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# A Review of Petroleum~~-~~Transport~~-~~Network Models and Their Applicability to a National Refinery Model

J. N. Hooker

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Regional and Urban Studies Section

Energy Division

# A REVIEW OF PETROLEUM-TRANSPORT-NETWORK MODELS AND THEIR APPLICABILITY TO A NATIONAL REFINERY MODEL

J. N. Hooker

Date Published - April 1982

OAK RIDGE NATIONAL LABORATORY
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# ABSTRACT

This report examines four petroleum transport network models to determine whether parts of them can be incorporated into the transportation component of a national refinery model. Two questions in particular are addressed. (a) How do the models under examination represent the oil transport network, estimate link capacities, and calculate transport costs? (b) Are any of these network representations, capacity estimates, or cost functions suitable for inclusion in a linear programming model of oil refinery and primary distribution in the U.S.? Only pipeline and waterway transport is discussed. The models examined are the Department of Energy's OILNET model, the Department of Transportation's Freight Energy Model, the Federal Energy Administration Petroleum Transportation Network Model, and an Oak Ridge National Laboratory oil pipeline energy model. Link capacity and cost functions are recommended for each transport mode. The coefficients of the recommended pipeline cost functions remain to be estimated.

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| "State-Level Stock System Model of Gasoline Demand," accepted for publication in <u>Transportation Research Record</u> | D. L. Greene | | forthcoming |
| <u>A Review of Petroleum Transport Network Models and Their Applicability to a National Refinery Model</u> | J. N. Hooker | ORNL/TM-7935 | 3/82 |
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# SUMMARY

This study examines four petroleum network models to determine whether parts of them can be used in the transportation component of a national refinery model. Two questions in particular are addressed:

- How do the models under examination represent the oil transport network, estimate link capacities, and calculate transport costs?
- Are any of these network representations, capacity estimates, or cost functions suitable for inclusion in a linear programming model of oil refining and primary distribution in the U.S.?

The following network models are examined:*

- The Department of Energy's (DOE) OILNET model, used to evaluate the location of Strategic Petroleum Reserve storage sites.
- The Department of Transportation's (DOT) Freight Energy Model, used to forecast the effect of policy decisions on freight transport energy use.
- The Federal Energy Administration (FEA) Petroleum Transportation Network Model, originally used to find optimal locations for deepwater ports.
- An Oak Ridge National Laboratory (ORNL) oil pipeline energy model, used to estimate the energy consumption and efficiency of U.S. oil pipelines under actual operating conditions.

Only transport by pipeline and water is discussed since truck and rail transport are not important in the movement of crude oil or in the primary distribution of oil products. Trucks are dominant in the final distribution of products to jobbers and retail outlets, but it is assumed that this portion of the network would not be explicitly represented in a national refinery model.

The findings of the study are as follows.

1. Of the four network representations studied, only the FEA model's oil product pipeline representation and the DOT model's inland waterway representation are potentially useful for a national refinery model.

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*The Refinery Analysis Support Package (RASP), under development for the office sponsoring this study (see Acknowledgments), is a national refinery model that already has a transportation component (DeNoya 1981). RASP is not examined here partly because it seems best to concentrate on models not already familiar to the sponsoring office, and partly because adequate documentation of RASP was not available at the time of writing.

The former distinguishes 484 Bureau of Economic Analysis (BEA) areas as demand nodes and for this reason may be too detailed. It would also require updating and validation. The waterway representation, originally obtained from the U.S. Army Corps of Engineers, has been upgraded and provided with coastal links at ORNL, and the result is easily adaptable to the purposes of a national refinery model.

2. A crude oil pipeline network representation, and a products pipeline representation if the FEA network is not used, should be developed from scratch by reducing the information on detailed pipeline maps to an aggregate form that suits the choice of regional nodes.

3. Only the DOT and OILNET models provide pipeline link capacities. The former are unrealistic, and the latter can be updated by the results of a recent National Petroleum Council (NPC) survey of pipeline capacities. It is recommended that the NPC capacities be supplemented when necessary by the capacity estimation method developed for the ORNL model.

4. Waterway capacities are governed by lock capacities, and these are satisfactorily estimated by the DOT model.

5. Only the DOT and FEA models estimate pipeline costs, and in neither case could the origin of the cost functions be traced. In view of this and the age of these cost data (~1970), it seems best to develop a pipeline cost function from scratch. Alternate methods of doing so, based on results obtained for the ORNL model, are presented here and the relative advantages of each discussed.

6. Only the FEA model estimates coastal tanker costs. These are too old to use (~1970), but they could be satisfactorily updated using FEA's straightforward method or even the cost-of-living index.

7. The DOT and FEA models offer inland waterway cost functions, but the DOT functions are superior because they take into account congestion at locks. They or a linear approximation of them are recommended. Some adjustments would be necessary to reflect changes since ~1976 and possible imposition of user fees by the Reagan administration.

8. The use of nonlinear cost functions, which are more realistic than linear ones, complicates the determination of an optimal solution for a mathematical programming model that is otherwise linear. Both the recommended pipeline and inland waterway functions are nonlinear. Yet linear approximations are available in either case, and this report discusses the merits of various linear approximations as over against the nonlinear originals.

9. If nonlinear cost functions are used, the Frank-Wolfe technique for obtaining an optimal solution through a solution of successive linear programs is recommended.

# ACKNOWLEDGMENTS

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# 1. INTRODUCTION

The aim of this study is to examine four petroleum transport network models to determine whether parts of them can be incorporated in the transportation component of a national refinery model. Two questions in particular are addressed:

- How do the models under examination represent the oil transport network, estimate link capacities, and calculate transport costs?
- Are any of these network representations, capacity estimates, or cost functions suitable for inclusion in a linear programming model of oil refining and primary distribution in the U.S.?

Typically a linear programming model of the U.S. refining industry seeks to maximize the profit of the industry subject to the constraints within which it must operate. The profit is the income derived from selling oil products (less the costs of obtaining, transporting, storing, and refining crude, and the cost of distributing the refined products). Constraints are imposed by the availability of the various types of crude oil, the logistics of transport and storage, the chemistry and physics of refining, and the behavior of the market. An optimal solution to the resulting linear program would specify how refineries should operate so as to maximize overall profit. Properly formulated, such a model would permit one to predict the response of the refining industry to specified changes in supply, demand, prices, etc., on the assumption that the industry seeks to maximize overall profit.

Since transport costs are a significant factor in overall costs, a transport network with link costs should form part of a national refinery model. The network should also show link capacities, because they can impose important constraints on the industry. This study concentrates on pipeline and water transport, since they deliver nearly all crude oil to refineries and provide nearly all of the primary distribution of oil products. Trucks become important only in the secondary distribution of oil products from major terminals to jobbers to retail distributors, and trains do not play a major role in the industry.

The report begins by devoting a section to each of four models that contain petroleum network submodels:

- The DOE's OILNET model, used to evaluate the location of Strategic Petroleum Reserve Storage sites (Sect. 2).
- The DOT's Freight Energy Model, used to forecast the effect of policy decisions on freight transport energy use (Sect. 3).
- The FEA's Petroleum Transportation Network Model, originally used to find optimal locations for deep-water ports (Sect. 4).

- An ORNL oil pipeline energy model, used to estimate the energy consumption and efficiency of U.S. oil pipelines under actual operating conditions (Sect. 5).

These sections have parallel subsections that deal with network representations, link capacities, and transport costs.

The concluding section of the report (Sect. 6) determines which of the models studied, if any, can supply suitable network representations, link capacities, and cost functions. When none are suitable, suggestions are made as to how these components can be developed. The section concludes by discussing the merits of using nonlinear transport cost functions and possible solutions to the mathematical difficulties posed by nonlinear cost functions.

# 2. THE OILNET MODEL

## 2.1 General Description

The OILNET model resides with DOE's Energy Information Administration (Osleeb 1979). It was developed by Jeffrey Osleeb to help evaluate the choice of Strategic Petroleum Reserve storage sites. Osleeb was interested in whether the crude oil transport network could accommodate the flows necessary to fill the sites or to empty them during an emergency.

OILNET's approach is straightforward. It solves a multicommodity network optimization problem on a simplified representation of the crude oil network. The objective is to move the oil from supply points to demand points while minimizing transport cost and observing capacity constraints on each link. The supply of each of four types of crude oil[*] at each source mode was based on current production of 250 major oil fields, and demand was based on refinery capacity. To determine whether the strategic storage sites could be filled, additional demands were entered at modes representing them. The existence of a feasible solution to the optimal flow problem would indicate that filling is possible. To determine whether oil could be removed from the sites in an emergency, additional supply, rather than demand, was placed at these modes, and supply was reduced at modes representing ports that receive foreign crude.

The optimal flow problem was formulated as follows.[†]

$$\text{minimize} \sum_{\underline{i}} \sum_{\underline{j}} (\underline{c_{ij}} + \underline{t_{ij}}) \sum_{\underline{k}} \underline{x_{ijk}}$$

$$\text{subject to} \sum_{\underline{j}} \underline{x_{ijk}} \le \underline{a_{ik}} \quad \text{for all } \underline{i},\ \underline{k}\ ,$$

$$\sum_{\underline{j}} \underline{x_{ijk}} \le \underline{b_{jk}} \quad \text{for all } \underline{j},\ \underline{k}\ ,$$

---

[*] Low sulfur/low gravity, low sulfur/high gravity, high sulfur/low gravity, high sulfur/high gravity.

[†] The formulation in Osleeb (1979) contains several errors that are corrected here.

$$\sum_{i} \sum_{k} a_{ik} - \sum_{j} \sum_{k} b_{jk} = 0 ,$$

$$\sum_{k} x_{ijk} \le u_{ij} \quad \text{for all } i, j ,$$

$$x_{ijk} \geqslant 0 \quad \text{for all } i, j, k ,$$

where

$t_{ij}$ = per-unit transport cost from mode $i$ to mode $j$,
$c_{ik}$ = price of crude of quality $k$ at production or import mode $i$,
$a_{ik}$ = crude supply of quality $k$ at $i$,
$b_{jk}$ = crude demand of quality at refinery mode $j$,
$x_{ijk}$ = crude flow of quality $k$ from $i$ to $j$,
$u_{ij}$ = capacity limit on link $(i, j)$.

The principal aim of OILNET, at least when applied to the Strategic Petroleum Reserve, is not to determine exactly how oil flows or would flow under a specified pattern of supply and demand. The aim is rather to determine whether there is *any* feasible flow pattern that satisfies supply and demand. Consequently, the cost terms $t_{ij}$ and $c_{ik}$ are superfluous. One could set them all to zero and just as easily determine whether a feasible solution exists.

Osleeb concluded that all the proposed storage sites could be filled by the existing pipeline system, except for an Ironton Mine site in Kentucky. Filling of this site would require heavy use of tanker barges on the Ohio River. He also concluded that stored oil could, given certain assumptions, be satisfactorily distributed from the strategic sites during an emergency. The assumptions included: (1) the Jones Act would be waived; (2) Canada would supply northern tier refineries in exchange for U.S. domestic oil delivered to east coast Canadian ports; and (3) California would lift restrictions on the refining of high-sulfur Alaskan crude.

## 2.2 The Network Representation

OILNET uses the simplified crude oil pipeline network shown in Fig. 1. Links connect major crude-producing and import zones with major refinery clusters. A Utah-to-California rail link was inserted to relieve a flow infeasibility that would otherwise arise. (A unit train provides the additional needed capacity.) The network data base shows arc lengths and geographic coordinates of the modes. The waterway network was not incorporated because water transport was a relevant factor only in the case of the Ironton Mine.

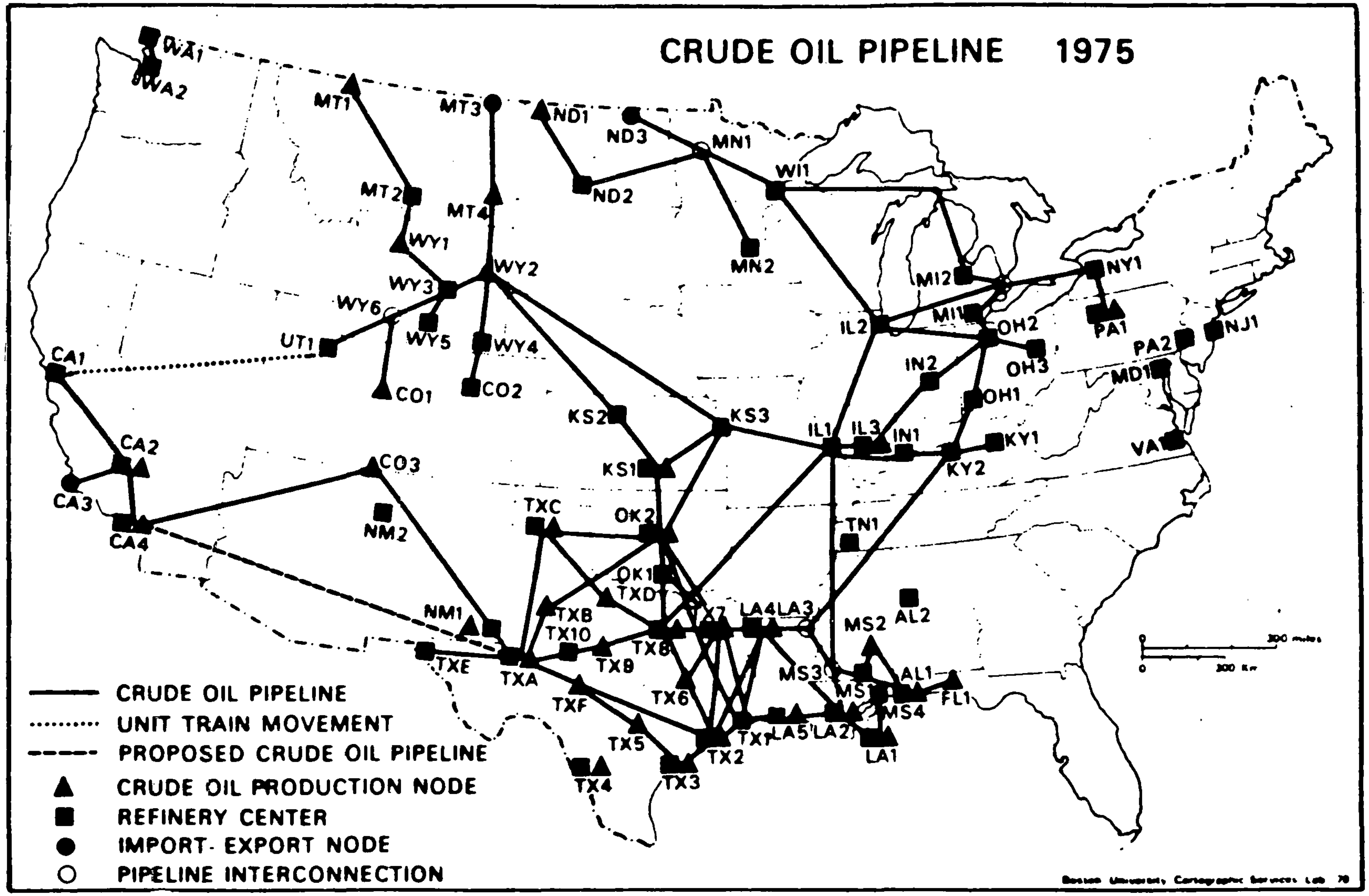


Fig. 1. OILNET's crude oil pipeline network representation, including unit-train movements. Reproduced from Osleeb (1979).

## 2.3 Link Capacities

Osleeb's article (1979) states that pipeline capacities were based on installed pumping horsepower along the main lines. Osleeb himself has credited Paul Chapman of DOE for supplying the capacity figures. Chapman, however, told the author that the capacities were not estimated on the basis of installed power but were obtained directly from the pipeline companies, as part of the planning phase of the Strategic Petroleum Reserve project.

The OILNET documentation could shed light on the matter, but inquiries revealed that the report was never officially released as a DOE publication. The staff of the sponsoring office was unable to find a copy. Osleeb has offered to provide the relevant portions of his personal copy, but the material had not been received at the time of writing.

In any case, it is unlikely that pipeline capacities can be reliably based on installed horsepower. The author has calculated that the pumping power used by the Colonial and Plantation products pipeline systems is substantially less than the installed power, even though these systems consistently run at or very near capacity (Hooker 1980). Presumably some of the pumps are reserved for backup or emergency purposes, or perhaps the logistics of product movements prevents full utilization of installed power. (See also p. S-16 of Hooker, 1980.)

