REPORT NO. DOT-TSC-OST-79-1, I

FREIGHT TRANSPORTATION ENERGY USE

Volume I

Summary and Baseline Results

CACI, Inc.-Federal
1815 North Fort Myer Drive
Arlington, Virginia 22209

October 1978
FINAL REPORT

Prepared for:
U.S. Department of Transportation
Transportation Systems Center
Cambridge, Massachusetts 02142

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16. Abstract

The overall design of the TSC Freight Energy Model is presented. A hierarchical modeling strategy is used, in which detailed modal simulators estimate the performance characteristics of transportation network elements, and the estimates are input to a multimodal transportation network model which emulates system performance. The purpose of the model is to predict the impacts of changes in modal technology and operations on transportation energy use, costs, service levels, and on shipper modal choice decisions. The model can also generate energy-optimal freight transportation usage patterns and predict the consequences to carriers and shippers of energy-use optimization. Model calibration results for a base year (1972) and baseline estimates for the year 1990 are presented. Other volumes of the report are:

Vol. II - Methodology and Program Documentation
Vol. III - Freight Network and Operations Database
Vol. IV - Analysis of Selected Energy Conservation Options

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PREFACE

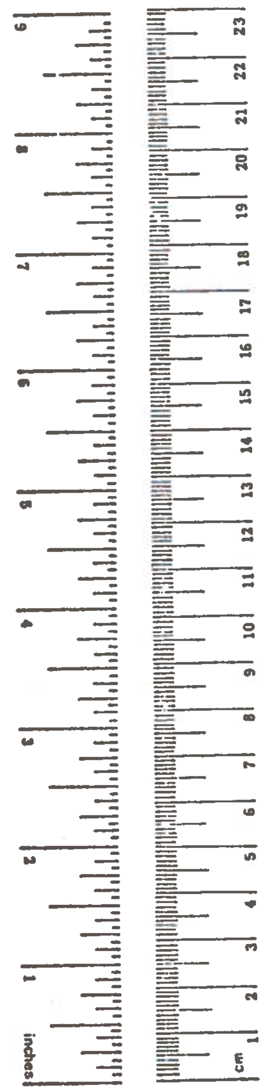
This study is one part of a larger Department of Transportation effort to examine transportation energy efficiency. The study was performed by CACI, Inc. - Federal for the DOT Transportation Systems Center. The TSC technical monitors were Dr. David Anderson and Dr. Russell Cherry. Their support, encouragement, and technical aid are gratefully acknowledged. Valuable guidance and assistance were also received from Paul Hoxie, Domenic Maio, and John Murphy of TSC. CACI participants in the study were Michael Bronzini, Roger Miller, John Sabo, Catherine Schourek, Conrad Strack, and Kenneth Wright. Both TSC and CACI also wish to acknowledge the cooperation of the Army Corps of Engineers, who made available for the study the multimodal network model and data developed under their inland navigation systems analysis program.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

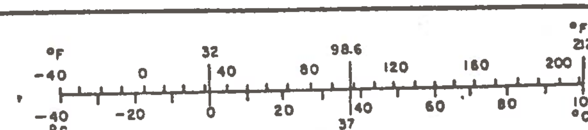
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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I. ENERGY CONSERVATION IMPACT ASSESSMENT

Introduction

The Department of Transportation (DOT) and other federal agencies are actively involved in developing and promoting methods for conserving energy in the transportation sector. The familiar statistics* spurring this activity bear repeating: transportation presently consumes some 19 quads** of energy annually, which represents over 26% of total U.S. energy consumption and over 53% of petroleum use. The movement of freight accounts for about 26% of transportation energy use, or roughly 6.75% of total U.S. energy consumption. Conserving energy in freight transportation, then, can make a significant contribution toward meeting national energy conservation objectives. In considering various strategies for reducing freight transport energy use, however, it is important to be able to accurately estimate both the amount of energy savings which might be realized and the impacts of energy conservation on the transportation industry and on shippers.

This report presents the overall design of a comprehensive methodology for assessing the impacts of energy conservation in U. S. intercity freight transportation. This methodology is designed to estimate the energy savings possible with new technology, new methods of operation, and network alterations within each mode of intercity freight transportation. National aggregate impacts on the cost of transportation of all freight, on overall service levels, and on modal market shares are also revealed. The methodology may also be used to generate energy-optimal freight transport system configurations and usage patterns to aid development of government policy. It may be used to estimate potential modal share impacts for specific markets which would result from specific energy conservation strategies.

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* Shonka, D. B., Loebl, A. S., and Patterson, P. D., "Transportation Energy Conservation Data Book: Edition 2," ORNL-5320, Oak Ridge National Laboratory, Oak Ridge, TN, Oct., 1977.

Gay, W. F., "Energy Statistics: A Supplement to the Summary of National Transportation Statistics," DOT-TSC-OST-76-30, DOT Transportation Systems Center, Cambridge, MA, Aug., 1976.

** 1 quad = 10^{15} British Thermal Units (BTU's).

The remainder of this chapter describes the structure and content of the assessment methodology. The impact prediction models used for energy conservation assessment are described in Chapter 2. Chapter 3 takes up database and data flow. Model calibration results for a base year (1972) and baseline energy-use, cost, and service estimates for the year 1990 are presented in Chapter 4.

System Overview

The basic concept of the energy conservation impact assessment methodology (hereafter referred to as the "TSC Freight Energy Model") is shown in Figure 1-1. Various options for conserving energy in the transport of intercity freight are specified externally by the analyst. These options are expressed in terms of data describing the structure and operation of the U. S. freight transportation system. A set of impact prediction models utilize these data to mimic the myriad transactions occurring within transportation markets. The models yield outputs which can be used to evaluate and compare the options.

System Architecture

The overall conceptual design of the TSC Freight Energy Model, shown in Figure 1-2, views freight transportation as a large and dynamic system whose components interact strongly with one another. Given this size and complexity, the model evaluates energy savings in freight transportation as follows.

Freight traffic moves primarily along four principal modes of ground intercity transportation: rail, waterway, highway, and pipeline. The modal shares of this traffic result from individual shipper decisions. Each shipper selects what appears, to the shipper, to be the best path between origin and destination. In making these selections, shippers react to two principal influences:

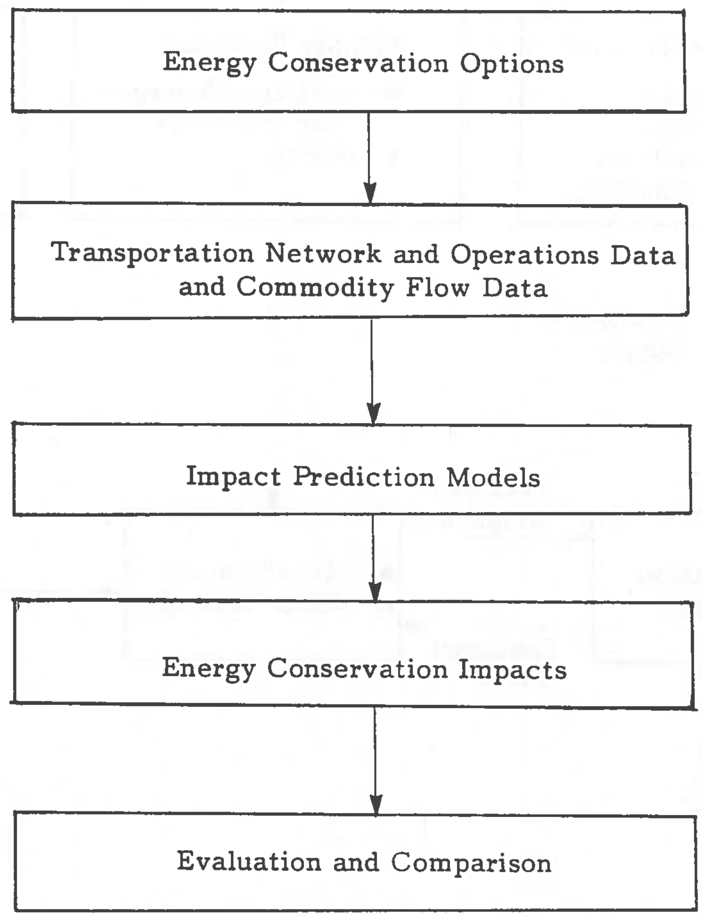


Figure 1-1. Strategy for Energy Conservation Impact Assessment

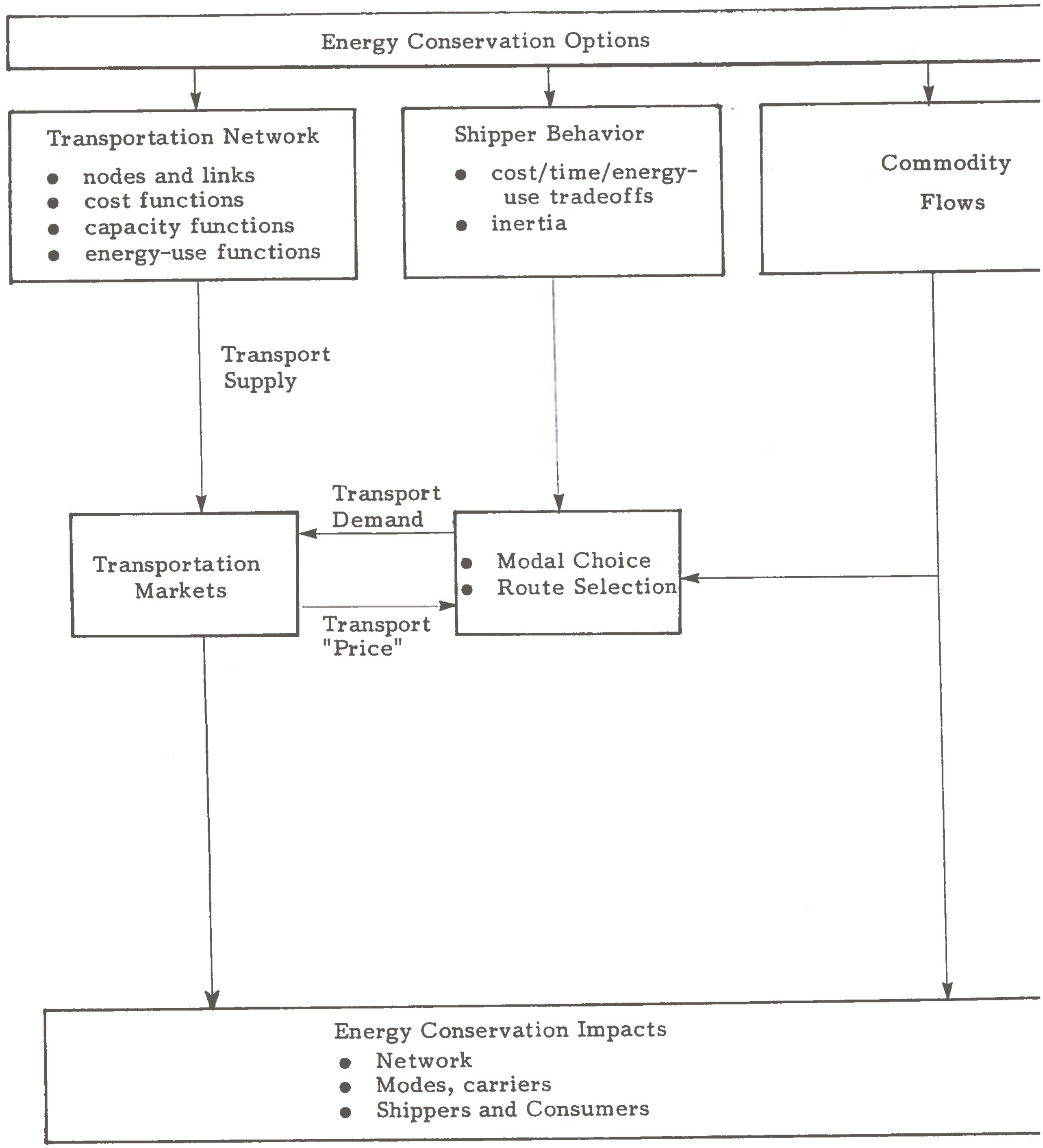


Figure 1-2. Energy Conservation Impact Prediction Methodology

- tradeoffs between transportation cost, transit time, and energy use
- long-term contracts, fixed physical distribution facilities, and similar arrangements collectively constituting an "inertia" effect which constrains shipper behavior in the short run.

The aggregate result of these individual shipper decisions is the effective demand for transportation by each mode.

Planned commodity flows, as mediated by modal selection decisions, define the demand for transportation. Transportation networks' structure, costs, capacity, and energy use define the supply of transportation. Transportation supply and demand then jointly determine transportation market prices and service levels.

