energy a/	Line-Haul Energy b/	Modal Energy c/
Rail - Overall	660	1,130	1,720
TOFC	1,000	1,420	2,040
Unit coal train	370	590	890
Truck			
Average intercity	2,100	2,800	3,420
Barge - Overall	420	540	990
Upstream	580	700	1,280
Downstream	220	340	620
Air			
All-cargo plane	26,250	27,250	28,610
Belly freight	3,570	3,710	3,900
Oil Pipeline	325	450	500
Coal Slurry Pipeline	1,000	1,150	1,270

a/ Propulsion energy including refinery losses.

b/ Combines operating energy with maintenance energy, vehicle manufacturing energy, and construction energy.

c/ Adjusts line-haul energy for circuity, but not for access energy.

Among the more interesting modal comparisons: trucks require over three times as much operating energy per net ton-mile as do railroads as a whole, and over twice as much as the more directly competitive TOFC service. Railroads in turn require about 60 percent more operating energy per net ton-mile than do barges, although the more directly competitive rail services such as coal unit trains are, on average, probably slightly more energy-efficient. But operating energy includes less than half the total energy requirements for some modes--barge and rail, for example--and is therefore not a good basis for long-term comparisons.

Line-Haul Energy

The second summary measure, called line-haul energy, adds to operating energy the energy required for maintenance, vehicle manufacturing, and the construction of guideways. When energy efficiency is measured in terms of line-haul energy, the transportation modes rank in the same order as with the operating energy measure, although the values are higher (Table 3). The differences are greatest for air freight (an increase of 1,000 BTUs per net ton-mile) and trucks (an increase of 700 BTUs per net ton-mile). The biggest percentage increase (about 70 percent), is for the rail mode--largely because propulsion energy requirements are relatively low for railroads.

While there is no shift in the overall ranking of the modes using the line-haul energy measure, some of the differences between them are smaller. Thus the coal slurry pipeline, which in terms of operating energy was about 60 percent less efficient than rail, is now only slightly less efficient. Also, within the rail mode, unit coal trains now appear slightly less energy-efficient than barges overall.

Modal Energy

The third summary measure, modal energy, is the most comprehensive since it adjusts line-haul energy to take account of the extra energy required for circuity. Circuity is measured as a ratio of the distance actually traveled to the great-circle distance. This has a significant influence on overall energy efficiency. Barges, with the largest circuity (1.83), are affected the most, followed by rail (1.52).

Taking circuity into account results in a slightly different ranking of the transportation modes with oil pipeline first, followed by barge, coal slurry, rail, truck, and air. Coal slurry now appears more efficient than rail movement overall, though less so than coal unit trains--the most directly competitive rail service. The importance of circuity is clearly seen in its effect on the energy efficiency of the barge and rail modes: barge energy needs increase by 450 BTUs, more than the operating energy used, while rail energy needs increase by 590 BTUs, only slightly less than the operating energy used. The biggest absolute increase (1,360 BTUs) is for all-cargo planes, because of the very large propulsion energy required for that mode.

Modal energy also includes energy used in gaining access to or from line-haul travel. The estimates shown in Table 3 do not include access energy, for lack of data. This introduces serious distortion for some modes. Most important, the inland barge industry often draws traffic over a distance of 200 or 300 miles from a navigable waterway. This has been particularly true in recent years as both the Rock Island and the Chicago, Milwaukee, St. Paul and Pacific railroads have deteriorated, forcing many farmers to truck their grain to the river. If truck access accounts for as much as one-third of the total movement by barge, it is enough to reduce average barge energy efficiency to roughly that of rail. This may also increase the circuity component for barge movement. On the other hand, the fact that most barge grain movements are downstream, where barge is a very efficient hauler, works to counteract some of these effects. Access energy requirements are also likely to be important for rail TOFC and air freight, and to a lesser extent for truck.

Rail vs. Truck. The rail mode is thought by some to have a four-to-one edge over the truck mode in energy efficiency. Table 3 shows that while rail is clearly more energy-efficient than truck, its lead is about two-to-one overall (1,720 BTUs per net ton-mile versus 3,420 for truck) and closer to 1.7-to-one for TOFC, which competes most directly with truck. This difference between modes varies considerably from commodity to commodity. For certain bulk commodities--coal, for example--rail may be as much as six times as efficient as truck, while for certain types of manufactured goods--such as electrical machinery--there is very little difference between the modes. 2/

Rail vs. Barge. Overall, the inland barge is a more energy-efficient mode than rail. The typical coal unit train appears, however, to be more energy-efficient than overall barge transport (but less efficient than downstream barge transport). For other bulk commodities the relative energy efficiency depends greatly on the commodity and the direction of movement. Since most petroleum products, for example, travel in an upstream direction, movement by rail is probably more energy-efficient for them. Grain, on the other hand, is more likely to travel downstream, and thus would use less energy on barges. If a commodity has to be transported a significant distance to or from the waterway, this may offset the advantage of barges.