The NPC (1979) has published the results of a survey of pipeline capacities that covers most major lines. These data could serve well to update Osleeb's capacities. The capacities of pipes not covered by the survey can be estimated as described in Sect. 5.3.

Osleeb adopted no formal procedure for estimating waterway capacity, since water transport was relevant to his purpose only in the case of the Ironton Mine. In this case, Osleeb simply observed that filling the mine would necessitate roughly a doubling of upstream Mississippi-Ohio River oil tanker-barge traffic, due to the lack of pipelines in the Ironton area. It is unlikely, he points out, that so drastic an increase could be accommodated.

## 2.4 Transport Costs

Distance is used as a surrogate for transport cost in OILNET. No attempt was made to reflect the higher unit cost of transport through smaller-diameter or more fully utilized pipelines. To do so was unnecessary for Osleeb's purposes, since he was interested only in gauging network capacity.

# 3. THE DEPARTMENT OF TRANSPORTATION'S FREIGHT ENERGY MODEL

## 3.1 General Description

The Freight Energy Model was developed for the DOT by Michael Bronzini and Roger Miller, then at CACI, Inc. (Bronzini and Miller 1979). Its aim is to forecast the effect of different governmental policies on freight transport energy use.

The model is comprehensive. It works from a network data base showing 3397 highway, rail, pipeline, and waterway links connecting 1789 nodes, as well as 642 access points. It computes cost and transit time as well as energy consumption. In doing so it takes into account delays and costs imposed by congestion and access. Demand for transport between 171 BEA regions is given exogenously for 19 commodities.

The model projects freight movements and the resultant energy use by solving for a least-cost-routing of freight. Since the cost functions are realistically nonlinear, the model estimates flow volumes on particular transport links as well as total energy consumption.

## 3.2 The Network Representation

The pipeline network is somewhat coarse: it connects 60 nodes with 96 links. (An essentially complete network described in Sect. 6.2 shows 2803 links.) It is coarse because pipes running roughly parallel are aggregated into a single pipe and because many less important lines are omitted. Each pipe in the network representation is assigned a fictitious diameter that would permit it to carry all the oil carried by the individual pipes it represents. The network and its characteristics are based on the work of Debanne (1976).

The waterway network representation provides a considerably more complete depiction of the network than the pipeline representation. Its 255 links connecting 252 modes were obtained by purging 145 of the less important links from the U.S. Army Corps of Engineers inland waterway data base (CACI 1976a). It omits all coastal and Great Lakes routes, but ORNL recently obtained the network representation and added these routes. A number of corrections were also made, resulting in a data base of fairly high quality.

## 3.3 Link Capacities

### 3.3.1 Pipelines

The flow capacity of a pipeline is assumed to be the "economic flow capacity" for its diameter, as given in Fig. 2 (Bronzini and Miller 1979, vol. 3, p. 101). This graph is taken from a U.S. Army Corps of Engineers publication (Kearney 1972, p. C-20), which in turn cites a Battelle Memorial Institute study (Cheaney 1968) prepared for the State Department. Although the latter study was never officially released, the pipeline chapter was obtained (Goldgraben and Leis, 1968, pp. 8-30, 8-31). This chapter derives its economic capacity curve, in a manner to be discussed shortly, from a graph of cost vs capacity vs diameter (Fig. 3). No source for the cost graph was cited, but coauthor Leis seems to recall that it came from a U.S. Steel loose-leaf bulletin. The writer has seen graphs similar to Figs. 2 and 3 in a number of publications, but in no case has examination of the publication or of its cited sources (if any) yielded documentation of how the graphs were derived. Section 4.4.1 discusses how cost curves like those of Fig. 3 could be derived.

It is important to understand that the "economic capacity" for a given diameter can be taken in two senses:

1. The minimum-cost capacity for the given diameter; this can be called the "optimal capacity."
2. The capacity such that the given diameter is the minimum-cost diameter for that capacity; this can be called the optimal-diameter capacity."

(Here, minimum-cost means minimum unit transport cost.) Examination of Fig. 3 reveals that for a given diameter the optimal capacity is larger. The optimal-diameter capacity, however, is used by the Kearney manual and hence by the Freight Energy Model to construct the economic capacity curve in Fig. 2. That is, for each capacity on the ordinate of Fig. 2, Fig. 3 is consulted to find the diameter that can provide this capacity most cheaply. This is also the policy of the FEA Network Model, and its appropriateness is discussed in Sect. 4.3.1.

The Corps of Engineers study refers to the capacities of Fig. 2 as "rated capacities," which are physical capacities, rather than "economic capacities." One might argue that a pipeline is likely to be designed so that its rated capacity is near its economic capacity, in one of the two senses distinguished above. It is remarked in Sect. 4.3.1 that pipelines are generally designed with a diameter that provides optimal capacity for a given throughput, and that horsepower is later added so as to approximate optimal capacity for the pipe's diameter. That is, in the first phase of a pipeline's development its capacity is generally the optimal-diameter capacity for its diameter, and in the second phase its capacity is the optimal capacity for its diameter. Since the Corps of Engineers study employs the optimal-diameter capacity, its equation of

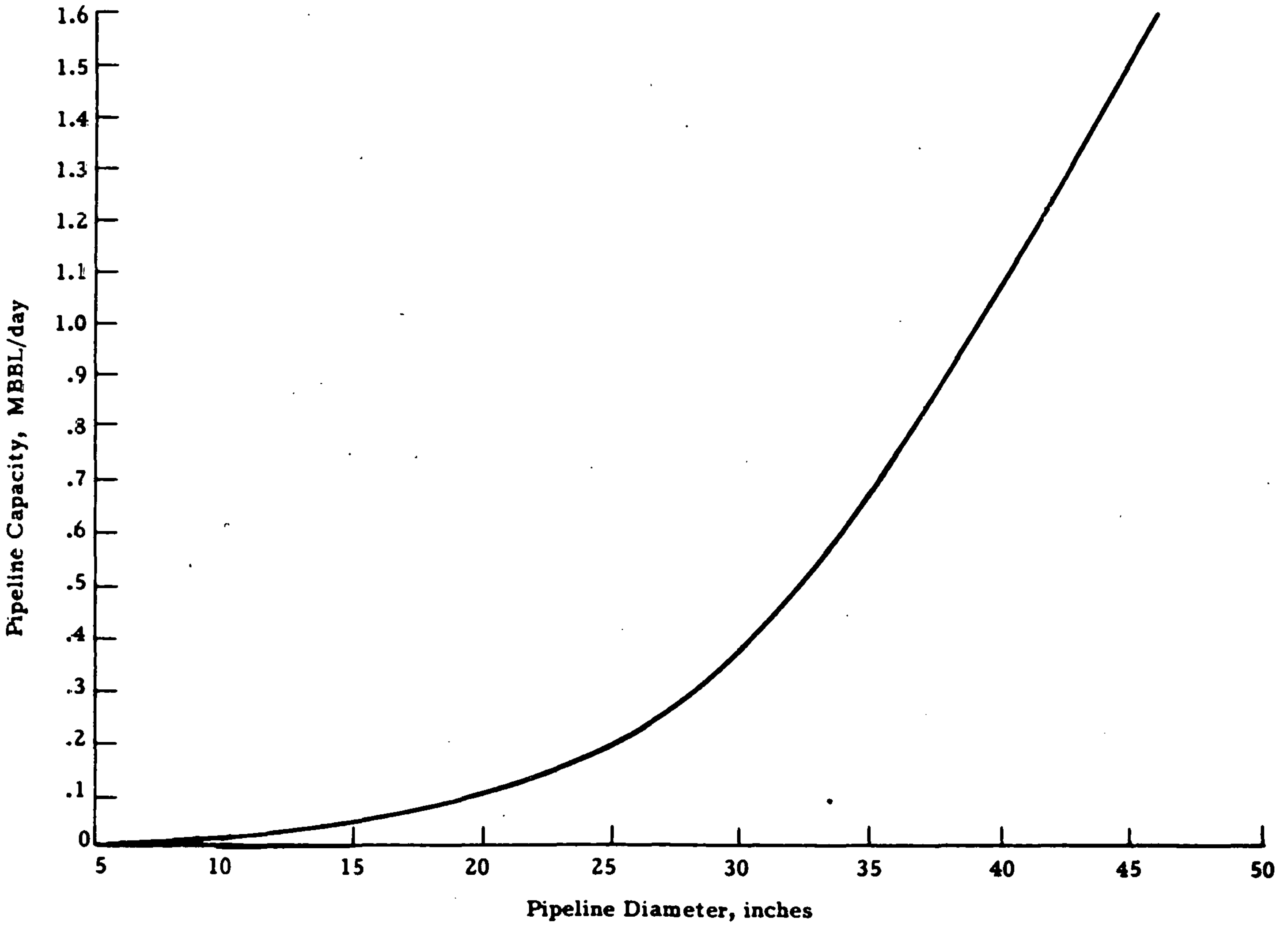


Fig. 2. Economic flow capacities for petroleum pipelines.

Source: A. T. Kearney, Transportation Technology for Development, ed. by E. S. Cheaney, Battelle Memorial Institute, Columbus, Ohio, 1968.

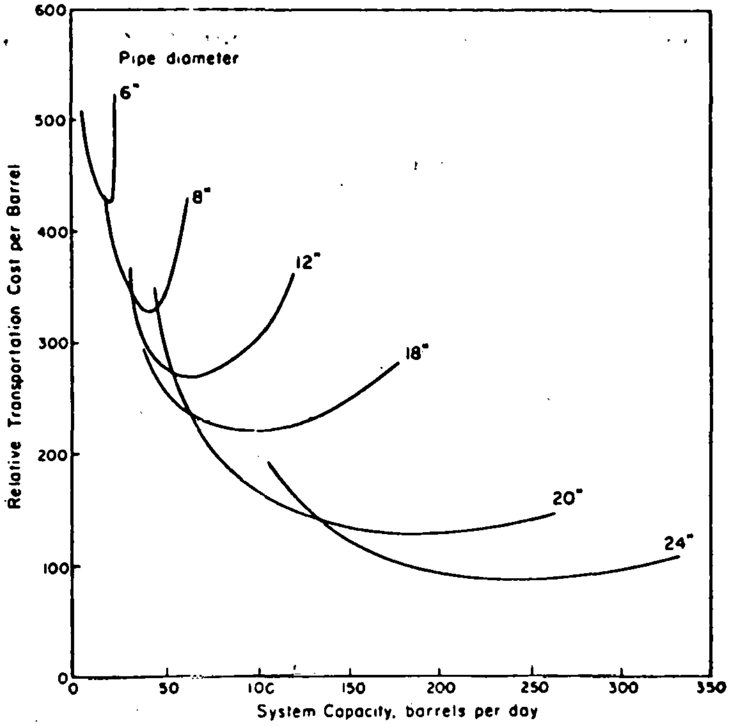


Fig. 3. Effect of pipe size on pipeline transportation cost. Reproduced from Goldgraben and Leis (1968, p. 8-31).

economic and rated capacity is tantamount to an assumption that pipelines are generally in the first phase of their development, prior to the addition of extra horsepower. It is not clear that this assumption is warranted.

In any case, the Bronzini capacities are clearly too small; no matter how they are interpreted. Table 1 compares some of them with capacities derived from NPC data as described in Sect. 5.3.1. Only for the very largest diameters are the Bronzini capacities realistic.

### 3.3.2 Waterways

The only capacity constraints placed on the waterway network were those of inland locks. The Army Corps of Engineers (see CACI 1976a, vol. 5, chap. 5) provided 1975 tonnage and transit time data collected by its Performance Monitoring System. These data were fed into the Transportation System Center's LOKCAP model (CACI 1976b), which uses queuing theory to predict average transit time for each lock. This model uses past tow sizes and their locking times to calibrate the parameters $T_0$, $T_1$, and $Q$ in the following hyperbolic function (Bronzini and Miller 1979, vol. 3, p. 84).

$$t = 2T_0 - T_1 + \frac{Q(T_1 - T_0)}{Q - q} , \tag{1}$$

where

$t$ = lock transit time including waiting time,
$q$ = annual lock traffic in kilotons,
$Q$ = theoretical lock capacity in kilotons,
$T_0$ = lock transit time at $q = 0$,
$T_1$ = lock transit time at $q = Q/2$.

Note that the theoretical capacity $Q$ is that rate of arrivals at which the steady-state waiting time would go to infinity. (It is characteristic of queuing models that the waiting time and length of the queue grow without bound when the average interarrival time is less than or equal to the average service time.)

The Bronzini study obtains estimates of $Q$ from LOKCAP for all of the important locks. The $Q$'s pertaining to locks within each of several lock classes are averaged to obtain a representative value. The results are displayed in Table 2 and Fig. 4 (Bronzini and Miller 1979, vol. 3, pp. 83 and 85).

Table 1. Comparison of crude oil pipeline capacities

| Diameter (in.) | Bronzini model,[a] Sect. 4.3.1 ($10^3$ $m^3$/d) | ORNL model, Sect. 6.3.1 ($10^3$ $m^3$/d) |
|---|---|---|
| 10 | 3 | 6 |
| 16 | 8 | 16 |
| 20 | 16 | 28 |
| 26 | 35 | 51 |
| 34 | 77 | 98 |
| 40 | 170 | 144 |

[a] From Fig. 3 and a similar graph in the Kearney study (Kearney 1972, p. C-20), from which Fig. 3 is taken. Table 5-1 in the Bronzini study (vol. 3, p. 102) also shows crude capacities, but they inexplicably differ radically from the graphs and are far too large to be realistic. A 20-in. pipe, for instance, is given a capacity of 53,000 $m^3$/d. The graphs are assumed to depict the intended capacities.

Table 2. Lock classes and time functions. Reproduced from Bronzini and Miller (1979, vol. 3, p. 83).

| Class | Locks included | | | | | Time functions | | |
|---|---|---|---|---|---|---|---|---|
| | River | Dimensions (ft) | | | | Q (kilotons) | $T_0$ (min) | $T_1$ (min) |
| | | Chamber A | | Chamber B | | | | |
| | | Length | Width | Length | Width | | | |
| UM600.110 | Mississippi | 600 | 110 | | | 50,000 | 65 | 100 |
| UM.LD26 | Mississippi | 600 | 110 | 360 | 110 | 70,000 | 100 | 150 |
| IL600.110 | Illinois | 600 | 110 | | | 50,000 | 75 | 125 |
| | Ohio | 600 | 110 | | | | | |
| | Tennessee | 600 | 110 | | | | | |
| | Cumberland | 800 | 110 | | | | | |
| AK600.110 | Arkansas | 600 | 110 | | | 45,000 | 40 | 60 |
| | Monongahela | 600 | 84 | | | | | |
| | GIWW[a] | 797 | 75 | | | | | |
| | Alabama/Coosa | 655 | 84 | | | | | |
| | Bl. Warrior/Tom- | 600 | 110 | | | | | |
| | bigbee/Mobile | 520 | 95 | | | | | |
| | Ouichita/Black | 655 | 84 | | | | | |
| OH12+6.110 | Ohio | 1,200 | 110 | 600 | 110 | 120,000 | 50 | 70 |
| | Mississippi | 1,200 | 110 | 600 | 110 | | | |
| | | 1,200 | 110 | 358 | 110 | | | |
| OH.NAVPASS | Ohio | (LD52, LD53) | | | | 195,000 | 40 | 60 |
| OH.GALLPLS | Ohio | 600 | 110 | 360 | 110 | 60,000 | 70 | 110 |
| OH600+360 | Ohio | 600 | 110 | 360 | 56 | 60,000 | 50 | 75 |
| | Tennessee | 600 | 110 | 360 | 60 | | | |
| | | 600 | 110 | 400 | 60 | | | |
| | | 600 | 110 | 292 | 60 | | | |
| | Atchafalya/Old | 1,200 | 75 | | | | | |
| MN360.56 | Monongahela | 360 | 56 | | | 40,000 | 60 | 90 |
| | Allegheny | 360 | 56 | | | | | |
| | Ouichita/Black | 300 | 55 | | | | | |
| MN720.XX+ | Monongahela | 720 | 84 | 720 | 84 | 100,000 | 38 | 60 |
| | | 720 | 56 | 360 | 56 | | | |
| | | 720 | 110 | 360 | 56 | | | |
| TNUM.360+ | Tennessee | 360 | 60 | | | 30,000 | 80 | 125 |
| | Mississippi | 400 | 56 | | | | | |
| XX400+.75+ | Clinch/Emory | 400 | 75 | | | 35,000 | 30 | 50 |
| | Cumberland | 400 | 84 | | | | | |
| | GIWW[a] | 425 | 75 | | | | | |
| | Ap/Ch/Fl[b] | 505 | 82 | | | | | |
| KW2X360.56 | Kanawha | 360 | 56 | 360 | 56 | 60,000 | 80 | 120 |
| | Mississippi | 400 | 56 | 400 | 56 | | | |
| GIWW.XXXX | GIXX[a] | 750 | 75 | | | 55,000 | 40 | 60 |
| | | 1,158 | 75 | | | | | |
| | | 1,204 | 75 | | | | | |
| | | 1,200 | 56 | | | | | |
| | | 640 | 75 | | | | | |
| | | 1,198 | 84 | | | | | |
| | | 800 | 75 | | | | | |
| KY145.XX | Kentucky | 145 | 38 | | | 4,500 | 55 | 90 |

[a] Gulf Intracoastal Waterway.