These market conditions are likely to change as both supply and demand adjust over time. The demand for transportation can change as shippers revise their modal selection decisions if actual transportation market prices differ from expected prices, or in response to energy-use constraints.

Similarly, the supply of transportation can also adjust to market conditions as modal operators attempt to capture traffic and design their systems to move expected traffic safely, efficiently, and reliably. These adjustments may include new equipment, linehaul and terminal facility investment, new methods and patterns of operation, and <u>energy conservation measures which may imply any or all of the other adjustments.</u>

The direct result of such modal carrier changes is a shift in modal cost, capacity, and energy-use functions, which implies a change in the supply of transporation. The impact of a change in a given mode's supply of transportation can cascade throughout the nation's multimodal transportation system. Adjustments in transport demand induced by energy conservation measures can have similarly pervasive effects.

Therefore, defining, measuring, and evaluating the impacts of energy conservation within freight transportation requires a comprehensive framework to capture the indirect impacts, interactions, and adjustments, as discussed above, which are likely to result from implementing energy conservation options. The TSC Freight Energy Model provides this comprehensive framework.

Energy Conservation Options

A suggestive listing of the types of energy conservation options which the TSC Freight Energy Model is designed to accomodate appears below.* All of these options are representable in terms of data inputs to the model.

- Network Options
  - construction of new transportation facilities designed to increase energy efficiency or to replace or augment older, less efficient facilities
  - abondonment of facilities with lower than desirable energy efficiency
- Transport Operations Options
  - improved energy conversion efficiency as a result of technological innovation or revised operating patterns
  - imposition of speed limits
  - reduced backhaul of empty cargo vehicles
  - centralized routing of traffic
  - priority schemes designed to give high volume traffic preferential access to energy-efficient facilities

---

* This listing is only meant to show the model's intended capabilities, and in no way implies that any or all of these options are presently under active consideration by DOT. Also, at this time the model has not yet been applied to all of these options. Applications to date are described in Volume 4.

- Economic Incentives
    - imposition of fuel taxes or increases in existing fuel taxes
    - segment tolls on energy-inefficient facilities
    - governmental subsidy of energy-efficient facilities
- Behavior Shifts
    - modal choice restrictions
    - altered shipper and carrier sensitivity to energy use
    - reduced consumption of energy-intensive goods
    - relocation of population and industry to energy-efficient regions

<u>Energy Conservation Impacts</u>

The TSC Freight Energy Model is designed to yield estimates of the impacts of energy conservation in freight transportation at several levels of detail, ranging from results for individual network elements to total systemwide transportation, economic, and energy-use data. Some estimates output by the model are:

- effect of energy-use changes on the costs of providing specific modal services
- traffic volume, transit time, transportation cost, and energy use for individual network elements
- volume, time, cost, and energy-use summaries by transport mode
- modal shares of freight traffic
- transport cost, transit time, and energy use for each shipment
- minimum energy-use traffic patterns.

II. TSC FREIGHT ENERGY MODEL

Figure 2-1 is a simple schematic of the system of data and predictive models which collectively constitute the TSC Freight Energy Model. The general market dynamics orientation embodied in the methodology is implemented in the form of a transportation network model. This model allocates intercity freight traffic to specific transport modes and routes, in response to postulated transportation prices, service levels, and energy intensiveness, and, in turn, predicts the consequent values of these measures. The transportation network model is described in this chapter. A set of modal simulators are used to provide modal operations and energy-use data to the transportation network model. These simulators are described in Chapter 3. A complete treatment of the TSC Freight Energy Model is provided in Volume 2 of this report.

Transportation Network Model

Intercity commodity flows (a model input) define the demand for transportation. The corresponding supply of transportation is defined by the structure and behavior of each transportation mode.

The multimodal transportation system is considered to be a network of nodes and links. Within the network, each element is described by a cost function, a transit time function, and an energy function. The effective supply of transportation offered by each network element is defined by combining the element's cost curve with its delay and energy functions, as indicated in Figure 2-2. Since the transportation network model is central to the entire impact prediction methodology, it is described in some detail below.

Network Structure

The network consists of:

- Regions — commodity Origin-Destination areas

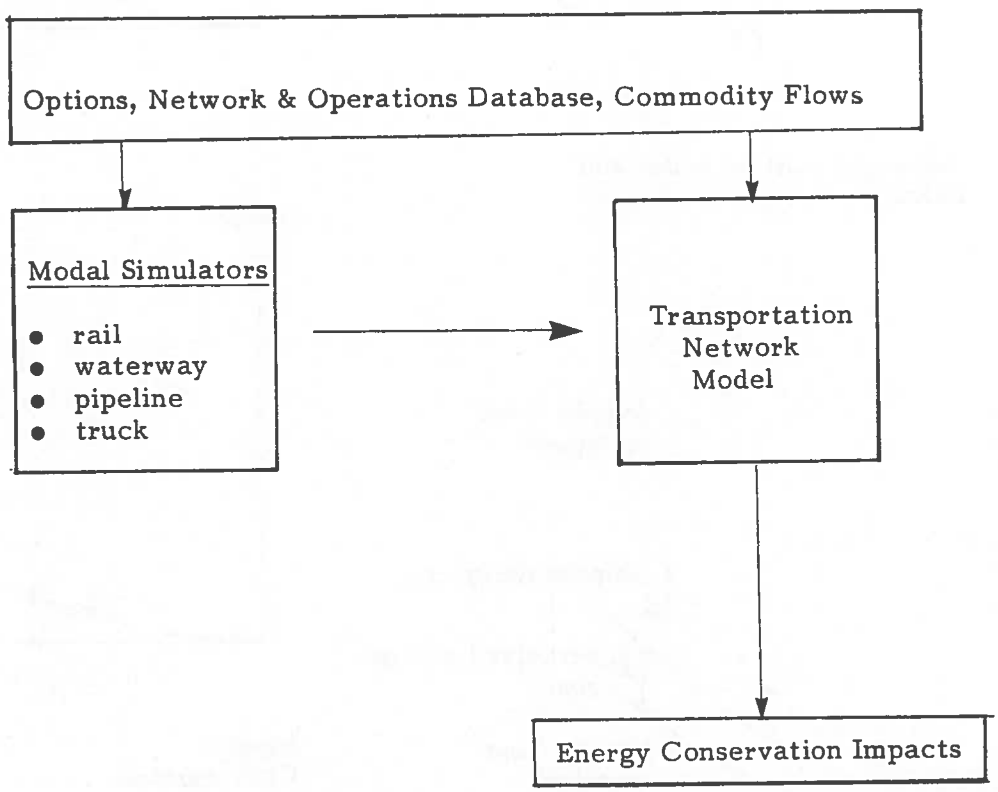
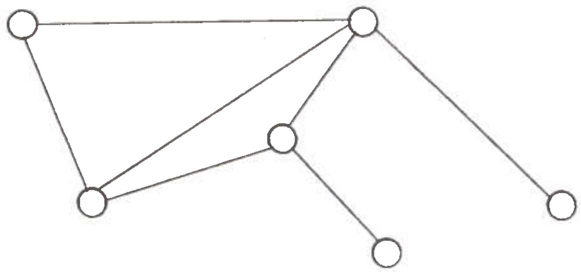
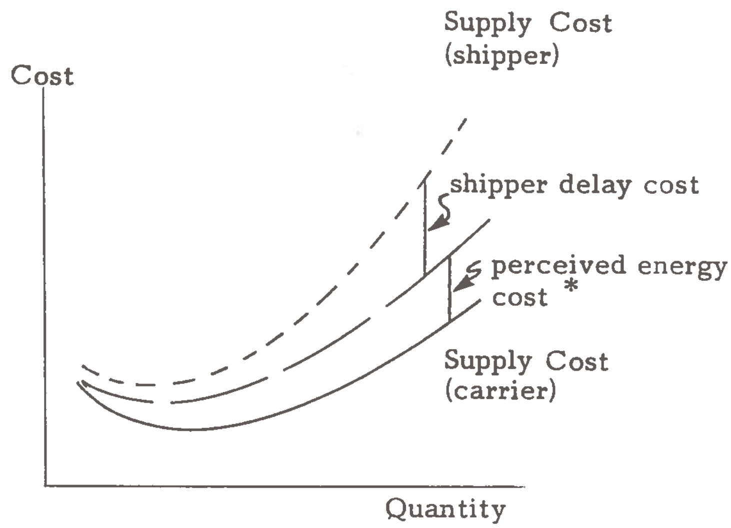


Figure 2-1. TSC Freight Energy Model

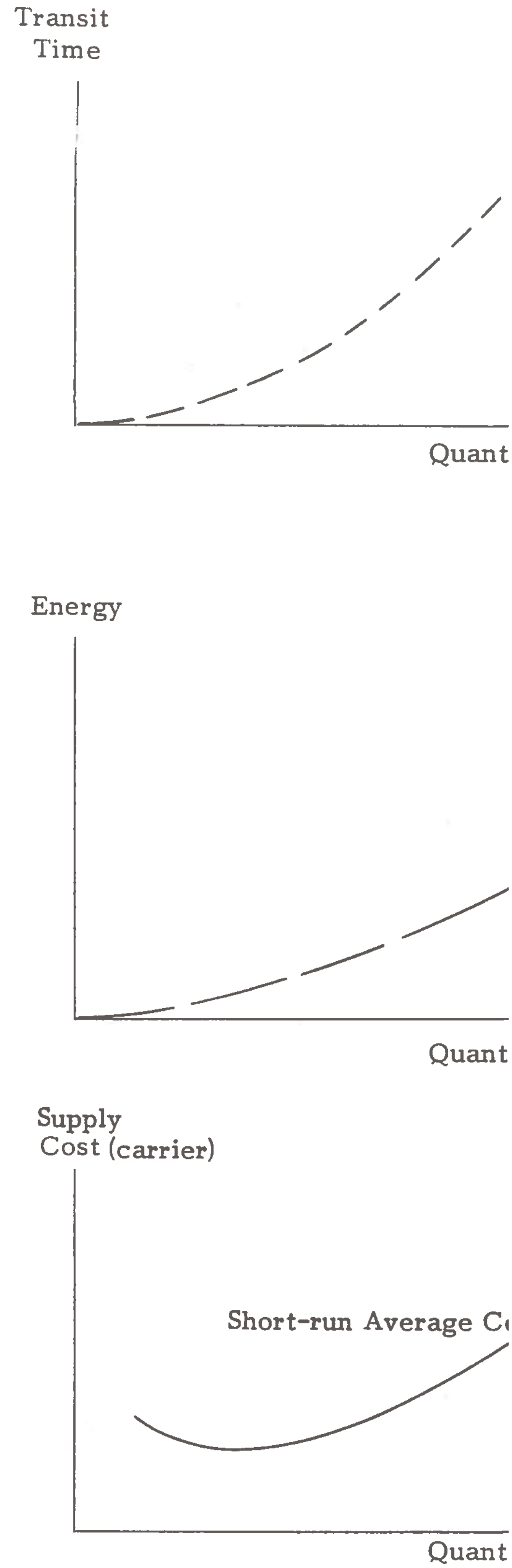


a) Networks contain nodes and links.



b) Each node and link supplies transportation.

* Any energy use cost perceived directly by the shipper, over and above that included in the carrier's cost. Under present U.S. shipper behavior, this componenet is normally zero.



c) Effective supply combine cost, time, and energy use

Figure 2-2. Transportation Supply

- Nodes — terminal points of linehaul transportation facilities, representing direction change, facility class change, intramodal switching, and point-located facilities such as navigation locks and rail yards.

- Access Links — connect regions to nodes, and represent local transportation

- Linehaul Links — linehaul transportation facilities

- Transfer Links — intermodal transfer facilities.

A simple schematic of a portion of a two mode transportation network is shown in Figure 2-3. Nodes R0980, R1025, and R1030 and their connecting links (solid lines) represent one mode. The second mode is represented by nodes H0435, H0560, and H0565 and their associated links (long dashes). Three regions, B, E, and A, are shown, and they are connected to each mode by access links (short dashes). An intermodal transfer link connects nodes R0980 and H0435, permitting traffic to switch modes there if it would be advantageous to do so. The entire network, which may contain thousands of nodes and links, is built up using the simple constructs shown in Figure 2-3.

<u>Network Operations</u>

Each link and node in the network is identified by a mode and facility class. Each class has associated with it a cost function, a time function, and an energy function (see Figure 2-2).

- Cost functions relate cost, in dollars per ton or ton-mile, to total tonnage using the facility.

- Time functions relate transit time, in hours or hours per mile, to total tonnage using the facility.

- Energy functions relate energy-use, in BTU (or other units) per ton or ton-mile, to total tonnage using the facility.

