ALLOCATION OF COAL TRAINS
THROUGH COLORADO

by

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ABSTRACT

Increased frequency of coal trains through Colorado to supply the Wyoming coal to Texas and other Southern and Southeastern utilities will be a major problem in the future to the state and the communities through which the trains will pass. This study used a cost-effective approach to find the alternative routes to the coal train movement and developed a strategy for the decision makers to select between alternative routes. The major finding in the study shows that the community of Littleton near Denver will not be affected by the enormous increase of frequency of coal trains as has been suggested by other similar studies.

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CHAPTER I

INTRODUCTION

A. Statement of the Problem

Transportation has been identified as a possible constraint to the planned production and consumption of a total of 1.2 billion tons of coal by the U.S. in 1985 (Project Independence Blue Print, 1974). The federal government has recognized the need for developing a more efficient coal movement network for the nation. This need is most urgent for the transportation of western coal, which will be developed as a major source of energy for the nation. The amount of coal that has to be moved transcontinent from the western states in 1985 is projected in Figure 1.

Many sectors of the society are becoming increasingly concerned about the technological, economic, and social problems that are inherent in transporting such large amounts of coal. Both the railroad and the mining industries are interested in decreasing the transportation cost of coal in order to keep coal competitive with other fuels. The communities through which the coal trains will pass are also concerned about the disrupting effects on their lives. For example, some studies have shown that as many as eight

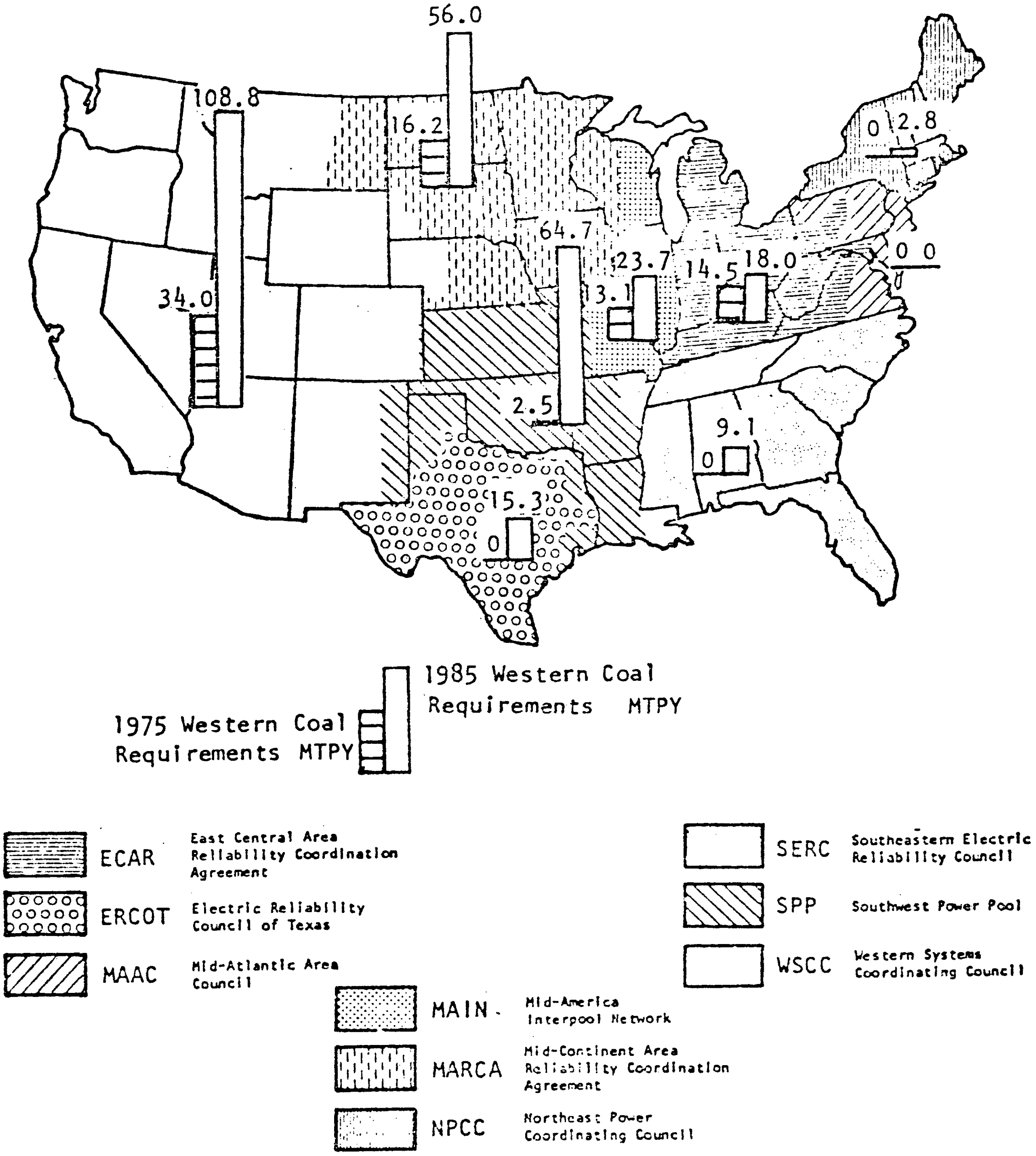


Figure 1: Electric Utility
Western Coal Requirements
1975-1985

two-mile long coal trains may pass through the city of Littleton, per day, in 1985 (URS, 1976). The increased noise, smog, delay at grade crossings, accidents, etc., will obviously create some inconvenience to the community life.

This study was prompted by the interests of the railroad industry in moving coal at the least possible cost, and at the same time, incurring the least possible disruption to the communities along the coal routes. The purpose of this study is to establish a strategy to select the "best" combination of routes which achieves a prestated goal of the communities at a minimum cost. The goal is to find an efficient coal transportation network through Colorado and the neighboring states to the south and southeast which will be acceptable to both the railroad industry and the communities.

The supply line for coal which affects Colorado is mainly that running from Montana and Wyoming to Colorado and Texas. At present the two routes that are used to move coal to the south and the southeast are 1) through Denver and Omaha over the plains of Nebraska, and 2) through Denver and Pueblo following the foothills. As the frequency of coal trains will increase, alternate routes will have to be sought to avoid congestion on the foothills route. This study presents a strategy to select the alternative routes.

B. Background

Extensive work has been done regarding evaluation of transportation alternatives, but careful review has indicated that no practical method has yet been developed to consider both the economic and the environmental aspects of the problem. While various approaches have been suggested in the literature, no consensus has been reached regarding the best evaluation method.

Two national coal transportation studies have been attempted. Both of them minimized total transportation costs on a simple unconstrained network from sources to destinations. The study done by the department of transportation for the Project Independence Blue Print in 1974 considered six sources and seven destinations. The U.S. Bureau of Mines (U.S.B.M., 1974) study took twenty-six coal producing and consuming districts into consideration. Both the studies assumed that the shortest rail route would be followed to transport coal from the major city of the producing region to the major city of the consuming region. The U.S.B.M. study also considered the delivered price of coal. None of the studies, however, has considered any social or environmental consequences. It is doubtful whether such a simplistic model would be of any use on a regional level.

Perhaps the most widely used criterion for evaluating transportation plans which considers social effects is benefit-cost analysis (BCA). Essentially this technique entails listing all the benefits and costs expressed in dollar terms for each alternative plan and a ratio of dollar benefits to dollar costs is determined. The plan with the highest benefit-cost ratio is then selected. The method is conceptually simple and easy to apply. It is quite efficient in public projects where all the outcomes and their dollar values are known.

One of the conditions of application of BCA is that the party who is paying for the costs of a project should get the full benefits. If a tunnel is built in the city of Littleton with taxpayers' money to avoid community disruptions due to increased train frequency and the railroad gets the benefit of running trains faster, a benefit-cost approach is not appropriate.

A strong objection to using a BCA analysis in transportation planning is that typically no provisions are included for nonuser costs and benefits. This is a vital consideration for coal transport. Communities through which trains pass will have few or no benefits. On the other hand, the existence of a rail line may help in the development of local industries. This dichotomy of users and nonusers in a community makes alternative rail plan selection more complicated. People are becoming increasingly conscious about aesthetics, inconvenience, irritation, and other community disruptions due to a transportation system; all of these, grouped together as community values and people's acceptance, are difficult to quantify and handle in a classical BCA. One author even suggested that one of the main reasons for previous deterioration of environment is the fact that it has been difficult to determine the value of such deterioration (Peter Bohm, 1968). Consequences which have a price tag have been taken into account,whereas priceless effects have been ignored.

A controversial two-step approach at quantifying intangible environmental effects has been suggested by George Klein (1968). With his method numerical values are assigned to various environmental effects according to their seriousness. For example, points are assigned arbitrarily from one to ten for low to high noise level. After points have been assigned for the effects, a corresponding monetary value is established for each point. These monetary values may range from a "few" cents per day for point one to a "few" dollars per day for point ten. Finally, all dollar values are summed for individual plans and compared. A major criticsm of this techniques is the arbitrary and subjective nature of point, and corresponding monetary value assignments.

Another technique called the "willingness-to-pay" approach involves estimating a dollar amount that the citizens are ready to sacrifice in order to avoid some community disruption. This dollar amount is used as a cost in BCA. An extensive survey resting on rational thinking of an average citizen is needed. The major drawback to this approach is that the relative value of a dollar is not the same for every man. It is very complicated to standardize the dollar value (Peter Bohm, 1968). Robert Wiederkehr (1968) estimated a ratio between the value of an intangible benefit to that of a calculable benefit. Using this ratio a dollar amount was given to the intangible benefit. However, this approach depends mainly on the judgement of the planner. The author argued that all the consequences could not be expressed as a ratio to some other benefit.

A coal train assessment study for Colorado was conducted by the Four Corners Regional Commission in 1976 (URS, 1976). A modified ranking technique was used to evaluate alternative routes. Points were assigned to individual routes based on number of communities, their population densities, and on the number of grade crossings on the track. Accident costs, delay costs, and level of noise were also calculated for maximum flow of trains on each route. The data were presented in a multidimensional table. However, neither any optimization approach was considered for proper allocation of trains through alternative routes, nor cost for coal transportation through alternative routes has been taken into account.

One of the objections to presenting multidimensional data is the simplifying assumption that all the cost and non-cost factors and their consequences are known and predictable. This is hardly the case, especially when we talk about such abstract ideas as community values, public acceptance, etc. To avoid this problem, some authors tried to express the effects as a whole unidimensionally. They believe a unidimensional value would be much more realistic, comprehensible, and easy to use.

David Pearce (1968) suggested that the slow rate of appreciation of land values around an environmentally disturbed zone such as a busy railroad can reflect the people's acceptance of the disturbances. Thus a market value can be obtained to express the environmental effects as a whole in a single dimension. It would be worthwhile and useful if such a survey was possible in real life. Available studies along this line are inconclusive (David Pearce, 1968). The apparent market price of the land reflects the real market price and consumer surplus. These two effects must be separated since the consumer surplus is the relevant aspect. It would also be difficult to establish the price of a nonmarketable property. Expected price is hardly representative of the real market price. More complications arise when the flow price of a property is considered against its stock price. The price of a parcel of land when sold alone is different from the price of that parcel when sold along with other property in that area. There is also doubt about the assumption that the relative depreciation of a property is the effect of the environment alone (David Pearce, 1968).

An ingenious approach was suggested by Barton and Mantel (1968) for placing a value on intangible factors. Realizing that market price cannot measure the costs of community disruption or reflect the community values, they introduced the "group-opposition" approach. A model was developed which estimated the expected costs of implementing a project that faced community opposition. The costs of reducing the opposition among the various groups were considered in the total costs. This, according to the authors, would reflect public acceptance. The problem of estimating such costs especially when the community is a nonuser of the facility is, however, enormous.

C. Uniqueness of Cost-Effectiveness Approach

The unfeasibility and questionable validity of the valuation processes discussed above has led to the introduction of a cost-effectiveness approach (CEA). Basically, this approach presents a strategy for making decisions in choosing between alternative plans. It attempts to measure the effectiveness of each plan in achieving a set of prestated goals at a minimum cost. Instead of trying to express all the consequences and costs in a single quantity (dollars) or to express every consequence in weighted values multidimensionally, CEA deals with two scalar dimensions: costs and indicators of effectiveness. These two factors are assigned as axes on a graph and all the alternative plans can be represented in a two dimensional graph. It would thus be easy to see at a glance how effective a plan is in attaining a prestated goal and at what cost.

Decision-makers are looking for a "satisficing" solution today instead of an "optimal" solution. It has been argued that optimizing models are not responsive to real world problems (E.C. Lindblom, 1963). The optimal solution to a particular problem can be defined as that alternative which satisfies the constraints of the problem while attaining the specified objective to a degree that is as high as or higher than that of any other alternative. This implies satisfaction of three basic requirements:

1. All feasible solutions must be known.
2. All consequences of an alternative solution must be known and quantifiable.
3. Optimality must be precisely defined.

Although it is expected that a number of alternatives could be identified for a transportation plan, the entire set of choices will be very difficult to specify. As has been already discussed, all the consequences of an alternative transportation plan cannot be identified with certainty and are difficult to quantify for inclusion in a mathematical model.

The programming definition of optimality refers to the greatest possible level of goal attainment; however, few transportation planning activities have a sufficiently detailed and comprehensive goal statement to provide a meaningful definition of optimality. In fact, defining an objective function in modelling a transportation problem is a highly controversial issue (Peter Steenbrink, 1974). In addition, of course, the goals of a community can be expected to exhibit general shifts with time, reflecting changing expectations, attainment of the previous objectives, technological changes, etc. This is why an evaluation technique should be flexible and open to alterations. In these days, people are increasingly getting involved in projects where community life is at stake. Thus the evaluation system should be direct and easy to understand.

To summarize, a cost-effectiveness approach has been proposed to use as an evaluation technique to assess coal train movement through Colorado. This technique has the following qualities:

1. It is simple to use.
2. It is easy to understand.
3. It is flexible.
4. It bypasses the problem of listing and quantifying all the consequences of an alternative plan.
5. It expresses the direct relationship between cost of transportation and the prestated goal of the communities very explicitly.

CEA has been used extensively in military applications. Each weapon is evaluated on the basis of its manufacturing cost and how many enemy targets it can destroy. This serves as a strategy to select a weapon which will have the best trade off between cost and effectiveness (P.D. Fox, 1965).

The cost-effectiveness approach to transportation problems was first suggested by Edwin N. Thomas and Joseph L. Shofer of Northwestern University in 1970. However, this approach has not yet been used. Nevertheless, it holds out promise as a feasible principle for a better evaluation and has great potential (Peter R. Stopher and Arnim H. Meyburg, 1975).

D. Scope of the Study

1. Time Period.

The proposed study is intended to address the coal demands in 1985. Data availability is limited beyond that period.

2. Study Area.

The study area (Figure 2) covers the western coal producing states and their markets in the South.