[b] Apalachicola/Chattahoochee/Flint.

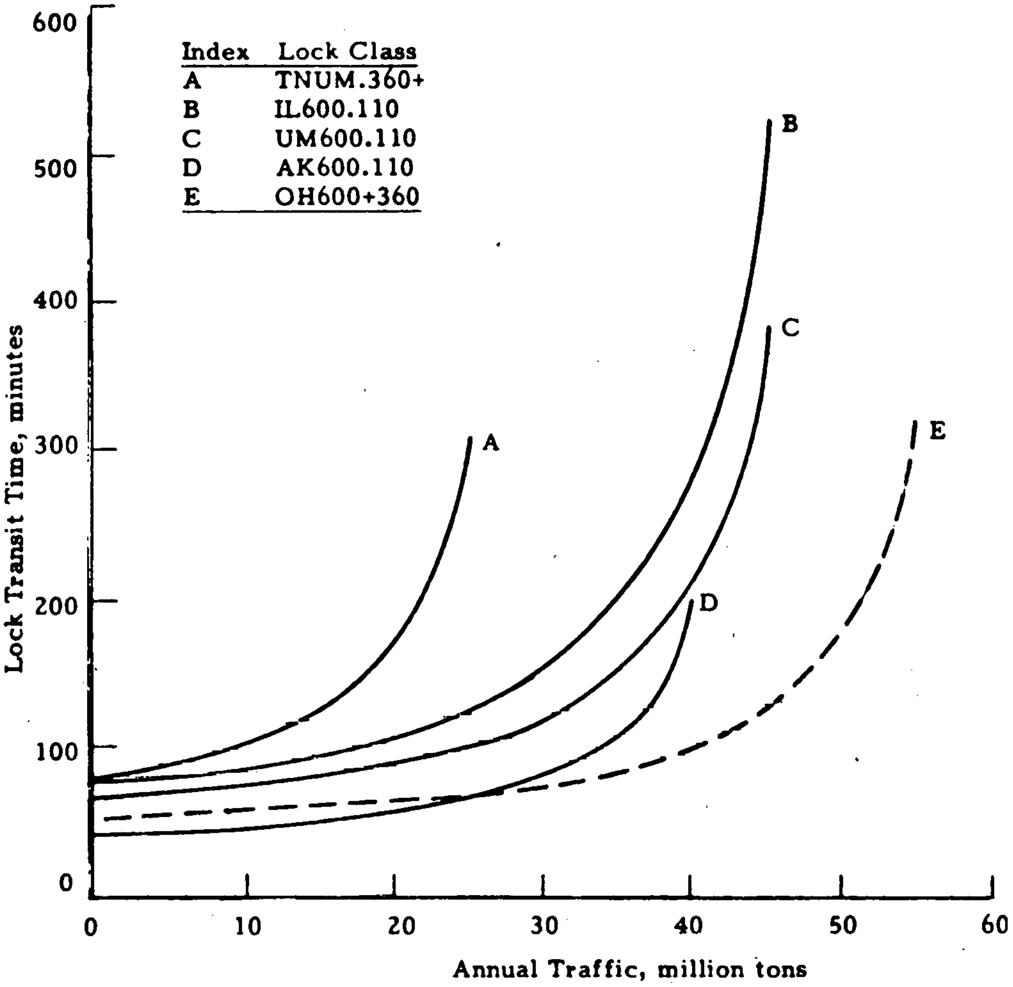


Fig. 4. Lock time functions.

Reproduced from Bronzini and Miller (1979, v. 3, p. 85).

## 3.4 Transport Costs

### 3.4.1 Pipelines

The Freight Energy Model uses the crude oil pipeline cost curves in Figs. 5-7. The model assumes that about 30% of pipeline costs are operating costs and that products pipelines use 50% more energy per ton-mile, so that operating costs are 50% higher than for crude lines. This results in an estimate that the unit transport cost for products is (30%)·(50%) = 15% higher than for crude.

The left half of the U-shaped curves in Figs. 5-7 are taken from the Corps of Engineers study mentioned earlier (Kearney 1972, p. C-11), which provides unit costs at various percentages of "rated capacity" flow for several diameters. It has been noted that the source of these capacities (Goldgraben and Leis 1968) intends them as economic capacities, and Bronzini preserves this original intent. Bronzini estimates unit costs for a wide range of flow rates higher than the economic capacity, again on the assumption that variable costs are 30% of total costs and proportional to energy use. This extension is perplexing, since it is unlikely that a pipeline would be designed to carry much more than its economic capacity. Furthermore, if Bronzini's model prohibits flows that exceed capacity, it is unclear why the corresponding costs are needed.

In any case the capacities Bronzini uses have already been observed in Sect. 3.3.1 to be very much below the more realistic, or at least far better documented figures proposed in Sect. 5.3.1. Consequently, the U-shaped curves should be shifted considerably to the right. It remains to determine how the unit costs at various percentages of capacity, provided by the Corps of Engineers study, are derived. This study cites a Soros Associates report, Deepwater Port Concepts, as its source (no further bibliographic data are provided). Since no such report exists, the reference is presumably to Offshore Terminal System Concepts (Soros Associates 1972), which may have been in preparation and not officially entitled when consulted. The Soros study presents the graphs shown in Figs. 8 and 9. It is remarked in the text that "whereas the construction cost is generally a function of the pipeline diameter, the annual cost is more a function of the square of the pipeline diameter," but no further explanation is offered (part 2, p. C11-7). The origin of the pipeline costs, then, is undocumented.

### 3.4.2 Waterways

Costs were estimated separately for lock transit, channel movement, and waterway access.

Lock transit costs were computed by multiplying the average operating cost per hour of a barge and tow by the average lock transit time (including waiting) for each lock class. The hourly costs were "based

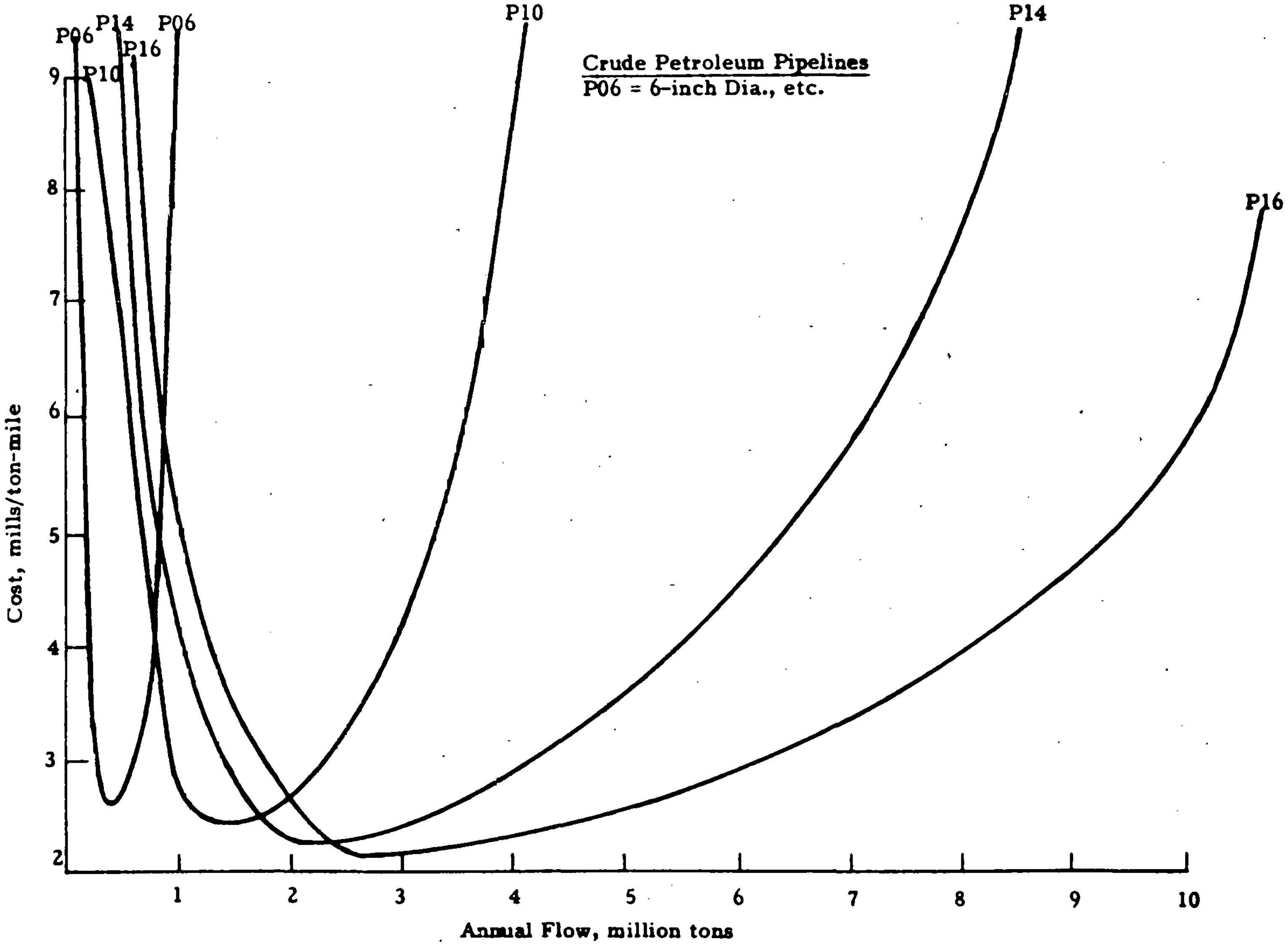


Fig. 5. Pipeline cost functions for diameters 6-16 in.
Reproduced from Bronzini and Miller (1979, v. 3, p. 108).

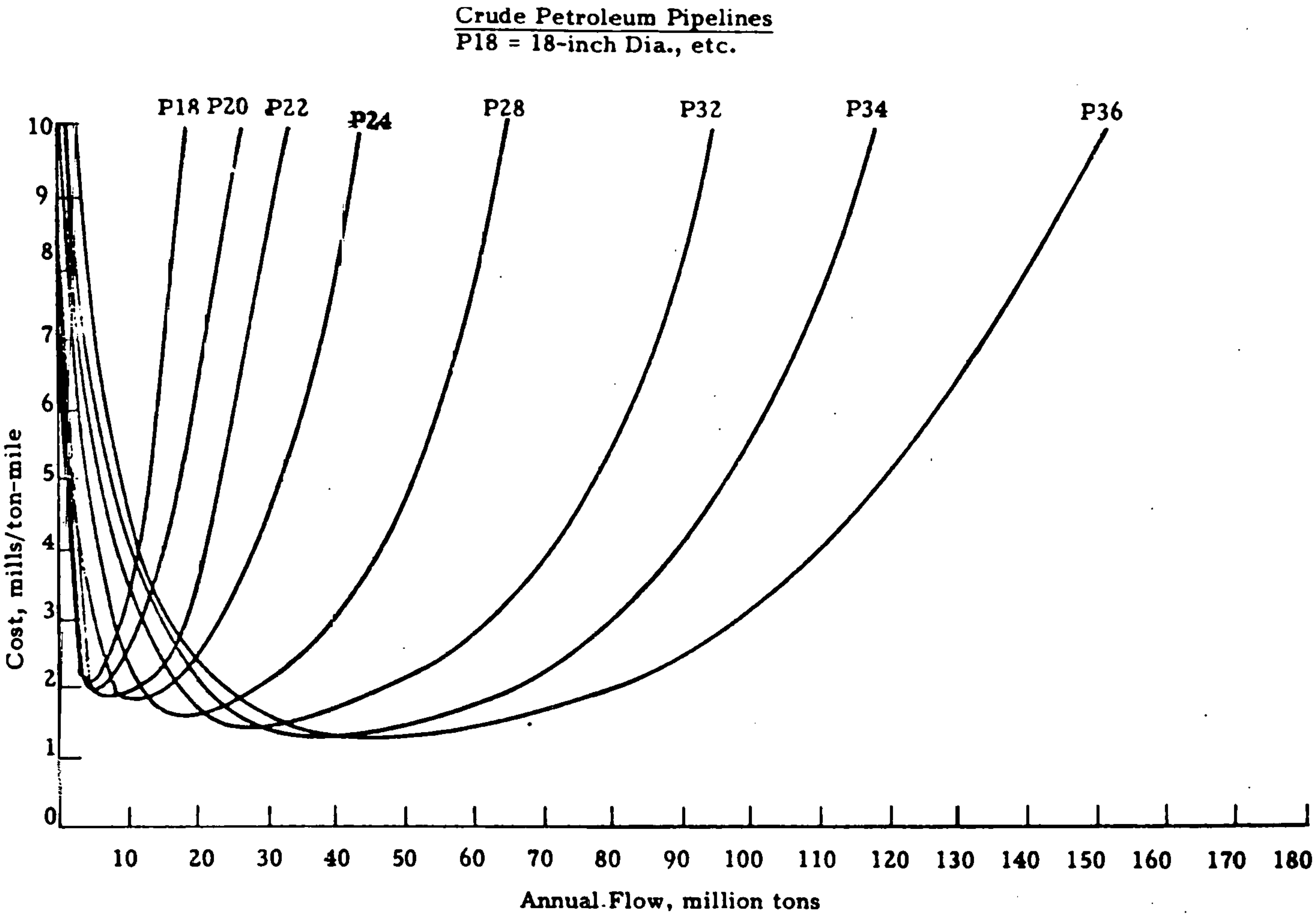


Fig. 6. Pipeline cost functions for diameters 18-36 in.

Reproduced from Bronzini and Miller (1979, v. 3, p. 109).

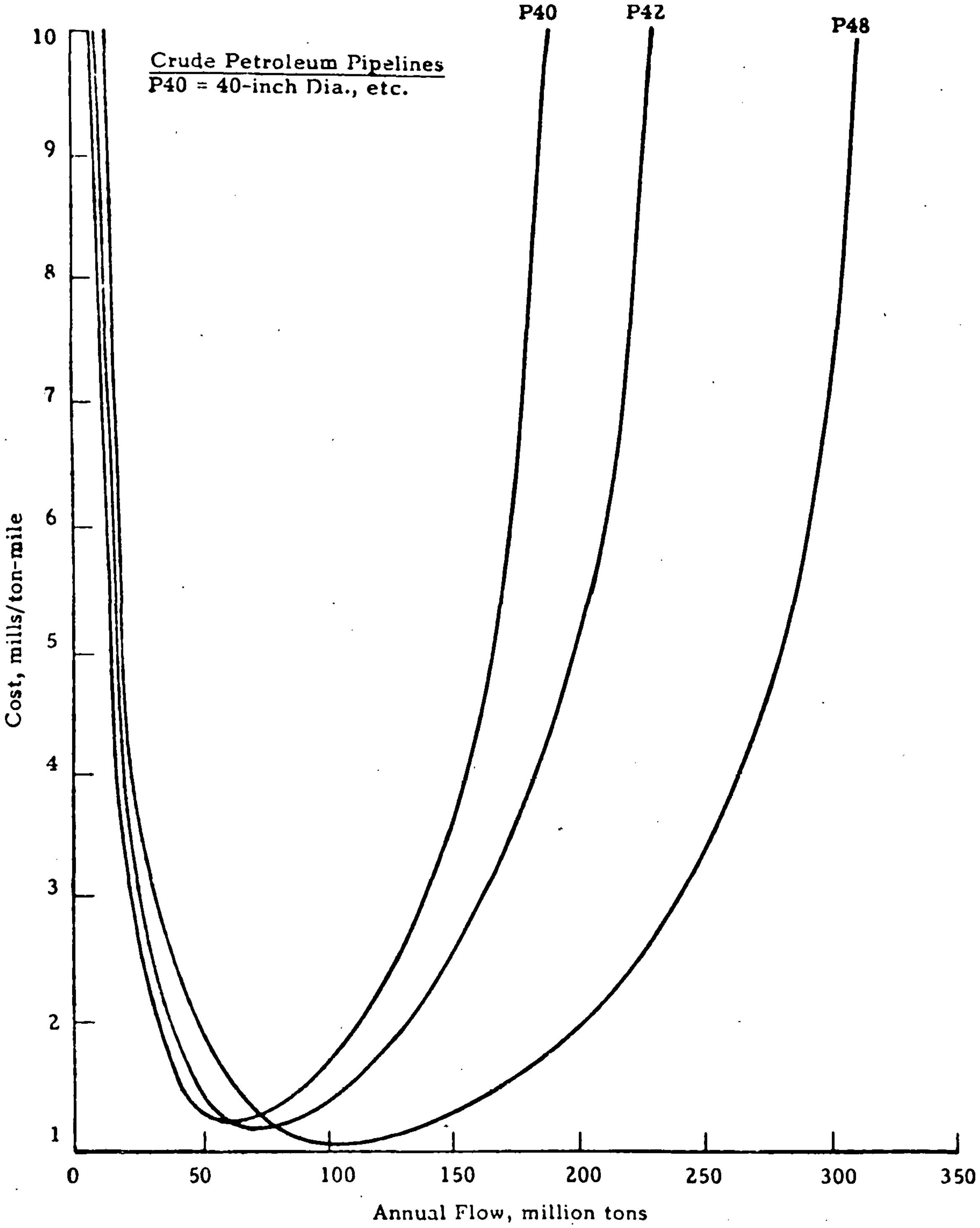


Fig. 7. Pipe cost functions for diameters 40-48 in.