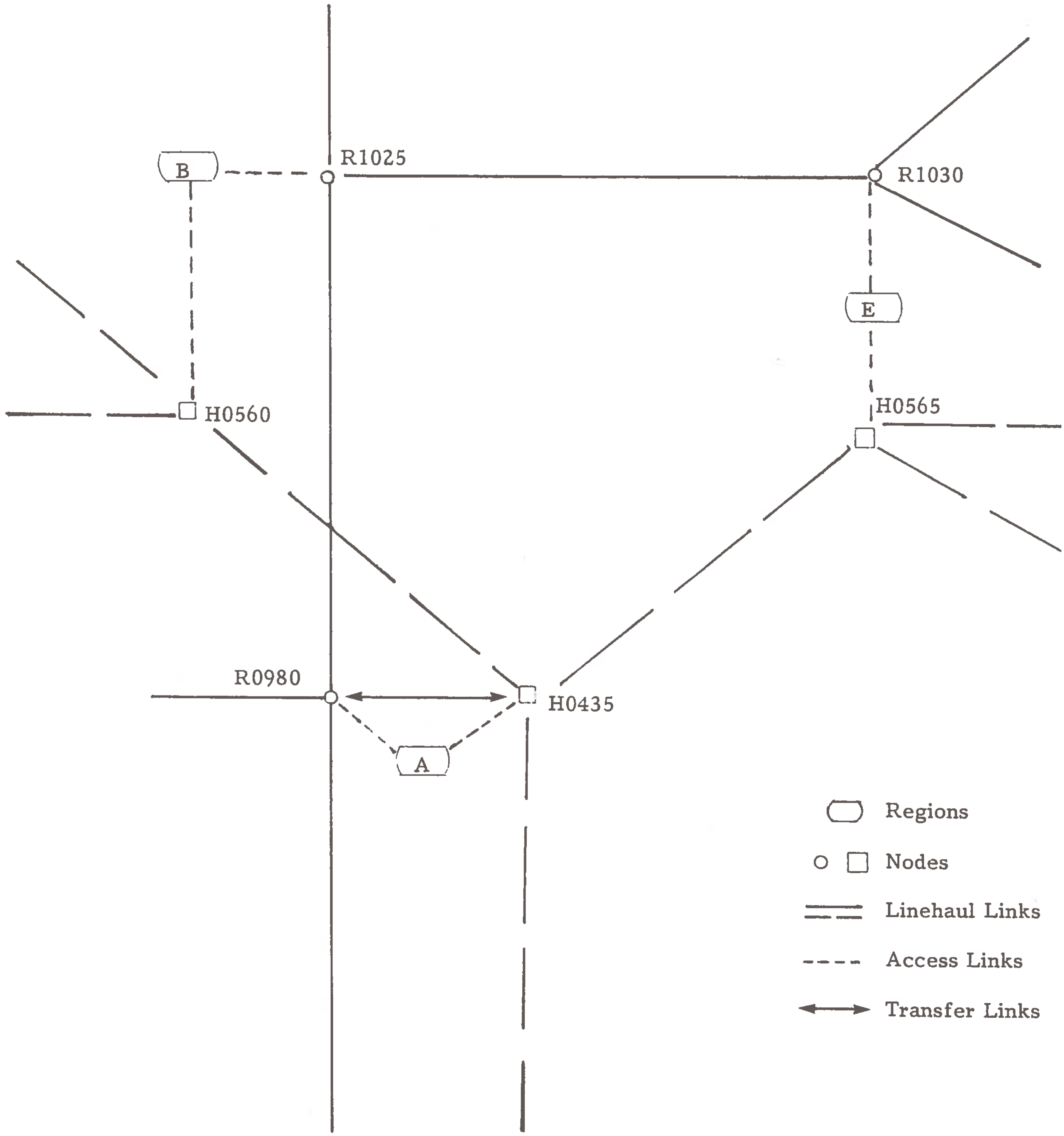


Figure 2-3. Multimodal Transportation Network

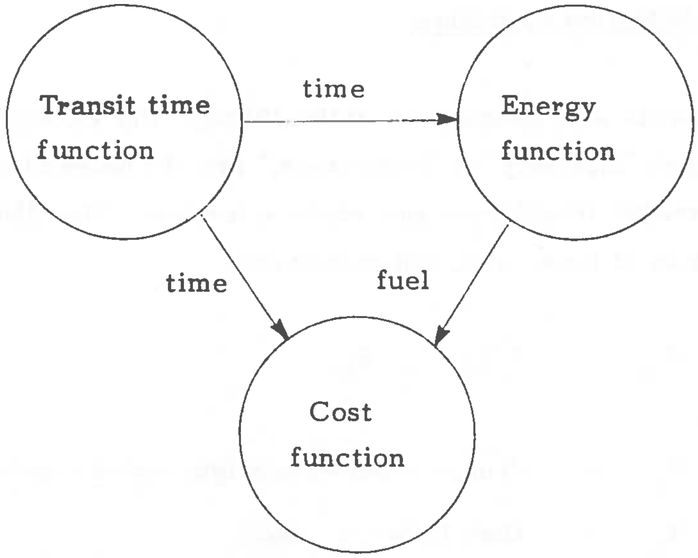


Figure 2-4. Relationships Between Network Operations Functions

As mentioned earlier, these three functions are estimated with a set of modal simulators. Some relationships between the functions are illustrated in Figure 2-4. Travel speed is an important determinant of energy use, and travel time and energy use are both determinants of transportation cost. These relationships are either built into the modal simulators, or are accounted for by the sequence in which separate simulators providing one or two of the functions are exercised.

Commodity Shipments

Commodities are identified by a two-digit commodity code and factors specifying the cost/time/energy-use tradeoff. Commodity flows are specified in the form of a list of shipments, each of which is described by:

- commodity
- origin region
- destination region
- tons to be shipped
- optional specified mode or route.

Path Selection Procedure

Shipments are assigned to paths through the network which minimize the shipper's "disutility" or "impedance," thereby determining modal selection(s), intermodal transfer(s), and route selection. The disutility of a path is a function of time, cost, and energy use:

$$Z_{ij} = f(T_{ij}, C_{ij}, E_{ij})$$

where

Z_{ij} = disutility between origin region i and destination region j

T_{ij} = time between i and j

C_{ij} = cost between i and j

E_{ij} = energy use between i and j.

Path disutility is computed as a function of facility transit time, t_k, facility shipping cost, c_k, and facility energy use, e_k, as determined by the facility's time, cost, and energy functions. A commodity-specific linear combination of these variables is used:

$$Z_{ij} = \sum_{k \varepsilon P_{ij}} a_m t_k + b_m c_k + w_m e_k$$

where

a_m = time weighting factor for commodity m. Depends on value per ton and "inventory charge"

b_m = cost weighting factor for commodity m

w_m = energy weighting factor for commodity m (zero in most applications, since energy costs are included in c_k)

P_{ij} = collection of network elements in the path from i to j.

The above equation is the model's operational equivalent of the concept of combining the cost, time and energy functions to produce a supply function.*

---

* The actual model code is a bit more complex than indicated here, as it provides for commodity-specific and direction-specific cost, time, and energy use, and allows the weighting factors in effect for a commodity to be overridden by shipment-specific weightings.

A variant of the standard labeling algorithm (usually attributed to Moore or Dantzig) is used to find minimum paths. Hence shipper optimal, rather than globally optimal, paths are generated. This corresponds quite well to usual transport market behavior, which is devoid of significant centralized control over mode and route selection by individual shippers. Particular shipments may be constrained to specified paths or modes. Links and nodes are limited to carrying flows below capacity.

A circuity constraint is applied to minimum path computations, by considering only those routes which lie within an ellipse of specified eccentricity with foci at the origin and destination regions. This constraint is invoked in order to speed up the process of searching out numerous paths through large networks.

An "inertia effect" is also included in the model, whereby a specified portion (or all) of each shipment may be constrained to repeat historical modal split patterns input by the user. This feature can be used to reflect the realities of long-term shipper contracts and other such commitments which prevent immediate shipper response to transportation market forces. The inertia feature has thus far been used as a model calibration aid, to obtain model output statistics under known modal split conditions.

Model Outputs

The following standard outputs are provided by the transportation network model:

- Path Traceback - optional for each shipment. Displays nodes along selected path from destination back to origin.
- Network Flow Report - traffic volume, transit time, cost, and energy use for each node, linehaul link, access link, and transfer link.
- Network Flow Summary
    - for each mode, traffic, cost, and energy use grouped by facility class

- for each commodity, traffic, cost, and energy use grouped by mode.

- Shipment Data - cost, transit time, and energy use for each shipment.

In addition, the model produces several types of output data files which may be used to generate specialized reports and various types of network-based computer plots. These files may be generated as mass storage, magnetic tape, or punch card data records, via program option switches and appropriate user-supplied job control statement. At this writing, no post-processor programs for using these files have yet been written.

Energy Use Analysis

The structure, logic, and outputs of the transportation network model allow flexible and convenient assessment of energy/shipper/transportation industry tradeoffs. Cost, service, and energy-use statistics are displayed side by side, hence the total consequences of energy conservation options are immediately apparent. Changes in modal shares of intercity freight traffic resulting from conservation options are also revealed. The effects on cost, service, and energy use of shifting traffic to energy efficient modes, and indeed the ability of the network to absorb such diversions, can be readily examined.

The model's path selection logic provides a capability to perform a variety of interesting and useful energy-use optimization analyses.

- Assignment of flows to energy-minimizing paths can be obtained by setting $a_m = b_m = 0$ and $w_m = 1$. If e_k is constant or is a relatively flat function of total volume, this assignment will be very close to that obtainable with a system-wide optimization formulation (in fact, constant e_k yields an exact correspondence if no network elements are capacitated).

- Links and nodes which attract heavy traffic loads due to their low energy-use characteristics can be identified, and singled out as locations where investments in additional capacity would yield energy savings.

- Similarities and contrasts between cost-minimizing and energy-minimizing freight flow patterns can be explored and evaluated.

- Varying sensitivities to time, cost, and energy use among commodity groups and individual shippers can be simulated by altering the relative values of a_m, b_m, and w_m. This allows testing of future development patterns which are energy conscious, among other applications.

- The effect of additional fuel taxes imposed to conserve energy can be simulated by incorporating the fuel tax in the value of w_m.

It should be noted that the transportation network model always assigns all shipments to the network. Hence energy-optimal flow patterns obtained with the approach suggested above will always satisfy the constraint of meeting regional commodity demands. Transportation service and cost requirements of shippers can be incorporated in the coefficients a_m and b_m.

The model outputs can also be used to calculate the conceptual equivalents of the "shadow prices" for any facility which would be yielded by a system-optimizing linear programming formulation of the network flow problem. Such values are useful for estimating the first order effects of increasing the capacity of a facility, thereby providing guidance as to which potential system improvements are worth investigating in detail.

III. DATABASE AND DATA FLOW

This chapter presents the source and content of the database component of the TSC Freight Energy Model, and describes the system's overall data flow. Volume 3 of this report provides complete documentation of the database.

Transportation Network

The transportation network model is completely general, and can be used in conjunction with any transportation network including any number of modes (subject to the capacity limitations of the computer system used). For initial applications, a national level network covering the rail, waterway, pipeline, and highway modes is available, as depicted in Figure 3-1. Network data sources are summarized below.