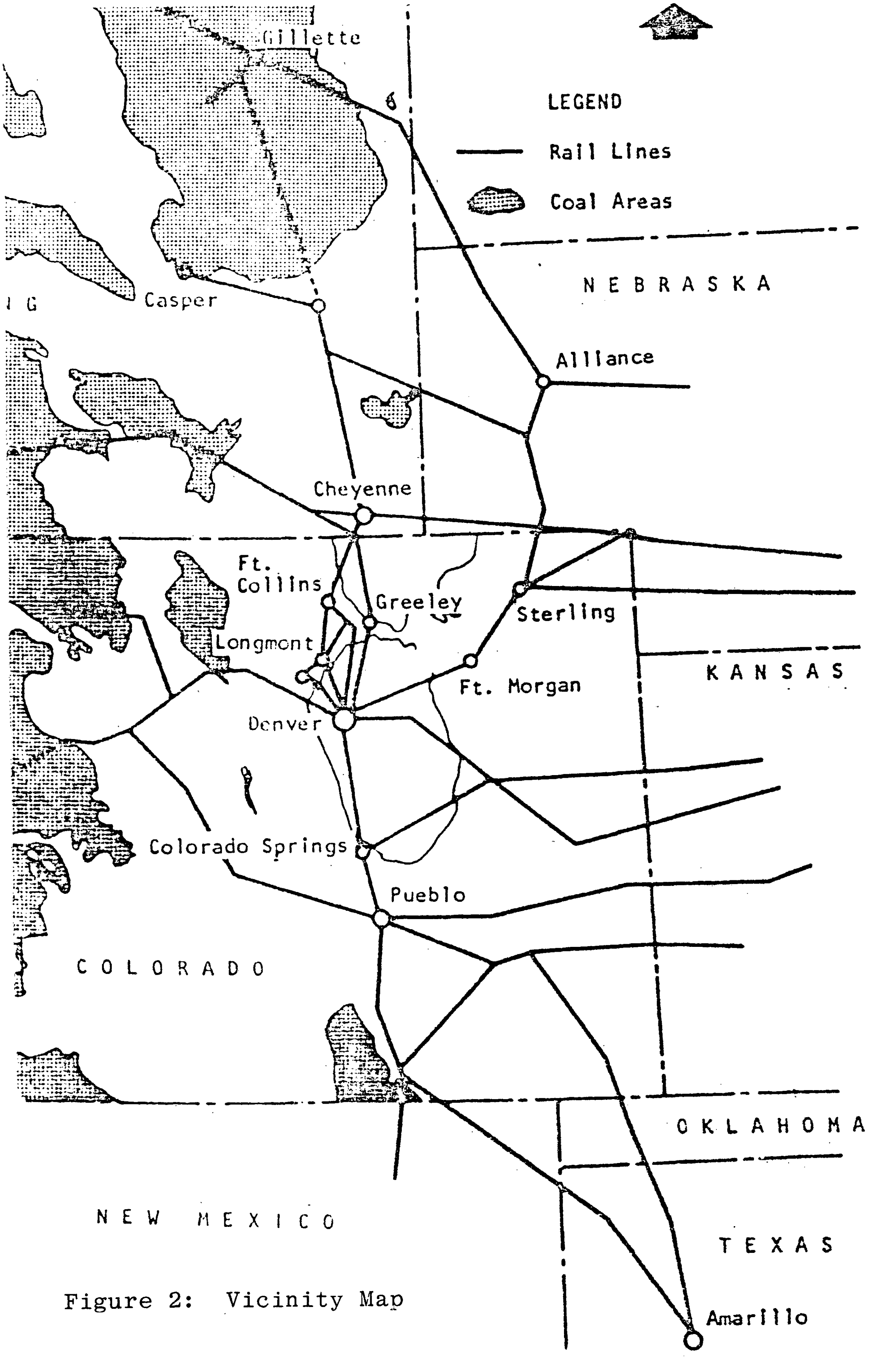


Figure 2: Vicinity Map

Only those railroad routes which directly or indirectly will affect the coal movement through Colorado will be considered.

3. Transportation Alternatives.

There are three major modes of transportation of coal or energy derived from coal.

Mine-mouth power generating stations.

Electricity can be generated at minemouth power plants and transmitted through extra high voltage lines. This does not seem to be attractive in the west for the following reasons.

a. There is a shortage of water in the western states.

b. Stringent air quality laws discourage big power plants.

c. Right of domain can be refused to the EHV transmission lines.

Coal-slurry pipelines.

The construction of interstate slurry pipelines has been proposed for transportation of coal over a long distance. There are many problems to be solved before this idea will be accepted.

a. Pipeline companies have to acquire the right of domain.

b. Shortage of water may be a problem in the western states.

c. The cost of slurry transportation may be greater than railroad transport over already existing railroad lines.

d. ICC regulation may prohibit long term "take-or-pay" contracts between pipeline and power companies.

Railroads.

The railroads are presently the single most important mode of bulk coal movement. All the studies (U.S. Congress, 1978) have shown that railroads will carry the major share of coal in the near future. It has been questioned whether the railroads can improve their capabilities in the face of their present poor financial condition. Through the Railroad Reorganization and Revitalization Act of 1973 the federal government has shown concern over this problem. Low interest federal loans are now available to the railroad industry to improve its present condition. The railroads are already committed to spending millions of dollars to upgrade their tracks and to buy additional rolling stock to handle the projected shipment of coal.

This study deals only with railroad transportation of coal. It will consider alternative railroad routes between sources in Montana and Wyoming and destinations in Colorado and Texas. It is assumed that the alternative tracks are freely interchangeable irrespective of which company owns the tracks. A unit train leaving Gillette, Wyoming, for example, can therefore theoretically take any available route to Houston, Texas. Recent studies, including one done by the United States Railroad Association, stressed the use of "integration" of railroads to some degree (A.L. Morton, 1974). Integration is the interchanging between railroad companies of their cars and common use of tracks, signals, and other facilities. Integral unit trains are quite common for agricultural products. They bypass all the changeover points and sometimes do not even change crews, thus reducing costs and increasing efficiency. Because coal is so vital to the existence of the railroad industry, integral coal trains are quite likely to be important in the near future. Therefore, a detailed systems approach to the problem of freight transportation is imperative.

CHAPTER II: DESCRIPTION OF THE MODEL

A. General Description

In the previous chapter the limitations of the classical evaluation techniques were established and a recent technique called cost effectiveness approach (CEA) was discussed. The essence of this approach is an attempt to measure the effectiveness of the alternative plans in achieving a set of prestated goals at minimum cost. The interrelationship among the alternatives and among particular properties of a single alternative are clearly presented for comparison. The preset goal of the communities is measured by an indicator, which is changed incrementally in order to estimate the marginal change of minimum cost. Thus a matrix between cost and effectiveness is developed. It can also be expressed in a series of graphs, one for each route. These are easy for the decision makers to understand and will be used to compare among alternative routes.

In CEA, the attributes of the alternatives are separated into two categories--costs, and measures of effectiveness.

Cost:

Cost can be defined in terms of all the resources necessary for design, construction, operation and maintenance of the system. It is generally expressed in dollars. Some authors have suggested including social and environmental costs such as delay cost, accident cost born by the society, cost due to noise and smog, etc., in the cost model. But as already discussed, CEA has the advantage that all the consequences do not have to be quantified as costs. In the author's opinion, cost should reflect only the direct and indirect costs incurred by the industry, whereas all social consequences should be reflected through the measures of effectiveness. This will keep the model parameters consistent. The total cost incurred by the industry is the sum of all the costs due to transportation of coal from source to destination and is really a measure of efficiency of the industry.

Some authors think that payment or compensation made by the railroad companies for accidents at grade crossings should be taken into account in total cost (URS Company, 1976). Through discussions with railroad people, it becomes evident that annual compensation paid for accidents is so small in comparison to total transportation costs, that it is not necessary to take it into consideration.

Effectiveness:

Effectiveness can be defined as the degree to which an alternative plan achieves its preset objectives. Cardinal numbers which may be assigned on a subjective basis, can be used as indicators for measurement.

Because the indicators of effectiveness in this study measure the people's acceptance to increased frequency of trains on a particular route, they are also indicators of community concern.

Communities through which the coal trains will pass are concerned about the following problems with higher frequency of trains.

a. If the track cuts a community in two, its integrity is disrupted with high frequency of trains. This is called the "barrier effect."

b. Delays at the grade-crossing will increase with the increased frequency of trains. Annoyance is more important here than the loss of time.

c. Disturbance due to noise will also increase, especially if the trains pass at unwanted hours.

d. Accidents may increase.

e. The communities think that the long trains damage the landscape.

These problems are more psycho-social than economic in nature. The effectiveness indicator should therefore be able to reflect the people's attitudes or feelings rather than any monetary loss.

Barrier effect cannot be quantified at all, but it is related to the number of trains running through the communities. Frequency of trains can thus be used as an indicator reflecting barrier effect. Number of trains accepted by a community is totally subjective and has no mathematical relationship with the barrier effect. It is the public opinion of a particular community which dictates what should be the number of trains to keep the barrier effect within an acceptable limit.

Some authors suggested that delay at grade crossings should be expressed in dollars (URS Company, 1976). The Department of Transportation has established a mathematical relationship between total cost of delay and number of trains. In the author's opinion, it is not worthwhile to get into the trouble of calculating the production lost due to delay, especially when each delay is generally of only a few minutes. Delay of this nature has no perceptible value to society (E.J. Mishan, 1976). Rather than money lost, the issue is irritation for the people waiting. But irritation is unquantifiable and can only be measured subjectively. Frequency of stoppages at grade crossing increases with the increased number of trains. Thus, frequency of trains can reflect a subjective measurement of increase in irritation.

Noise is quantifiable, but its consequences are not clearly known. Here again, the disturbance is more important than its health hazard. Level of noise in decibels for a running train has been measured for different distances, but these data will hardly serve any purpose for decision making. In airport location studies, it has been noted that people's objection to the total number of planes flying is more due to increase in disturbances rather than any specific health hazard (Edwin Thomas, 1970). Frequency of trains will reflect the people's acceptance of noise and can be used as an indicator to effectiveness.

Cost of accidents can be estimated using figures developed by the National Safety Council. Such general statistical figures have very little use for any particular community, however. It is also doubtful whether the loss of a human being, the grief, suffering, etc., can really be quantified in money values. It is the effect as a whole rather than the price paid for a single accident which is more important. This can be reflected through frequency of trains. Increased frequency of trains will increase the accident rate.

The list of community effect due to increased frequency of coal trains presented here is not complete and comprehensive. But to use CEA all the consequences do not have to be known. Community concern as a whole is more important here than concern over individual effects. In its entirety, the effectiveness of the alternatives can best be measured by the number of trains tolerated by the communities.

The purpose of this model is to find a suitable alternative for coal transportation from Wyoming to Texas through Colorado. The effectiveness of the system is measured in a single dimension, the number of trains running through the communities. Cost of coal transportation is measured in dollars.

The model is tested on the community of Littleton, Colorado. A series of cost minimizing problems are solved for different effectiveness levels. Considerations are given to the effectiveness of other communities on the alternative routes as well and recommendations are made as to the most cost effective allocation of coal trains through Colorado.

B. Mathematical Model

In the previous section the cost-effectiveness model has been verbally described. A series of cost-minimizing problems is solved for preset effectiveness indicators for each route and a cost effectiveness matrix is generated. The most effective number of trains to be assigned on each route is decided upon from the matrix.

In this section, the mathematical expression of the model is discussed.

Network Representations of the Transportation Problem

The railroad transportation system can be represented by a network. Figure 3 shows such a system.

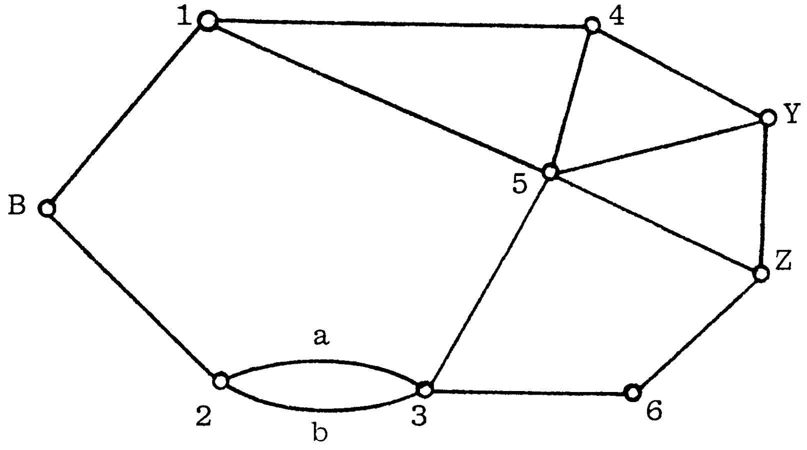


Figure 3. A Transportation Network.

A network consists of a collection of elements called nodes, some of which are connected by arcs. The nodes may be divided into three categories: a) "sources" at which the flow is generated, b) "destinations" at which the flow is terminated, and c) "intermediate" at which the flow is conserved. In the rail network depicted in Figure 3 the source is the producing center (B), destinations are the consuming centers (Y and Z), and the "Intermediate" nodes (1 through 6) are the junction points where two or more routes meet and an incoming train has an option to take any of the routes. A destination may also serve as an intermediate or junction node. Both Y and Z are such examples.

An arc is a route connecting two nodes. Any arc can be defined by A_{ij} where i is the origin node and j is the terminal node. When more than one arc connects two consecutive notes, a subscript r is used. Thus A_{ijr} is the arc between i and j following route r. In Fig. 3 an arc between nodes 2 and 3 is expressed as A_{23a} when the arc on route a and A_{23b} when the route is b.

The amount of material that moves per unit time from origin i to terminal j through route r on the arc A_{ijr} is represented by the flow variable f_{ijr}. Thus for each arc in Fig. 3 there is an associated flow variable. This flow cannot take any negative value ($f_{ijr} \geq 0$). For each arc there is a lower and an upper bound on the amount of flow. The lower bound is usually zero, as there is no route on which flow is mandatory. The upper bound depends on the level of effectiveness or any other physical constraint.

Conceptually, a railroad network is an undirected graph. Trains can move in any direction on the track. In reality, however, it can be treated as a mixed network. For some of the arcs the flow direction can be predicted heuristically, while on others the direction of flow will not be known until the final solution. For the purpose of solution, each such arc will be represented by two arcs connecting the same modes and pointing in opposite directions.

There is also a cost associated with each unit of flow on every arc. Marginal transportation cost of moving coal is expressed in dollars per unit size train per mile. For individual routes the mileage is known and cost per unit train moved can be estimated. Unit cost per train per mile on arc i, j, and route r is represented by C_{ijr}.

Formal Mathematical Expression

Objective Function

The decision variable in the model is the frequency of coal trains per unit time from sources to destinations. The cost function is expressed in dollars per train per mile. Mileage for each route is known and cost per train can be calculated. Each unit train consists of 100 cars of 100 tons capacity each. Total capacity of each train is thus 10,000 tons of coal. The unit of time is taken as one week.

The objective function is to minimize total transportation cost (Z) from sources to destination and is expressed mathematically as

$$\text{Minimize } Z = \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{r=1}^{R} C_{ijr} M_{ijr} f_{ijr}$$

where n = total number of nodes (population centers)

R = total number of routes from i to j

C_{ijr} = marginal cost of transportation per mile per train from i to j over route r.

M_{ijr} = mileage of route r from i to j

f_{ijr} = coal shipped in number of trains per week from i to j through r.

As M_{ijr} is fixed for each arc

$$C_{ijr} * M_{ijr} = c_{ijr}$$

$$\text{or} \quad \text{Min } Z = \sum_{i} \sum_{j} \sum_{r} c_{ijr} f_{ijr}$$

Constraints

The optimal operations model includes a number of additional relationships between parameters in the form of constraint equalities and inequalities. The indicators of effectiveness are also included in the constraints.

The first set of constraints in the model relates to technological limitations. These are imposed because of inherent physical properties of the system. Some tracks are not capable of carrying more than a specified number of unit trains per unit of time.