Reproduced from Bronzini and Miller (1979, v. 3, p. 110).

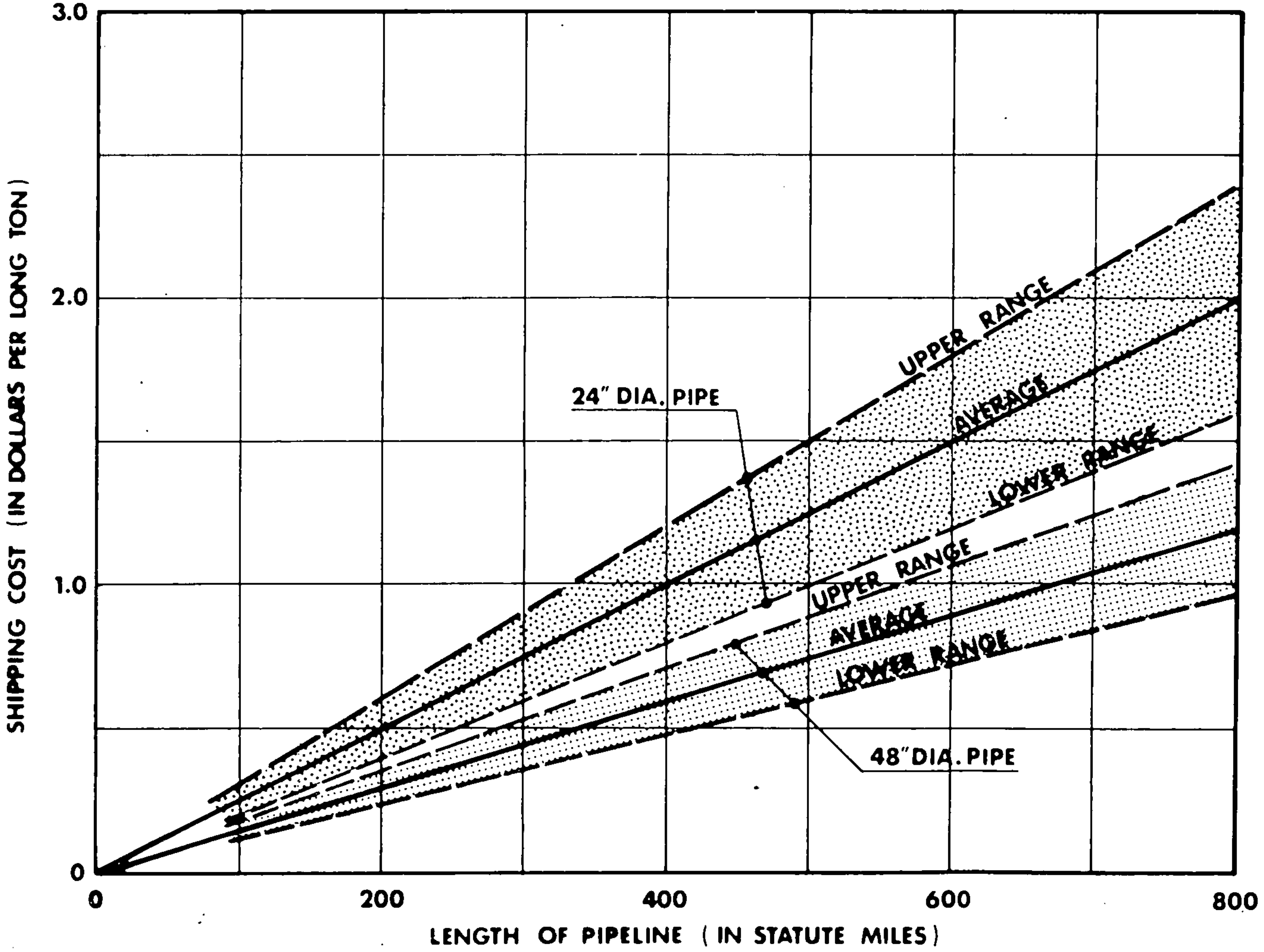
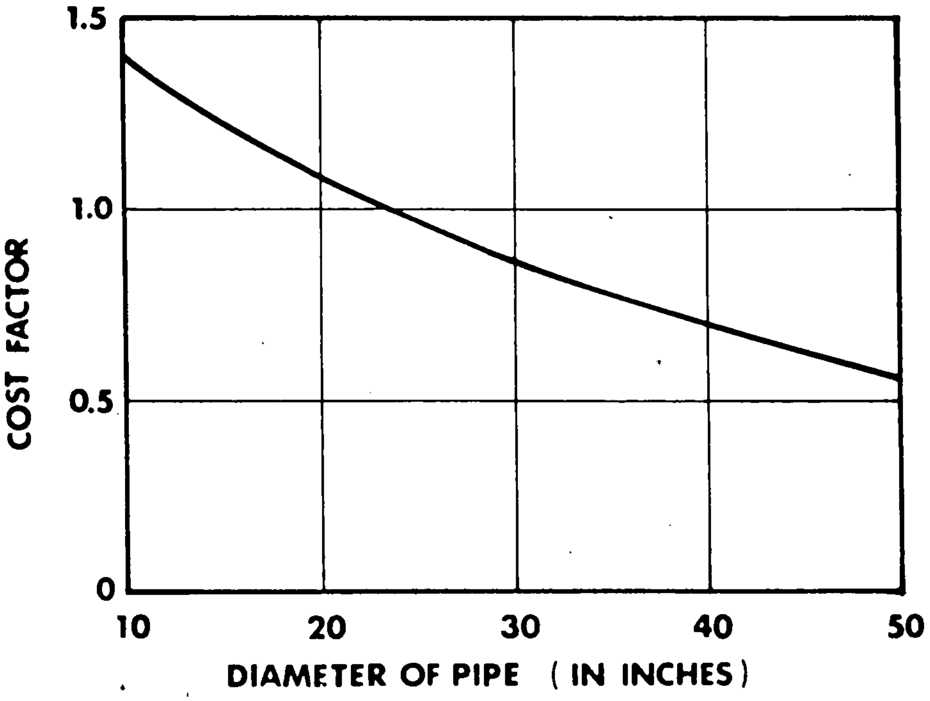
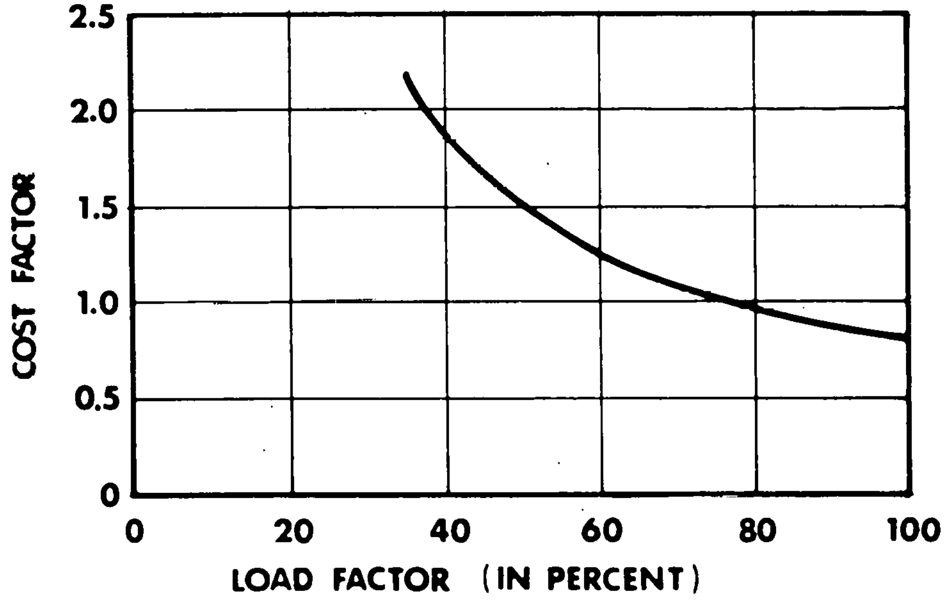


Fig. 8. Pipeline unit transport cost vs distance.
Reproduced from Soros Associates (1974, Fig. 2-44).



PIPE SIZE FACTOR



PERCENT LOAD FACTOR

Fig. 9. Relative pipeline unit transport cost vs pipe diameter and vs load factor.

Reproduced from Soros Associates (1974, Fig. 2-44).

on industry surveys conducted by the Corps of Engineers" (Bronzini and Miller 1979, vol. 3, p. 88), and they appear in Table 3.* The equation in Sect. 3.3.2 gives the average transit time, where the arrival rate is $q$. Multiplication of this equation by the average hourly cost per kiloton of cargo yields

$$\text{S/kiloton} = 2C_0 - C_1 + \frac{Q(C_1 - C_0)}{Q - q} , \qquad (2)$$

where

$C_0$ = cost per kiloton for transit time $T_0$,
$C_1$ = cost per kiloton for transit time $T_1$,
$Q$, $q$, $T_0$, $T_1$ are defined in Sect. 4.3.2.

The results appear in Table 4 and Fig. 10.

Costs of channel operations "were obtained from the same source as the locking costs" (Bronzini and Miller 1979, vol. 3, p. 94). They appear in Table 5.

The access costs were taken to be the cost of transporting the freight to the port, always via pipeline in the case of crude oil and oil products. This cost element is not likely to play a role in an RPMS refinery model.

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*These data are listed in Appendix A of the TSC Waterway Cost Model documentation (CACI, 1977). They derive from the same source used by the FEA model (Sect. 5.4.2).

Table 3. Towboat and barge operating costs. Reproduced from Bronzini and Miller (1979, vol, 3, p. 88).

Towboat costs

| Towboat horsepower | Max. tow size[a] | Labor cost ($/h) | Other cost ($/h) | Total variable cost ($/h)[b] | | Annual fixed cost ($) |
|---|---|---|---|---|---|---|
| | | | | Operating | Maneuvering | |
| 300 | 2 | 15.70 | 3.63 | 20.83 | 20.09 | 54,600 |
| 600 | 4 | 15.70 | 3.63 | 22.33 | 20.83 | 54,600 |
| 1,200 | 8 | 26.30 | 11.10 | 43.40 | 40.40 | 117,000 |
| 1,800 | 12 | 28.80 | 13.70 | 51.50 | 47.00 | 152,000 |
| 2,500 | 14 | 34.30 | 18.30 | 65.08 | 58.85 | 222,000 |
| 3,300 | 17 | 39.30 | 22.60 | 78.46 | 70.16 | 293,000 |
| 4,300 | 23 | 39.50 | 26.90 | 87.88 | 77.15 | 358,000 |
| 5,000 | 26 | 41.10 | 29.40 | 95.46 | 82.98 | 396,000 |
| 5,700 | 28 | 42.30 | 31.80 | 102.66 | 88.38 | 437,000 |
| 7,000 | 33 | 42.90 | 36.00 | 113.94 | 96.42 | 524,000 |
| 8,400 | 36 | 45.30 | 40.80 | 128.10 | 107.10 | 611,000 |
| 9,000 | 38 | 45.30 | 42.30 | 132.60 | 110.16 | 646,000 |
| 10,100 | 40 | 45.30 | 44.90 | 140.72 | 115.40 | 706,000 |

Barge costs

| Barge class | Capacity (tons) | Variable cost ($/h) | Annual fixed cost ($) |
|---|---|---|---|
| Open hopper jumbo | 1700 | 0.55 | 19,300 |
| Covered hopper jumbo | 1700 | 0.66 | 22,900 |
| Tank barge jumbo | 1700 | 1.75 | 37,900 |

[a] Number of jumbo barges. Tow size may also be limited by channel characteristics.

[b] Sum of previous two columns plus fuel cost (based on 12¢/gal and fuel consumption of 1.0 gal/hp-d while operating and 0.5 gal/hp-d while maneuvering).

Table 4. Lock cost functions. Reproduced from Bronzini and Miller (1979, vol, 3, p. 89).

| Lock class | No. of locks | Average locking cost ($/kiloton-h) | | Cost function[a] | | |
|---|---|---|---|---|---|---|
| | | Mean | Std. dev. | $Q$ kilotons | $C_0$ $/kiloton | $C_1$ $/kiloton |
| UM600.110 | 23 | 17.26 | 0.21 | 50,000 | 18.70 | 28.80 |
| UM.LD26 | 1 | 16.92 | | 70,000 | 28.20 | 42.30 |
| IL600.110 | 24 | 16.92 | 1.35 | 50,000 | 21.20 | 35.20 |
| AK600.110 | 32 | 16.39 | 7.30 | 45,000 | 10.90 | 16.40 |
| OH12+6.110 | 10 | 15.59 | 1.35 | 120,000 | 13.00 | 18.20 |
| OH.NAVPASS | 2 | 18.58 | 1.46 | 195,000 | 12.40 | 18.60 |
| OH.GALLPLS | 1 | 15.49 | | 60,000 | 18.10 | 28.40 |
| OH.600+360 | 7 | 17.30 | 1.65 | 60,000 | 14.20 | 21.30 |
| MN360.56 | 12 | 25.22 | 12.21 | 40,000 | 25.20 | 37.80 |
| MN720.XX+ | 4 | 14.33 | 0.37 | 100,000 | 9.10 | 14.30 |
| TNUM.360+ | 4 | 22.07 | 1.55 | 30,000 | 29.40 | 46.00 |
| XX400+.75+ | 5 | 31.91 | 12.99 | 35,000 | 16.00 | 26.60 |
| KW2X360.56 | 4 | 16.86 | 2.85 | 60,000 | 22.50 | 33.70 |
| GIWW.XXXX | 7 | 17.09 | 3.95 | 55,000 | 11.40 | 17.10 |
| KY145.XX | 6 | 46.29 | 0.04 | 4,500 | 42.40 | 69.40 |

[a] Dollars/kiloton = $2C_0 - C_1 + \frac{Q(C_1 - C_0)}{Q - q}$, where $q$ = annual traffic in kilotons.