- Rail

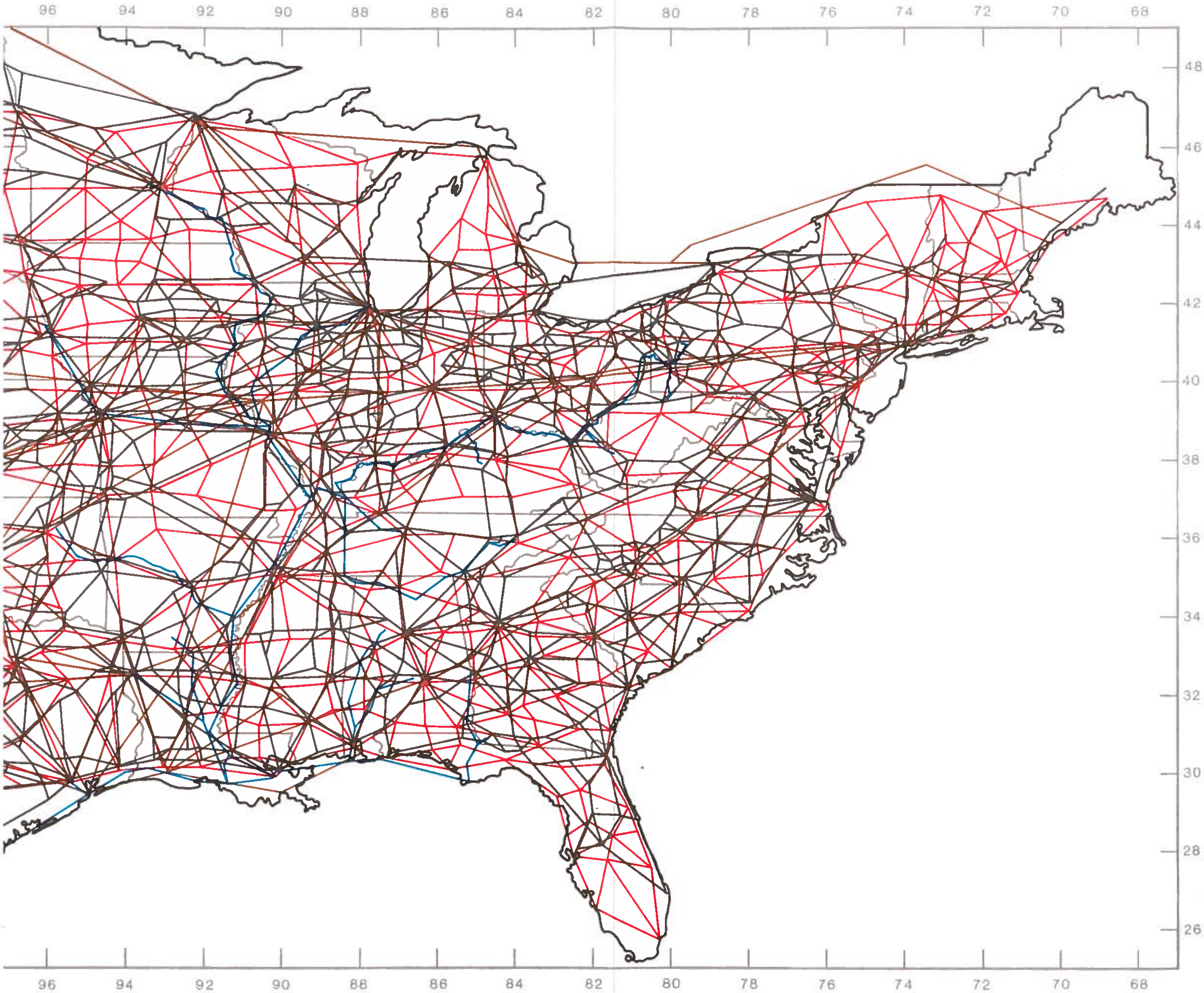
The railroad network is an aggregated version of a large and detailed national network developed by the Federal Railroad Administration (FRA). The original network contains 16,341 nodes and 19,476 links. The aggregated version contains 895 nodes and 1,754 links. Basic data describing the rail network include link length, number of tracks, type of signal system, average train speed, and owning railroad.

- Highway

The intercity highway network is based on a national network provided by the Federal Highway Administration (FHWA). The FHWA network contains 3,041 nodes and 4,528 links. For the TSC database, it was aggregated to 582 nodes and 1,292 links. Highway link data include length, physical type, terrain, and identification of toll roads.

- Waterway

The inland waterway network is that developed for the Corps of Engineers' Inland Navigation Systems Analysis (INSA) program. This network covers e Transportation Networks



/e been suppressed on this summary plot.
network elements giving economic regions
ıs well as traffic-dependent transportation
produced here, 1 inch equals approximately
:ifying small regional "windows" for larger plots.

Highway
Pipeline
Rail
Waterway

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September 1977

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the Mississippi River-Gulf Coast and tributaries inland waterway system, and contains 397 nodes and 400 links. It has been reduced to 252 nodes and 255 links for the TSC version. For complete national waterway coverage, West Coast, Atlantic Coast, New York-New England waterways, the Great Lakes, and all coastwise shipping lanes will have to be added. Detailed lock and channel data and preliminary port data are available for the inland waterway network.

- Pipeline

Crude petroleum, petroleum products, and natural gas pipelines in the United States and Canada are represented in a pipeline network developed for TSC by J. G. Debanne. The petroleum pipeline network extracted from this source contains 60 nodes and 96 links, and represents a combination of crude and products pipelines. Key data elements for pipeline segments include length, mean flow temperature, and flow capacity.

Modal Simulators

The transportation network model does not treat flows of individual vehicles. Average operating characteristics, vehicle load factors, empty vehicle redistribution, equipment availability limitations, etc., must be accounted for in the cost, time, and energy functions which represent node and link operations. Accordingly, separate modal simulators are used to generate these functions.

Table 3-1 identifies the modal simulators presently included in the TSC Freight Energy Model. These simulators are central to the model's data flow structure, since they provide the necessary linkages between detailed transport operations data and the more abstract operations representation required for network analysis. They also are the means by which direct energy savings due to technological innovations and other measures designed to reduce modal energy use are incorporated into the network.

Table 3-1. Modal Simulators

Mode	Simulator	Ref.*	Functions Provided**		
			Cost	Time	Energy
Rail	TSC rail cost model	1	X		
	CACI rail capacity model	2,3		X	
	CACI train delay simulator	4		X	
	TSC train performance calculator	4			X
Highway	TSC truck cost model	4	X		
	ORNL truck speed model	5		X	
Waterway	CACI lock capacity function generator	3		X	
	TSC waterway cost model	6	X		X
	INSA inland navigation simulation model	7		X	
Pipeline	Debanne pipeline model	8	X	X	X

* References:

1. J. F. Murphy, "Rail Cost Modeling, Vol. I, Rail Freight Operations Cost Methodology," DOT Transportation Systems Center, Cambridge, MA, Sept., 1976.

2. CACI, Inc., "A Train Dispatching Model for Line Capacity Analysis," Interstate Commerce Commission, Rail Services Planning Office, Washington, D.C., Jan., 1976.

3. CACI, Inc., "Waterway and Rail Capacity Analysis," DOT Transportation Systems Center, Cambridge, MA, Sept., 1976.

4. See Volume 2 of this report.

5. R. J. Olsen and G. W. Westley, "Synthetic Measures of Truck Operating Times Between the Metropolitan Centers of BEA Economic Areas: 1950, 1960, and 1970, with Projections for 1980," Report No. ORNL-NSF-EP-78, Oak Ridge National Laboratory, Oak Ridge, TN, Jan., 1975.

6. CACI, Inc., "Inland Waterway Transportation Cost Model," DOT Transportation Systems Center, Cambridge, MA, June, 1977.

7. CACI, Inc., "Inland Navigation Systems Analysis, Vol. 5, Waterway Analysis," Office of the Chief of Engineers, Corps of Engineers, Washington, D. C., July, 1976.

8. J. G. Debanne, "Regional Oil, Gas, and 'Other' Supply Distribution Model," DOT Transportation Systems Center, Cambridge, MA, Aug., 1976 (draft).

** These modal simulators are supplemented by published data and procedures, particularly for the highway and pipeline modes. See Volume 3 of this report for details.

Commodity Flow Data

Flows of 19 commodities between BEAR's (Bureau of Economic Analysis regions, as defined by the Department of Commerce) recently developed by TSC for a DOT national transportation planning effort are the basic source of commodity flow data for the TSC Freight Energy Model. Estimated flows in the base year of 1972 and projections for the years 1975, 1980, and 1990 are included in the data. Each data record indicates the commodity, origin, destination, transportation mode, and annual shipment tonnage.

Energy Conservation Options

Options for conserving energy in intercity freight transportation are represented in the TSC Freight Energy Model, via changes to one or more of the following types of data:

- network structure
- modal simulator inputs (produces revised cost, time, and energy functions)
- route selection parameters
- commodity flows.

Table 3-2 indicates which data types must be changed to accomodate the types of energy conservation options which were listed in Chapter 1.

Data Flow Structure

Figure 3-2 displays the overall data flow structure of the TSC Freight Energy Model. Energy conservation options are represented as described above, and the resulting network structure and operations data and commodity flows are processed by the transportation network model. The output reports produced by the model capture the impacts of most general interest. In addition, the model outputs data files which can be used to generate special purpose impact reports. At this writing, the post-processor programs needed to obtain such reports have not been developed.

Table 3-2. Representation of Energy Conservation Options

Energy Conservation Options	Means of Representation: network structure	modal simulators*	routing parameters	commodi flows
Network Options				
• construction of energy-efficient facilities	X			
• abandonment of energy-inefficient facilities	X			
Transport Operations Options				
• improved energy conversion efficiency		X		
• speed limits		X		
• reduction of empty backhauls		X	X	
• centralized traffic dispatching		X	X	
• reduction of route circuity			X	
• traffic priority schemes			X	
Economic Incentives				
• fuel taxes		X	X	
• segment tolls on energy-inefficient facilities		X		
• subsidy of energy-efficient facilities		X		
Behavioral Shifts				
• modal choice restrictions			X	
• altered sensitivity to energy use			X	
• reduced consumption of energy-intensive goods				X
• locational shifts				X

* Used to generate revised cost, time, and energy functions. Alternatively, the functions themselves may be modified directly.

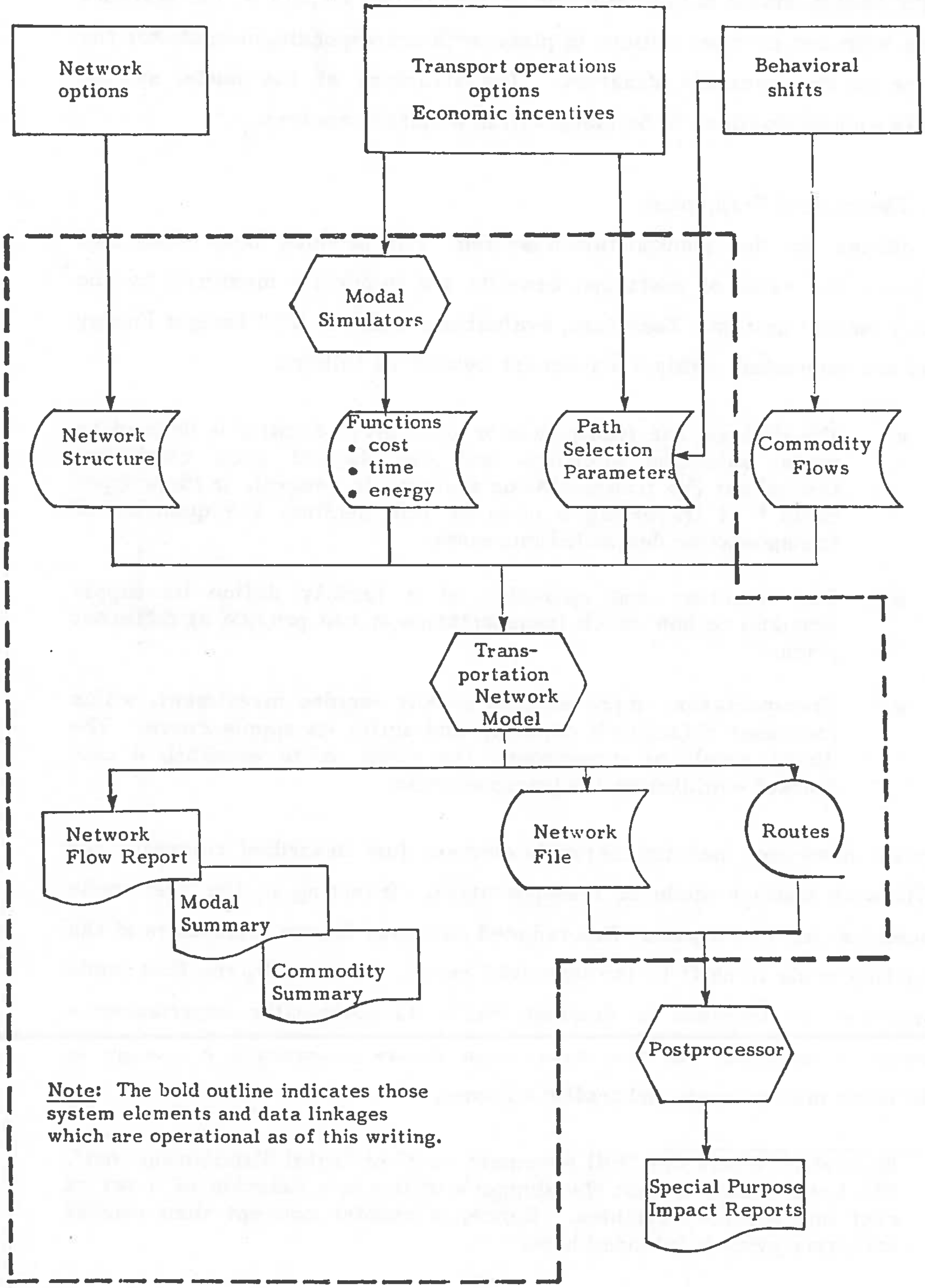

Figure 3-2. TSC Freight Energy Model Data Flow Structure

Evaluation Procedures

The procedure for evaluating energy conservation options with the TSC Freight Energy Model is basically one of comparing outputs of the system's models with one or more options in place with corresponding outputs for the base or no improvement situation. The structure of the model system permits such evaluations to be made within a market context.