Thus the upper bounds are expressed as

$$f_{ijr} \leq U_{ijr} \qquad (1)$$

for all i, j, r

where U_{ijr} = upper bound of carrying capacity of a track r from i to j.

The lower bound of the capacity is zero.

The second set of constraints is the conservation of flow or the material balance constraints. In the railroad facility trans-shipment through intermediate cities or junction points is permitted. Every source or destination node can also serve as an intermediate node. For every city, there will be a material balance equation. For source nodes, the amount shipped out minus that shipped in is positive, showing the production. For destination nodes, the amount shipped out minus that shipped in is negative, showing the consumption. For intermediate nodes, the amounts shipped out and shipped in are equal. By definition, there is no production or consumption in these nodes. Thus for every city

Net Supply = Amount Shipped In + Produced

= Amount Shipped out + Consumed

For intermediate nodes the above equation reduces to

Net Supply = Amount Shipped In = Amount Shipped Out

Local production for local consumption is not considered here.

Mathematically,

$$\sum_{\substack{i=1\\i\neq j}}^{n} \sum_{r=1}^{R} f_{ijr} + S_j = \sum_{\substack{k=1\\k\neq j}}^{n} \sum_{r=1}^{R} f_{jkr} + D_j = f_{jj}$$

for all j's.

where f_{jj} = net supply at j

f_{ijr} = total quantity shipped from i to j (i≠j) through r.

S_j = production at j.

D_j = consumption at j.

f_{jj} is called the trans-shipment variable which is the amount trans-shipped through node j. In the complete tableau these are also the diagonal variables.

This constraint can be broken up into two.

$$D_j = f_{jj} - \sum_{\substack{k\\k\neq j}} \sum_{r} f_{jkr} \tag{2}$$

$$S_j = f_{jj} - \sum_{\substack{i\\i\neq j}} \sum_{r} f_{ijr} \tag{3}$$

The fourth set of constraints is the upper bound on flow due to the number of trains, tolerated by a community on a specific route. In the model this upper bound is incremented for every run of the problem and the effect on the minimum cost circuit is determined.

This is expressed as

$$f_{ijr} \leq F_{ijr} \text{ for all } i,\ j,\ r \tag{4}$$

where F_{ijr} = upper bound as an indicator on route r from i to j, or accepted frequency of trains on that route.

The nonnegativity constraint states that the flow on any arc cannot be negative.

$$f_{ijr} \geq 0$$

F_{ijr} in equation (4) is incremented gradually, whereas U_{ijr} in (1) is the maximum upper bound. F_{ijr} cannot exceed U_{ijr}. The capacity of the track is normally higher, thus equation (1) becomes redundant.

<u>Linear Programming Formulation of the Problem</u>

The problem can be expressed in the mathematical form as follows:

$$\text{Minimize } Z = \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{r=1}^{n} c_{ijr}\, f_{ijr}$$

Subject to

$$f_{ijr} \leq F_{ijr} \text{ for all } i,\ j,\ r \qquad (1)$$

$$-\sum_{\substack{i=1\\ i\neq j}}^{n} \sum_{r=1}^{R} f_{ijr} + f_{jj} = S_j \text{ for all } j \qquad (2)$$

$$-\sum_{\substack{k=1\\ k\neq j}}^{n} \sum_{r=1}^{R} f_{jkr} + f_{jj} = D_j \text{ for all } j \qquad (3)$$

$$f_{ijr} \geq 0$$

c_{ijr} = cost on arc ij through route r in dollars per train

F_{ijr} = acceptable maximum number of trains on route r per week.

D_j = net consumption at j

S_j = Net production at j

f_{ijr} = flow of coal trains per week from i to j via route r.

Network Formulation of the Problem

Instead of considering the trans-shipment variables f_{jj} which really is a self loop on node j, the nodes representing producing or consuming centers can be capacited. A fictitious arc is imagined for each such center. For the producing center it terminates on the node and for the consuming center it originates there. Figure 3 thus becomes Figure 4.

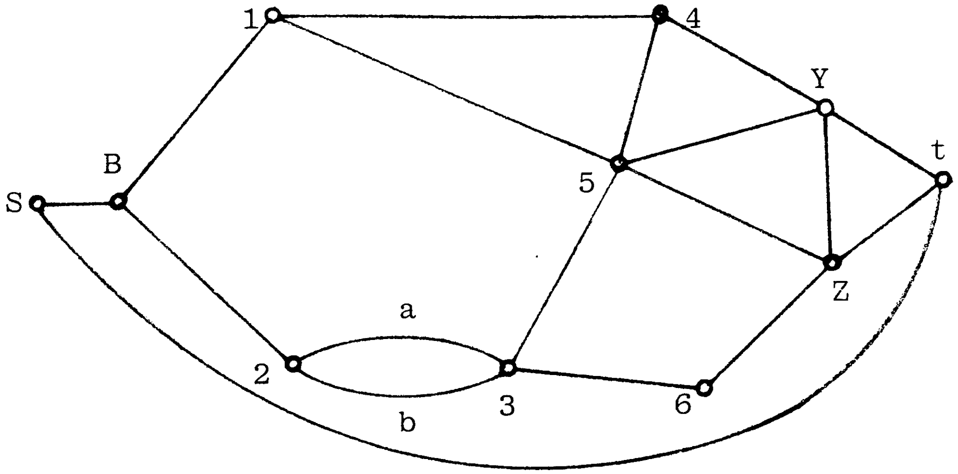


Fig. 4 . Modified Railroad Network.

S and t are thus two fictitious nodes connected to B and Y and Z. A flow which originates at S has to terminate at t, to meet the conservation of material. Thus the flow conservation equations (2) and (3) can be transformed to

$$\sum_{\substack{k=1\\k\neq j}}^{n} \sum_{r=1}^{R} f_{jkr} - \sum_{\substack{i=1\\i\neq j}}^{n} \sum_{r=1}^{R} f_{ijr} = \begin{cases} v \text{ when } j=s,\ i\neq t,\ k\neq t \\ 0 \text{ when } j\neq s,\ t \\ -v \text{ when } j=t,\ i\neq s,\ k\neq s \end{cases} \tag{4}$$

where v is the value of the total flow through the systems, originating at S and terminating at t. A positive value means the flow is leaving the node and negative means it is arriving at the node.

If these two fictitious arcs Yt and Zt are lower and upper bounded by the demands at Y and Z, respectively, then the flow through the system will satisfy the demand constraints.

Now another fictitious arc directed from t to S is drawn to connect the supersink t with supersource S, thus transforming the railroad network to a closed circuit. Every node has a set of incoming and outgoing arcs. Flow is conserved at every node. The conservation of flow equation thus becomes

$$\sum_{\substack{k=1\\k\neq j}}^{n} \sum_{r=1}^{R} f_{jkr} - \sum_{\substack{i=1\\i\neq j}}^{n} \sum_{r=1}^{R} f_{ijr} = 0 \qquad (5)$$

The complete mathematical expression for the network becomes

$$\text{Minimize } Z = \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{r=1}^{n} c_{ijr} f_{ijr}$$

Subject to

$$f_{ijr} \leq F_{ijr} \text{ for all } i, j, r \qquad (6)$$

$$\sum_{\substack{k=1\\k\neq j}}^{n} \sum_{r=1}^{R} f_{jkr} - \sum_{\substack{i=1\\i\neq j}}^{n} \sum_{r=1}^{R} f_{ijr} = 0 \text{ for all } j \qquad (7)$$

$$f_{ijr} \geq 0$$

C. Solution Methods

In a network there are a large number of potentially feasible flow patterns. The most powerful computational method for solving minimum cost network flow problems with linear cost functions is Ford-Fulkerson's "out-of-kilter" algorithm which minimizes total cost on the network while circulating feasible flow through it.

As already explained, the railroad network can be transformed to a minimal cost circulation flow network and expressed as

$$\text{Minimize} \sum_{ijr \varepsilon A} c_{ijt} \; f_{ijr} \qquad (6)$$

$$\text{Subject to } L_{ijr} \leq f_{ijr} \leq F_{ijr} \text{ for all arcs } ijr \varepsilon A \qquad (7)$$

$$\sum_{\substack{i \varepsilon N \\ i \neq j}} f_{ijr} - \sum_{\substack{k \varepsilon N \\ k \neq j}} f_{jkr} = 0 \text{ for all nodes } j \varepsilon N \qquad (8)$$

where N is the collection of all nodes in the network

A is the collection of all arcs

(ijr)	is the directed arc from i to j through r
f_{ijr}	is the flow in trains per week on arc ijr
L_{ijr}	is the lower bound on flow in arc ijr
F_{ijr}	is the upper bound on flow in arc ijr
c_{ijr}	is the marginal cost of coal transportation per train on arc ijr.

The out-of-kilter algorithm accepts multiple arcs as input between two nodes.

It is clear that equations (6) and (7) define a linear program. Dual variables π_i for each $i \varepsilon N$ may be defined for the constraint in equation (8). γ_{ij} can be defined for upper bound constraint and δ_{ij} for lower bound.

Primal Constraints		Dual Variables
$\sum_{i\varepsilon N} f_{ij} - \sum_{k\varepsilon N} f_{jk}$	$= 0$	π_j for each $j\epsilon N$
f_{ij}	$\leq F_{ij}$	γ_{ij} for each $ij\varepsilon A$
f_{ij}	$\geq L_{ij}$	δ_{ij} for each $ij\varepsilon A$

Then the dual linear programming problem for $ij\varepsilon A$ becomes

$$\text{Maximize } \sum_{ij\epsilon A} \{- F_{ij}\ \gamma_{ij} + L_{ij}\ \delta_{ij}\} \tag{9}$$

$$\text{Subject to } \pi_j - \pi_i - \gamma_{ij} + \delta_{ij} \leq c_{ij} \tag{10}$$

π_i is unrestricted in sign for all $i\varepsilon N$

$\gamma_{ij}, \delta_{ij} \geq 0$ for all $ij\varepsilon A$

The optimality conditions derived from complimentary slackness and feasibility conditions for all arcs $(ij)\epsilon A$ yield

$$c_{ij} + \pi_i - \pi_j > 0 \text{ implies } f_{ij} = L_{ij} \tag{11}$$

$$c_{ij} + \pi_i - \pi_j < 0 \text{ implies } f_{ij} = F_{ij} \tag{12}$$

$$c_{ij} + \pi_i - \pi_j = 0 \text{ implies } L_{ij} \leq f_{ij} \leq F_{ij} \tag{13}$$

Also

$$\gamma_{ij} = \text{Max } \{0, -\pi_i + \pi_j - c_{ij}\} \tag{14}$$

$$\delta_{ij} = \text{Max } \{0, +\pi_i - \pi_j + c_{ij}\} \tag{15}$$

Equations (11) and (15) represent the necessary and sufficient conditions for optimality of the solution to the minimum cost flow problem.

The out-of-kilter algorithm, starting with an arbitrary set of integer node prices π_i and any set of integer flows f_{ij} satisfying conservation of flow builds flow circulations and/or changes π_i's in the network with the goal of fulfilling the optimality criteria of equations (11) to (13). Any arc for which any of these equations is contradicted is said to be out-of-kilter. Otherwise, the arc is in kilter. The algorithm brings out-of-kilter arcs into kilter while maintaining in-kilter arcs as such and also conserving the flow. Eventually, all arcs are put in kilter to reach optimality. If certain arcs cannot be brought to kilter, the problem has no feasible solution.

In this thesis a series of cost minimizing problems are solved with gradual increments of upper bounds F_{ij} on Littleton track. From the minimum cost-effectiveness graph thus developed it will be easy to estimate the effect of changing upper bounds on cost.

D. Sensitivity Analysis

An important aspect of the evaluation process is the development of sensitivity analyses for the alternative plans. Sensitivity analyses are designed to show the effects of changes in the attributes of the alternatives on the cost or consequences.

Cost is basically a stochastic function. For the base problem it is considered as deterministic and is the expected value of the probabilistic data. Through this analysis it is established how sensitive the solution is, if the unit cost is allowed to change within its probable boundaries.

Three scenarios are developed for different consumption levels of coal. The effect of these scenarios on the optimal flow solution is established through sensitivity analysis.

E. Assumptions Inherent in the Model

There are some crucial assumptions inherent in a linear programming model. They are discussed below.

1) Proportionality.

For each activity, the total amounts of each input and associated cost is strictly proportional to the level of output. Each activity is capable of continuous proportional expansion or reduction. If the number of trains on a specific route is doubled, the transportation cost on that route is also doubled.

2) Additivity

The total amounts of each input and the associated cost are the sums of the inputs and cost for each individual activity. The number of coal trains on each parallel route is added to find the total number of trains through the system. Similarly costs on individual routes in series are added to find the total transportation cost.

These two assumptions are equivalent to stating that the underlying mathematical model can be formulated in terms of linear relations. Strictly interpreted, these assumptions imply constant return to scale and preclude the possibility of economies or diseconomies of scale. The errors generated by assumptions 1 and 2, especially of proportionality, are tested through sensitivity analysis.

3) Divisibility

Another limitation of the linear programming model is that fractional levels of decision variables must be permissible in the optimal solution. A fraction of a coal train means a train with fewer cars than scheduled. But the cost of running a complete train is not directly proportional to the cost of running a half trainload. However, this error is eliminated by approximating the supply and demand of coal by the number of unit trains required and using integer numbers for the parameters.

4) Deterministic

All the coefficients such as costs, demand and supply constraints, etc., are assumed to be known constants. The errors generated by this assumption are tested with sensitivity analysis. Different cost models and three scenarios for demands and supplies are tried.

F. Data Requirements

In this section, the data required to run the model and their validity are discussed.

1) Producing Centers and Projected Supply

The producing mines with the potential and commitment to supply Texas and Colorado are grouped together if they are served by a single rail line. Commitments and projected productions are compiled from the Keystone manual and through personal correspondence.

2) Consuming Centers and Projected Demands

All major power plants in Texas and Colorado are considered. Those which are served by a single rail line are grouped together. Sources of the data are National Electric Reliability Council and personal correspondence. Different scenarios have been developed by different agents through Federal Power Commission and Electric Power Research Institute.

3) Physical Characteristics of the Alternative Routes.

This information is mostly gathered from individual railroad companies by personal correspondence and from published maps by U.S. Geologic Survey and Rand McNally.

4) Costs

The source of cost data is the Railroad Form A submitted to Interstate Commerce Commission by the railroad companies in which they include the variable cost of transportation of individual commodities. The data for cost of coal transportation by unit trains by Class I railroads only are considered. A statistical cost function is developed from these data and adjusted for differences in terrains and other bottlenecks. These cost data are also checked with the engineering and other available unit train costs.

G. Shortcomings of the Model

The total system of railroad transportation of coal from mines to plants comprises the nation as a whole, whereas only a regional subsystem is considered in the model. However, as all the viable alternative transportation routes were considered in the model, the error, if any, generated by this limitation is minimal.

It is assumed that coal will be transported only on unit trains of a fixed capacity. This assumption is valid because it has been found that the stated capacity is most effective and least costly. It is also assumed that loaded and empty trains returning will use the same track. This means total number of trains running both ways on a track is double the number of loaded trains. This is normally the case.

CHAPTER III

APPLICATION OF THE MODEL

A. Western Coal Supply Demand Scenarios

The role of electric utility industry is becoming vital as the United States moves to an energy economy based on minimizing the use of oil and natural gas. Coal has been--and will continue to be--the principal fuel for the production of electrical energy. The proposed National Energy Plan (NEP) also leads to increased use of coal as a primary fuel supply.