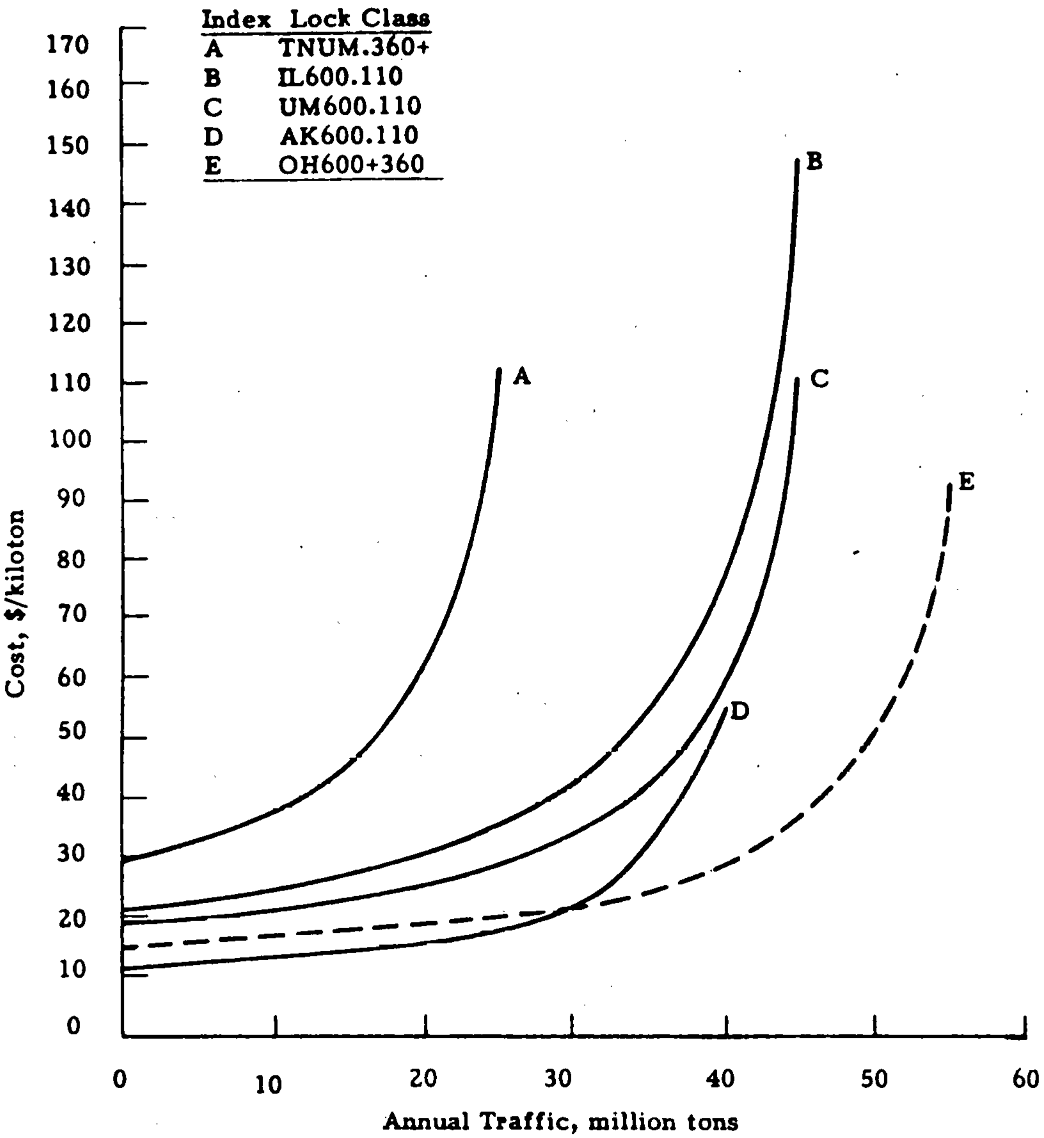

Fig. 10. Lock cost functions.

Reproduced from Bronzini and Miller (1979, v. 3, p. 91).

Table 5. Waterway linehaul link energy and cost functions. Reproduced from Bronzini and Miller (1979, vol. 3, p. 94).

| Link class | Fuel use (gas/tow-h) | Avg. tow cargo load[a] |  | Downstream energy use (Btu/ton-mile)[b] |  | Upstream factor[c] | Downstream cost (mills/ton-mile) |
|---|---|---|---|---|---|---|---|
|  |  | A | B | C | D |  |  |
| LWR.MISS.R | 191 | 5960 | 58 | 178 | 0.678 | 1.5 | 2.75 |
| UPR.MISS.R | 111 | 5960 | 58 | 277 | 0 | 1.25 | 3.40 |
| ARKANSAS.R | 45 | 4950 | 0 | 195 | 0 | 1.46 | 3.90 |
| OHIO.RIVER | 75 | 5440 | 25 | 191 | 0 | 1.0 | 2.75 |
| L.MONONGHL | 26 | 2190 | 35 | 187 | 0 | 1.0 | 3.15 |
| U.MONONGHL | 26 | 2190 | 35 | 187 | 0 | 1.0 | 3.15 |
| ALLEGHENY | 23 | 2240 | 0 | 198 | 0 | 1.0 | 2.75 |
| TENNESSEE | 78 | 6450 | 0 | 193 | 0.286 | 1.0 | 3.15 |
| CLINCH/EMY | 41 | 3260 | 0 | 223 | 0 | 1.0 | 3.00 |
| CUMBERLAND | 41 | 3260 | 0 | 223 | 0 | 1.0 | 3.00 |
| KANAWA.R | 33 | 3600 | 0 | 187 | 0 | 1.0 | 3.00 |
| KENTUCKY.R | 25 | 670 | 0 | 719 | 0 | 1.0 | 5.50 |
| ILLINOIS.R | 82 | 6190 | 0 | 248 | 0 | 1.0 | 3.15 |
| GIWW.WEST | 25 | 3070 | 0 | 175 | 0 | 1.0 | 3.60 |
| GIWW.EAST | 27 | 3070 | 0 | 164 | 0 | 1.31 | 3.80 |
| BW/TOMB/MO | 25 | 3280 | 0 | 164 | 0 | 1.0 | 3.15 |
| ALABA/COOS | 25 | 960 | 0 | 527 | 0 | 1.0 | 5.00 |
| MISSOURI.R | 73 | 3530 | 0 | 315 | 0 | 2.05 | 5.50 |
| AP/CHAT/FL | 25 | 970 | 0 | 379 | 0 | 1.65 | 9.40 |
| ATCHAF/OLD | 25 | 2100 | 0 | 175 | 0 | 2.13 | 7.50 |
| RED.RIVER | 25 | 910 | 0 | 514 | 0 | 1.0 | 6.30 |
| OUACHTA/BL | 25 | 910 | 0 | 556 | 0 | 1.0 | 5.50 |
| P.ALLEN.RT | 25 | 1600 | 0 | 293 | 0 | 1.0 | 3.60 |

[a] Tons/tow = *A* + *Bq*, where *q* = annual traffic in million tons.

[b] Btu/ton-mile = *C* = *Dq*.

[c] Ratio of upstream energy use and cost to downstream energy use and cost.

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# 4. THE FEDERAL ENERGY ADMINISTRATION PETROLEUM TRANSPORTATION NETWORK MODEL

## 4.1 General Description

The FEA network model was originally designed by C. P. Schumaier, A. Gezen, and M. Kendrick (1974) while in the employ of the DOT. Its purpose was to find least-cost locations of refinery capacity and deep-water ports for supertankers. Gezen (1976) later modified the model to find least-cost locations of refinery capacity and transport routes for Alaskan oil. Gezen did the latter work for the FEA while at TERA, Inc.

The FEA model aims to find the assignment of capacities to refineries and locations to transport links that permits a fixed amount of petroleum products to be supplied most cheaply to consumers. It takes into account the cost of transporting crude oil, operating refineries, transporting oil products, and importing oil products. For each of several ways of allocating capacity to refineries and placing transport links, it computes the least-cost way of transporting crude oil and oil products. A heuristic algorithm is used to choose transport modes and to direct refinery output to market areas in an optimal fashion. The minimum cost incurred by each way of allocating capacity and placing links is then compared with the costs of other ways so as to find the one that results in the least minimum cost.

The FEA model acknowledges that pipeline transport unit costs depend on the flow volume and distance traveled as well as on the pipe diameter. This causes difficulties in the selection of mode, since pipeline transport must somehow be selected on the basis of whether it is cheaper than a competing water route, even while the cost of pipeline transport cannot be determined unless it is already known how much oil is to travel by pipe.

The model solves this problem for oil product transport as follows. Once the market areas to be supplied by a given refinery district are chosen by a heuristic technique,* the cost of directing each refinery-to-market flow through pipelines is computed on the assumption that it

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*The technique is straightforward. In each iteration each refinery district is assigned the closest market area not already assigned, unless that refinery's output capacity has been exhausted. The algorithm cycles through the refinery districts until all market areas are assigned. The quantity of oil that must flow to each market area is observed. This is the procedure described on p. 2-20 of Schumaier, Gezen and Kendrick (vol. 1, 1974) and by the flow chart on p. 6 of Gezen (1976). The flow chart on pp. 2-19 of the former volume, however, computes transport costs during each of several iterations of the market-assignment algorithm.

represents the only oil in each of the pipelines through which it passes. If this cost is less than transport by water, the flow is sent by pipe, and otherwise by water (if a water route is available). Since pipeline flows to the various markets often must share a pipe along part of the way, they are aggregated so as to determine the total flow in each pipe. Corrected pipeline transport costs are computed on the basis of these new flow rates. (Short or small shipments are sent by truck, and large shipments of nonpipeable products are sent by truck unless a water route is available.) The resulting solution is clearly not truly optimal, since only an accurate equilibration of transport costs over the available routes would provide an optimum. In fact, it seems likely that the selection of mode would unrealistically favor water transport, since unit pipeline transport costs are high when the throughput is low. Nonetheless, the error may not be serious, since water routes are unavailable in most cases.

Crude oil transport costs are set a priori. The flow along each route is largely determined by supplies and demands fixed before the model is run. As a result, the unit costs can be calculated beforehand and need not be updated as the model runs.

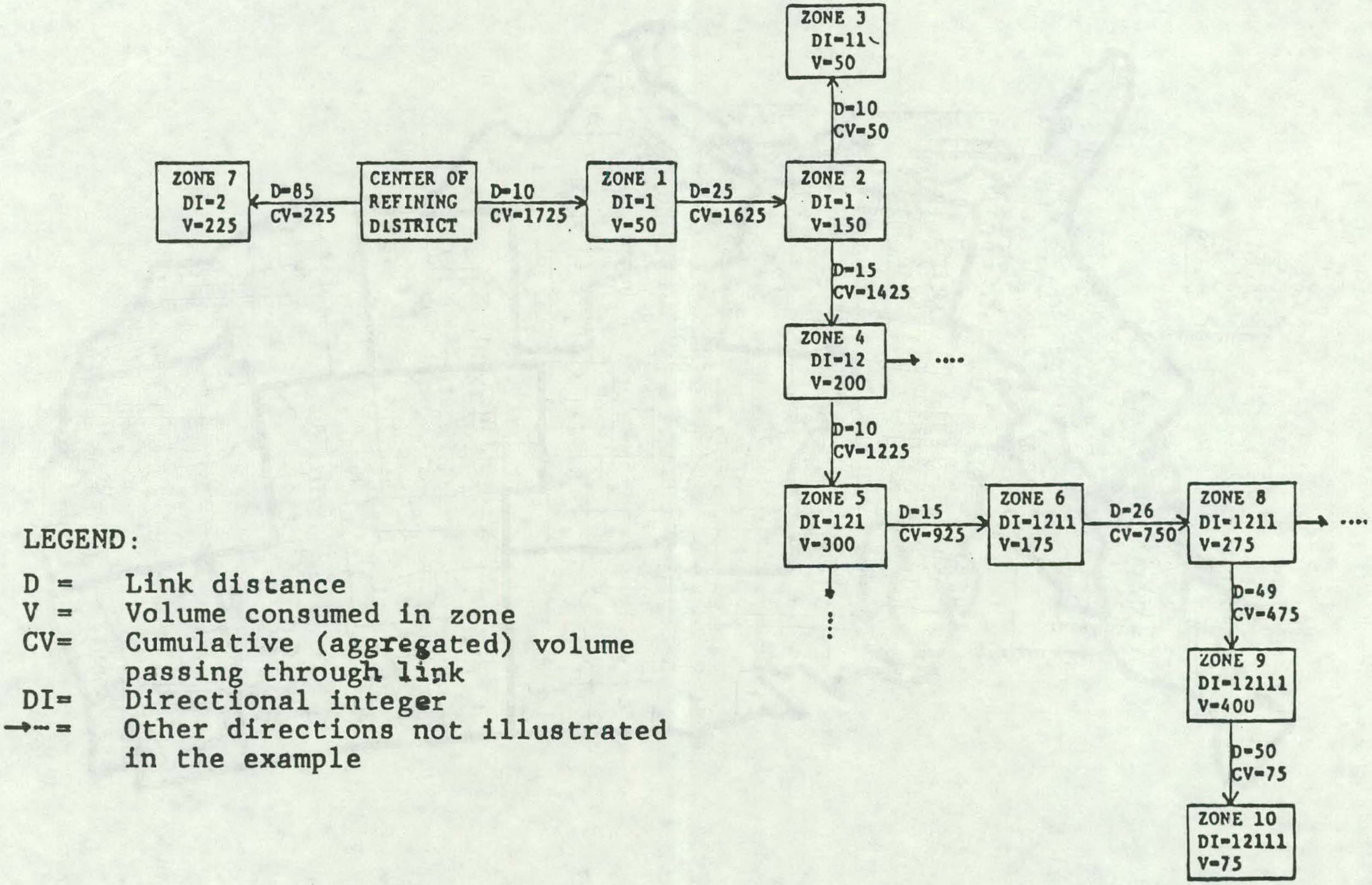
## 4.2 The Network Representation

### 4.2.1 Oil products

Since the FEA model bases oil product pipeline unit costs on the total flow in each major pipeline link, as it should, it requires a products network representation that indicates how oil streams diverge on their way to market. The model's network representation does this in the following way. To each market area are assigned several "directional integers," one for each refinery district from which that area might receive oil. Each integer is a series of digits that indicates which branch one must take at each pipeline junction along the way from refinery to market. For example, the integer describing the route from the refinery to market zone 3 in Fig. 11 could be 11 (i.e., take branch 1 at the refinery and branch 1 at the junction in zone 2). The route from the refinery to zone 10 could be described as 12111.

It is clear that this representation can instruct one how to aggregate flows to the several market areas so as to determine the total flow in each segment of pipe. It is less clear how directional integers should be assigned when the network connecting a refining center with market areas does not have the tree structure of Fig. 11 (i.e., when there are sometimes multiple ways to get from here to there). This matter is dealt with in Sect. 6.2.

The resolution of the products network representation is rather high. Figure 12 shows the 18 refinery districts and 484 market areas



LEGEND:

D = Link distance
V = Volume consumed in zone
CV= Cumulative (aggregated) volume passing through link
DI= Directional integer
→·· = Other directions not illustrated in the example

Fig. 11. A hypothetical pipeline link structure.

Reproduced from Gezen (1976, p. 14).

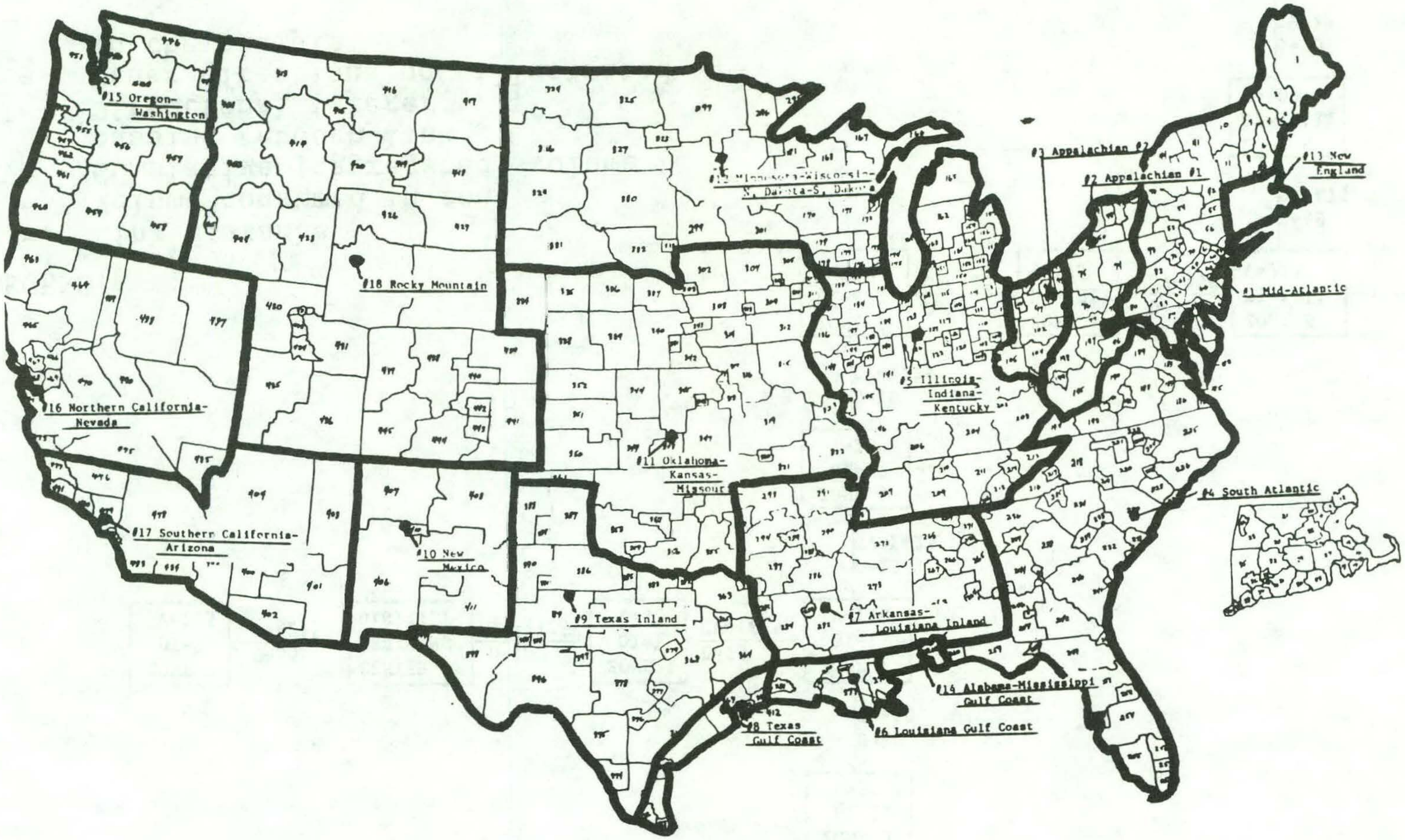


Fig. 12. Refinery districts and market areas for FEA model. Reproduced from Schumaier, Gezen, and Kendrick (1974, p. 3-11).

chosen. Sixteen hundred forty-five directional integers describe the connecting links. Besides these, a number of proposed links are added where none now exist.