- Theoretical Framework

Any change to the transportation system will produce both costs and benefits. The value of costs and benefits are implicitly measured by the nation's market system. Therefore, evaluations with the TSC Freight Energy Model are conducted within a market framework as follows:

- The demand for transportation on a given facility is defined by modal selection decisions and can depend upon conditions throughout the transportation system. In general, as the shipper costs * of traversing a node or link decline, the quantity of transportation demanded increases.

- The structure and operation of a facility define its supply schedule or how much transportation it can provide at different prices.

- Transportation improvements usually require investment, which increases a facility's capacity and shifts its supply curve. The direct result of investment, therefore, is to establish a new market equilibrium for transportation.

Suppose, however, that the network element just described competes for traffic with another mode of transportation. Investing in the first mode reduces its cost to shippers. This reduced cost may induce some users of the competing mode to shift to the improved mode. As a result, the first mode experiences an increase in demand, while its competitor experiences a decrease in demand. In this case, both modes experience a change in equilibrium market costs and traffic volumes.

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* Equivalent terms are "full economic cost" or "total distribution cost". The basic notion is that the shipper's utility is a function of a set of cost and service variables. Hence, a broader concept than market monetary price is intended here.

These market changes can create both costs and benefits for participants in the transportation market. Hence the direct net benefit of government investment in transportation is the resulting increment to real income of transportation producers and users. Direct net benefits (or disbenefits) must be balanced against net energy savings to properly evaluate energy conservation impacts.

Direct net benefits of transportation improvements are of four types:

- The increment to shippers' real income for the traffic using the improved mode both before and after improvement occurs.
- The increment to shippers' real income for the traffic that shifts to the improved mode.
- The increment (or decrement) to shippers' real income for the traffic that remains on the alternative mode.
- The increment (or decrement) to the excess profits of carriers operating in imperfectly competitive, yet unregulated, transportation markets.

All of these benefit components are captured within the model system.

- Evaluating Energy Conservation Options

As noted above, the TSC Freight Energy Model evaluates transportation system adjustments within a market context; net benefits are defined as the increment (or decrement) in shippers' total costs resulting from a change in the transportation system. The output produced by the transportation network model allows direct net energy savings to be evaluated in conjunction with net transportation cost and service increases or decreases. The model output also displays the regional, modal, and commodity incidence of costs and energy use, thus allowing equity issues to be addressed in the evaluation process.

The TSC Freight Energy Model does not contain any elaborate automated procedures or special software for conducting evaluations of energy conservation options.* It is incumbent on the analyst to select appropriate options for testing, input the options to the models, collect the model output reports, and compare the results using whatever evaluation criteria are relevant for the problem at hand. In short, it is the model's role to provide useful information to analysts and decision makers, not to replace them.

* It is expected that postprocessors (see Figure 3-2) of this genre will be added to the system as specific applications occur.

IV. RESULTS AND BASELINE PROJECTIONS

Some initial results obtained with the TSC Freight Energy Model are summarized * in this concluding chapter. Model calibration results and baseline projections for the year 1990 are considered in some detail, as are a set of 1990 projections obtained by assuming that energy-use minimization is the sole concern in freight modal choice and routing. Two additional applications not discussed here are presented in Volume 4 of this report.

The reader is cautioned at this point that a complete appreciation of the significance and limitations of these results is contingent upon a thorough understanding of the model system and of the freight network and operations database. Serious study of Volumes 2 and 3 of this report prior to making use of these findings is heartily recommended.

Model Calibration

Results obtained by running the model for the 1972 base year are presented below. The objective of these runs was to select model parameters and make minor data adjustments so as to get the model to reproduce known conditions as closely as possible. The primary test of model accuracy employed was comparison of the modal traffic shares in an "unconstrained" run of the transportation network model with the modal shares resulting from a "constrained" run. In a constrained run, the model is directed to repeat the modal shares given in the commodity flow data, while in an unconstrained run the model makes all mode choice decisions. The principal input parameter subject to adjustment between (unconstrained) runs was the relative importance of cost and transit time for each commodity. A total of six unconstrained runs were made before the model's behavior was deemed acceptable for the purposes of the present study. The constrained run was then repeated, in order to obtain final values for base year cost, transit time, and energy use.

* This chapter is based on the summary reports printed by the transportation network model computer program. Reproductions of these reports may be found in the Appendix to Volume 4.

- Database Accuracy

The first series of tables appearing in the following pages compare the output of the final constrained model run with independent estimates of the performance of the U. S. intercity surface freight transportation system in 1972. Since the model's modal choice logic is not involved here, these comparisons essentially address the accuracy of the database component of the TSC Freight Energy Model.

Table 4-1 compares the freight traffic included in the commodity flow data with total traffic by mode as reported by the Transportation Association of America (TAA) in the annual Transportation Facts and Trends publication. The traffic in the database falls considerably short of the national totals; in general, the coverage of ton-miles is better than that of tonnage. The main reason for these discrepancies is that the TAA data includes all intercity traffic, while the TSC flow data includes only inter-BEA traffic. Hence a substantial amount of relatively short haul intercity traffic which moves entirely within BEA regions — on the order of 1 billion tons in 1972 — is necessarily excluded. This is borne out by the average haul distance estimates shown in the last two columns of Table 4-1. Some additional sources of "missing" traffic are:

- The great difficulty of capturing commodity flow data for intercity trucking
- The lack of petroleum products flows via pipeline in the TSC data*
- Inclusion of Atlantic Coast and Pacific Coast waterways in the TAA data
- Inclusion of Alaska and Hawaii in the TAA data.

The main practical implication of these differences in the traffic base is that the model should only be used to evaluate differences in system performance. If absolute estimates of national freight statistics are desired, it is necessary to scale up the model outputs to reflect the actual national intercity traffic.

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* The basic source for the TSC manufactures commodity flow data was the Bureau of Census Commodity Transportation Survey which does not report petroleum products by pipeline.

Table 4-1. Estimated vs. Observed Intercity Freight Traffic (1972)

Mode	Tons (millions)		Ton-Miles (billions)		Average Haul (miles)	
	Observed*	Estimated**	Observed	Estimated	Observed	Estimated
Rail	1,531	1,005	784	580	512	577
Highway	1,934	546	470	204	243	374
Waterway#	507	263	178	129	351	490
Pipeline	876	278	476	169	543	608
Total	4,848	2,092	1,908	1,082	394	518

* Observed traffic from Transportation Association of America, Transportation Facts and Trends, 13th ed., Washington, D.C., July, 1977; hereafter cited as "TAA".

** Estimated traffic from the final calibration run of the TSC Freight Energy Model, with the model constrained to repeat the modal traffic shares given in the commodity flow data.

\# Excludes Great Lakes and domestic deep draft shipping.

Table 4-2 compares estimated and observed freight transportation cost and energy-use totals. In this case, the model results have been scaled up to represent the TAA traffic base, as indicated in the footnotes to the table. An important point to note here is that the model results for a mode include the cost and energy for access to that mode, while this distinction is not addressed very well, if at all, in the observed totals. This is particularly noticeable in the case of the waterway mode, where access via truck and rail consumes considerable resources (which are presumably included in the observed totals for these modes). For the most part the estimated and observed totals agree quite well. The only major dicrepancy is intercity truck transport, where fixed costs and terminal costs appear to be underestimated.* These results indicate that the underlying cost and energy-use data are reasonably accurate and contain no major omissions nor double counting.

Energy intensiveness and average cost comparisons are presented in Table 4-3. Again, the agreement between the estimated and observed values is quite good. The energy intensiveness estimates produced by the model are roughly the same as the popularly accepted values for the various modes. It is interesting to note that including access-mode energy raises the energy intensiveness of inland waterway transport by over 40%, and accounting for route circuity would likely push its energy use close to that of the railroads.

- Model Accuracy

The ability of the transportation network model operated in an unconstrained fashion to reproduce the results of a run with completely specified modal shares is addressed next. Since both the constrained and unconstrained runs use the same data, this constitutes a test of model accuracy.

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* Also, one would expect long haul trucking to enjoy lower unit costs than short haul trucking. Hence extrapolating long haul unit costs to the total traffic base should produce a significant underestimate.

Table 4-2. Estimated vs. Observed Operating Results (1972)

Mode	Cost ($ million)		Energy (trillion BTU)		Est. Ton-Days (million)@
	Observed*	Estimated**	Observed	Estimated	
Rail	13,105	13,038	538	496	9,131
Highway#	41,669	28,325	1,101	1,176	1,458
Waterway##	582	2,588	48	79	3,746
Pipeline	1,583	1,196	134	134	8,789
Total	56,939	45,147	1,821	1,885	23,124

* Observed costs are from TAA (see Table 4-1) , and actually represent estimated revenue based on data reported to the ICC by regulated carriers. Observed energy use is from Peat, Marwick, Mitchell & Co., "Energy and Economic Impacts of Projected Freight Transportation Improvements," DOT Transportation Systems Center, Cambridge, MA, Nov., 1976, factored to reflect the same traffic base as TAA. These energy use estimates agree reasonably well with DOT data compiled by Gay (see reference on p.1).

** Estimated results are constrained model output (see Table 4-1), adjusted to cover the same traffic base as TAA. Linehaul results (includes links and nodes) were adjusted by the ratio of observed to estimated ton-miles, while access results were adjusted by tonnage ratios.

\# If highway linehaul cost is adjusted by tonnage rather than ton-miles, the estimated highway cost is $39,034 million and the corresponding system total is $55,856 million.

\## The observed results for waterway exclude the cost and energy for access to waterway via rail, truck, or pipeline. Comparable waterway estimates which exclude access are $836 million, 49 trillion BTU, and 1,857 million ton-days.

@ There is no source which reports observed ton-days. The estimated ton-days are included here to show relative modal service results.

Table 4-3. Estimated vs. Observed Resource Intensiveness (1972)

Mode	Cost (mills/ton-mi)		Energy (BTU/ton-mi)		Est. Travel Rate
	Observed*	Estimated**	Observed	Estimated	(days/100 mi.)
Rail	16.7	15.9	686	626	1.13
Highway	88.7	54.0	2,343	2,369	0.23
Waterway#	3.3	11.7	270	396	1.80
Pipeline	3.3	2.5	282	279	1.84
Average	29.8	20.5	954	873	1.15

* Observed calculated from Tables 4-1 and 4-2.

** Estimated calculated from unadjusted model output (hence a different traffic base is reflected).

\# The observed data for waterway exclude the cost and energy for access to the waterway. Comparable waterway estimates which exclude access are 4.7 mills/ton-mi, 277 BTU/ton-mi, and 1.04 days/100 mi.

Table 4-4 displays estimated and observed modal shares of tons and ton-miles. In this table the "observed" data are from the final constrained model run, and the "estimated" data are from the final unconstrained run. The ton-mile data are also plotted in Figure 4-1, where each point is a single commodity-mode combination. The modal split accuracy of the model is remarkably good. In virtually all cases the predicted ton-mile share is within ±5% of the observed share, and this accuracy level is maintained across all share levels and across 3-mode and 4-mode competition situations. Indeed, the simple 45-degree line in Figure 4-1 could easily be mistaken for a least-squares fit to the data points. The only notable exception is petroleum products* for which, as noted earlier, the commodity flow data are highly suspect.

Figure 4-2 plots the estimated average traffic load on various classes** of network links against the observed traffic, based on the unconstrained and constrained runs, respectively, of the model. Although there is some scatter in the data, it appears that the estimated and observed network traffic patterns are quite similar. In fact, inspection of the model convergence statistics indicates that over two-thirds of the links and nodes in the network have an estimated traffic load that is within ±15% of the observed load.

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* This commodity accounts for the three outliers in Figure 4-1.

** Link classes are distinguished as follows:
Rail - geographic region, terrain, number of track, hp-to-tonnage ratio
Highway - physical type, terrain, toll vs. free
Waterway - river system
Pipeline - nominal diameter.
A single class may include from one to several hundred links. See Volume 3 for details.