The National Electric Reliability Council (NERC) estimated an increase of coal use by 445 million tons for electricity production during the ten-year period, 1977-1986, reaching a consumption level of 879 million tons in the year 1986 (NERC Report, 1978). Combined with other demands for coal, this would indicate an overall 1986 requirement of about 1,300 million tons. These figures compare with the proposed NEP projections of 779 million tons for the utility sector and a total of 1,265 million tons by 1985.

The NERC estimated an overall increase of electricity generating capability of about 62 percent from 1976 to 1986. In 1986 it will be approximately 796,000 megawatts. In 1976 a total of 191,000 MW was obtained from coal fired boilers;

this will increase to 326,000 MW in 1986.

Coal Availability

Increasing coal production to 1,265 million tons by 1985 will be an exceedingly difficult task. The coal industry has added on the average no more than 10 million tons of new coal mining capacity per year over the past 25 years. The average increase in production from 1960 to 1976 was 2.6 percent per year. Expanding coal production by about 662 million tons over the next ten years would require on the average 66 million tons per year of new production, plus about 15 million tons per year to replace depleted mines (Keystone, 1978).

Investigating the trends in production and productivity in the underground and surface coal mines for the recent past years, it becomes apparent that surface mines are becoming more important in total coal production for the nation. This is mainly true for the western states (Keystone, 1978). Production cost for surface mines is definitely lower than it is for the underground mines (ICF, 1975). The recovery factors for surface mining are generally above 80 percent. If the goals for coal production are to be met, surface mining must play a major role. The high volume reserves of subbituminous coal in the West offers the best, and probably the only, means of expanding production quickly enough to meet the coal needs of the nation.

Among the four major coal producing states in the west, Wyoming and Montana have the lowest coal price and highest production from strip mining (Table 1)

Table 1

1973 Average Value and Productivity

State	Average Value $/T	Productivity Tons/Man Day	Mining Type Strip %
Colorado	7.41	17.46	46
Montana	2.83	132.26	100
Utah	11.91	14.36	0
Wyoming	4.09	55.94	97
U.S. Average	8.53	17.58	

Source: U.S. Bureau of Mines, 1974.

Based upon mining and transportation economics, it is likely that mines in Wyoming and Montana will capture the major share of the utility market in South and Central regions. Announced Wyoming and Montana contracts in Texas total about 25 MTPY for 1985. Wyoming captured about two-thirds of the market in Nebraska and Oklahoma. The Powder River Basin area is the most important coal producing area at this time. This is reflected by the recent behavior of coal buyers. The environmental assessment process for production from coal leases has progressed further at this time in the Powder River Basin than in any other major western coal fields. The Powder

River Basin has an estimated strippable reserve of about 65 billion tons, which is much larger than the Hanna or Green River formation in Wyoming (Keystone, 1978). Coal from the Uinta region of Colorado and Utah is of superior quality; but due to high cost of underground mining and higher transportation cost across the Rockies, it is handicapped compared to the Powder River Basin coal for the utilities east of the rockies.

Total estimated production capacity in Colorado, Wyoming, Utah, and Montana in 1985 is 350 MTPY, as shown in Table 2. Western coal available for export after local consumption is 293.6 MTPY by 1985, of which about 159 MTPY has already been committed. This leaves about 145.5 MTPY as surplus to be distributed among uncommitted destinations. However, according to the NERC report total uncommitted utility demand in 1985 is 61 MTPY.

Demand for Coal

The National Electric Reliability Council (NERC, 1977) has developed the most comprehensive forecasts of fossil fuels requirements on a regional basis. The council has divided the country into nine regions as illustrated in Figure 5. Among these ERCOT (Texas), SPP (Kansas, Oklahoma, Louisiana, Arkansas and a part of Texas), MAPCA (part of Nebraska) and WSCC (including Colorado and Nebraska) are the major regions which

Table 2

1985 Western Coal Production and Distribution - Major States
(thousand tons)

State	1978 Production	1985 Capacity	1985 Utility Demand in State	1985 Utility Imports	1985 Coal for Other Uses	1985 Available for Export	1985 Committed Export	1985 Surplus
Colorado	6,896	29,600	22,000	8,500	4,000	12,000	1,600	10,400
Montana	13,775	75,100	11,000	0	1,000	63,100	39,000	24,100
Utah	5,858	42,500	6,500	0	4,000	32,000	12,500	19,500
Montana	20,703	220,500	22,000	0	12,000	186,500	95,000	91,500

Compiled from Keystone Manual

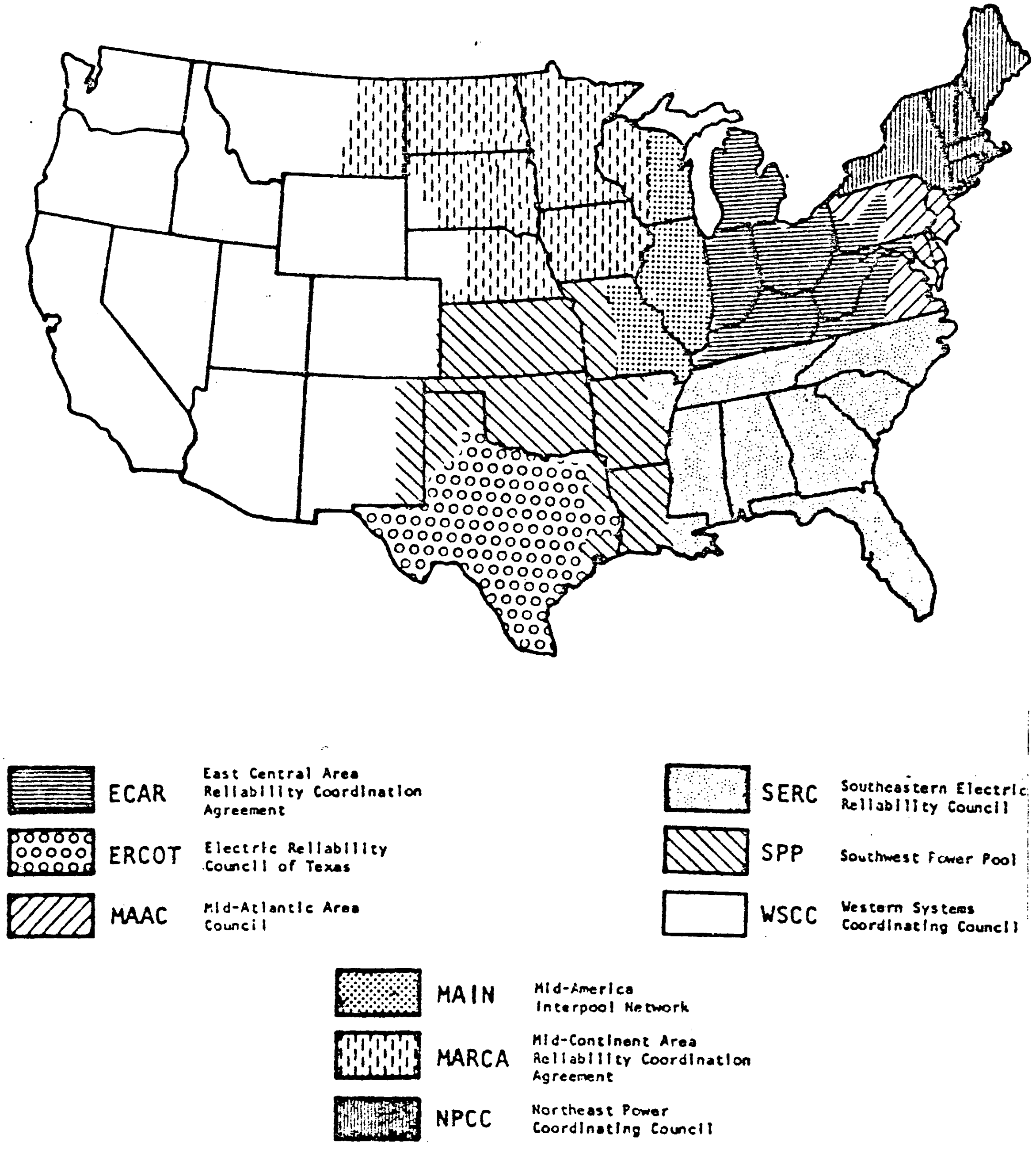


Figure 5: National Electric Reliability Council
Regional Reliability Councils

have the potential to influence the frequency of coal trains running through Colorado. According to the NERC study total coal requirements in the U.S. for the electric utilities will increase slightly over 100 percent (from 404 MTPY to 827 MTPY) during the 10-year period from 1975 to 1985. At the same time demand for western coal will increase by about 270 percent, from 80 to 308 MTPY. Rapid growth in coal field capacity and demand for western coal occurred for SPP, ERCOT, and WSCC.

For the present study more specific information for coal requirements by individual utilities with destination stations are needed rather than the regional coal demand. The coal contracts signed by the utility companies with the mines in Montana, Wyoming, and Colorado and fuel required for the planned power plants in 1985 have been collected through personal communication with these companies and from McGraw-Hill's utility survey (Keystone, 1979). The coal and other fuel requirements for 1985 and the destination points for each utility company is attached in the Appendix A. Except for the SPP region, coal requirements for the other three as estimated by NERC are very close to the requirements established by personal communication. In SPP, however, about 50 MTPY have been estimated to be needed in 1985, but no commitments have yet been made. The reason for this discrepency is that Louisiana and Arkansas are looking into the possibility of using the local lignite deposits.

Though the utility companies have plans and commitments for coal use in 1985, the exact amount will depend upon the state and federal environmental and other FEA regulations delivered price of western coal and economics of using other fuels. To cover such uncertainties three scenarios have been considered in this study.

Scenario #1 - Announced Contracts

The base scenario represents the projected volume of coal for which commitments or plans have already been made between utility companies and the mines. The information on the coal requirements and their destinations have been collected from personal communication and McGraw-Hill's utility survey.

Scenario #2 - Conversion

Under Federal Energy Administration directives, the fossil fuel power plants in the south are requested to convert all of the oil and gas burning plants to coal by 1985. Though it has not been formally approved by Federal Energy Regulatory Commission, a strong possibility exists to encourage the utility companies to make such a conversion due to dwindling supply and high price of oil and gas. The second scenario considers a complete conversion of oil and gas to western coal.

Scenario # 3 - NERC Estimated Growths

As discussed earlier, NERC came up with projections of increase in western and other coal requirements by each council region, based on the region's industrial and residential growth rates. In scenario #3 all uncommitted coal requirements for 1985 are assigned to the western coal. This increases the coal demand in scenario #2 by about 50 MTPY for Arkansas and Lousiana, and about 52 MTPY for Texas Power and Light Company. However, Texas Power and Light may switch to Texas Lignite.

The demand for western coal under three different scenarios by major public utilities is illustrated in Table 3.

B. Transportation Alternatives

The major source of western coal is the Powder River Basin on Wyoming-Montana border. Most of the coal for west, south, and southeast states is committed to be supplied from this area. One other minor source of coal is Green River Region of Southern Wyoming and Northwest Colorado. Except for one power plant in Texas all of Green River coal from Wyoming is shipped to the mideastern states. Coal from Northwestern Colorado is shipped to Texas through Denver.

There are three major railroad routes available for coal shipment from the above regions to their respective destinations in South and Central United States.

Table 3

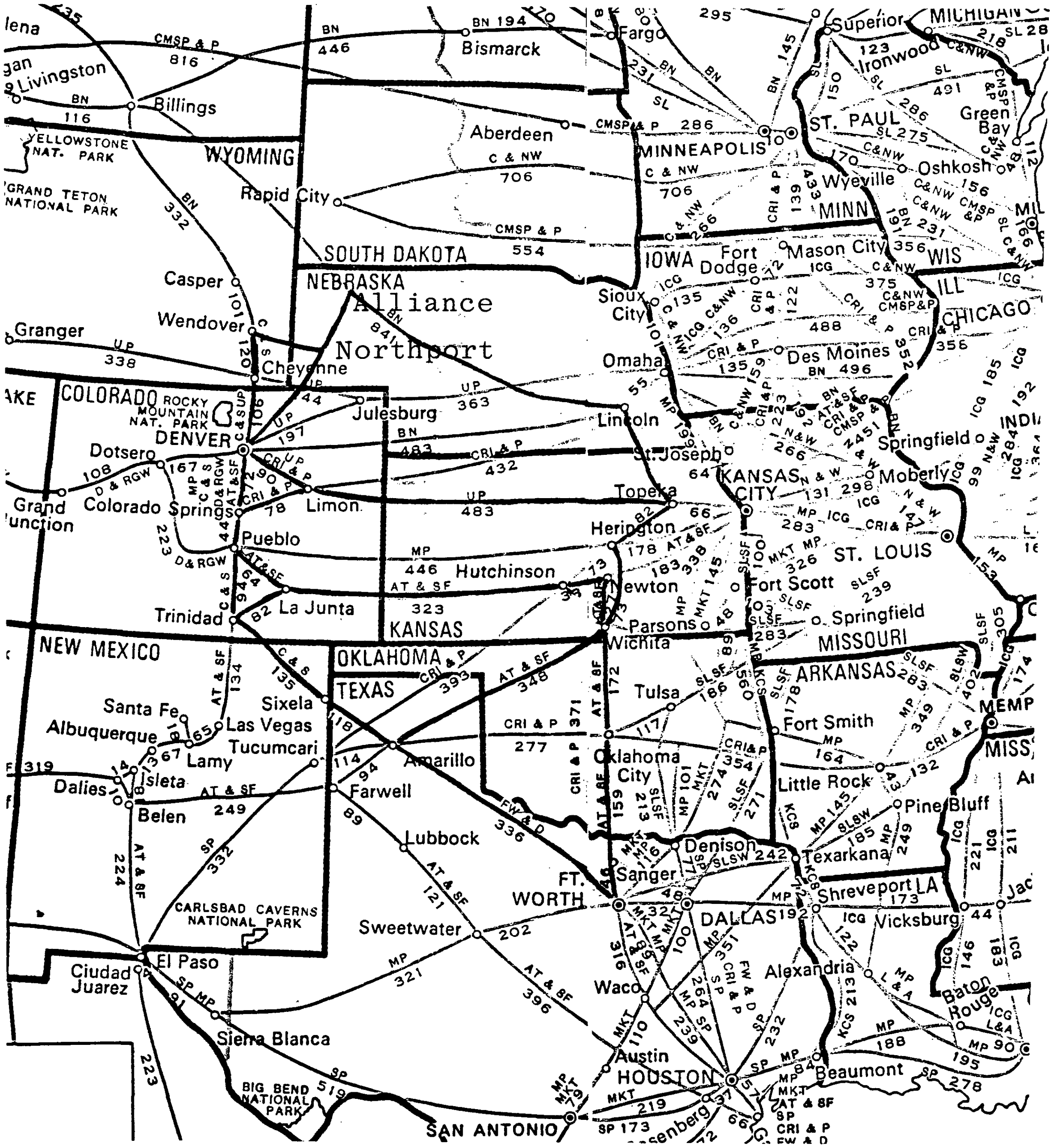
Western Coal Demand for Utility Companies Under three Different Scenarios (in thousands)

State	Utility Company	Coal Demand Under Scenario #1	Coal Demand Under Scenario #2	Coal Demand Under Scenario #3
Nebraska	Fremont Dept. of Utility	253	257	257
	Nebraska Public Power Dist.	5,400	8,113	8,113
	Omaha Public Power Dist.	3,462	3,610	3,610
Kansas	Kansas Power and Light	15,101	17,441	17,441
Oklahoma	Public Service Co. of OK	3,516	13,303	13,303
Texas	City of Austin Water, Light and Power	1,620	2,420	2,420
	Central Power and Light Co.	1,600	8,315	8,315
	Lower Colorado River Auth.	6,000	6,000	6,000
	SW Public Service	4,300	7,415	7,415
	Houston Lighting and Power	10,069	35,609	35,609
	Texas Power and Light Co.	-	-	52,872
	City Public Service Board of San Antonio	3,000	5,073	5,073
Colorado	Public Service Co. of CO	6,185	6,185	6,185
Arkansas	Arkansas Power & Light Co.	7,465	11,115)	98,000
Louisiana	Central Louisiana Electric	1,750	4,998)	
	Louisiana Power and Light	1,935	9,968)	
	Southwestern Electric Power	8,298	10,874)	
Total		79,954	150,696	264,613

One comes directly down from the Powder River Basin to Cheyenne, Wyoming and on to Denver, Pueblo, Trinidad, in Colorado and then to Amarillo, Dallas, and finally to Houston in Texas. The second route runs eastward to Lincoln, Nebraska via Alliance, Nebraska and then southward to Dallas, Texas through Salina, Kansas and Wichita, Oklahoma. The third route runs through Kansas City, Kansas between Lincoln and Dallas. Kansas City route is already overused by transcontinental trains serving various other commodities and is not considered in this study. The first two routes, one through the foothills and the other through great plains will serve as the major alternative rail routes for coal shipment in the near future. These two routes are again crisscrossed by a number of lines and there are a multitude of alternatives available for coal shipment that can be considered.