The mode representing each refinery district is located at a weighted average location of the refinery capacity in that district. The average location, given by coordinates $(\underline{x}, \underline{y})$, is presumably computed

$$(\underline{x}, \underline{y}) = \Big(\sum_{\underline{i}} \underline{c_i}\,\underline{x_i}/\underline{C},\ \sum_{\underline{i}} \underline{c_i}\,\underline{y_i}/\underline{C}\Big)\ , \tag{3}$$

where

$\underline{c_i}$ = the capacity of refinery $\underline{i}$,

$C = \sum_{\underline{i}} \underline{c_i}$,

$(\underline{x_i}, \underline{y_i})$ = the location of refinery $\underline{i}$,

The refinery districts appear to be fairly well chosen, so that refining capacity is usually concentrated in a small area within the district.

The oil products waterway network is described simply by a matrix showing the distance between each refining center and market area when a water route connects them.

### 4.2.2 Crude oil

Opportunities for crude oil movement are described by a cost matrix linking ten production areas to the 18 refining centers. The production areas are the five PAD districts, the Alaska North Slope, Venezuela, Canada, Indonesia, and the Persian Gulf. The transport mode (pipeline or tanker or both) connecting each source with each destination is chosen judgmentally. The cost of transport from the PAD districts is computed with respect to district centers located by taking a weighted average location of oil reserves.

## 4.3 Link Capacities

The FEA model makes no provision for link capacities. It is assumed that, in the long run, oil carriers would adjust capacities to accommodate a least-cost flow pattern.

## 4.4 Transport Costs

### 4.4.1 Pipelines

Unit transport cost by pipeline is sensitive to both the pipe diameter and the volume carried. The FEA model relates these three quantities as shown in Fig. 13 (Schumaier, Gezen and Kendrick 1974, p. N-15), which is based on a paper presented by W. H. McCollough (1972). The envelope defined by the several U-curves was taken to represent pipeline costs for modeling purposes. The absolute costs are out of date, but a similar curve could be fitted to recent selected tariffs.

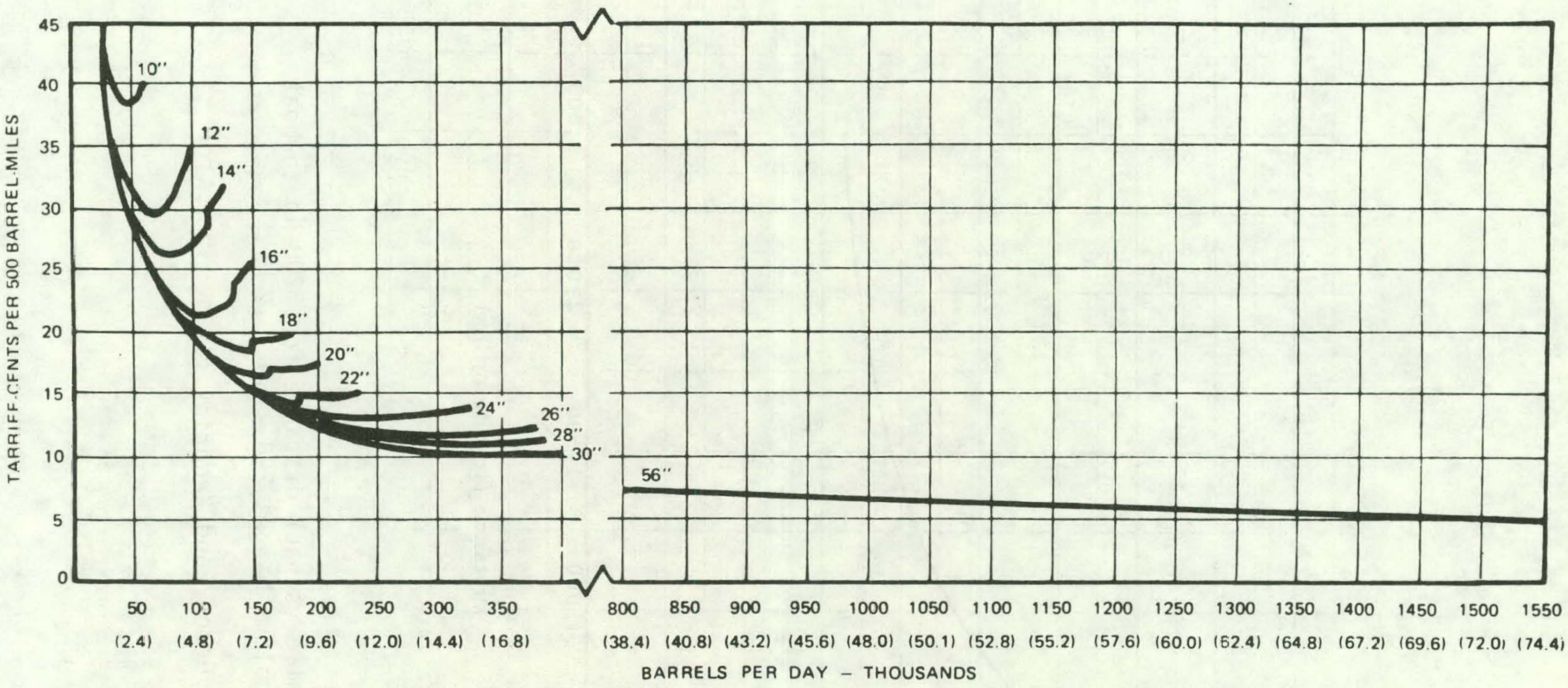
The writer was unable to locate Mr. McCollough so as to learn by what method the cost curves of Fig. 13 were derived. The difficulty of finding documentation for pipeline cost curves in general is discussed in Sect. 3.4.

Figure 13 makes it evident that the pipe size providing the smallest unit cost for a given throughput generally does not operate most efficiently at that throughput. Rather, a pipeline generally operates at its lowest unit cost when carrying a larger throughput than the given one. It is, in fact, a common practice to size a pipeline to carry an initial desired throughput at minimum cost and later to increase the capacity of the line, by adding horsepower, and in so doing decrease unit costs still more. (Once capacity is increased however, the pipe may no longer be the most efficient size for the throughput it is carrying.) As a result the true relation between diameter and economic capacity is probably not the envelope defined by the U-curves in Fig. 13, but a curve somewhat above it. A better account of this relation is described in Sect. 5.3.1.

### 4.4.2 River barges

Transport costs for river barges were estimated by computing the hourly operating cost of a typical towboat pulling four typical tanker barges at a typical speed of 5 mph upstream and 10 mph downstream. Cost per ton-mile was estimated for several typical trip lengths. The cost of 12 h of loading time and 12 h of unloading time per trip was included.

The hourly operating cost was derived from 1967 and 1970 cost elements (U.S. Army Corps of Engineers 1967, 1970). These cost elements include such fixed costs as depreciation and interest and such variable costs as wages, fuel, and maintenance. The costs were assumed to rise by the same fraction between 1970 and 1972 as they did between 1967 and 1970. The resulting hourly costs were $72 for a typical 3200-horsepower towboat and $5.90 for a typical 2900-ton products barge. The resulting costs per ton-mile appear in Fig. 14 (Schumaier, Gezen and Kendrick 1974, p. N-6).



Notes:

(1) The numbers in parentheses along the abscissa indcate annual throughput in million long tons assuming 7.5 barrels per ton.

(2) The 56" curve is a linear approximation of the exponential curve. For all practical purposes a linear approximation beyond 30 m.t.a. significantly represents the theoretical exponential.

(3) The series of cost curves are drawn for crude oil for a distance of 500 miles. Product pipeline costs are approximately 25% higher (based on national barrel/mile averages of tariff revenues on crude trunk and product trunk lines).

(4) The true behavior of the 56" line's cost at throughput levels lower than 30 m.t.a. is unknown and accurate knowledge of same is irrelevant. The high capital cost required for this size is not justified at low levels of throughput. The little data available strongly indicates that at throughput levels less than 30 m.t.a. the cost per barrel is significantly higher than the envelope establishing the minimum cost range.

(5) Pipeline tariffs are true indicators of costs.

Fig. 13. Pipeline tariff vs throughput vs pipe diameter, including 7% return on investment.

Source: Cost curves for 0-350 throughput range from a paper presented by W. H. McCollough on "Pipeline Economics" at the Association of Oil Pipelines Educator's Tour, July 26, 1972.

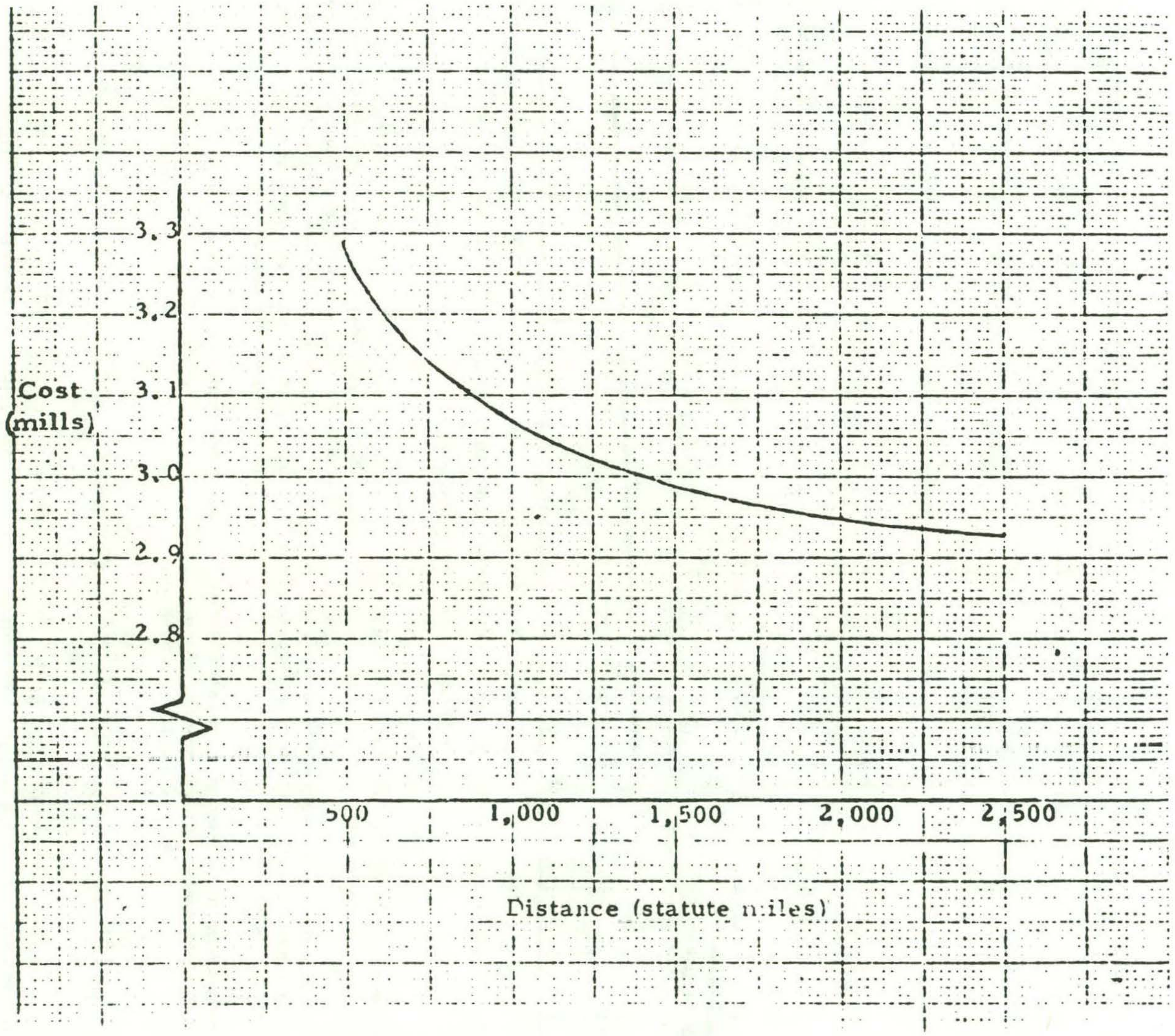


Fig. 14. Cost per ton-mile vs haul distance for 3200-hp towboat and four petroleum barges 290 × 50 × 12 ft.

Reproduced from Schumaier, Gezen, and Kendrick (1974, p. N-6).

### 4.4.3 Coastal tankers

The hourly operating costs of 26,000, 35,000, and 60,000 deadweight tons (dwt) were computed along the same line as those of river barges. Cost element data for 1971 and 1972 were obtained from the U.S. Army Corps of Engineers. Returning tankers were presumed empty, and speed was taken to be 16.5 knots in both directions. Resulting ton-mile costs as a function of distance appear in Fig. 15 (Schumaier, Gezen, and Kendrick 1974, p. N-13). The 26,000-dwt costs were taken to be representative for modeling purposes.