Table 4-4. Estimated vs. Observed Modal Traffic Shares (1972)

Commodity	Obs/ Est**	Rail (%) tons	Rail (%) ton-mi	Highway (%) tons	Highway (%) ton-mi	Waterway (%) tons	Waterway (%) ton-mi
1. Farm Products	Obs	56.9	56.5	25.0	15.6	18.1	27.8
	Est	47.5	60.3	36.3	12.6	16.2	27.0
2. Forest and Marine Products	Obs	8.4	36.6	0.0	0.0	91.6	63.4
	Est	6.1	29.3	4.1	0.0	89.8	70.7
3. Coal	Obs	82.6	83.9	0.1	0.0	17.2	16.1
	Est	80.8	85.1	0.4	0.4	18.8	14.5
4. Crude Petroleum*	Obs	2.1	1.7	0.0	0.0	11.9	5.6
	Est	5.2	3.0	0.1	0.1	6.0	3.1
5. Metallic Ores	Obs	90.5	82.0	0.0	0.0	9.5	18.0
	Est	91.0	86.2	4.3	4.4	4.7	9.3
6. Nonmetallic Minerals	Obs	78.4	71.8	0.0	0.0	21.6	28.2
	Est	87.1	77.5	2.2	0.2	10.7	22.3
7. Food and Kindred Products	Obs	41.9	58.0	53.6	38.0	4.5	4.0
	Est	24.9	54.8	71.7	41.9	3.4	3.3
8. Textiles and Apparel	Obs	9.3	17.6	90.7	82.4	0.0	0.0
	Est	6.5	23.3	93.5	76.7	0.0	0.0
10. Chemicals	Obs	45.9	59.4	41.8	24.8	12.3	15.7
	Est	38.1	64.5	52.1	20.8	9.7	14.8
11. Lumber and Furniture	Obs	55.2	84.1	44.7	15.8	0.1	0.0
	Est	51.0	84.7	48.3	14.8	0.7	0.5
12. Machinery (nonelectrical)	Obs	21.6	34.3	78.4	65.7	0.0	0.0
	Est	12.1	29.3	86.5	68.8	1.3	1.8
13. Electrical Machinery	Obs	28.0	40.3	72.0	59.7	0.0	0.0
	Est	17.1	44.0	82.9	56.0	0.0	0.0
14. Transportation Equipment	Obs	48.9	71.3	50.8	28.3	0.3	0.4
	Est	45.4	75.0	54.6	25.0	0.0	0.0
15. Unidentified Manufactures	Obs	44.8	64.7	48.6	31.3	6.6	4.0
	Est	43.0	69.1	55.5	29.0	1.5	2.0
16. Paper and Allied Products	Obs	54.8	76.0	45.0	23.9	0.2	0.2
	Est	49.6	74.0	46.5	21.8	3.9	4.2
17. Petroleum Products*	Obs	21.5	25.6	24.0	10.7	52.9	62.8
	Est	52.8	53.6	10.6	1.3	36.6	45.1
18. Primary Metal Products	Obs	38.5	51.0	57.7	42.0	3.8	7.0
	Est	25.5	48.1	71.8	46.1	2.7	5.8
19. Fabricated Metal Products	Obs	26.7	39.6	73.0	60.0	0.3	0.4
	Est	15.5	37.0	84.5	63.0	0.0	0.0
20. Miscellaneous Manufactures	Obs	28.7	41.0	70.4	58.5	0.9	0.5
	Est	15.8	41.1	83.4	58.0	0.8	0.9
Total*	Obs	48.0	53.6	26.1	18.9	12.6	12.0
	Est	45.4	56.3	31.3	18.2	9.7	9.8

* Pipeline Share (%):

	Crude tons	Crude ton-mi	Products tons	Products ton-mi	Total tons	Total ton-mi
Obs	86.0	92.7	1.6	1.0	13.3	15.6
Est	88.7	93.7	0.0	0.0	13.6	15.7

** Observed shares are TSC Freight Energy Model output with the model constrained to repeat the modal shares given in the commodity flow data. Estimated shares are model output with the model making all mode choice decisions.

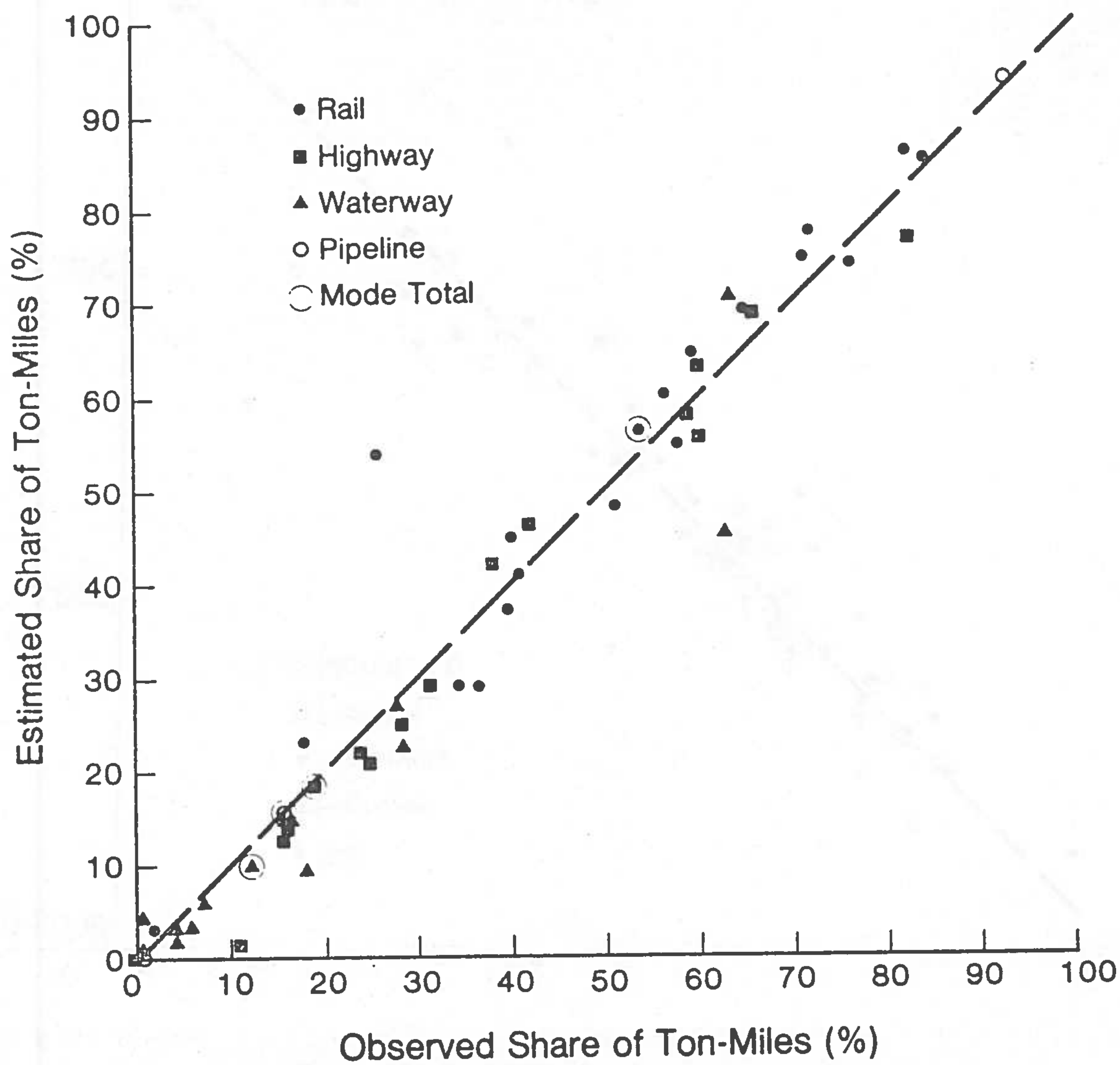

Figure 4-1. Estimated vs. Observed Modal Shares of Commodity Traffic (1972)

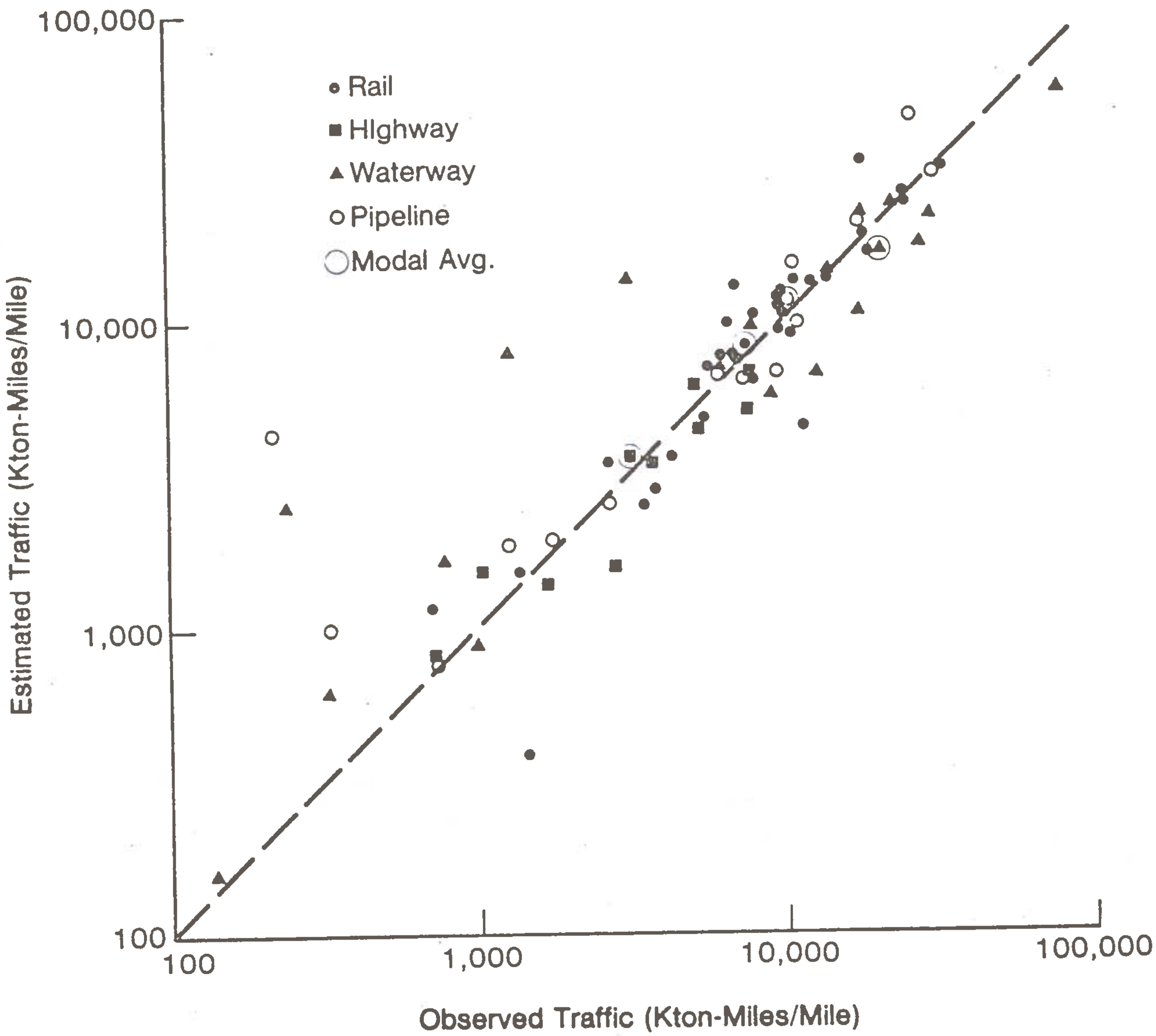

Figure 4-2. Estimated vs. Observed Average Traffic Density (1972)

• Summary

Model calibration is inherently a subjective process. The error level deemed acceptable depends entirely on the particular analysis to be attempted, the resources at hand, and the known error characteristics of the substitute methodologies available. The experience of calibrating the TSC Freight Energy Model indicates that further improvement is certainly possible, but not without substantial cost. Furthermore, the gains in accuracy which can be achieved are likely to be rather modest. The model is performing well enough to support a wide variety of applications. The major sources of error are known and can be eliminated as the need arises. In short, it appears that there is more to be gained from applying the model and improving the commodity flow data than from further extensive model calibration efforts.

Baseline Projections: 1990

As a point of departure for several initial applications of interest, the TSC Freight Energy Model was used to develop baseline projections of the performance of the freight transportation system in 1990.

• Assumptions

The basic assumption embedded in the baseline projections is that intercity freight transportation will change very little in the coming decade. This assumption is more in the nature of an expediency rather than an article of faith. It is also in keeping with the intent of the model, which is designed to trace the impacts of prospective system developments.