Map 1 shows the network of main lines in the central USA. The lines marked darker are the main lines capable to handle unit coal trains, and will be considered in this study.

From Alliance, one route goes to Denver and the other to Wichita via Lincoln. The Denver route is owned by the Burlington Northern (BN) railroads and it passes through Brush and Sterling. Alliance-Lincoln track is owned by BN, but the rest up to Wichita by Chicago Rock Islands and Pacific (CRI&P).



Map 1: U.S. Railroad Map showing the probable coal shipment network

From Wendover one track is connected to Alliance via Northport and the other to Denver via Cheyenne. The lines belong to the Colorado and Southern (C&S), a subsidiary of BN and Union Pacific (UP).

From Denver, one line joins with Pueblo, owned by the Denver and Rio Grande Western (D&RGW) and leased to BN. The other goes to Topeka via Limon and belongs to UP. Littleton is on the Denver-Pueblo Route. Another bypass is Denver-Limon-Colorado Springs-Pueblo, which belongs to CRI&P.

Pueblo is connected to Amarillo, Texas through C&S lines. This route follows a mountainous terrain and presents a difficult journey. Another line from Pueblo joins with Wichita through Newton.

Amarillo is connected to Fort Worth through the Fort Worth and Denver railroads, a subsidiary of BN.

Wichita is connected to Ft. Worth through Atchinson, Topeka, and Santa Fe (AT&SF) rail lines. Both the routes meet at Bowie, and then continue to Fort Worth.

Power plants of Houston and San Antonio can be considered in the hinterland of Fort Worth.

A detailed study of the routes, their physical characteristics and description of communities on the way is given in Appendix B.

Destination points for coal shipment to individual utility companies are the major junctions on the main railroad network under consideration from which the shipment is diverted to secondary lines or to a different rail route. These junctions are being presently used for those utility companies as diversion points. Thus Northport is the destination for coal to be used by Fremont Department of Utilities and Nebraska Public Power District. Lincoln is the destination for coal to Omaha Public Power District though the final destination of that coal is Omaha. Similarly, Topeka is the destination for coal to Kansas, Arkansas and Louisiana and Bowie for Dallas, Houston, Austin, San Antonio and Corpus Christi. Table 4 illustrates source and destination of the coal shipment for each utility company considered in this study. Wyoming and Powder River coal can use any of the sources, Wendover and Alliance interchangeably.

C. Transportation Cost

The present study is cost based. All the analysis will be done with costs instead of tariffs or rates and a cost function is developed from available data.

It is important to note the difference between cost and tariff. Tariff is what the recipient of the coal pays to the carrier. It comprises of actual cost plus a normal and monopoly profit. Tariff depends on varied factors like existing

Table 4

Sources and Destinations of Western Coal for Utility Companies

Utility Companies	Source on the Network	Destination on the Network
Fremont Department of Utilities	Wyoming	Northport
Nebraska Public Power District	Powder River	Northport
Omaha Public Power District	Powder River	Lincoln
Kansas Power and Light	Lincoln	Topeka
Public Service Company of Oklahoma	Powder River	Topeka
City of Austin, Water Light & Power	Powder River	Bowie
Central Power and Light Company, Corpus Christi	Denver	Bowie
Lower Colorado River Authority	Powder River	Bowie
Southwestern Public Service, Amarillo	Powder River	Amarillo
Houston Lighting and Power Company	Powder River	Bowie
Texas Power and Light Co., Dallas	Wyoming	Bowie
City Public Service Board of San Antonio	Powder River	Bowie
Public Service Company of Colorado	Powder River	Pueblo
Arkansas Power & Light	Powder River	Topeka
Central Louisiana Electric Co.	Powder River	Topeka
Louisiana Power and Light Co.	Powder River	Topeka
Southwestern Electric Power Co.	Powder River	Topeka

competition, value of the commodity, market of the commodity, ICC intervention, etc.

Cost, however, is the lowest limit of a tariff in the long run. The cost function developed in this study will be verified with specific tariffs. Main advantages of using costs rather than tariffs are that 1) the treatment is consistent with the principles of resource allocation and 2) cost is a good measure of the alternatives.

Generally cost in railroad studies is measured in dollars and output is expressed in ton miles. Ton miles are calculated by multiplying total tons of commodity shipped by the distances in miles over which it is shipped. For each observation the total variable cost is plotted against each ton mile of output. Thus Graph 1, total transportation costs versus ton miles, is generated from the railroad cost data illustrated in Table 5. These data were collected by the Bureau of Mines from the Interstate Commerce Commission (USBM, 1974). They specify the cost of transportation of coal solely through unit trains by Class I railroads throughout the United States. Transportation cost is a function of ton miles and physical and environmental characteristics of the track, so for every ton mile there may be a number of cost data points depending upon the route characteristics or "bottlenecks." Bottlenecks occur because of poor track,

Table 5

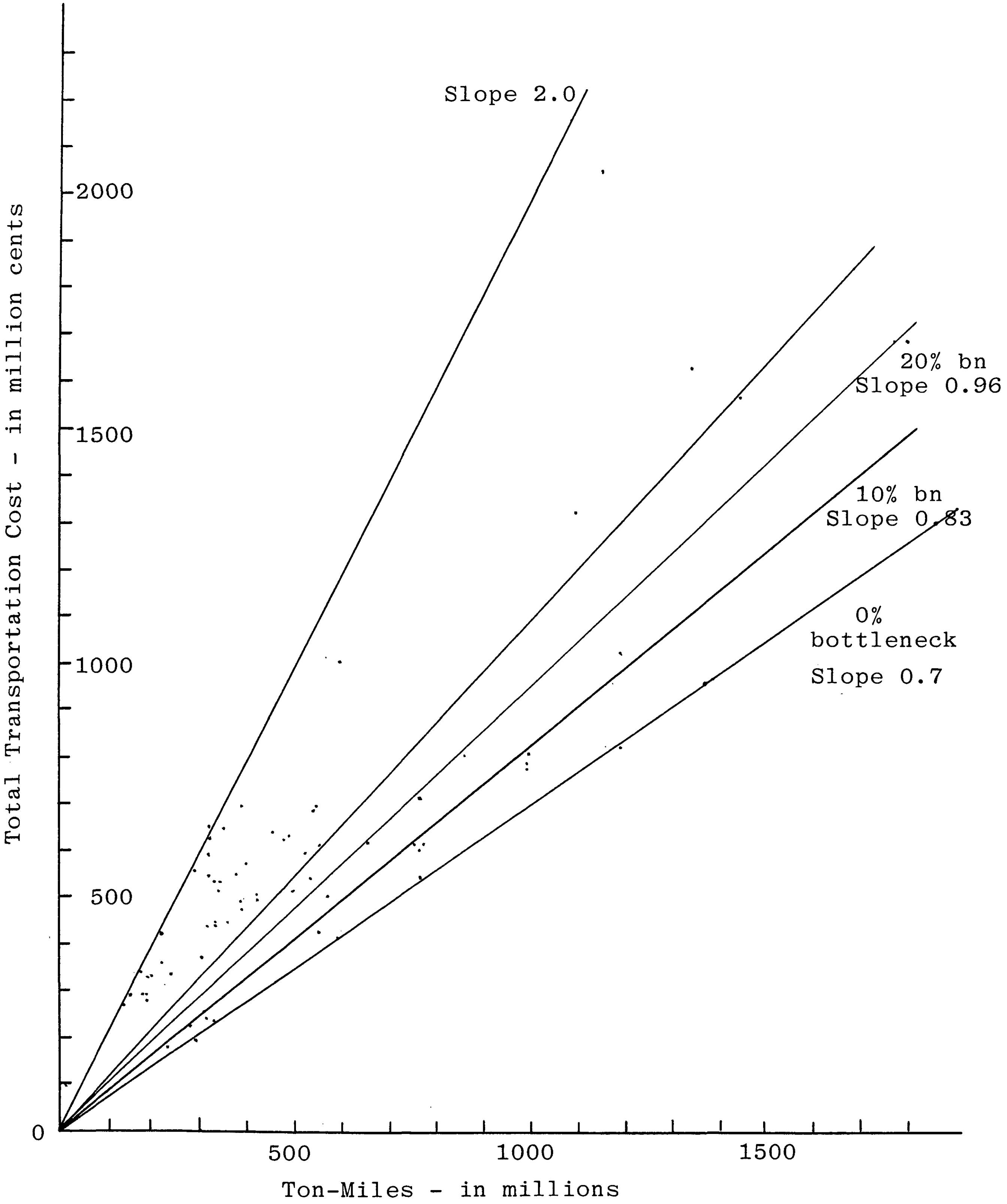
Cost Data for Different Shipping Distance and Tonnage Shipped

Shipping Distance in Miles	Annual Tonnage in Thousands	Ton-Miles in Millions	Total Cost in Million Cents	Cost Cents per Ton-Mile
270	720	194	282	1.45
397	480	190	298	1.57
155	2500	388	701	1.81
188	720	135	280	2.07
387	480	180	298	1.65
187	1800	337	545	1.62
182	1800	328	544	1.66
190	1800	342	544	1.59
152	1800	274	544	1.99
175	1800	315	580	1.84
208	1800	374	577	1.54
187	1800	337	650	1.93
218	1800	392	694	1.77
197	1800	355	546	1.54
187	1000	187	331	1.77
182	1000	182	329	1.81
190	1000	190	331	1.74
175	1000	175	346	1.98
208	1000	208	354	1.70
218	1000	218	414	1.90
197	1000	197	331	1.68
212	1100	233	336	1.44
212	1500	318	426	1.34
271	1100	298	358	1.20
271	1500	406	484	1.19
375	1100	412	384	0.93
375	1500	562	512	0.91
471	1000	471	419	0.89
627	1000	627	470	0.75
438	1000	438	420	0.96
327	850	278	228	0.82
674	500	337	240	0.71
533	1500	800	640	0.80
1600	1500	2400	1896	0.79

Source: Interstate Commerce Commission.

Table 5 (continued)

Shipping Distance in Miles	Annual Tonnage in Thousands	Ton-Miles in Millions	Total Cost in Million Cents	Cost Cents per Ton-Mile
500	1400	700	665	0.95
442	1400	619	427	0.69
300	1000	300	180	0.60
1200	1000	1200	1044	0.87
341	1600	546	556	1.02
215	1500	322	631	1.96
215	1500	322	651	2.02
215	1500	322	558	1.73
357	1000	357	428	1.20
336	1000	336	433	1.29
336	1000	336	507	1.51
412	1000	412	498	1.32
430	1200	516	624	1.21
445	1200	534	598	1.12
438	1200	526	631	1.20
348	4000	1392	2158	1.55
400	4000	1600	2544	1.59
400	4000	1600	2960	1.85
290	4000	1160	1348	1.24
290	4000	1160	1612	1.39
220	4000	880	1452	1.65
341	4000	1364	1650	1.21
244	2500	610	1006	1.65
351	2500	877	1132	1.29
357	1000	357	560	1.57
376	1000	376	451	1.20
336	1000	336	427	1.27
468	1200	562	618	1.10
400	1200	480	643	1.34
985	1000	985	803	0.82
985	1000	985	768	0.78
985	1000	985	778	0.79
800	700	560	431	0.77
789	400	316	243	0.77
789	1000	789	552	0.70
789	1500	1183	817	0.69
789	1750	1381	966	0.70
802	300	241	190	0.79
859	900	773	634	0.82
859	900	773	727	0.94
870	900	783	626	0.80
350	1540	539	695	1.29
312	1750	546	710	1.30
282	1750	494	524	1.06
313	1200	376	488	1.30
196	720	141	282	2.00
330	480	158	299	1.89



Graph 1: Cost/Ton-Mile Relation

difficult terrains or human habitation along the line. As bottlenecks increase, the speed decreases and as a result transportation cost increases (J.A. Ferguson, 1972). All the data points could thus be enveloped within two such "best" and "worst" lines from the origin and the scatter diagram is fan shaped (Graph 1). The lower boundary has a slope of 0.70 and this is interpreted as the lowest possible incremental cost of unit coal train transportation is 0.70 cents per ton mile. On the other hand, the upper boundary has an incremental cost of 2.00 cents per ton mile. The incremental cost for any specific ton mile will lie anywhere between these two extremes depending on the characteristics or "bottlenecks" on the track.

The fanshaped scatter diagram between total cost and ton miles is subdivided into ten groups or equivalently the complete angle between best and worst slopes is partitioned into ten smaller angles. The best slope is assumed to have a zero bottleneck and worst to have a bottleneck of 100 percent. The cost range from 70 cents to 2.00 cents is also subidivided into ten groups of 0.13 cents per ton mile. Thus each smaller angle represents 10 percent change in bottleneck and a change of 13 cents per ton mile incremental cost. So any track with a bottleneck of 0-10 percent has a cost which varies between 70 to 83 cents per ton mile.

To find out incremental cost of unit coal train transportation on a specific track, the bottleneck of the track is first estimated and the cost is then found out from the appropriate subgroup. An average cost per ton mile of that particular subgoup is used as a first approximation and then the two extreme costs for the specified subgroup are used to test the sensitivity of the cost on the result of the study. Incremental cost per ton mile is multiplied by the mileage of the track between junctions to find the unit transportation cost per ton shipped over the specified distance. All costs are as of 1978.

Incremental cost per ton of coal shipped on different routes under consideration in this study is summarized in Table 6. For detailed calculations of bottlenecks and costs see Appendix B.

Testing of Cost Regions

The validity of estimating unit cost by partitioning the cost data points in segments according to the bottlenecks on the specific track is tested in this section with three different sets of data.

a) Confidential Cost Data.