2/ Axel Rose, Energy Intensity and Related Parameters of Selected Transportation Modes: Freight Movements, Oak Ridge National Laboratories (June 1979). See Tables 5.11 and 6.5 for estimated commodity breakdowns.

Air vs. Truck. Freight transport in the belly of passenger planes is only about 15 percent more energy-intensive than truck traffic, even though service quality is higher. The space available for belly freight is quite limited, however, although increased use of wide-body planes should make more belly space available. All-cargo planes are the least energy-efficient mode of transport, requiring more than eight times as much energy as trucks. The difference would probably appear even greater if data on access energy were available, since most metropolitan areas have many truck terminals but rarely more than one air freight terminal.

SHORT-TERM VERSUS LONG-TERM ENERGY USE

In any discussion of alternative energy policies, it is important to distinguish between the short term and the long term. Short-term comparisons of energy efficiency need not give much weight to the costs of constructing new guideways for vehicles. This is particularly true for a country such as the United States with a well-developed transportation infrastructure. Thus, any analysis of the likely short-term energy effects of a particular policy change should exclude construction energy. Table 4 adjusts the modal energy estimate in Table 3 to exclude construction energy. Also shown in Table 4 is the energy required for propulsion and the related effects of circuity--excluding all the "overhead" energy of vehicle manufacturing, guideway construction, and maintenance. Except for oil and coal slurry pipeline, almost all the energy used for propulsion and circuity is derived from petroleum.

Clearly, there are potential energy savings from switching traffic from one mode to a more efficient one—as, for example, from air to truck or from rail to barge. Table 5 shows the hypothetical savings if 10 percent of the traffic currently carried by each mode were switched to the next most efficient mode. Changes of this magnitude are unlikely to occur without drastic changes in current policy. In any case, the potential savings are modest, equal to a total of 68,000 barrels of oil per day at a time when U.S. energy consumption totals 36 million barrels per day.

CONCLUSIONS

Of the major modes of domestic freight transportation, oil pipelines are, on average, the most energy-efficient, followed by barges, coal slurry pipelines, railroads, trucks, and air freight. Such generalizations can be misleading, however, since they conceal wide variations among commodities hauled, levels of service offered, and specific geographic circumstances.

TABLE 4. ESTIMATES OF ENERGY USE OVER THE SHORT TERM FOR SIX MODES OF FREIGHT TRANSPORTATION (In BTUs per net ton-mile)

Mode	Propulsion Energy and Circuity Alone a/	Modal Energy Excluding Construction Energy
Rail - Overall	1,000	1,410
TOFC	1,440	1,760
Unit coal train	560	740
Truck		
Average intercity	2,560	3,050
Barge - Overall	770	900
Upstream	1,060	1,190
Downstream	400	530
Air		
All-cargo plane	27,560	28,510
Belly freight	3,750	3,870
Oil Pipeline	360	470
Coal Slurry Pipeline	1,100	1,220

a/ Excludes energy used for vehicle manufacture, guideway construction, and maintenance.

For example, oil pipelines and coal slurry pipelines are both specialized modes of transportation, each designed to move only one commodity. The relative efficiency of oil pipelines is useful in analyzing alternative ways of moving petroleum (barges and tankers, for example), but has little relevance for freight transportation in general. Similarly, while barges, on average, are more energy-efficient than railroads, the gap narrows when comparison is restricted to the bulk commodities that barges carry almost exclusively. Coal unit trains, for example, are roughly comparable to barges in energy efficiency.

TABLE 5. POTENTIAL ENERGY SAVINGS FROM SWITCHING FREIGHT TRAFFIC TO MORE EFFICIENT MODES

		Savings From Switching 10 Percent of Traffic to Next Most Efficient Mode	
Mode	1980 Intercity Traffic (In billions of ton-miles) a/	Total Savings (In thousands of barrels of oil equivalent per day)	Savings per Ton-Mile (In BTUs) b/
Oil Pipeline	575	N/A	N/A
Barge c/	307	6	430
Rail	921	22	510
Truck d/	565	34	1,290
Air e/	5	6	25,460

N/A = Not Applicable.

a/ Transportation Association of America.

b/ Based on estimates in Table 4.

c/ Traffic on rivers and canals. Excludes 113 billion ton-miles of domestic freight on the Great Lakes.

d/ Assumed to switch to TOFC.

e/ Assumed to switch from all-cargo plane.

This analysis should provide a useful basis for weighing alternative national policies in the field of transportation. It should also be applicable to more limited problems. For example, the effects of railroad deregulation on energy use could be estimated in terms of reduced circuity, changes in average load, and the amount of traffic attracted from other modes. To estimate the energy effects of a specific project such as the Tennessee-Tombigbee Waterway, however, would require modification of the energy estimates in this report.

APPENDIXES

APPENDIX A. DESCRIPTION OF INPUT DATA

This appendix describes the data used in estimating the basic components of energy use given in Chapter III. Each component--propulsion energy, vehicle manufacturing energy, guideway construction energy, maintenance energy, access energy, and circuity--is discussed separately, and typical or representative values are selected for each mode of transportation. These are used in Chapter III to calculate the measures of overall energy efficiency for each mode.