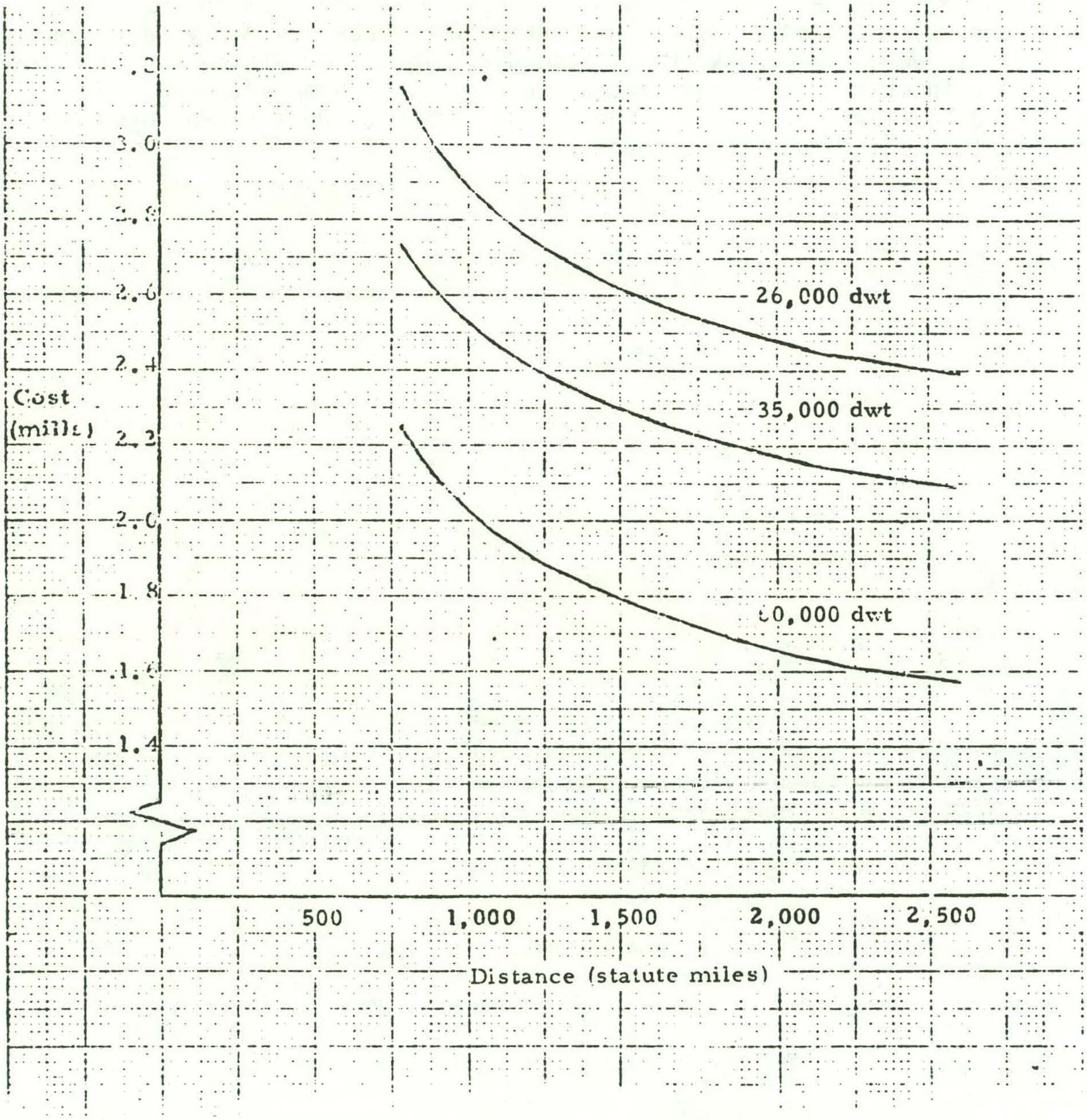


Fig. 15. Cost per ton-mile vs haul length for U.S. coastal petroleum tankers.

Reproduced from Schumaier, Gezen, and Kendrick (1974, p. N-13).

# 5. THE ORNL OIL PIPELINE ENERGY MODEL

## 5.1 General Description

A model for estimating oil pipeline energy consumption and intensiveness was developed by the writer at ORNL (Hooker 1980). The old DOE Conservation and Solar Energy Division sponsored the work.

The model was used to estimate pipeline energy use in 1978. The estimates are based on a simulation of the actual movement of oil on a very detailed representation of the pipeline network, and the model uses engineering equations to calculate the energy that pipeline pumps must have exerted on the oil to move it in this manner. The efficiencies of pumps and drivers are estimated so as to arrive at the amount of energy consumed at pumping stations. The throughput in each pipeline segment is estimated by distributing each pipeline company's reported oil movements (barrel-miles) over its segments in proportions predicted by regression equations that show typical throughput and throughput capacity as functions of pipe diameter. The form of the equations is justified by a generalized cost-engineering study of pipelining, and their parameters estimated by techniques developed for the purpose. A simplified model of flow scheduling is chosen on the basis of actual energy use data obtained from a few companies.

The model yielded energy intensiveness estimates of 180, 350, and 220 J/kg-km (250, 490, and 300 Btu/ton-mile) for crude oil trunk lines, crude oil gathering lines and oil products lines, respectively. These three classes of pipelines respectively consumed $86 \times 10^{15}$, $10 \times 10^{15}$, and $64 \times 10^{15}$ J (0.082, 0.010, and 0.061 quads) in 1978. The model also yielded estimates by state and by pipe diameter. It characterized the efficiency of typical pipelines of various diameters operating at capacity. Ancillary results included estimates of oil movements by state and by diameter and approximate pipeline capacity utilization nationwide.

## 5.2 The Network Representation

Since the ORNL study was concerned only with pipelines, no waterway network was used. Its pipeline network, however, covers essentially all oil products lines and all crude oil trunk lines in the nation, a total of 2803 links. Each link is a segment of one or more parallel pipes operated by the same company such that no diameter changes, no junctions and no state line crossings occur along the segment. The machine-readable representation shows pipe diameters, operating company, segment length, and the county and state in which the segment originates. It also shows known throughput capacities, which sometimes pertain to groups of parallel segments (National Petroleum Council 1979), as well as some actual 1974 throughputs, which usually pertain to groups rather than individual pipes (U.S. Congressional Research Service 1975).

The ORNL network is not in its present form suitable for use in a national refinery model. The difficulty is that no care was taken to ascertain which lines interconnect at a node, since this information was irrelevant to an energy study. That is, when several links converge at a node, as often happens in refinery centers, there is no indication as to which links connect with other links and which links simply terminate. Without this information it is impossible to know how oil can be routed over the network. Moreover such information is often not discernible on the pipeline maps used (American Petroleum Institute 1977), and considerable additional research would be required to obtain it.

If present expectations are fulfilled, ORNL will prepare a complete machine-readable oil pipeline data base during 1981-82 which would show geographic coordinates and in which all questions of interconnection would be resolved. It would be a simple matter to reduce such a network representation to one having the lesser detail required by a national refinery model.

## 5.3 Pipeline Capacities

The ORNL study investigated the matter of pipeline capacities in some depth. The investigation had two phases: The determination of a suitable functional form for expressing pipeline capacity as a function of pipe diameter, and an estimation of the parameters in this function.

The functional form was determined by first performing the cost-engineering study described in Sect. 5.4 and then deriving from the resulting cost function a formula relating capacity and diameter when economic optimality is achieved. The unit cost function at capacity is $(c_o + c_h + c_p + c_i)/C$, where $c_o$, $c_h$, $c_p$, and $c_i$ are given by Eqs. (12)-(15) in Sect. 5.4. If the capacity $C$ is fixed and the optimal diameter is chosen for that capacity (i.e., the diameter resulting in the lowest unit cost), then the partial derivative of the unit cost function with respect to $D$ should equal zero. If the optimal capacity $C$ is chosen relative to a fixed diameter $D$, the partial derivative with respect to $C$ should equal zero. In either case, after rearranging terms, the same equation results, except for a difference in the constants $a_1$, $a_2$, $a_3$:

$$1 = a_1 \left( \frac{C^{(t_3+1)t_1 t_2}}{D^{t_4 t_1 t_2 + t_8}} \right) + a_2 \left( \frac{C^{(t_3+1)t_5}}{D^{t_4 t_5 + t_8}} \right) + a_3 \left( \frac{C^{t_3 t_6}}{D^{t_4 t_6 - t_7 + t_8}} \right) . \qquad (4)$$

If it is observed that $t_1 t_2 \doteq t_5 \doteq 0.7$ and

$$\frac{(t_3 + 1)t_0}{t_4 t_0 + t_8} = \frac{t_3 t_6}{t_4 t_0 - t_7 + t_8} \doteq 0.47 \ , \tag{5}$$

the simpler expression

$$1 = b_1\left(\frac{C^{0.47}}{D}\right)^{e_1} + b_2\left(\frac{C^{0.47}}{D}\right)^{e_2} \tag{6}$$

results, where $e_1 \doteq 4.1$ and $e_2 = 2.8$. Equation (6) can be solved numerically for the ratio $C^{0.47}/D$, yielding

$$\frac{C^{0.47}}{D} = f \ , \tag{7}$$

where $f$ is a constant. This says that, at optimality, capacity is approximately a power function of diameter:

$$C = fD^g \ , \tag{8}$$

where $g \doteq 2.13$ at optimality.

If Eq. (8) is used as a functional form, 786 actual capacity observations (National Petroleum Council 1979) can be used to estimate $f$ and $g$. Since many capacity observations $C_i$ are the combined capacity of several pipes with diameters $D_{i1}$, ..., $D_{in_i}$, the irreducibly nonlinear regression function below must be used:

$$C_i = \sum_{j=1}^{n_i} (fD_{ij}^g + \varepsilon_{ij}) \ , \tag{9}$$

where $\varepsilon_{ij}$ is a random error term. If the variance $\sigma_{ij}^2$ of $\varepsilon_{ij}$ is expressed as a function $pD_{ij}^q$ of $D_{ij}$, and values of $p$ and $q$ chosen so that the resulting maximum likelihood estimates of $f$ and $g$ cause the distribution of residuals to be as nearly normal as possible, the following regression formulas ensue:

where

$$\begin{aligned} C &= \begin{cases} 26.95\, D^{2.339} & \text{for crude lines} \\ 26.48\, D^{2.383} & \text{for products lines} \end{cases} \\ \sigma &= \begin{cases} 3.937\, D^{2.75} & \text{for crude lines} \\ 3.228\, D^{2.95} & \text{for products lines} \end{cases} \end{aligned} \tag{10}$$

and where $C$ and $\sigma$ are expressed in cubic meters per day, and $D$ in inches. Note that the exponents 2.339 and 2.383 are near the exponent 2.13 estimated to apply at optimality.

Since the products pipeline capacity data were all adjusted to indicate capacity for pumping No. 2 fuel oil, which has a kinematic viscosity of about 3 *cSt*, the predicted capacity in Eq. (14) must be adjusted for other oil products:

$$C' = C(3/\nu)^{0.144} , \tag{11}$$

where $\nu$ is the kinematic viscosity of the fluid in question, $C'$ is the pipeline's capacity for pumping it, and $C$ its capacity for pumping No. 2 fuel oil, as given by Eq. (14). Typical viscosities are 0.64 *cSt* for gasoline, 2.2 *cSt* for kerosene, 1.2 *cSt* for jet fuel, and 0.3 *cSt* for liquefied petroleum gases (at 30°F). Due to the small exponent 0.144, capacity is not highly sensitive to viscosity, which need only be roughly estimated.

## 5.4 Pipeline Transport Costs

The ORNL pipeline energy study did not develop pipeline transport costs. It did, however, derive a general unit cost function as one stage in determining the relation between capacity and diameter at economic optimality, as described in Sect. 5.2. This cost function can be useful in estimating actual transport costs, as noted in Sect. 6.4.1.

The cost function expresses unit transport cost $c/V$ as a function of diameter $D$, throughput capacity $C$ and actual throughput $V$ (Hooker 1980, pp. 6-1 to 6-10). Total cost $c$ is a sum of operating cost $c_o$, pumping equipment cost $c_h$, pipe and fittings cost $c_p$, and pipe installation cost $c_i$.

These are given below. (In the definition of exponents $t_i$, to say that $t_i$ is the "economy of scale" of some item is to say that the cost $c_q$ of the item is given by $c_q = kq^{t_i}$ for an appropriate coefficient $k$, where $q$ is the quantity of the item used.)

$$c_o = k_1 \frac{V^{t_3 + 1}}{D^{t_4}}^{t_1 t_2} , \qquad (12)$$

where

$t_1$ = exponent relating operating cost $c_o$ and power cost $c_{pw}$ in the formula $c_o = kc_{pw}^{t_1}$, or about 0.7,
$t_2$ = economy of scale for electricity use, or about 0.94.
$t_3$ = 2.75, from an engineering formula relating power use and flow rate,
$t_4$ = 4.75, from an engineering formula relative power use and pipe diameter.

$$C_h = k_2 \left( \frac{C^{t_3 + 1}}{D^{t_4}} \right)^{t_5} , \qquad (13)$$

where $t_5$ = economy of scale for installed pumping power, or about 0.7.

$$c_p = k_3 \frac{C^{t_3 t_6}}{D^{t_4 t_6 - t_7}} , \qquad (14)$$

where

$t_6$ = economy of scale for pipe pressure yield point at a fixed pipe diameter, or about 0.75,
$t_7$ = economy of scale for pipe diameter at a fixed pressure yield point, or about 1.72.

$$c_i = k_4 D^{t_8} , \qquad (15)$$

where $t_8$ = economy of scale for pipe diameter, or about 0.90.

The exponents $t_1$, $t_2$, $t_5$, $t_6$, $t_7$, and $t_8$ were estimated by simple regression studies based on data from a number of sources. The coefficients $k_1$, ..., $k_4$ were not estimated.

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# 6. APPLICABIITY OF THE MODELS

## 6.1 General Remarks

The four network models canvassed in the previous pages serve different purposes that, with the exception of OILNET, go far beyond the task of merely routing oil over a network. As a result it makes no sense, again with the exception of OILNET, to speak of adapting any one of these models to serve as the transportation module of a national refinery model. Nonetheless, bits and pieces of these models can profitably be incorporated into a transportation submodel. One model might supply part of the network representation, another some of the capacity functions, and still another some of the cost functions. This section discusses how this might be done. It ends with a proposed solution to the problem raised by the nonlinearity of any realistic transport cost function.

## 6.2 Network Representation

A network representation showing geographic coordinates, like those used by OILNET and the DOT Freight Energy Model, is not required for a national refinery model. Such a model does not care what geographic route a pipeline or waterway follows to get from oil field A to refinery B. On the other hand, merely an origin-destination matrix, containing in each cell a link capacity and a cost function, would not suffice. This is because the amount of oil transportable from origin A to destination B, and the cost of its transport, depends on how much oil must flow through the same pipelines between other origins and destinations. The proper degree of detail is to be found, rather, in a representation like that of the FEA Network Model (Sect. 4.2): one that shows sources and destinations as modes on a tree structure in which each link's capacity and cost function is indicated.

Such a tree representation would be easily adaptable to a national refinery model, once the producing, refining, and consuming regions are chosen. In the crude oil network, each refinery would lie at the root of a tree, and sources of oil (oil fields, ports) would be branch nodes. The products network would be similar, except that the tree's branch modes would be consuming regions. There is nothing to prevent one refinery's crude oil or products tree from sharing modes and links with another refinery's tree.

Occasionally there may be more than one path between an origin and destination, so that the connecting network does not have a tree structure.

It has been shown that for any undirected, capacitated network there is a tree on the same modes that permits the same maximum flow between any two modes (Ford and Fulkerson 1962, pp. 177-87). But there is no analogous result for directed networks, and the networks in question are directed. When the physical network is not a tree, then it seems best not to try to transform it into a tree. This would require that the FEA model's "directional integer" tree representation be forfeited, but this is no loss, since such a representation is not convenient for a linear programming model.

The FEA model's oil products network representation could, if updated and checked for accuracy, be used in a national refinery model that recognized the same refining and consuming regions. Yet it is likely that the FEA model's consuming regions (BEA areas) are too numerous to permit demand estimates for all of them. If not, the FEA products network may be usable, but with three caveats.

1. It is not clear that the directional integers always permit an inference of which links are shared by the distribution trees of two or more refineries. This inference would be possible only if all junctions were at market nodes at which deliveries are made, and if the link connecting two nodes in one tree were identical with the link (if any) connecting those two nodes in another tree.
2. The node representing a refining region is sometimes placed where there are no existing transport links and connected to existing links via "proposed" links. This seems an unnecessary complication.
3. It requires nearly as much work to update and validate this sort of network representation as to build it from scratch.

The FEA model does not have a similar crude oil network.

If the FEA network representation is not usable, it seems best to consult a detailed map of the pipeline network (American Petroleum Institute 1979) and to aggregate lines as best suits the chosen producing and consuming refining regions, rather than to try to adapt one of the other representations examined in this study. This is because these other representations are, with one exception, not only out of date but lack detail, so that if their nodes do not mesh well within the desired regions it may be difficult to tell how links and nodes should be aggregated. The exception is the ORNL network, which is very detailed but does not distinguish pipes that merely cross from those that interconnect.

## 6.3 Link Capacities

### 6.3.1 Pipelines

It was seen that FEA model does not require link capacities. The DOT Freight Energy Model requires capacities, but its pipeline capacities were found to be unrealistic. The OILNET model evidently uses capacities obtained directly from pipeline companies, but a more recent and more complete survey of pipeline capacities has been conducted by the National Petroleum Council (1979).

The best course seems to be to use the National Petroleum Council capacities when available and to assign capacities to the remaining lines according to the ORNL regression formula given in Sect. 5.3.1.

### 6.3.2 Waterways

Of the four models studied only the DOT Freight Energy Model provides waterway capacities. These capacities apply to all freight movement by water, however, whereas a national refinery model would generate petroleum flows only. Consequently, it is impossible to infer capacities for petroleum movement unless one can estimate the volume of other traffic. A reasonable approach is to assume that nonpetroleum traffic remains constant at, say, its current level and to add the petroleum flows generated by the refinery model.