Confidential unit transportation cost data from different railroad companies with specific source, destination,

Table 6

Specific Routes with Bottlenecks and Transportation Cost

From	To	Distance Miles	Bottleneck %	Cost Cent per Ton High	Cost Cent per Ton Low	Cost Cent per Ton Average
Wendover	Cheyenne	120	0-10	99.6	84	91.2
Wendover	Northport	102	0-10	84.7	71.4	77.5
Alliance	Northport	34	0-10	28.2	23.8	25.8
Northport	Denver	219	0-10	181.8	153.3	166.4
Cheyenne	Denver					
	Rt. 1	120	10-20	115.2	99.6	109.2
	Rt. 2	121	0-10	100.4	84.7	92.0
	Rt. 3	95	0-10	78.9	66.5	72.2
Denver	Colo. Spgs.	72	10-20	59.8	50.4	54.7
Denver	Limon	90	0-10	74.7	63.0	68.4
Limon	Colo. Spgs.	78	0-10	64.7	54.0	59.3
Colo. Spgs.	Pueblo	44	0-10	36.5	30.8	33.4
Pueblo	Trinidad	94	20-30	102.5	90.2	96.8

Table 6 (continued)

From	To	Distance Miles	Bottleneck %	Cost Cent per Ton High	Cost Cent per Ton Low	Cost Cent per Ton Average
Pueblo	La Junta	64	0-10	53.1	44.8	48.6
La Junta	Trinidad	82	0-10	68.1	57.4	62.3
La Junta	Wichita	383	0-10			291.1
Alliance	Topeka	535	0-10	444.1	374.5	406.5
Limon	Topeka	483	0-10	338.1	400.9	367.0
Topeka	Wichita	60	10-20	57.6	49.8	54.6
Wichita	Bowie	303	0-10	251.5	212.1	230.3
Wichita	Amarillo	348	0-10	243.6	288.8	264.5
Trinidad	Amarillo	253	10-20	242.9	210.0	230.2
Amarillo	Bowie	268	0-10	222.4	187.6	203.7

route followed and cost per ton were used in this analysis. Sources of these data are internal memos, letters, and cost figures in accounting books from two major railroad companies. These cost data are for internal use and not available for public disclosure.

i) Source - Belle Ayr, Wy.
Destination - Houston, Texas
Distance - 1600 miles

Actual Cost per ton - $12.73

Estimated cost per ton - between $11.20 to $13.28 with mean $12.16

ii) Source - Cordero, WY.
Destination - San Antonio, Texas
Distance - 1820 miles

Actual Cost per ton - $14.42

Estimated cost per ton - between $12.74 to $15.11 with mean $13.83

iii) Source - Black Thunder, Wy.
Destination - Amarillo, Texas
Distance - 943 miles

Actual cost per ton - $7.90

Estimated cost per ton - between $7.82 to $9.05

iv) Source - Colstrip, Mont.
Destination - Minneapolis, MN
Distance - 780 miles

Actual cost per ton - $6.10

Estimated cost per ton - between $5.46 and $6.47

v) Source - Reliance, Wy.
Destination - Hastings, Nb.
Distance - 674 miles

Actual cost per ton - $4.88

Estimated cost per ton - between $4.72 to $5.59

vi) Source - Sinclaire, Wy.
Destination - Westwood, Nb.
Distance - 533 miles

Actual cost per ton - $4.30

Estimated cost per ton - between $3.73 to $4.42.

As these examples show the confidential cost data as collected from different railroad companies are contained within respective angles in Graph 1 as indicated by the bottlenecks.

b) Rate Structures

Rates for coal shipment on any route should be around the upper bound of the transportation cost range. Table 7 shows a comparative study between the cost per ton and the rate per ton for some specific routes. Source of rate

Table 7

Estimated Cost and Rate per ton of Coal with the Source and Destination

Source	Destination	Distance	Bottleneck %	Estimated Cost per Ton High	Estimated Cost per Ton Low	Rate Per Ton
Belle Ayr	Pueblo, Co	596	0-10	$4.95	$4.17	$ 4.85
Belle Ayr	Ft. Gibson, Ok	1118	0-10	$9.28	$7.83	$ 9.80
Belle Ayr	Amarillo, Tx	986	0-10	$8.18	$6.90	$ 7.98
Belle Ayr	Jeffrey, Kn	705	0-10	$5.85	$4.93	$ 5.58
Cordero	Elmendor, Tx	1648	0-10	$11.54	$13.68	$12.42
Black Thunder	Amarillo, Tx	943	10-20	$9.05	$7.82	$ 7.98
Black Thunder	Wallace, Nb	516	0-10	$4.28	$3.61	$ 4.99
Belle Ayr	Flint Creek, Ak	1054	10-20	$10.12	$8.73	$10.65
Colstrip	Minneapolis, MN	780	0-10	$6.47	$5.46	$ 6.98
Black Thunder	Houston, TX	1600	0-10	$13.28	$11.20	$15.60

data are railroad companies, power plants, ICC circulars and the Keystone Coal Manual. Because the adjustments in the rates are slow, the rates are low in some cases in proportion to the costs except where they have been adjusted recently.

c) Engineering Cost Estimates

Michael Rieber and S.L. Soo (1976) did a detailed study on coal transportation costs by different modes. They established unit train costs between two points of production and consumption. The study depended on engineering estimates of individual components of total cost. Utilization of facilities was taken as 80 percent, 100 percent, and 120 percent. They estimated six route specific unit train costs.

Source:		Colstrip, Wy.	Gillette, Wy.
Destinations:		Minneapolis,MN	Houston, Tx
Distance		780 mi	1600 mi
Engineering Estimates:	80%	6.41	14.13
	100%	5.74	12.79
	120%	5.35	12.22
Costs as estimated in this study	high	6.47	13.28
	low	5.46	11.20

For the two routes shared by this study and Rieber and Soos' study, similar costs are evident.

The specific routes of coal shipment for which the unit costs or rates have been collected have bottlenecks from 0 to 20 percent. There is no example for poor cases with higher bottlenecks. This is because all the poor cases are in the eastern United States. However, all except one route segments that are considered in this study have bottlenecks within 20 percent. For the purpose of this study, the estimated costs can be assumed to reasonably represent the actual costs as depicted in the above comparison.

Linearity of Transportation Cost

Total variable cost of coal transportation on a specific track is linearly related to the units of output. In the present study unit of output is considered as one unit train of coal. Total variable cost of shipping two unit trains loaded with coal from Denver to Ft. Worth is twice the cost of one unit train running over the same route between the same source and destination. A unit train was always considered to have one hundred (100) cars of one hundred tons (100) each. Thus the capacity of one unit train is 10,000 tons.

The assumption of linear transportation cost in this study is consistent with the findings of the few published econometric studies of this subject. All the previous studies show that there is very little or almost no evidence of economies of scale in the railroad industry considering the large roads only (Zvi Griliches, 1972). Four are discussed here.

Zvi Griliches (1972) established the linearity between total cost per railroad and total ton miles travelled by individual road. For larger roads with more than 500 miles of track the relationship follows the equation:

$$\underset{(9718)}{C = 1473} + \underset{(0.25)}{6.42\,X}$$

where C = total cost per railroad in mills

X = ton-miles per railroad

Numbers in the bracket are the standard error for the respective parameters.

Correlation coefficient (R^2) is 0.929.

The estimated intercept in the statistical cost function or "the fixed cost" is practically undistinguishable from zero since its estimated standard error is very large. The percentage variable or the ratio between marginal cost and average cost is 99.1 which also established that the fixed cost is virtually zero.

For coal transportation throughout the United States the U.S. Bureau of Mines (1974) developed the linear equation:

$$C = 175.11 + 3.6X$$

where C = total cost in mills

X = ton miles for individual shipment

Correlation coefficient (R^2) is 0.64.

The data were collected from Interstate Commerce Commission reports for the year 1970-71. If cost of coal shipment for a specific region is considered only the estimated statistics are improved. For Montana coal only, shipped mainly to northcentral states, the relation becomes

$$C = 56.97 + 4.39X$$

with correlation coefficient (R^2) or 0.94.

The U.S.B.M. study demonstrates the regional or route specific variances in coal shipment.

Anther study to establish a cost output relationship was done by a MIT group (J. Kneafsay, 1975). They investigated the specification and empirical testing of six alternative forms of a production function for railroad operation. The accepted one is the Cobb-Douglas production function of the form

$$Z = A\ K^{\alpha 1}\ L^{\alpha 2}\ E^{\alpha 3}$$

$$\text{and } \alpha_1 + \alpha_2 + \alpha_3 = k$$

where

Z = output measure

A = intercept term

K = capital intput

L = labor input

E = energy input

$\alpha_1, \alpha_2, \alpha_3$ = elasticities of output with respect to capital, labor, and energy.

This is a homogeneous production function of degree one and hence the cost function is linear.

D. Description of the Network

The network is developed from the railroad route map described in subsection B (Map 1). Wendover and Alliance are the two source nodes, any one of which can serve as terminal for Powder River coal. Denver serves as the source of Northwest Colorado coal, which crosses the Rockies through the Moffat tunnel. Coal from the Green River region and Hanna fields in Wyoming is shipped through a separate route up to Lincoln where it enters the network under consideration. Thus Lincoln serves as a source for Green River coal. Northport and Omaha are the two destination nodes for the coal shipped to Nebraska utility companies; Pueblo for Colorado utilities; Amarillo and Ft. Worth for Texas and Topeka serves as the destination for all the utilities in Kansas, Oklahoma, Arkansas, and Louisiana.

For the purpose of the model the railroad map is converted to a network with major junctions as nodes and alternative routes as arcs. Figure 6 illustrates the network and Table 8 lists the junctions with their corresponding node numbers. In columns 4, 6, and 8 of Table 8, the demand of coal at each destination under three different scenarios are also illustrated. Demand is assumed to be matched by the

Table 8: Important Junctions with Demand and Supply of Coal

No.	Junction	Remark	Scenario #1 Annual Coal Demand (000's)	Scenario #1 Unit Trains per wk.	Scenario #2 Annual Coal Demand (000's)	Scenario #2 Unit Trains per wk.	Scenario #3 Annual Coal Demand (000's)	Scenario #3 Unit Trains per wk.
1		Super Source						
2	Wendover	Source						
3	Alliance	Source						
4	Northport	Destination	5,653	11	8,370	16	8,370	16
5	Cheyenne							
6	Denver	Source	1,600	3	1,600	3	1,600	3
7	Limon							
8	Colo. Spgs.							
9	Pueblo	Destination	6,185	12	6,185	12	6,185	12
10	La Junta							
11	Trinidad							
12	Amarillo	Destination	4,300	9	7,415	15	7,415	15
13	Lincoln	Source	15,101	29	17,441	34	17,441	34
		Destination	3,462	7	3,610	7	3,610	7
14	Topeka	Destination	38,065	74	67,699	130	128,744	248
15	Wichita							
16	Bowie	Destination	22,287	43	57,417	111	110,289	212
17		Super Sink						

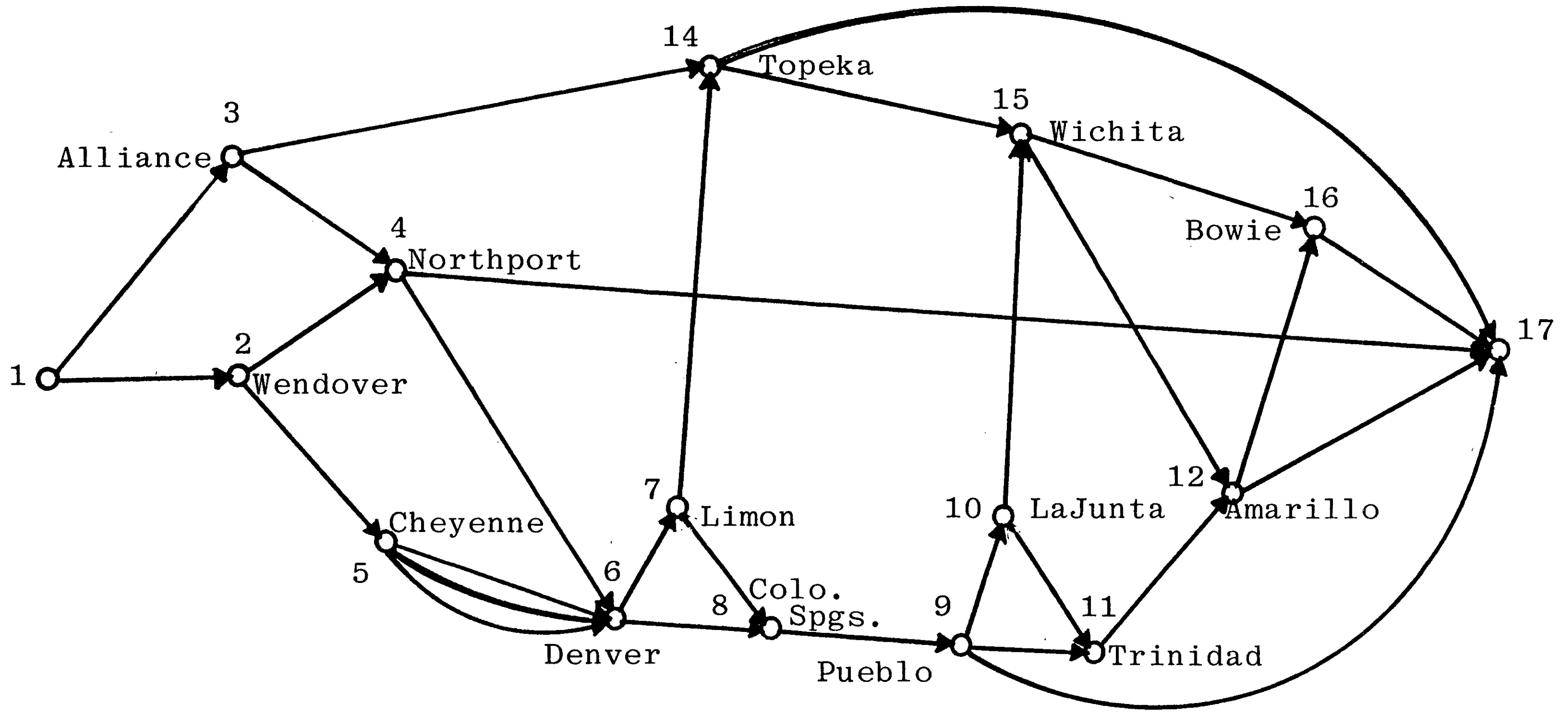


Figure 6: Railroad Network

supply. The table also illustrates the number of unit trains required per week to meet the demand at individual destination (columns 5, 7, and 9). Coal requirements per week is calculated by dividing the annual coal demand by 52 weeks. Number of unit trains per week is the weekly coal requirements divided by 10,000 or capacity of each unit train. The requirement is approximated by the next higher integer number. Unit trains per week shown in the table are loaded only.

Multicommodity Flow

When a flow of commodity in a network must terminate in a preassigned destination from a particular source, it is necessary to distinguish this specific flow from other flows in the network. This class of problems is called the multicommodity network flow problem. In the coal transportation model discussed in this study, Corpus Christie Power Company has commitments to purchase coal from Northwestern Colorado, whereas Public Service Company of Colorado is buying coal for its Pueblo power plants from the Powder River Basin of Wyoming. The Northwest Colorado coal with its source at Denver and preassigned destination at Corpus Christie (Bowie in the network) is considered as a different commodity than the rest of the coal in the circuit.

If coal can be shipped from Wyoming to Ft. Worth through Wichita and Topeka at a lower cost than shipping through

Denver and Pueblo, then in a single commodity cost minimizing network formulation of the present problem,coal for Corpus Christie (destination Bowie) will come from Wyoming and coal from Denver will be shipped to Pueblo. The total cost of coal transportation thus generated will be lower than if it is formulated as a multicommodity transportation problem.