PROPULSION ENERGY

Propulsion energy is the most important single component of energy consumption. It represents between 40 percent (for barges and railroads) and 90 percent (for air cargo) of the total energy required to transport goods.

Railroads

The average amount of energy used in rail propulsion varies widely. It is lowest for unit trains with 100 or more similar, heavily loaded cars on an uninterrupted long-distance journey. It is highest for TOFC (trailer-on-flat-car) trains carrying lower-density cargos, usually manufactured goods, for shorter distances at much higher speeds and on shorter trains. Between these two extremes is the more typical general-purpose train consisting of boxcars, hopper cars, or gondolas.

Table A-1 summarizes recent estimates of railroad freight propulsion energy use in terms of BTUs per ton-mile of cargo. The first group of estimates show averages for all rail freight in either the United States or Canada for recent years. The U. S. figures are all based on data submitted to the Interstate Commerce Commission (ICC) by U. S. Class I railroads (those with annual revenues greater than $50 million). Since they all derive from the same source, there is very little difference among most of the estimates, which range between 630 and 690 BTUs per ton-mile of cargo. They have not changed much in recent years, the average fluctuating

TABLE A-1. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR RAILROADS

Source a/	BTUs Per Ton-Mile b/	Comments
Rose	630	Per revenue ton-mile, 1979 preliminary estimate
	670	Per revenue ton-mile, 1977, ICC data
	274	Per gross ton-mile, 1977, ICC data
Pollard	664	1977
Leilich	687	1972
CACI	594	Estimated for 1975
DelCan	548	1976, Canada
IBI Group	1,200	General freight, Canada
	500	Bulk commodities, Canada
	289	Per gross ton-mile, 1975 actual for Canada
USRA	262	Conrail, 1977, per gross ton-mile
	594	Conrail, 1977, all traffic
	319	Conrail, 1977, unit trains
	1,272	Conrail, 1977, TOFC
	470	Conrail, 1977, local service
	613	Conrail, 1977, road service
Sebald	515	1971, area served by Mississippi River and Gulf Intracoastal Waterway

(Continued)

TABLE A-1. (Continued)

Source a/	BTUs Per Ton-Mile b/	Comments
Office of Technology Assessment	390	Weighted average for four proposed coal unit trains, range = 340-580
Western Railroad Association	222	Coal unit train
Zucchetto	400	Coal unit train from Colstrip, Wyoming to St. Paul, Minnesota
Reebie Associates	1,205	Portland-Los Angeles, door-to-door, 1971
	1,723	TOFC; Portland-Los Angeles, door-to-door, 1971
	1,358-2,905	Advanced TOFC, Portland-Los Angeles, door-to-door
Iowa DOT	1,500	10 car train, ½ TOFC, 50 mph, no grade
	4,100	10 car train, ½ TOFC, 50 mph, 1 percent grade

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

b/ Per ton-mile of cargo unless stated otherwise. Gross ton-miles include the weight of cars and locomotives, and empty backhauls.

between 630 and 710 BTUs per net ton-mile. 1/ ICC data show about 275 BTUs per gross ton-mile (including the weight of cars and locomotives). The two Canadian estimates are similar to those for the United States.

A comparison of energy used per gross ton-mile and ton-mile of cargo indicates that only about 40 percent of the load moved by railroads is actual cargo, the remaining 60 percent representing dead weight due to empty backhauls and the weight of the freight cars and locomotives themselves. Some railroads are experimenting with lighter equipment and new designs. For example, the Santa Fe claims that its lightweight "Ten Pack" TOFC cars reduce energy use by 10 percent. The Bi-Modal (railroad/highway) car developed by Reebie Associates promises even greater energy savings.

Empty backhauls are a very significant factor in reducing the inherent efficiency of railroads. (Wind resistance both on the locomotive and between cars is also important, particularly for TOFC and COFC.) The ICC estimates that, on average, a rail car travels 79 miles empty for every 100 miles it travels with a load (an empty/loaded ratio of 0.79). 2/ There is some variation around this average, and certain specialized types of cars travel more miles empty than full--covered hopper cars and tank cars, for example. Since the typical rail car weighs between 60,000 and 65,000 pounds, considerable energy is required just to move an empty car. Some of these empty car miles represent inefficient use of resources, while others merely reflect the inherent characteristics of the railroad business. For example, most unit trains (devoted to hauling a particular commodity such as coal, usually between the same origin and destination), travel as many miles empty as they do loaded. Empty backhauls are a striking illustration of the difference between technical efficiency and practical efficiency.

The lower part of Table A-1 contains estimates of propulsion energy for specific railroads, regions, or types of movement. These indicate the considerable variability underlying the modal averages shown in the upper

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1/ Axel B. Rose, Energy Intensity and Related Parameters of Selected Transportation Modes: Freight Movements, Oak Ridge National Laboratory for U.S. Department of Energy, Office of Conservation and Solar Applications (June 1979), pp. 5-12. Rose, in a personal communication, reports the 630 BTU figure as a preliminary estimate for 1979.