## 6.4 Transport Costs

### 6.4.1 Pipelines

Only the DOT Freight Energy Model and the FEA model estimate pipeline costs, and in neither case could the origin of the cost functions be traced. In view of this, and in view of the age of these cost data (~1970), it seems best to develop a pipeline cost function from scratch.

Such a development should not be difficult. Pipeline unit costs are proportional to a sum of fixed costs $\underline{k}$ divided by the flow rate $\underline{V}$ and operating costs. If unit operating costs are proportional to power consumption, then

$$\text{unit cost} = \underline{k_1}/\underline{V} = \underline{k_2V}^{1.75} \qquad (16)$$

since, for a fixed diameter, power consumption is proportional to $V^{1.75}$ (Hooker 1980, p. 2-3). If several current rates are known for each diameter, the parameters $k_1$ and $k_2$ can be estimated by a simple linear regression procedure. Although pipeline rates need not reflect the true unit cost of transport, they may be roughly proportional to the true cost, thus permitting a rough estimate of the parameters. The pipeline capacities or, if known, the actual throughputs would supply the values of the independent variable $V$.

If insufficient rate data are available for each diameter, it may be possible to combine data for all diameters so as to estimate parameters in a cost function in which pipe diameter plays a role. One such function is given by summing Eqs. (12)-(15) in Sect. 5.4 and dividing by $V$ (Hooker 1980, p. 6-9):

$$\text{unit cost} = k_1 \frac{V^{0.81}}{D^{3.13}} + k_2 \frac{C^{1.93}}{VD^{3.33}} + k_3 \frac{C^{1.31}}{VD^{1.84}} + k_4 \frac{D^{0.9}}{V} , \qquad (17)$$

where $C$ is throughput capacity. The first term covers operating costs, the second term pump station costs, the third term the cost of line pipe and fittings, and the fourth term the cost of installing the pipe.

A difficulty with either of the above approaches is that actual throughput data are generally unavailable, so that one must make do with capacity data as surrogates. Pipelines, especially older ones, commonly run below capacity. However, since rates are to be used as surrogates for actual unit costs, this may not be a serious problem. It is arguable that pipeline rates, whatever the throughput, are roughly proportional to the unit transport cost at capacity. A pipeline is generally designed to be competitive and achieve a reasonable profit when operating at capacity. If rates were raised to reflect the higher unit costs of reduced throughput, the pipeline would soon cease to be competitive. This argument does not apply to a monopoly situation or to a pipeline that ships only or predominately its owners' oil, as often happens. In such cases one might assume that government regulation keeps pipeline rates from rising too far above unit costs at capacity.

Undeniably, rates are generally somewhat higher than capacity unit costs even when a line is running at capacity, since otherwise there would be no profit. Yet if rates are roughly proportional to costs, and if waterway rates, rather than costs, are likewise used, then there is no harm in using rates rather than unit costs at capacity. The profit margin for waterway transport may be different, but such quibbles are meaningless in view of the inevitable lack of precision in cost estimates.

If rates are in fact indicative of unit costs at capacity, then it is appropriate that capacities, rather than actual throughputs, serve as values of the independent variable $V$ in the cost functions above. Once the parameters are estimated using capacity and rate data, unit costs can be approximated for values of $V$ other than capacity throughput.

Another difficulty of using rates as surrogates for observations of the dependent unit cost variable is that rates commonly depend not only on the characteristics of the pipeline but also on the size of the batch to be transported, and perhaps on other factors as well. In such cases it seems best to calculate an average rate equal to the pipeline's total annual revenues divided by its annual throughput. When total revenues are known not for individual lines but only for a company owning several lines, further estimation is necessary.

### 6.4.2 Waterways

The DOT Freight Model and the FEA network model estimate transport costs on inland waterways, whereas only the latter estimates costs for coastal tankers. The FEA coastal data are old (~1972), but they could be updated using the same straightforward method and the same sources that the model uses (Sect. 4.4.3). In a pinch one could update the costs using the cost-of-living index.

Of the inland waterway cost functions, the DOT function is superior because it takes into account the higher cost of operating in congested waterways, where there is greater delay at locks. It expresses unit costs as a function of total freight movements on a link, not just petroleum movements, but this can be accommodated as described in Sect. 6.3.2. That is, the total movement can be taken to be the sum of the petroleum movement generated by the refinery model and exogenously supplied constants for other freight movements on each link, perhaps current movements. Cost function [Eq. (6)] in Sect. 3.4.2 thus becomes

$$\text{unit cost} = 2\underline{C}_0 - \underline{C}_1 + \frac{\underline{Q}(\underline{C}_1 - \underline{C}_0)}{\underline{Q} - \underline{V}_p + \underline{V}_0} , \tag{18}$$

where $\underline{V}_p$ is the oil tanker traffic and $\underline{V}_0$ other freight traffic, provided exogenously and fixed. The other variables are defined as for Eqs. (1) and (2).

The constants $\underline{C}_0$ and $\underline{C}_1$ in Eq. (18) can be adjusted to reflect the rise in costs since the development of the function (~1975). All of the cost functions discussed here are based on Army Corps of Engineers surveys of the industry, and more recent surveys can be sought to provide updates. Failing this, the cost-of-living index can be used.

Section 6.4.1 suggests that pipeline rates be used to calibrate a pipeline cost function. The resulting function delivers values that are somewhat higher than actual unit costs, since rates allow for a profit margin. A valid comparison of the pipeline and water modes requires that one either subtract profits from the pipeline costs or add profits to the waterway costs. It should not be difficult to ascertain an industry-wide average profit margin from financial statements submitted to regulatory agencies.

## 6.5 Accommodating Nonlinearity in Cost Functions

### 6.5.1 Importance of nonlinearity

A linear transport cost function is one that expresses the cost of transport over a fixed distance as a linear function of the quantity of goods transported. Since the cost of transporting zero goods can be taken to be zero, a linear cost function is of the form

$$\text{cost} = \underline{kV} ,$$

where $\underline{V}$ is the volume of goods transported. Consequently, when a cost function is linear, the corresponding unit cost function is a constant:

$$\text{unit cost} = \underline{k} .$$

It is characteristic of transportation that unit costs vary with the volume carried so that realistic cost functions are nearly always nonlinear.

It is important to determine whether, for modeling purposes, the true nonlinear cost functions must be used, or whether an ersatz linear approximation will suffice. This is important because the incorporation of nonlinear costs into the objective function of a linear programming refinery model poses problems. This section discusses separately whether it is necessary to use nonlinear costs for pipeline and for water transport. It concludes with a brief review of techniques for solving a linear program when the underlying objective function is nonlinear.

### 6.5.2 Pipeline cost functions

Section 7.4.1 suggests two nonlinear cost functions for pipeline transport, whose corresponding unit cost functions are Eqs. (16) and (17). There are at least three ways to incorporate either of these into a refinery model, one of which uses linear approximations.

1. Use the Eqs. (16) and (17) as they stand, thus making pipeline transport unit cost a function of both the actual throughput, which is generated by the model, and the pipeline capacity, which is given a priori. The resulting model would route oil so as to minimize unit transport costs (other things equal). If rates do not reflect unit costs at current throughput, as suggested earlier, the resulting routing may be unrealistic.

2. Assume that pipeline rates reflect unit costs at capacity, and design the model to minimize the tariffs paid to pipelines (other things equal). This results in constant unit costs, which are given by substituting $\underline{C}$ for $\underline{V}$ in Eqs. (16) and (17), yielding:

$$\text{unit cost} = \underline{k_1}/\underline{C} + \underline{k_2}/\underline{C}^{1.75} \,, \tag{19}$$

$$\text{unit cost} = \underline{k_1}\frac{\underline{C}^{0.81}}{\underline{D}^{3.13}} + \underline{k_2}\frac{\underline{C}^{0.93}}{\underline{D}^{3.33}} + \underline{k_3}\frac{\underline{C}^{0.31}}{\underline{D}^{1.84}} + \underline{k_4}\frac{\underline{D}^{0.9}}{\underline{C}} \,. \tag{20}$$

   In other words, a linear approximation of the original cost functions is used, setting the unit cost at the value it assumes at capacity flow. If this method is used, it is of course better to use a pipeline's actual rate, when it is known, rather than an estimate based on Eqs. (19) or (20). Section 6.4.1 notes that when rates depend on batch size or other factors, an average rate must be calculated.

3. If the refinery model is to project operations over a long-time horizon, it may be reasonable to assume that pipeline capacity will adjust itself to match demand for transport. In this case, the unit cost function in Eqs. (19) or (20) can be used and the capacity C treated as a variable whose value is assigned by the model. That is, whatever throughput the model assigns to a link is taken to be the capacity of that link, and the unit cost is calculated accordingly using Eqs. (19) or (20). The resulting cost functions are of course nonlinear.

The choice of a linear or nonlinear function should rest on two considerations. First, a nonlinear function is obviously more accurate, albeit considerably less convenient. One way to assess whether the added accuracy of a nonlinear function is worth the trouble is to solve the refinery linear programming model using linear transport cost functions and then to recalculate transport costs, at the flow levels generated by the model, using the nonlinear functions. One can then assess the significance of the difference. Any easier way to make the assessment is simply to guess what the flow on certain representative links will be, and to compare the corresponding unit costs predicted by the linear and nonlinear functions. One's choice must of course be conditioned by his confidence in the data used to calibrate the cost functions. There is no point in going to a nonlinear cost function for accuracy when the coefficients in any cost function can be only roughly approximated.

A nonlinear cost function has an advantage that goes beyond its greater accuracy, however, and this is the second factor that one should consider. The advantage derives from the fact that in a linear network programming model, the number of links that, in an optimal solution, receive a flow other than zero or capacity flow is mathematically required to be no greater than the number of nonredundant constraints in the linear program. Since there is ordinarily one constraint for each node, the number of noncapacity and nonzero flows is ordinarily no greater than the number of nodes.* It is likely, then, that an unnaturally large number of links, which generally outnumber nodes, will be assigned zero or capacity flow. The problem is particularly acute when two nodes are connected by, say, two links. The optimal solution will necessarily route all of the flow between these nodes on one link and place no flow on the other link. Or, if one link has insufficient capacity to carry all of the flow, it carries all it can and the other link carries the rest. A more realistic situation, of course, is for the flow to be shared by the links even when one link could carry it all.

An advantage of a nonlinear cost function is that it permits parallel links to share flow even when one could carry it all, and, in general, provides for a more realistic routing of flow. If the routing does not matter, and only the total flow between every pair of nodes is of interest, this consideration does not apply. In this case only the general inaccuracy of a linear cost function, and resulting inaccuracy in the predicted total internodal flows, counts against it.

### 6.5.3 Waterway cost functions

The cost function [Eq. (18)] suggested in Sect. 6.4.2 for lock transit costs is the only nonlinear element in the waterway costing procedure recommended in that section. If desired, it can be linearly approximated by fixing the total traffic $\underline{V_P} + \underline{V_0}$ through each lock at a value typical for that lock. Since oil tankers generally comprise only a fraction of traffic in a given lock, the resulting error should not be great in most cases.

### 6.5.4 Aggregated pipeline costs

Aggregation of links in a network representation raises a difficulty for pipeline costing that does not arise in the case of waterways. It is that several pipelines that connect the same two nodes must be represented by a single link and therefore a single cost function, even though the individual pipelines may have different cost functions. This problem does not arise with water transport because water links are sufficiently few that it's unlikely that two or more links would connect the same pair of nodes.

If the entire network model is to be based on an assumed least-cost routing of oil, it is only reasonable that a volume $\underline{V_0}$ of oil will pass through pipelines 1, ..., $\underline{n}$ connecting the same two nodes in such a way

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[*] Actually, the number of nodes minus the number of connected components that make up the network.

as to minimize cost. A function that computes the minimum cost of routing oil through these $n$ pipelines can therefore serve as a reasonable cost function for the aggregated link.

A minimum cost function can be approximated by assuming that the optimal flow in each pipeline never exceeds that pipeline's capacity when the aggregated flow does not exceed the aggregate capacity. Since a pipeline's minimum unit cost is generally incurred at or near its capacity flow, an aggregate flow equal to aggregate capacity should distribute itself by assigning roughly capacity flow to each line. If aggregate flow drops below aggregate capacity, it is clearly not advantageous to increase the flow in one of the pipelines. The assumption, then, is reasonable.

Let the unit cost function $c_i(V_i)/V_i$ for pipeline $i$ be of the form

$$c_i(V_i)V_i = a_i V_i^{t-1} + b_i + \frac{d_i}{V} . \tag{21}$$

This function is chosen because it allows for a fixed overhead component (third term), an operating cost component that is proportional to flow (second term), and an economy or diseconomy of scale component (first term). All recommended cost functions, except Eq. (20) when $C$ is a variable, are of this form. The unit cost for the aggregated link is

$$\frac{\sum_i c_i(V_i)}{\sum_i V_i} = \frac{1}{\sum_i V_i} \sum_i a_i V_i^{t} + \sum_i b_i V_i + \sum_i d_i . \tag{22}$$

If $C/V_0$ is to be minimized, we must have

$$\frac{\partial}{\partial V_j} \frac{\sum_i c_i(V_i)}{\sum_i V_i} = 0, \quad j = 1, \ldots, n , \tag{23}$$

and

$$\sum_i V_i = V_0 . \tag{24}$$

Equations (22) and (23) yield that

$$t a_j V_j^{t-1} + b_j = t a_1 V_1^{t-1} + b_1 , \quad j = 1, \ldots, n . \tag{25}$$

Solving Eqs. (24) and (25) for $V_1$ yields

$$V_1 t^{-1} = \left(V_0 - \sum_i \frac{b_1 - b_1}{t a_i}\right)\left(\sum_i \frac{a_1}{a_i}\right) . \tag{26}$$

Equations (25) and (26) can be used to calculate the minimum-cost flows $V_1, \ldots, V_n$, which can be substituted into Eq. (22) to derive the minimum aggregate unit cost function.

When costs are linear, so that $b_i = 0$, the above derivation breaks down. In this case, the optimal routing is to allow the cheapest pipeline to carry all of the flow, even if in reality its capacity would be insufficient. A more practical course is to use an aggregate unit cost function that is a weighted average of the individual unit cost functions:

$$\text{unit cost} = \sum_i C_i b_i / \sum C_i + \sum_i d_i / \sum C_i , \tag{27}$$

where the weights $C_i$ are the capacities of the individual pipelines.

### 6.5.5 Solution techniques

The simplex method, which is universally used to find optimal solutions for linear programs, will not accommodate an objective function with nonlinear terms. One recourse is to retain the nonlinear objective function and solve the resulting nonlinear program using one of the many techniques designed for the purpose. The difficulty is that nonlinear programs, especially large ones, are often difficult or impossible to solve.

A more practical approach in the present context is to use one of the simple iterative techniques that permit one to apply the simplex method repeatedly. One such technique is the Frank-Wolfe algorithm (Bradley, Hay, and Magnanti 1977, pp. 580-83). It works as follows. The following nonlinear program is to be solved by solving a sequence of linear programs.

$$\begin{aligned} &\max f(x_1, \ldots, x_n) \\ &\text{subject to } \sum_{j=1}^{n} a_{ij} x_j \leqslant b_i, \; i = 1, \ldots, m \\ &x_j \geqslant 0, \; j = 1, \ldots, n. \end{aligned} \tag{28}$$

An arbitary feasible solution $\underline{x}^0 = (\underline{x}_1{}^0, \ldots, \underline{x}_n{}^0)$ to Eq. (28) is chosen, and a linear program having the constraints of Eq. (28) and the objective function of Eq. (29) below is solved optimally.

$$\underline{f}(\underline{x}^0) + \sum_{\underline{j}=1}^{n} \underline{c}_j(\underline{x}_j - \underline{x}_j{}^0) \ , \tag{29}$$

where

$$\underline{c}_j = \frac{\partial \underline{f}}{\partial \underline{x}_j}\bigg|\ \underline{x}^0 \ .$$

Let $\underline{y}^1 = (\underline{y}_1{}^1, \ldots, \underline{y}_n{}^1)$ be an optimal solution to the linear program, and let $\underline{x}^1$ be the point along the line segment connecting $\underline{x}^0$ and $\underline{y}^1$ that minimizes the nonlinear objective function $\underline{f}(\underline{x})$. Any of the standard line search procedures may be used to find $\underline{x}^1$. Continue the process so as to generate a series of solutions $\underline{x}^0$, $\underline{x}^1$, $\underline{x}^2$. Any solution to which this sequence converges is an optimal solution to Eq. (28).

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