If the two flows are separately upper bounded in each route, then two distinct images of network could be separated and solved individually. But the routes are restricted to capacities common to both the commodities and so cannot be separated out. To solve the problem this author developed an expanded network from the original one. The expanded network is demonstrated in Figure 7. A fictitious network 18, 19, 20, 21, 22 is developed. This network is topologically similar to the part 6, 7, 8, 9, 11, 12, 14, 15, 16, of the main network. Nodes 6, 7, 8, 14 and 16 are represented by the nodes 18, 19, 20, 22, and 21. Arc 6, 7 is represented by the arc 18, 19 7,8 by 19, 20; 7, 14 by 19, 22; 8, 9, 11, 12, 16, by 20, 21; 14, 15, 16 by 22, 21. Unit transportation cost on the fictitious arcs are same as the costs on the original arc or the sum of unit costs on combination of arcs. Mutually common upper bound restrictions are shared by both topologically similar arcs. Arcs 9, 10; 10, 11; 10, 15, and 15, 12 are redundant in the fictitious network.

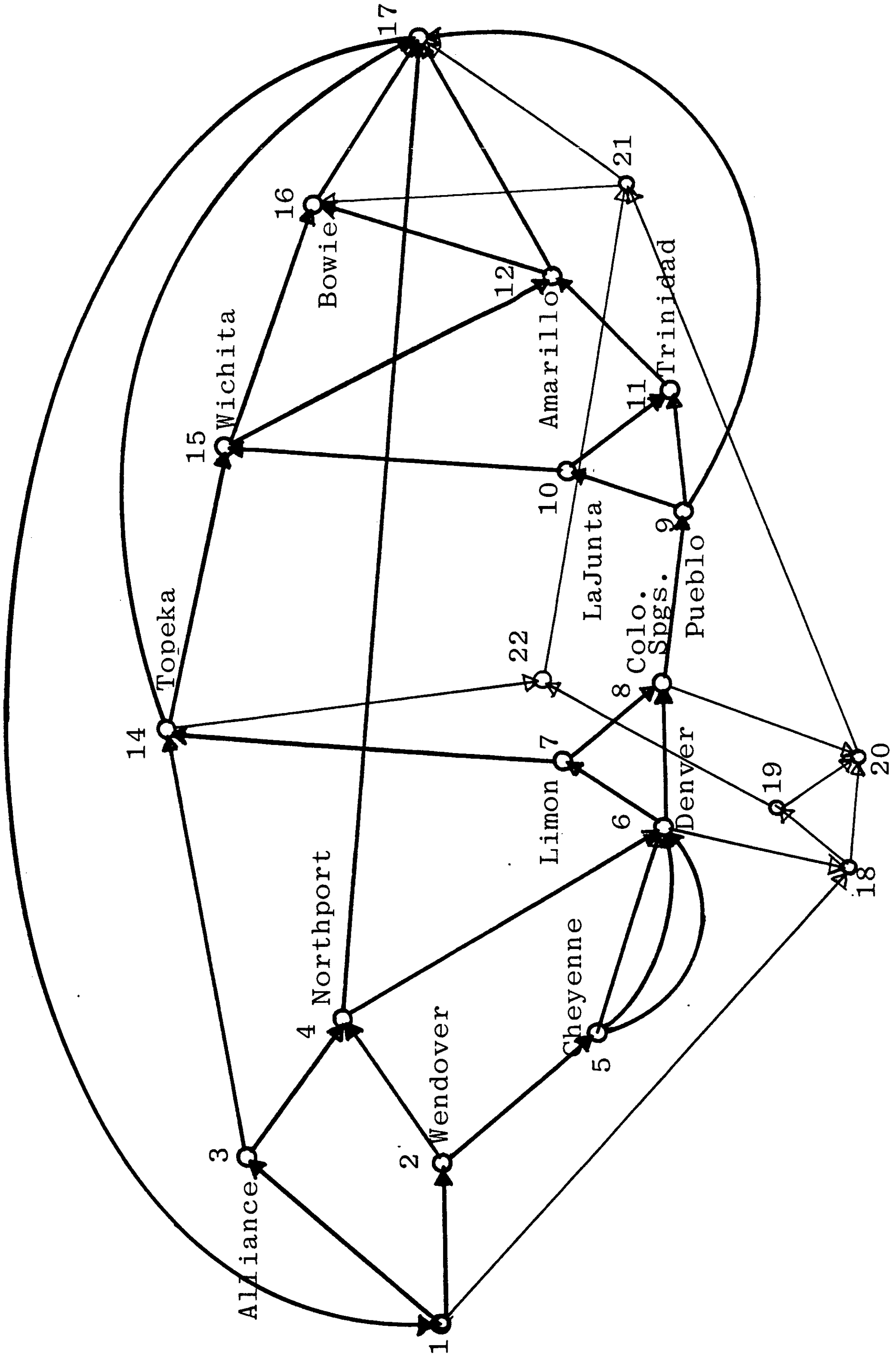


Figure 7: Railroad Network with Expansion and Fictitious Nodes

Arcs 6, 18; 8, 20; 14,22; 19, 22 and 21, 16 are connected with directed arcs in those orders. Lower bonds on these arcs are zero; upper bounds infinity and unit costs zero. These arcs serve as passages to overflow from the original network to the fictitious network if any extra capacities are left unused in the fictitious network.

Similarly, Lincoln is the destination for coal shipped to Omaha and also the source for coal to Arkansas going via Topeka. Because there is no alternative route from Lincoln to Topeka, the coal to Arkansas is not considered in the network problem, instead the upperbound on Alliance-Topeka line is decreased by the required number of coal trains going to Arkansas.

The complete network with units of lower bounds and upper bounds for Scenario #1 and mean unit cost for the base case are listed in Table 9. Nodes 1 and 17 are super source and supersink, respectively. Arcs 1, 3 and 1,2 are supplying the total demand of Wyoming coal. Arc 1, 18 represents Colorado coal and has an upperbound of 6 loaded and empty trains. Maximum number of coal trains that can run on a specific route is technically very high. Keeping in mind the effect on communities the upperbound on each route is assumed to be one train per hour or 84 loaded and 84 empty trains per week. Upper bound on Denver-Colorado Springs route on which lies the city of Littleton is increased by increments of 7 coal trains per week.

CHAPTER IV

RESULTS AND CONCLUSIONS

The transportation network has been developed in the previous chapter. A schematic diagram of the railroad routes, the sources, the destinations and intermediate junctions was illustrated in Figure 7. The diagram also includes the fictitious nodes and arcs and the expansion of the network. Table 9 shows a complete listing of arcs, nodes, upper bounds, and the unit cost of transportation. Supplies from the sources are considered very large and demands for individual power plants are according to their projections under three different scenarios. Upper bound on track capacity has been considered to be twelve loaded trains per day or eighty four per week. This translates to a frequency of trains, loaded or empty, as one train every hour. On the Littleton route the frequency of loaded trains is increased by an increment of seven trains per week for each run of the program. An out-of-kilter algorithm was used to solve the transportation network. Results are discussed separately for three different scenarios.

Scenario #1

The demand for coal by individual power plant under this scenario is the signed contracts for coal supply between the

Table 9

Input to the Network with Source and Destinations

From I	To J	UB	LB	COST	
1	2	500	0	0	
1	3	500	0	0	
1	18	3	3	0	- Source Denver
2	4	84	0	775	
2	5	84	0	912	
3	4	84	0	258	
4	6	84	0	1664	
4	17	11	11	0	- Destination Northport
5	6	84	0	1092	
5	6	84	0	920	
5	6	84	0	722	
6	18	84	0	0	
6	7	42	0	684	
6	8	21	0	547	
18	19	42	0	684	
18	20	0	0	547	
7	8	42	0	593	
7	14	42	0	2670	
19	20	42	0	592	
20	21	42	0	5641	
8	9	42	0	334	
8	20	84	0	0	
3	14	84	0	4065	
9	10	84	0	486	
9	11	42	0	968	
9	17	12	12	0	- Destination Pueblo
10	11	84	0	623	
10	15	84	0	2911	
11	12	42	0	2302	
12	16	84	0	2037	
12	17	9	9	0	- Destination Amarillo
14	15	42	0	546	
14	17	52	52	0	- Destination Topeka
14	22	84	0	0	
22	21	42	0	2849	
15	12	42	0	2645	
15	16	84	0	2303	
23	21	42	0	2037	
16	17	43	43	0	- Destination Bowie
21	16	84	0	0	
21	17	3	3	0	- Destination Bowie from Denver
17	1	1000	0	0	

plant and the coal company. This scenario is further divided into two cases. Upper bounds of all the routes are set to 84 loaded trains per week for Case 1. In Case 2 the route between Alliance and Topeka (arc 3-14) is assumed to have an unrestricted upper bound.

Case 1

The upper bound on individual routes of the network is considered to be 84 loaded trains on topographically similar arcs. A series of programs was run with an increment of seven trains on Littleton track until the cost stabilizes. A typical flow pattern on the railroad network is illustrated in Table 10. Two routes have been fully utilized in this particular case. Denver-Colorado Springs route has utilized its upper bound of seven trains and Alliance-Topeka has reached its upper bound of 62 trains. As the upper bound on Littleton track (Denver-Colo. Spgs.) is relaxed with an increment of seven trains per week, the flow going through to Denver-Limon-Colo. Spgs. is diverted through Littleton and the cost stabilizes at a flow of 57 trains through Littleton route. Table 11 shows increasing frequency of trains on Littleton track and corresponding total shipment cost per week decreasing gradually. For every increment of seven loaded trains on Littleton, decrease in the total shipment cost per week to meet the power plants demands is $51,100. The cost stabilizes at

Table 10

Allocation of Coal Trains on Different Route
under Scenario 1, Case 1

From	To	Flow
Wendover	Cheyenne	54
Alliance	Northport	11
Cheyenne	Denver	54
Denver	Limon	50
Denver	Colo. Spgs.	7 (Littleton)
Limon	Colo. Spgs.	50
Colo. Spgs.	Pueblo	57
Pueblo	Trinidad	45
Amarillo	Bowie	36
Alliance	Topeka	62
Topeka	Wichita	10
Wichita	Bowie	10

Table 11

Frequency of Trains Through Littleton and Associated Total Cost of Coal Shipment

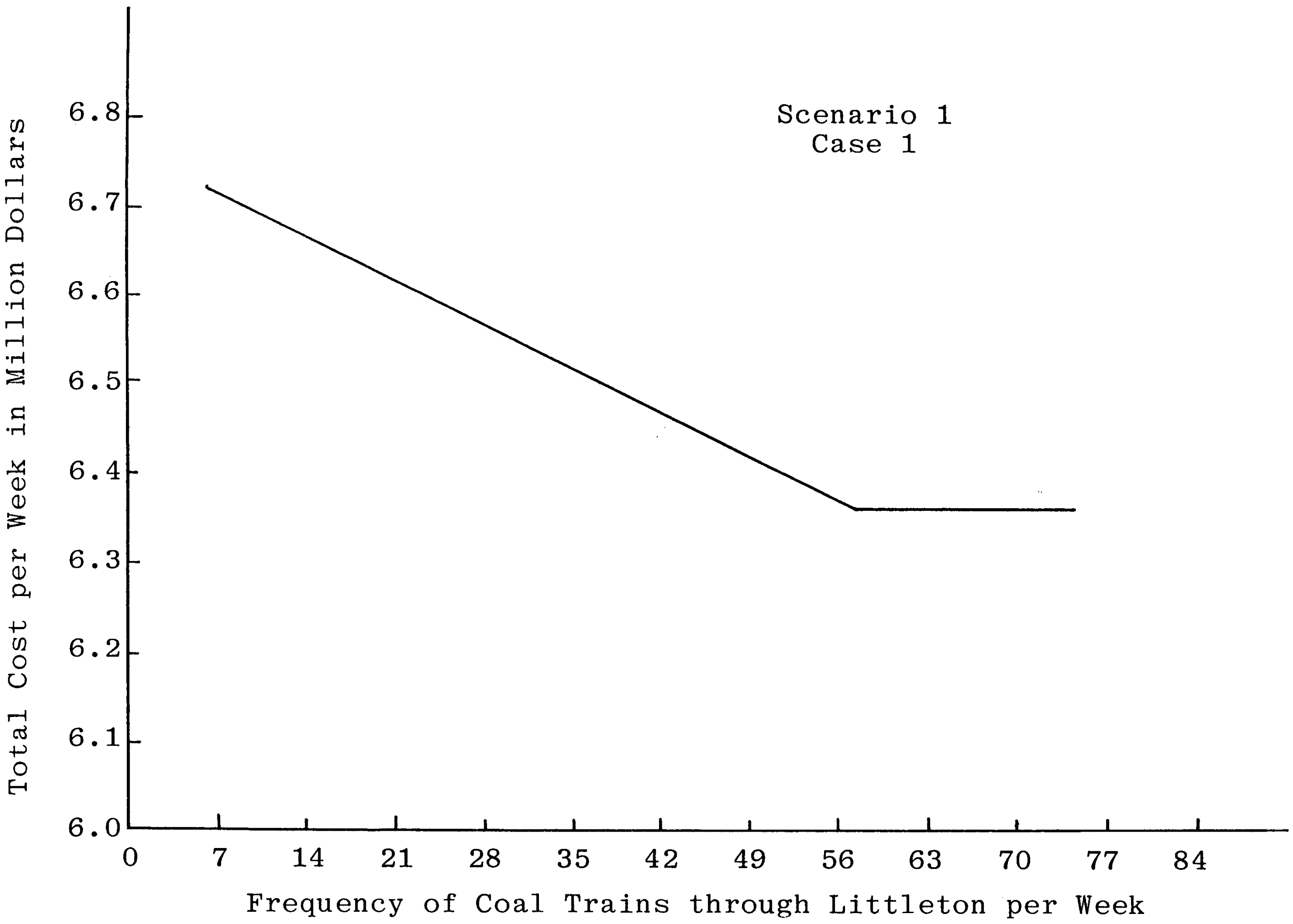
Scenario 2, Case 1

Upper Bound on Littleton route permitted	Actual Frequency of trains on Littleton route	Total Cost of shipment per week (in dollars)
7	7	6726820
14	14	6675720
21	21	6624620
28	28	6573520
35	35	6522420
42	42	6471320
49	49	6420220
70	57	6361820

a total of $6,361,820 when the frequency of trains through Littleton is 57 trains per week. Graph 2 illustrates the drop in total shipment cost until it is stabilized. This is the most efficient or least-cost allocation of coal trains from Wyoming to its market. Under this condition one train, loaded or empty, per one and one-half hours will run through Littleton. If, however, Littleton people would like to decrease the frequency of the trains further, a penalty of 51,100 dollars is due for a decrease of two trains per day. Under such a case the trains will be diverted through Limon-Colorado Springs route. The final decision of train frequency rests upon the interested parties like the Littleton people, railroad companies, etc. The crux of the decision lies in the point whether pushing two more trains through Littleton is worth 51,100 dollars. Under extreme conditions of no decision, it should be considered that whether the extra money saved by running more trains through Littleton can be utilized to build a viaduct or a manned crossing in Littleton, as the case may be.

Case #2

In Case 2 the capacity on the arc 3,14 or route from Alliance to Topeka is unrestricted. Since this route is designed to handle heavy traffic and has less community restriction, the assumption for Case 2 is not unrealistic. Table 12



Graph 2: Frequency of Coal Trains and Total Shipment Cost

shows the frequency of coal train on different routes under Case 2 assumptions when Littleton route has a restriction of seven trains. The Alliance-Topeka route has a frequency of 95 loaded trains per week. As the frequency of trains through Littleton is increased with an increment of seven trains per week, they are diverted from Denver-Limon-Colo. Springs route. At a maximum of 24 loader trains the cost stabilizes. Table 13 shows the effect on cost due to changing frequency of trains through Littleton. The minimum total cost is $6,123,290 per week and increment of cost is $51,100 for every seven loaded trains per week. Graph 3 illustrates the drop in cost with increase of trains through Littleton. A maximum of 24 loaded trains per week or one train, loaded or empty, per three and one-half hours is allocated through Littleton on the average.