In defining the 1990 network very few changes were made to the 1972 network. Only major projects and operational changes which are fairly assured of being in place by 1990 were included. The inland waterway network was changed the most, in that several projects completed since 1972 or currently underway affect a substantial portion of the system's mileage. The following waterway developments were assumed:

- Completion of the Ohio River modernization program,* including new locks and dams at Hannibal, Willow Island, Cannelton, Newburgh, Uniontown, and Smithland (the last project, which is under construction, is the only one not presently in service);

- Completion of the Tennessee-Tombigbee Waterway, which is presently under construction;

- Capacity increments of 20 million tons per year at Locks and Dam 26 on the Mississippi River and at Gallipolis on the Ohio River, via either operational or structural improvements.

The only alteration in the rail data was for coal operations, where it was assumed that unit trains would account for 50% of all rail coal movements by 1990 (vs. 33% in the 1972 data). The only other rail trend which might prove to be significant is branch line abandonment, which would adversely affect access to the rail network. Time did not permit the required detailed study of pending abandonments and incorporation of any indicated access function modifications. The implicit assumption, then, is that abandonment of light density rail lines will not significantly alter access cost, time, and energy use for interregional rail shipments.

There were no changes made in the highway and pipeline networks. Modest increases in freeway mileage might be expected by 1990, due to progress on the Interstate Highway System. Time did not permit identifying all of these projects. In any event, much of this mileage is in urban areas, and the remaining rural mileage yet to be completed is widely scattered. Hence including these projects,** while potentially valuable for future model applications, would have virtually no noticeable impact on the model results. The only significant pipeline projects expected deal with the distribution of Alaskan oil, which is not included in the commodity flow projections.

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* The Mound City project was not included.

** Links which consist of divided highways for at least 50% of their length are already represented as freeways in the network data.

The nature of the commodity flow estimates for 1990 is the principal limitation on the baseline model results. As explained in Volume 3, the commodity projections were derived from estimated existing flows in 1972, using the OBERS regional economic activity forecasts. The resulting flow estimates represent "business as usual," and ignore such current developments as increasing use of western coal, availability of Alaskan oil, differential growth of the Sun Belt, fuel shortages, increased agricultural exports, and so on. This in itself is not necessarily a serious shortcoming, since one use envisioned for the model is analyzing the impacts of some of these trends. Nonetheless, this aspect of the commodity flow data does constrain the applicability of the baseline model projections. This also removes much of the impetus for significant alteration of the network data (i.e., the commodity flow forecasts are essentially contingent on the 1972 network characteristics).

Some additional assumptions of significance are as follows:

- There will be no changes in modal technology and operations; in particular, prospective improvements in fuel efficiency are not included.
- There will be a 22¢ per gallon increase in the real price of diesel fuel between 1972 and 1990.
- There will be no differential inflation (other than in the fuel price) affecting freight transportation; accordingly, all costs are expressed in 1972 dollars.
- All model relationships developed for the 1972 calibration are assumed to carry through intact to 1990.

- Results

Table 4-5 presents a summary of 1990 freight operations as projected with the TSC Freight Energy Model. The first two columns display raw outputs from the transportation network model for 1972 and 1990, respectively. The third column indicates the change expected between 1972 and 1990.

Table 4-5. Baseline Projections of 1990 Freight Operations

Item/Mode	Unadjusted 1972	Estimate * 1990	% Δ
Tons (million)			
Rail	950	1,505	+58.4
Highway	655	932	+42.3
Waterway	203	236	+16.3
Pipeline	286	352	+23.1
Total **	2,094	3,026	+44.5
Ton-Miles (billion)			
Rail	600	1,004	+67.3
Highway	195	265	+35.9
Waterway	105	157	+49.5
Pipeline	167	201	+20.4
Total	1,067	1,626	+52.4
Cost ($ million)			
Rail	8,882	15,509	+74.6
Highway	10,406	15,584	+49.8
Waterway	1,184	1,675	+41.5
Pipeline	402	614	+52.7
Total	20,874	33,382	+59.9
Energy (trillion BTU)			
Rail	371	624	+68.3
Highway	455	606	+33.3
Waterway	41	57	+38.8
Pipeline	45	75	+64.7
Total	912	1,362	+49.4
Service (million ton-days)			
Rail	6,200	9,925	+60.1
Highway	512	727	+42.0
Waterway	1,759	2,630	+49.5
Pipeline	3,041	3,088	+ 1.5
Total	11,512	16,370	+42.2

* Outputs from unconstrained runs of the transportation network model.

** Totals may differ because of rounding.

The main impression created by Table 4-5 is "more of everything for everyone." Total traffic will increase by 45% (or 52% if measured in ton-miles) and will be accompanied by roughly commensurate increases in transportation cost and energy use. Total cost will increase by 60%, while energy use will be up 50%. The increased traffic will apparently not stress the transportation system in aggregate, since service time, as measured in ton-days, will rise by 42%, which is 10% less than the anticipated growth in ton-miles.

Although all modes share in the increases noted above, they do not share equally. Rail and highway enjoy larger traffic gains than do waterway and pipeline. The fact that waterway ton-miles exhibit a growth three times greater than that of waterborne tonnage indicates the waterways will be gaining long haul traffic and losing some shorter haul coal traffic to rail unit trains. Similarly, the railroads will gain traffic in the longer haul sectors of their markets, while truck gains will be in the short haul market. These trends are primarily a result of the changing commodity mix in the flow projections, which show much higher increases in manufactures than in bulk commodities.

Rail energy use increases about as much as rail ton-miles. Truck energy use lags its ton-mile increase a little because the increased truck traffic causes a small reduction in average truck speeds, which saves energy. Growth in waterway energy use is 10% less than its ton-mile growth because energy for waterway access increases by only 8%, due to the loss of some coal traffic and to the differential growth of shipments from locations relatively close to the waterways. Pipeline energy use grows substantially faster than its traffic. This is due to the increase in average flow velocity required to provide greater throughput with the same physical plant (note that pipeline ton-days grow by only 1½% despite a 20% increase in ton-miles). Modal cost increases follow much the same pattern as energy use, with deviations explainable in terms of the relationships between fuel costs and total costs.

Resource intensiveness projections for 1990 are given in Table 4-6. Increased rail efficiencies are due to the shift of coal traffic into unit trains. Average highway costs increase in spite of greater fuel efficiency because of the offsetting impact of increased travel time on productivity.* Waterway efficiency gains accrue to the access function, as noted previously. Finally, pipeline efficiency losses are caused by higher fluid velocities. On an overall basis, it appears that average cost will not change much, despite increased fuel prices; energy intensiveness will show a modest decrease; and service quality, as measured in average travel speed, will improve.

Table 4-7 provides projections of average traffic density and capacity utilization by mode. Traffic flows on network links will increase by 2 million to 6 million tons per year on the average. There seems to be plenty of spare capacity available to handle these increases, particularly in the rail and highway systems. These averages can be misleading, however, since there is a good deal of variation in traffic density. There are some facilities of each mode which are operating under near capacity flow conditions in the 1990 model results. Furthermore, the economic capacity of a petroleum pipeline occurs with a flow that is in the neighborhood of 30% of its physical capacity. Hence these results indicate that there will probably be some capacity augumentation projects implemented by 1990, particularly petroleum pipelines, which are not included in the 1990 network data. This, of course, would improve modal performance efficiencies, so the projections presented here are probably somewhat conservative.

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* This argument has been raised by the trucking industry in opposition to lower speed limits for trucks.

Table 4-6. Projected Baseline Resource Intensiveness (1990)

Mode	Cost (mills/ton-mi)			Energy (BTU/ton-mi)			Service (days/100 mi)		
	1972	1990	% Δ	1972	1990	% Δ	1972	1990	% Δ
Rail	15.9	15.4	- 3.1	626	622	- 0.6	1.13	0.99	-12.5
Highway	54.0	58.8	+ 8.9	2,369	2,287	- 3.5	0.23	0.27	+17.4
Waterway	11.7	10.7	- 8.5	396	363	- 8.3	1.80	1.68	- 6.7
Pipeline	2.5	3.1	+24.0	279	373	+33.7	1.84	1.54	-16.3
Average	20.5	20.5	± 0.0	873	838	- 4.0	1.15	1.01	-12.2

Table 4-7. Projected Baseline Average Traffic Density (1990)

Mode	Kton-Miles per Mile			Avg. Volume/Capacity (%)*		
	1972	1990	% Δ	1972	1990	% Δ
Rail	8,408	13,085	+55.6	8.7	13.7	+5.0
Highway	3,573	5,372	+50.3	8.8	12.4	+3.6
Waterway	16,926	23,680	+39.9	20.1	28.5	+8.4
Pipeline	11,746	14,138	+20.4	30.1	37.1	+7.0
Average	7,293	11,082	+52.0	--	--	--

* Based on linehaul links for all modes except waterway, where average lock capacity utilization is reported.

Table 4-8 displays projected modal traffic shares in 1990. Modal share changes between 1972 and 1990 help to explain many of the aggregate effects noted above. Rail exhibits the only overall gain in traffic share, spurred by large increases in coal, chemicals, machinery, and miscellaneous manufactures. The only major loss of rail traffic is in metal ores, which is the major source of increased waterway traffic. The waterways also pick up considerable petroleum products, but register major traffic share reductions in coal and chemicals. Minor traffic share losses occur in nearly all commodities for highway,* due to the restraining influence of increased fuel and congestion costs on traffic growth. The only big losses occur in chemicals, machinery, and miscellaneous manufactures. The changing commodity mix between 1972 and 1990, however, causes the overall truck share to remain stable. The projected reductions in the pipeline share of crude petroleum traffic will probably not acctually occur; instead, increased petroleum traffic in a corridor will lead to pipeline capacity increases.

In summary, the baseline projections for 1990 indicate substantial traffic growth for all modes, with rail and highway leading the way. The major forces at work in the freight system appear to be the increasing proportion of manufactured goods in the traffic stream, escalated fuel prices, waterway modernization and expansion, use of unit trains for the movement of coal, and the operation of existing pipelines at a near economic capacity. Capacity insufficiency is not a pervasive problem, although individual elements within each modal network are approaching capacitation. In many ways the system has a natural tendency toward fuel efficiency, due to the impact of fuel prices on operating costs. Service quality requirements resulting from shipper cost/service tradeoffs made through decades of cheap energy, however, place some bounds on the ability of the system to achieve further energy savings. The results of relaxing service quality demands are explored in the next section.

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* This observation must be tempered by the fact that truck traffic is underrepresented by the largest margin in the commodity flow data.

Table 4-8. Projected Modal Shares of Commodity Traffic (1990)

Commodity	Tons						Ton-Miles					
	Rail		Highway		Waterway		Rail		Highway		Waterway	
	%	Δ	%	Δ	%	Δ	%	Δ	%	Δ	%	Δ
1. Farm Products	52.1	+ 4.6	33.6	- 2.7	14.4	-1.8	65.7	+ 5.4	11.1	- 1.5	23.1	-3.9
2. Forest and Marine Products	4.9	- 1.2	4.4	+ 0.3	90.7	+0.9	20.7	- 8.6	0.2	+ 0.2	79.1	+8.4
3. Coal	91.4	+10.6	0.3	- 0.1	8.3	-10.5	92.5	+ 7.4	0.3	- 0.1	7.2	-7.3
4. Crude Petroleum *	5.6	+ 0.4	0.1	0	9.8	+3.8	3.1	+ 0.1	0.1	0	9.8	+6.7
5. Metallic Ores	81.8	- 9.2	4.5	+ 0.2	13.8	+9.1	54.4	-31.8	4.2	- 0.2	41.4	+32.1
6. Nonmetallic Minerals	88.3	+ 1.2	2.0	- 0.2	9.7	+1.0	78.2	+ 0.7	0.2	0	21.7	-0.6
7. Food and Kindred Products	31.1	+ 6.2	66.1	- 5.6	2.7	-0.7	63.7	+ 8.9	34.1	- 7.8	2.2	-1.1
8. Textiles and Apparel	5.7	- 0.8	94.3	+ 0.8	0.0	0	21.8	- 1.5	78.2	+ 1.5	0.0	0
10. Chemicals	50.7	+12.6	44.0	- 8.1	5.3	-4.4	79.2	+14.7	14.5	- 6.3	6.3	-8.5
11. Lumber and Furniture	56.2	+ 5.2	43.1	- 5.2	0.7	0	85.9	+ 1.2	13.6	- 1.2	0.5	0
12. Machinery (Nonelectrical)	18.5	+ 6.4	79.2	- 7.3	2.3	+1.0	44.7	+15.4	52.8	-16.0	2.5	+0.7
13. Electrical Machinery	15.0	- 2.1	85.0	+ 2.1	0.0	0	38.8	- 5.2	61.2	+ 5.2	0.0	0
14. Transportation Equipment	47.5	+ 2.1	52.5	- 2.1	0.0	0	76.2	+ 1.2	23.8	- 1.2	0.0	0
15. Unidentified Manufactures	49.8	+ 6.8	48.6	- 6.9	1.5	0	75.5	+ 6.4	22.9	- 6.1	1.6	-0.4
16. Paper and Allied Products	52.5	+ 2.9	41.7	- 4.8	5.8	+1.9	74.6	+ 0.6	18.5	- 3.3	6.9	+2.7
17. Petroleum Products	48.8	- 4.0	9.4	- 1.2	41.9	+5.3	43.9	- 9.7	1.0	- 0.3	55.1	+10.0
18. Primary Metal Products	28.0	+ 2.5	68.3	- 3.5	3.7	+1.0	54.8	+ 6.7	38.9	- 7.2	6.3	+0.5
19. Fabricated Metal Products	19.0	+ 3.5	81.0	- 3.5	0.0	0	46.6	+ 9.6	53.4	- 9.6	0.0	0
20. Miscellaneous Manufactures	24.5	+ 8.7	75.4	- 8.0	0.1	-0.7	55.8	+14.7	44.1	-13.9	0.1	-0.8
Total*	49.7	+ 4.3	30.8	- 0.5	7.8	-1.9	61.7	+ 5.4	16.3	- 1.9	9.7	-0.1

* Pipeline Share	Tons		Ton-Miles	
	%	Δ	%	Δ
Crude Petroleum	84.5	-4.2	87.0	-6.7
Total	11.6	-2.0	12.3	-3.4

Note: Δ = change from 1972 share, based on unconstrained model results.