2/ Interstate Commerce Commission, Bureau of Accounts, Ratio of Empty to Loaded Freight Car-Miles by Type of Car and Performance Factors for Way, Through and All Trains Combined - 1972 (December 1973), Statement No. 1S2-72, p. 10.

part of the table. For example, Conrail's overall energy efficiency per ton-mile of cargo is estimated to be somewhat higher than the rail industry average (594 BTUs as against 670 BTUs) although there is little difference per gross ton-mile (262 BTUs as against 274 BTUs). The several estimates of energy requirements for unit coal trains are all significantly less than the average for all traffic (222-400 BTUs versus 630-670 BTUs). In contrast, the estimates for TOFC traffic are substantially greater than the overall average. The estimates prepared by Reebie Associates for traffic between Portland and Los Angeles include access energy--the energy used in moving the cargo to and from the railroad—and are thus not fully comparable with the other estimates in the table.

Most of the rail propulsion energy estimates in Table A-1 are based on aggregate data, or on engineering projections. None are measurements of actual fuel use under controlled conditions. Such controlled experiments are difficult to perform, since measurement of locomotive fuel use requires either cumbersome before-and-after comparisons of the fuel consumed or the installation of a temporary fuel gauge. Moreover, freight cars are often added to or removed from a train at intermediate points, making it difficult to estimate the actual load carried.

In recent years, some railroads have made field tests of fuel use under operating conditions. Table A-2 summarizes a number of the results. Two general conclusions are apparent.

First, except for branch-line operations as measured by the Missouri Pacific Railroad (see the first line of Table A-2), energy use increases with the speed and quality of service provided. High-speed, high-priority TOFC and COFC trains require significantly more energy per ton-mile of cargo than does the typical freight (boxcar) train, which in turn requires significantly more energy per ton-mile of cargo than do trains carrying bulk commodities, such as coal unit trains. These results appear to confirm the more aggregative estimates presented in Table A-1. With one or two exceptions, most of the boxcar and mixed freight trains are close to the average for rail freight as a whole (650-700 BTUs per ton-mile of cargo). TOFC service tends to be 50 percent or more above this while coal unit trains are about half the average--both of these results being in line with the estimates of Table A-1.

Second, the energy required per ton-mile of cargo increases directly with the horsepower per gross ton-mile. The extra horsepower is needed to provide high-speed service for higher-value movements such as with TOFC or COFC. At the other extreme, unit trains hauling bulk commodities

TABLE A-2. FIELD MEASUREMENTS OF RAIL FREIGHT PROPULSION ENERGY USE

Railroad	Car Type	BTUs per Gross Trailing Ton-Mile	BTUs per Ton-Mile of Cargo	Number of Cars per Train	Horse-power per Gross Trailing Ton	Train-Miles in Sample
Missouri Pacific-1974 a/	Box	510	1,445	10	8.6	964
Burlington Northern-1975 b/	TOFC	326	895	27	6.0	19,528
Burlington Northern-1976 c/	Mixed	314	644	44	4.2	9,220
Southern Pacific-1975 d/	Box	145	309	125	0.9	1,148
	TOFC	232	766	39	2.6	574
	Mixed	206	672	76	1.5	574
Santa Fe-1976 e/	TOFC	316	1,372	56	3.7	6,853
	Box	281	709	63	3.2	1,747
	Mixed	234	638	69	3.2	1,604
Illinois Central Gulf-1976	TOFC f/	400	970	32	5.4	3,222
	Box g/	198	521	108	1.6	1,945
	COFC h/	255	731	72	2.6	1,052
	Mixed	314	917	82	3.0	405
Union Pacific i/	TOFC	423	1,012	41	5.7	3,038
Burlington Northern j/	Coal Unit Train	158	256	111	0.8 l/	1,264
Boston and Maine k/	Coal Unit Train	254	412	91	1.0 l/	414
Canadian National-1974 m/	Box	189	329	92	1.2	6,666

(Continued)

TABLE A-2. (Continued)

Railroad	Car Type	BTUs per Gross Trailing Ton-Mile	BTUs per Ton-Mile of Cargo	Number of Cars per Train	Horse-power per Gross Trailing Ton	Train-Miles in Sample
Milwaukee Road						
1979 n/	TOFC	295	850	23	N/A	2,472

SOURCE: All except last two lines, Hopkins and Newfell, Railroads and the Environment: Estimation of Fuel Consumption in Rail Transportation, vol. II, U.S. Department of Transportation, Transportation Systems Center (September 1977).

a/ Six round trips over 87-mile branch line in Arkansas and Louisiana.

b/ Runs between Chicago and Seattle, 2,179 total miles broken into two segments at Minot, North Dakota. Two-thirds of measurements were for Chicago-Minot segment.

c/ Ten trips between Chicago and Minot, N. D.

d/ A total of eight trains over 287-mile route in Central Valley of California.

e/ Three round trips between Kansas City and Los Angeles or Barstow, California.