Energy-Use Minimization: 1990

How much potential for energy savings is there in the intercity freight transportation industry? Put another way, how much energy is presently being traded off for reduced cost and/or improved service? To obtain some answers to these questions, a run of the transportation network model was made in which the model was directed to make all mode choice and routing decisions so as to minimize energy use. The results of this run are presented below.

Predicted overall modal operating results are given in Table 4-9. The dominant impact of energy-use minimization is the substantial loss of truck traffic coupled with concomitant increases in rail and waterway traffic. The differential changes in tons and ton-miles show that rail is the major recipient of the lost truck traffic, with waterway also playing a role. The pipeline system loses short haul traffic and gains long haul traffic, which explains the apparently contradictory result that tons decrease while ton-miles increase.

Changes in cost and energy consumption are comparable in magnitude to traffic changes. Overall, a 31% reduction in energy use and a 21% cost reduction are achieved. These savings accrue entirely from shifts of modal choice, and are entirely independent of any savings achievable through modal technology and operational improvements.

The savings in cost and energy use are obtained at the price of a 46% loss of service quality, as measured in ton-days. This increase in shipping time causes a net 12% increase in total disutility or full economic cost, which has a perceived value of $6 billion. In other words, the economic gain to shippers resulting from the 21% cost reduction is more than offset by the economic value of the lost service quality.

Table 4-9. Freight Operations for Minimum Energy Use (1990)

Item/Mode	Unadjusted Estimate * Base	Min Energy	% Δ
Tons (million)			
Rail	1,505	2,269	+ 50.8
Highway	932	16	- 98.3
Waterway	236	413	+ 75.0
Pipeline	352	329	- 6.5
Total **	3,026	3,027	0
Ton-Miles (billion)			
Rail	1,004	1,135	+ 13.0
Highway	265	4	- 98.5
Waterway	157	248	+ 58.0
Pipeline	201	236	+ 17.4
Total	1,626	1,623	- 0.2
Cost ($ million)			
Rail	15,509	21,755	+ 40.3
Highway	15,584	373	- 97.6
Waterway	1,675	3,595	+114.6
Pipeline	614	729	+ 18.7
Total	33,382	26,452	- 20.8
Energy (trillion BTU)			
Rail	624	749	+ 20.0
Highway	606	11	- 98.1
Waterway	57	107	+ 87.3
Pipeline	75	76	+ 1.6
Total	1,362	943	- 30.8
Service (million ton-days)			
Rail	9,925	15,487	+ 56.0
Highway	727	13	- 98.2
Waterway	2,630	4,438	+ 68.7
Pipeline	3,088	3,967	+ 28.5
Total	16,370	23,906	+ 46.0
Disutility ($ million)			
Rail	28,721	45,462	+ 58.3
Highway	17,126	388	- 97.7
Waterway	3,446	9,256	+168.6
Pipeline	645	768	+ 19.1
Total	49,938	55,874	+ 11.9

* Outputs from unconstrained runs of the transportation network model.

** Totals may differ because of rounding.

Resource intensiveness values with the energy-minimal network flow pattern are given in Table 4-10. All modes, save pipeline, experience increases in average cost and energy intensiveness, and all modes operate at lower average speed. Overall, however, modal traffic changes produce decreases in cost and energy intensiveness. Changes in average traffic density and capacity utilization, reported in Table 4-11, are in agreement with these results. Traffic congestion does not appear to be a problem, with the possible exception of the inland waterways. In particular, the 50% increase in rail tonnage is accommodated easily, primarily through utilization of idle capacity.

The commodity-by-commodity pattern of modal traffic share adjustments for energy-use minimization is displayed in Table 4-12. Rail scores major gains in manufactured goods and a small but significant increase in coal traffic. The inland waterways draw modest increases in bulk commodities with the exception of coal, and make some inroads in the manufactures trade.

The implications of these results are not entirely obvious. It appears that a nearly one-third savings in the energy used for intercity surface freight transportation is achievable, strictly through altered modal choices. In other words, all of the freight in 1990 could be moved with the same quantity of energy consumed in 1972. Technological improvements under active development within each mode could slash energy use even further (figures of 10 to 30 percent are often cited).

But is modal choice realignment a realistic option? Departing from a perceived cost-minimizing network flow pattern to an energy-minimizing pattern reduces shipper service quality, and shippers presently place a rather high economic value on service quality. Hence some type of shipper incentive program would be required, to provide compensation for their perceived losses. Alternatively, improvements in the quality of service provided by energy-efficient modes could be undertaken.

Table 4-10. Resource Intensiveness with Minimum Energy Use (1990)

Mode	Cost (mills/ton-mi)			Energy (BTU/ton-mi)			Service (days/100 mi)		
	Base	ME	% Δ	Base	ME	% Δ	Base	ME	% Δ
Rail	15.4	19.2	+24.7	622	660	+ 6.1	0.99	1.36	+37.4
Highway	58.8	93.2	+58.5	2,287	2,850	+24.6	0.27	0.32	+18.5
Waterway	10.7	14.5	+35.5	363	430	+18.5	1.68	1.79	+ 6.5
Pipeline	3.1	3.1	0	373	323	-13.4	1.54	1.68	+ 9.1
Average	20.5	16.3	-20.5	838	581	- 30.7	1.01	1.47	+45.5

ME = result from minimum energy model run.

Table 4-11. Average Traffic Density with Minimum Energy Use (1990)

Mode	Kton-Miles per Mile			Avg. Volume/Capacity (%)*		
	Base	ME	% Δ	Base	ME	% Δ
Rail	13,085	13,400	+ 2.4	13.7	13.8	+ 0.7
Highway	5,372	978	-81.8	12.4	4.3	-65.3
Waterway	23,680	36,970	+56.1	28.5	44.0	+54.4
Pipeline	14,138	13,215	- 6.5	37.1	31.4	-15.4
Average	11,082	14,368	+29.7	--	--	--

* Based on linehaul links for all modes except waterway, where average lock capacity utilization is reported.

ME = result from minimum energy model run.

Table 4-12. Modal Traffic Shares with Minimum Energy Use (1990)

Commodity	Tons						Ton-Miles					
	Rail		Highway		Waterway		Rail		Highway		Waterway	
	%	Δ	%	Δ	%	Δ	%	Δ	%	Δ	%	Δ
1. Farm Products	72.9	+20.8	0.0	-33.6	27.1	+13.7	59.0	- 6.7	0.0	-11.1	41.0	+17.9
2. Forest and Marine Products	5.2	+ 0.3	0.0	- 4.4	94.8	+ 4.1	19.3	- 1.4	0.0	- 0.2	80.7	+ 1.6
3. Coal	98.6	+ 7.2	0.3	0	1.1	- 7.2	96.8	+ 4.3	0.3	0	2.9	- 4.3
4. Crude Petroleum *	10.9	+ 5.3	0.1	0	10.1	+ 0.3	4.6	+ 1.5	0.1	0	4.4	- 5.4
5. Metallic Ores	72.7	- 9.2	4.5	0	22.8	+ 9.0	43.7	-10.7	4.1	- 0.1	52.2	+10.8
6. Nonmetallic Minerals	78.0	-10.3	0.2	- 1.8	21.8	+12.1	67.8	-10.4	0.0	- 0.2	32.2	+10.5
7. Food and Kindred Products	75.2	+44.1	0.7	-65.4	24.1	+21.4	79.6	+15.9	0.0	-34.1	20.4	+18.2
8. Textiles and Apparel	85.7	+80.0	1.3	-93.0	13.0	+13.0	83.5	+61.7	0.4	-77.8	16.1	+16.1
10. Chemicals	79.2	+28.5	0.5	-43.5	20.3	+15.0	74.5	- 4.7	0.1	-14.4	25.4	+19.1
11. Lumber and Furniture	89.9	+33.7	0.2	-42.9	9.9	+ 9.2	92.8	+ 6.9	0.0	-13.6	7.2	+ 6.7
12. Machinery (Nonelectrical)	75.5	+57.0	0.0	-79.2	24.5	+22.2	82.2	+37.5	0.0	-52.8	17.8	+15.3
13. Electrical Machinery	96.6	+81.6	3.4	-81.6	0.0	0	99.3	+60.5	0.7	-60.5	0.0	0
14. Transportation Equipment	100.0	+52.5	0.0	-52.5	0.0	0	100.0	+23.8	0.0	-23.8	0.0	0
15. Unidentified Manufactures	88.3	+38.5	0.5	-48.1	11.2	+ 9.7	90.4	+14.9	0.2	-22.7	9.3	+ 7.7
16. Paper and Allied Products	81.9	+29.4	0.1	-41.6	18.0	+12.2	81.6	+ 7.0	0.0	-18.5	18.4	+11.5
17. Petroleum Products	62.3	+13.5	0.4	- 9.0	37.3	- 4.6	67.0	+23.1	0.0	- 1.0	33.0	-22.1
18. Primary Metal Products	92.8	+64.8	0.0	-68.3	7.2	+ 3.5	88.3	+33.5	0.0	-38.9	11.7	+ 5.4
19. Fabricated Metal Products	88.9	+69.9	0.9	-80.1	10.2	+10.2	88.9	+42.3	0.0	-53.4	11.0	+11.0
20. Miscellaneous Manufactures	94.5	+70.0	1.2	-74.2	4.3	+ 4.2	94.4	+38.6	0.1	-44.0	5.5	+ 5.4
Total*	75.0	+25.3	0.5	-30.3	13.6	+ 5.8	69.9	+ 8.2	0.2	-16.1	15.3	+ 5.6

* Pipeline Share	Tons		Ton-Miles	
	%	Δ	%	Δ
Crude Petroleum	78.9	-5.6	91.0	+4.0
Total	10.9	-0.7	14.6	+2.3

Δ = **Difference from 1990 Baseline, based on unconstrained model results**

In any event, the total savings achieved through changes in modal choice behavior are likely to fall short of the one-third maximum suggested by this research. Numerous factors not considered here, such as availability of modal services, shipment size requirements, additional elements of service quality, special packaging, and so on, all militate against radical modal share alterations. Also, there may be some hidden energy implications which counteract direct transport savings. For example, switching from truck to rail may require additional warehousing or stockpiling facilities, which will use energy to construct and operate.

Closure

The initial applications of the TSC Freight Energy Model presented here are suggestive rather than definitive. They were undertaken primarily as a demonstration of capability rather then for policy analysis. In this regard, the applications are quite successful. The ability of the model to entertain various scenarios and produce results useful for policy and program analyses is clearly evident. The quantitative results, properly interpreted and caveated, also provide some indication of what a more comprehensive analysis of energy conservation in freight transportation might reveal.

APPENDIX - REPORT OF NEW TECHNOLOGY

The work performed under this contract, while leading to no new invention, has led to innovative methods for analyzing the performance of large scale multimodal freight transportation networks. New concepts of hierarchical modeling, use of detailed modal simulators, and representation and aggregation of large networks were introduced. New computer models and computerized data bases were also developed in this research.