f/ Two round trips between Chicago and New Orleans.

g/ Round trip between Chicago and New Orleans plus two short segments.

h/ Round trip between Chicago and Council Bluffs, Iowa.

i/ Round trip between North Platte, Neb., and Los Angeles.

j/ Round trip from Lincoln, Neb. to Metropolis, Ill.; net vertical drop of 700 feet.

k/ Round trip from Mechanicsville, N. Y. to Bow, N. H.

l/ Horsepower per gross trailing weight ratio refers to loaded portion of trip only.

m/ Ten round trips between Montreal and Toronto. Source: DelCan, "A Comparison of Modal Energy Consumption in Intercity Freight."

n/ Six trips of Sprint TOFC train between Chicago and Minneapolis/St. Paul. Includes operations in railroad TOFC terminal. Source: Department of Energy.

require reliability of service more than high speed, make few if any intermediate stops, and typically carry much greater tonnage relative to their horsepower than do other trains.

Intercity Trucks

Truck freight service is of two broad types: intercity and local pick-up and delivery. Intercity service is typically in large (up to 80,000 pounds gross weight) combination trucks with one or more trailers pulled by a tractor. After the intercity truck delivers its cargo to a terminal, smaller delivery trucks may take it to its ultimate destination. In terms of ton-miles of cargo, the large intercity trucks are usually more energy-efficient than the smaller delivery trucks. This paper considers only intercity truck transportation. 3/

Intercity truck transport, in turn, is of two types: truckload (TL) and less-than-truckload (LTL). Truckload service is used mostly by larger shippers in regular service. It is more energy-efficient on a ton-mile basis than less-than-truckload service.

Table A-3 summarizes recent estimates of truck freight propulsion energy use. Those in the top part represent averages for all intercity truck freight in either the United States or Canada. In contrast to the estimates for railroads, there is greater variation among these estimates--which range between 1,800 and 2,500 BTUs per ton-mile of cargo.

Most of these estimates use two sets of data: the average load and the average miles per gallon for a certain type of truck. The ICC collects data on average load, but there is no consistent source of data on truck fuel economy. Thus, there is greater uncertainty associated with each particular estimate than is the case for railroads. Further uncertainty is caused by the existence of many different types of trucks. For example, the Transportation Systems Center estimate in Table A-3 is for combination trucks, of which the Class VIII diesel trucks (over 30,000 pounds gross weight) considered by Rose are a subset.

3/ The exclusion of urban freight transportation presents a somewhat optimistic view of truck energy use. Of course, other modes (notably railroads and air freight) depend on local truck service for pick-up and delivery and are thus also affected by this exclusion.

As with other modes of transportation, extra energy is consumed in empty backhauls. These are included in most of the estimates in Table A-3. The ICC estimates that in 1976 some 20.4 percent of trucks operated empty and an additional 14.4 percent were only partially loaded. In total, 27.1 percent of the available truck capacity was empty. 4/ For trucks engaged in interstate service the estimates are slightly lower, while for trucks that are unregulated by the ICC the estimates are higher. The comparable estimate by the ICC for railroads is 44 percent. 5/ Adjusting some of the estimates in Table A-3 for the effect of empty backhauls is not easy. For example, Rose estimates that a Class VIII truck (the largest truck class, typically used for long-haul service) achieves about 4.5 miles per gallon when loaded. 6/ At an average load of 18.04 tons, this yields about 1,710 BTUs per ton-mile. Rose adjusts this for the percent of truck capacity that is empty (using a 1974 estimate by the Department of Transportation of 30.7 percent empty, rather than the estimate for 1976 by the ICC of 27.1 percent), arriving at an overall estimate of 2,470 BTUs per ton-mile of cargo. This estimate should be adjusted, however, for the greater fuel economy achieved when a truck is empty. 7/

4/ Interstate Commerce Commission, Bureau of Economics, Empty/Loaded Truck Miles on Interstate Highways During 1976 (April 1977). This includes all trucks whether or not they are regulated by the ICC.

5/ This number is different from that used in the rail section above since the ICC presents its rail survey in terms of the ratio between empty miles and loaded miles. The resulting rail ratio, 0.79, is equivalent to the figure of 44 percent empty mentioned here (79/179).

6/ Rose, op. cit., pp. 6-10.

7/ This fuel economy can be estimated using an engineering relationship such as Smith's formula for resistance (G.L. Smith, Commercial Vehicle Performance and Fuel Economy, SAE SP-355, Warrendale, Pa., 1970):

$$R_t = (W_e + W_c)\ (a + bV)\ S + c\,DAV^2$$

where

R_t = total resistance to straight-line movement over level terrain (lbs)

TABLE A-3. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR INTERCITY TRUCKS

Source a/	BTUs per Ton-Mile b/	Comments
Rose	2,470	Class VIII diesel trucks at 4.5 mpg and average load (2,140 if adjusted for higher mpg when empty)
	1,860-4,120	Depends on commodity carried
Pollard	2,530	1977, combination trucks only (5.42 mpg)
Leilich	2,343	1972
AAR Factbook	1,980	1978, regulated common carriers
CACI	2,403	1975, estimated
DelCan	1,900	1976, Canada, estimate
IBI Group	2,100-3,400	Canada, depends on weight of cargo (5-5.5 mpg)
Paxson	2,170	15-ton load; intercity TL service
	1,690	20-ton load; intercity TL service
	1,415	25-ton load; intercity TL service, 6 mpg empty, 4.5-5 mpg loaded, 1977-1979
Department of Energy	1,596	1979, 12 trips between Chicago and Minneapolis/St. Paul, 45-foot trailers
National Highway Traffic Safety Administration	1,207	1979 road test near Frederick, Maryland, over 53 mile course, 72,000 lb. gross vehicle weight
	2,514	48,000 lb. gross vehicle weight

(Continued)

TABLE A-3. (Continued)

Source a/	BTUs per Ton-Mile b/	Comments
Yellow Freight		1976, trip between Baxter Springs, Kansas, and Dallas, 420 miles, with 22 tons of ballast, 10-15 mph wind
	1,560	Bias-ply tires (with headwind)
	1,383	Radial tires (with headwind)
	1,333	Bias-ply tires (with tailwind)
	1,148	Radial tires (with tailwind)
Reebie Associates	1,723	Portland-Los Angeles, twin 27s door-to-door, 1971
Iowa DOT	3,000	10 tons of cargo per truck, 50 mph, no grade
	4,400	10 tons of cargo per truck, 50 mph, 1 percent grade
Jack Faucett Associates (Case Studies)	1,510	1975, bulk commodity, common carrier, 4.6 mpg, 20 tons average load
	2,030-2,190	1975, general freight, common carrier, 4.37-4.71 mpg, 14.5 tons average load
	1,950-2,240	1975, general freight, common carrier, 4.42-5.07 mpg, 14 tons average load
American Trucking Association	1,335	Truck loaded at federal maximum 80,000 lbs. gross vehicle weight

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

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

The calculations in footnote 7 indicate that the typical loaded truck that averages 4.5 miles per gallon will average 6.6 miles per gallon when empty. Combining these numbers with the ICC's finding that 27.1 percent of truck-miles are run empty results in an estimate of 2,140 BTUs per ton-mile of cargo as against the 2,470 BTUs used by Rose. Rose's estimate would be correct if, as he apparently assumed, the base estimate of 4.5 miles per gallon were already adjusted for better fuel economy when empty.

The lower part of Table A-3 contains estimates of truck energy use under particular conditions. While the first three of these are based on road tests, only the Department of Energy results represent actual operating conditions. The National Highway Traffic Safety Administration and the Yellow Freight Company tests were not conducted under normal operating conditions, and thus should be interpreted with caution. In particular, the

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7/ (Continued)

W_e = empty vehicle weight (lbs)

W_c = cargo weight (lbs)

a, b = coefficients of tire rolling resistance:
a = 0.0068, b = 0.000074

V = velocity (miles per hour)

S = road surface factor: 1 = normal road

C = coefficient for drag: 0.00253

D = aerodynamic drag coefficient: 0.71

A = vehicle frontal area (square feet)

From this relationship the relative resistance for a loaded truck as against an empty truck can be calculated. With certain additional assumptions (empty weight = 29,000 pounds, loaded weight = 65,000 pounds, velocity = 55 miles per hour, vehicle frontal area = 96 square feet) the resistance of a loaded truck is estimated as about 1.47 times that of an empty truck. This implies that if a loaded truck averages 4.5 miles per gallon, an empty truck should achieve 6.6 miles per gallon.

tests were for trucks with full loads in relatively flat terrain and very little traffic congestion.

The estimate by Reebie Associates 8/ includes energy used in pick-up and delivery. The estimates by the Iowa DOT are based on engineering relationships. They are useful since they show the effect of hills on energy consumption. The last set of estimates represent averages for particular, unnamed trucking companies as reported by Jack Faucett Associates.

Water Transportation

Water transportation in the full sense includes several modes of transportation: towboats pushing barges on inland waterways, tugs and barges on the intracoastal waterways and the Great Lakes, deep-draft vessels on the Great Lakes or in coastal trade, and deep-draft vessels in international commerce. This report focuses on inland barge transportation, but estimates for intracoastal shipping and deep-draft domestic shipping are given here for the sake of comparison.

The estimates in Table A-4 vary considerably, reflecting the generally uneven quality of the data and the difference between the various forms of water transport. In contrast to rail, truck, and air, only about 8 percent of the inland barge industry is regulated by the federal government. Since little information is available on the unregulated sector, data on propulsion energy must be patched together from several sources, including private barge companies, the Interstate Commerce Commission, the U. S. Army Corps of Engineers (for tonnage data), and engineering studies.

Estimates of overall propulsion requirements for the inland waterways range from 272 to 680 BTUs per ton-mile of cargo. Most estimates cluster in the 300-500 BTUs range. Direct comparisons are difficult because of inconsistencies in the underlying data.

Rather than attempt to combine data from several disparate sources, Booz, Allen, and Hamilton selected what they believed to be typical or generic types of vessels: for example, a 1,350 horsepower towboat was selected to represent inland barge movements and then BTUs per ton-mile were calculated on the basis of engineering estimates of fuel economy under

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

TABLE A-4. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR WATER TRANSPORTATION

Source a/	BTUs per Ton-Mile b/	Comments
Rose	440	1977, all domestic water including inland, lakes, and coastal
Pollard	438	1977, all domestic water modes
	559	1977, inland and local
	376	1977, coastal and lake
Leilich	272	1972, inland
	226	1972, coastal and lake ship
	281	1972, coastal and lake barge
Booz, Allen, Hamilton	481	Inland, based on generic ship (1,350 horsepower)
	380	Coastal average: tug/barge = 355; tanker = 278; other = 941; based on generic vessels
	511	Great Lakes average: dry bulk = 484-543; tanker = 587-652; tug = 304-320 based on generic vessels
CACI	350	1975, estimated for inland
	387	1973, estimated for deep-draft
Sebald	459	1971, Mississippi River and Gulf Intracoastal, does not include all switching energy (adjusted to exclude circuity)
DelCan	932	1976, Canada, shallow and deep-draft

(Continued)

TABLE A-4. (Continued)

Source a/	BTUs per Ton-Mile b/	Comments
Eastman (American Waterways Operators)	352	1977, average for 27 inland barge
Eastman (Water Transport Association)	326	1978, 2 inland barge operators; Lower Mississippi = 278, Ohio River = 329, Illinois River = 366
Zucchetto	249	Dedicated towboat and 15-jumbo-barge tow between St. Louis and St. Paul--data from Federal Barge Lines
Eastman (American Commercial Barge Line)	325	Average for 1978. Range: 264 on lower Mississippi to 605 on Gulf Coast Waterway
Iowa DOT	500	7-barge tow
Hooker and Others	587	1972, coastal tanker for one U.S. firm (Metrics, Inc.)
	638	1975, coastal tanker for one U.S. firm (Metrics, Inc.)
	480	Recalculation of Booz, Allen, and Hamilton estimate of 355 for coastal tanker

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

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

typical operating conditions for that vessel. In general, estimates based on such engineering relationships predict lower levels of fuel consumption than those drawn from experience under actual operating conditions. Another study found that the Booz, Allen, Hamilton engineering-based estimates for coastal tankers had to be increased by about one-third in order to match estimates of actual fuel consumption by the industry. 9/

Although all forms of water transport are relatively energy-efficient, at least in terms of propulsion energy, there is considerable variation among the different types of water movement. One study found that two to four times as much energy per ton-mile is required on the Gulf Intracoastal Waterway as on the Lower Mississippi River, because the Lower Mississippi is wider and deeper, has no delays associated with locks or congestion, and typically has larger tows. 10/ Performance on the Lower Mississippi also differs widely from that on other rivers, such as the Ohio. Moreover, typical upstream movement requires about 2.7 times as much energy per ton-mile as does movement downstream. 11/

There have been no controlled measurements of fuel use for barges under actual operating conditions. This is partly because of the difficulty involved in making precise measurements. Several barge lines have reported company-wide averages for their fuel consumption per ton-mile. As given by American Waterways Operators, they average about 350 BTUs per ton-mile of cargo. These results may be somewhat low since they do not appear to include energy used by switch boats.

9/ John Hooker, Axel Rose, and Kenneth Bertram, Comparison of Operational Energy Intensities and Consumption of Pipelines Versus Coastal Tankers: U.S. Gulf Coast to Northeast Coast Routes, U.S. Department of Energy, Office of Transportation Programs (January 1980), p. 10.

10/ R. H. Leilich and others, Energy and Economic Impacts of Projected Freight Transportation Improvements, prepared by Peat, Marwick, Mitchell and Company for Transportation Systems Center (November 1976), pp. 2-29. This analysis is based in large part on a modified version of the Howe formula for Still-Water Speed, p. C-4. The American Commercial Barge Lines reports (in "Modal Productivity Improvement and Related Energy Problems," Traffic Quarterly, April 1980, p. 221) results of 264 BTUs per ton-mile on the Lower Mississippi and 605 BTUs on the Gulf Coast waterway.

11/ Leilich and others, Energy and Economic Impacts.

Air Freight

Air freight is carried either in planes specially designed for the purpose or in the luggage compartments of regular passenger planes. Table A-5 presents estimates of propulsion energy requirements. They vary much more than the findings for other modes, primarily because of differences in method.

TABLE A-5. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR AIR FREIGHT

Source a/	BTUs per Ton-Mile b/	Comments
Rose	3,400	1976, belly freight, incremental energy
	25,360	1976, domestic freight aircraft
	23,310	1976, international freight aircraft
	14,070	1976, average all air freight
Pollard	3,300	1977, belly freight, incremental energy
	25,000	1977, freight aircraft
	11,775	1977, all domestic air freight
	12,409	All air freight
Leilich	14,188	1972, belly cargo, incremental energy
	29,949	1972, belly cargo, average energy
DelCan	45,200	1976, Canada, international and domestic
IBI Group	28,633	Boeing 707, 750-mile trip
Iowa DOT	10,000	Boeing 747, 1,000 miles with 100-ton payload

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

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

The calculation of propulsion energy needed for aircraft that carry only freight is straightforward, requiring only data for total fuel consumption and total ton-miles of cargo. A typical estimate is about 25,000 BTUs per ton-mile of cargo.

The calculation of freight energy intensity for aircraft carrying both freight and passengers is more complex. The fuel consumed by the plane must be allocated in some way between freight and passengers. Two approaches have been used. One is to give freight and passengers equal importance, and use a measure such as relative weight to allocate fuel. A typical answer using this approach is about 40,000 BTUs per ton-mile of cargo. An alternative approach is to assume that these combination aircraft exist primarily for passenger service, with freight carried only on a space available basis. The bulk of the fuel use is then allocated to passenger service on the assumption that the plane would not be scheduled without passengers, so that freight need only be responsible for the marginal or incremental energy needed to move its weight. A typical estimate is about 3,300 BTUs per ton-mile of cargo. Of the two approaches, the last is preferable since it appears to correspond most closely with airline priorities. 12/ The growth in passenger load factors under deregulation shows that airlines favor passengers at the expense of freight. Also, in the last few years, the air freight industry appears to have made more use of all-freight aircraft because of the better service they provide.

Overall air freight energy intensity can be estimated by combining energy for all freighter aircraft and for combination aircraft. Using the incremental approach for combination aircraft, a typical overall estimate is 12-14,000 BTUs per ton-mile of cargo.

Pipelines

Table A-6 presents estimates of the propulsion energy requirements for pipelines. In general, petroleum pipelines are one of the most energy-efficient modes of transportation.

As with other modes, there is considerable variation depending on the commodity moved, the speed and conditions under which it is being moved (most obviously, uphill or downhill), and the size of the pipeline. Table A-6 indicates that natural gas requires about six times as much energy per ton-

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12/ This is also the conclusion reached by Rose after a careful review of existing data.

TABLE A-6. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR PIPELINES

Source a/	BTUs per Ton-Mile b/	Comments
Hooker	270	Crude petroleum
	320	Petroleum products, natural gas
W. F. Banks	286	1976, crude petroleum
	330	1976, oil
	388	1976, petroleum products
	2,000	1974, natural gas
Leilich	158	1972, regulated pipelines only
	281	1980, projected, regulated pipelines only
CACI	475	1975, estimated
	411	1975, estimated for crude petroleum
	537	1975, estimated for petroleum products
DelCan	752	1976, Canada
Hooker and Others	283	Petroleum products, estimates
	326	for two separate companies

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

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

mile of load as most petroleum products since gas is much less dense than oil. Gas pipelines are also more energy-intensive, using about 2.5 percent of the energy transported or five to six times as much as for oil or oil-product pipelines. 13/ A small pipeline (say 4 inches in diameter) requires about

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

eight times as much energy per ton-mile to move crude oil as does a very large one (say 48 inches in diameter). 14/

Most of the estimates in Table A-6 are based on aggregate data. Hooker and others, however, give data for two separate firms, with the larger of the two reporting lower energy requirements (283 BTUs per ton-mile of cargo).

Coal Slurry Pipelines

Slurry pipelines represent a relatively new technology in which solid material, such as coal, is ground into a powder, mixed in solution with a liquid such as water, and pumped through a pipeline. While many combinations of materials are possible, coal/water slurries currently receive the greatest attention. One coal/water slurry pipeline is now in operation moving coal from Black Mesa, Arizona, to a power plant at Mohave, Nevada. There are several active proposals to build other large pipelines mostly in the West.

Table A-7 presents several estimates of energy requirements for coal/water slurry pipelines. The first four sets of estimates are based on analyses of the Black Mesa pipeline, while the last two represent engineering-based analyses of proposed pipelines.

Coal slurry pipelines require energy at several distinct stages: collection (via pumps and pipelines) of the required water; preparation of the slurry (pulverizing the coal and mixing it with the water); pumping of the slurry; dewatering or separating of the coal and water at the end of the pipeline; and finally, disposal of the dirty water. The estimates for energy use by the Black Mesa line vary quite widely, from about 300 BTUs per ton-mile of load to over 4,000. The lowest estimate is clearly faulty since it excludes the energy used in generating electricity; because of thermal losses, generation requires about three times the energy content of the electricity itself. Even after correcting for this factor, the range of estimates for the energy requirements of this facility is surprisingly wide. Some of the variation may be the result of failure to consider all the energy

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14/ J.N. Hooker, Oil Pipeline Energy Consumption and Efficiency. The average velocity is another very important factor, with energy requirements increasing in proportion to velocity raised to the power of 1.852. See Leilich and others, pp. 3-49, 3-50.

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

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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

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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 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.

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

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

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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)

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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

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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.

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[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.

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