Comparing between the results of Case 1 and 2, it becomes apparent that the coal trains assigned to Bowie or South Texas power plants should be assigned to the route through Nebraska and Kansas whereas the coal trains assigned to power plants in Colorado and West Texas with termination as far as Amarillo should be assigned to Foothills route. Under similar conditions the difference between the total costs of coal shipment per week for the Case 1 and 2 is $479,430. So a better allocation of funds should be to put the money to improve Alliance-Topeka route than to improve the Littleton route.

Table 12

Allocation of Coal Trains on Different Route Under Scenario 1, Case 2

From	To	Flow per Week
Wendover	Cheyenne	21
Alliance	Northport	11
Cheyenne	Denver	21
Denver	Limon	17
Denver	Colo. Springs	7
Limon	Colo. Springs	17
Colo. Springs	Pueblo	24
Pueblo	Trinidad	9
Trinidad	Amarillo	9
Amarillo	Bowie	3
Alliance	Topeka	95
Topeka	Wichita	43
Wichita	Bowie	43

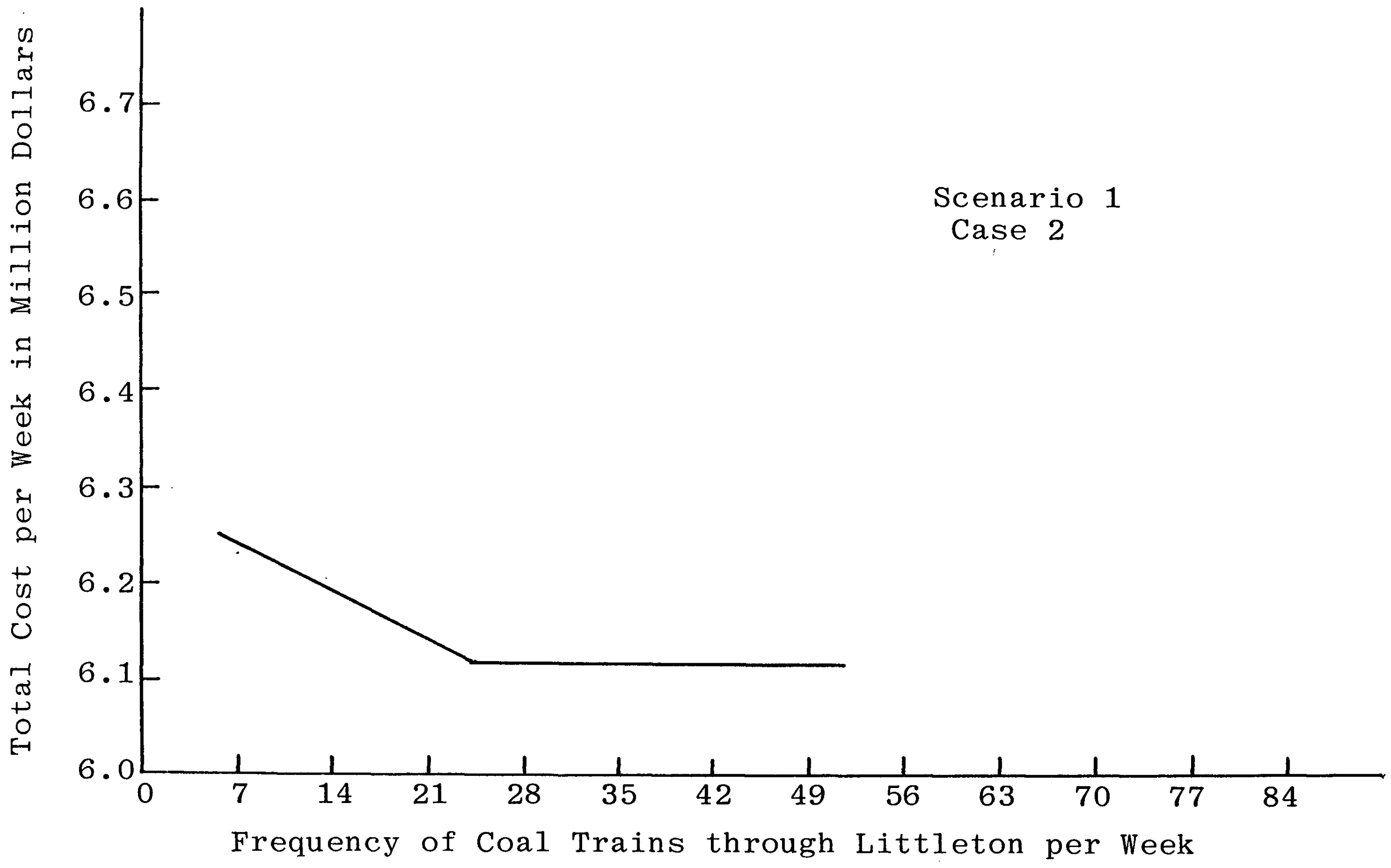
Table 13

Frequency of Trains Through Littleton and Associated Total Cost of Coal Shipment

Scenario 1

Case 2

Upper Ground Permitted on Littleton Route	Actual Frequency of Trains through Littleton	Total Cost of Shipment per week (in dollars)	Frequency of Trains on Alliance-Topeka Route
7	7	6,247,390	95
14	14	6,196,290	95
21	21	6,145,190	95
70	24	6,123,290	95



Graph 3: Frequency of Coal Trains and Total Shipment Cost

Scenario #2

It is assumed in scenario 2 that the total power used in 1985 by the respective power plant considered in this study will be generated from Powder River coal. This probably is the maximum amount of coal that may be shipped from Powder River Basin in the near future. This is a realistic assumption for the late eighties. The same network as used in the scenario 1 is also valid. The only change is the demand of coal at individual demand points. Table 14 illustrates the source and sink nodes, upper bounds, cost and the final destination with the demand. As before the upper bound on Littleton route has been increased by an increment of seven until the cost stabilizes. An out-of-kilter algorithm was used to run the series of programs with changing upper bound on the Littleton route. The minimum cost is $13,503,120 per week to ship the total coal supply. The cost is stabilized at a frequency of 57 loaded trains per week or two every three hours through Littleton. Graph 4 shows the decrease in total transportation cost on the upperbound on Littleton route is relaxed. The frequency of trains through other routes is illustrated in Table 15. It should be noted that the route between Topeka and Bowie reached the upper bound limit of 84 trains per week. As before as the restriction on Littleton route is relaxed, the trains through Denver-Limon-Colorado

Table 14

Input to the Network Under Scenario 2

From I	To J	UB	LB	COST	
1	2	500	0	0	
1	3	500	0	0	
1	18	3	3	0	
2	4	84	0	775	
2	5	84	0	912	
3	4	84	0	258	
4	6	84	0	1664	
4	17	16	16	0	- Destination Northport
5	6	84	0	1092	
5	6	84	0	920	
5	6	84	0	722	
6	18	84	0	0	
6	7	42	0	684	
6	8	28	0	547	
18	19	42	0	684	
18	20	0	0	547	
7	8	42	0	593	
7	14	42	0	3670	
19	20	42	0	593	
19	22	42	0	3670	
8	9	42	0	334	
8	20	84	0	0	
20	21	42	0	5641	
9	10	84	0	486	
9	11	42	0	968	
9	17	12	12	0	- Destination Pueblo
10	11	84	0	623	
10	15	84	0	2911	
11	12	12	0	2302	
12	16	84	0	2037	
12	17	15	15	0	- Destination Amarillo
3	14	500	0	4065	
14	15	42	0	546	
14	17	103	103	0	- Destination Topeka
14	22	84	0	0	
22	21	42	0	2849	
15	12	42	0	2645	
15	16	84	0	2303	
16	17	111	111	0	- Destination Bowie
21	16	84	0	0	
21	17	3	3	0	- Destination Bowie from Denver
17	1	1000	0	0	

Table 15

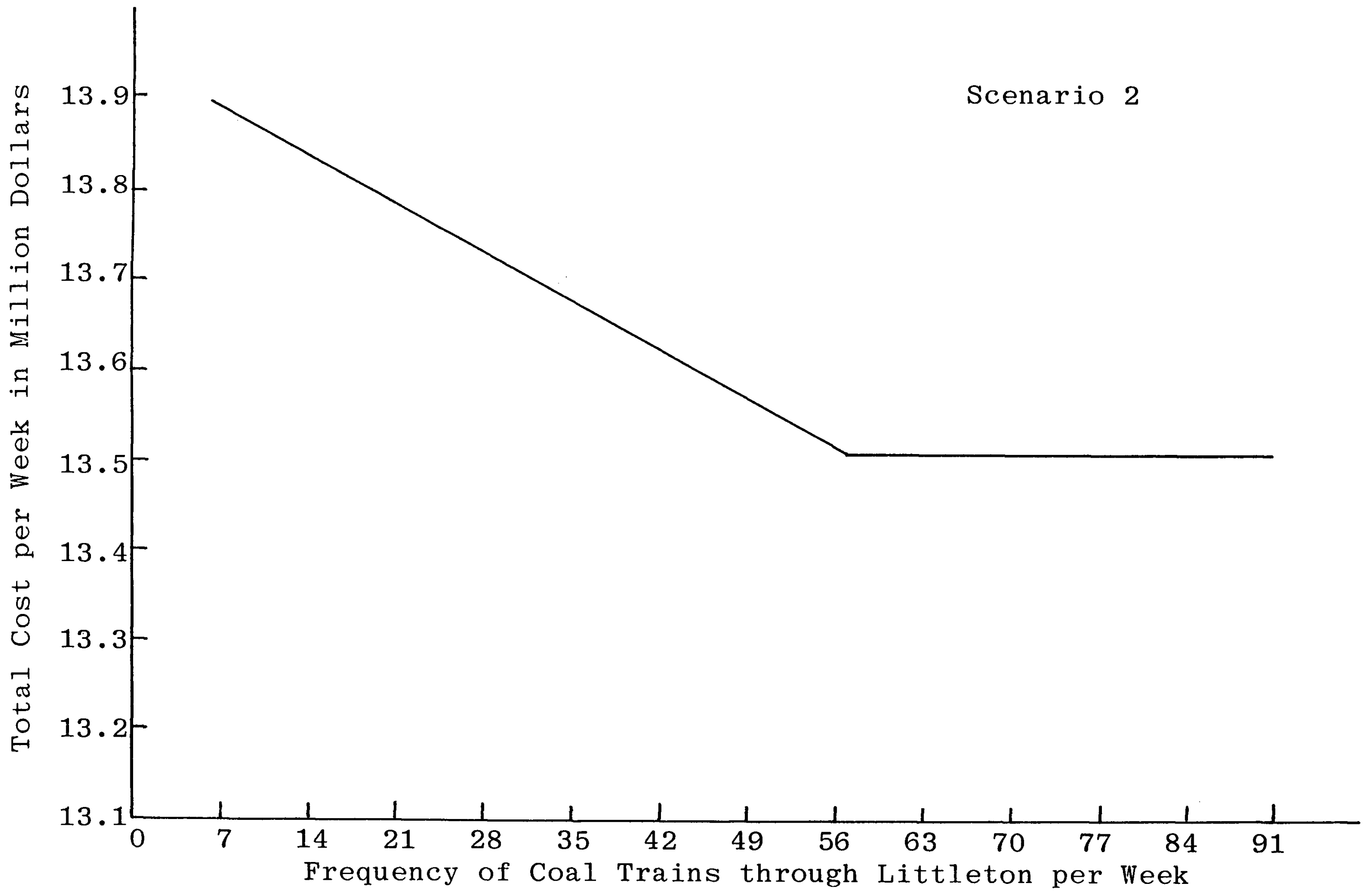
Allocation of Coal Trains on Different Route Under Scenario 2

From	To	Frequency per Week	
Wendover	Cheyenne	54	
Cheyenne	Denver	54	
Alliance	Topeka	187	
Alliance	Northport	16	
Denver	Colorado Springs	14	(Littleton)
Denver	Limon	43	
Limon	Colorado Springs	43	
Colorado Springs	Pueblo	57	
Pueblo	Trinidad	45	
Trinidad	Amarillo	45	
Amarillo	Bowie	39	
Topeka	Wichita	84	
Wichita	Bowie	84	

Table 16

Frequency of Trains Through Littleton and Associated Total Cost of Shipment

Frequency Permitted on Littleton	Actual Frequency on Littleton	Total Shipment Cost (dollars/week)
7	7	13,868,120
14	14	13,817,020
21	21	13,765,920
28	28	13,714,820
35	35	13,663,720
42	42	13,612,620
49	49	13,561,520
56	56	13,510,420
84	57	13,503,120



Graph 4: Frequency of Coal Trains and Total Shipment Cost

Table 17

Allocation of Coal Trains on Different Routes Under Scenario 2, Case 2

From	To	Frequency
Wendover	Cheyenne	27
Alliance	Northport	16
Cheyenne	Denver	27
Alliance	Topeka	214
Denver	Colo. Springs	30 (Littleton)
Denver	Limon	0
Limon	Colo. Springs	0
Colo. Springs	Pueblo	30
Pueblo	Trinidad	18
Trinidad	Amarillo	18
Amarillo	Bowie	3
Topeka	Wichita	111
Wichita	Bowie	111

Total Cost =$13,257,960

Springs are diverted through Littleton. For an increase in every seven loaded trains through Littleton the total cost is decreased by $51,100 until the cost is stabilized. Table 16 illustrates the changes in total shipment cost with different restrictions on Littleton route.

In Scenario 2, Case 2, the upper bound on Topeka-Bowie route is relaxed to investigate the importance of that specific route. Under such conditions the maximum frequency of trains per week through Littleton is 30 and total optimum cost is $13,257,960. Table 17 illustrates the frequency of loaded trains under the minimum cost condition.

A comparison between Cases 1 and 2 for Scenario 2 illustrates a difference of cost of $340,060 between these two cases under a similar upper bound condition on Littleton.

Scenario #3

Scenario 3 follows NERC projections for 1985. The major contribution of this projection is a higher electricity demand in Texas, Louisiana, and Arkansas. In this scenario, it has been assumed that the extra electricity demand will also be supplied by Western coal mainly from Powder River Basin. This scenario is not a likely possibility in this century. However, this illustrates an extreme case and the transportation problems associated with it show the limitations of railroads.

The major difference between this scenario and the last one is the extra demand at the destinations of Topeka and Bowie. As a result it does not affect the Foothills route as long as the Nebraska-Kansas route can handle the extra shipment. This route has been assumed to have a large capacity and the results of the program is shown in Table 18. Littleton route has a maximum frequency of 30 loaded trains per week. The Alliance-Topeka route has a frequency of 460 loaded trains per week or about six trains, loaded or empty, per hour. This is physically impossible and so either more trains have to be diverted through the Littleton route or some other route. Because this is not a very likely scenario, the problem has not been pursued any further. See conclusions for more discussion on validity of different scenarios.

Sensitivity Analysis

So long as the average cost of transportation has been used on individual arc, the sensitivity analysis defines the range of cost on each arc within which the cost may vary without affecting the optimum flow in the network. It will be checked whether this range covers the cost region between low and high lines as explained in Chapter III. In the common textbooks on network flow, no method for sensitivity analysis has been suggested. Available literature is generally case specific. So this author has devised a method which is simple and will serve the purpose of this thesis.

Table 18

Allocation of Coal Trains Through Different Routes Under Scenario 3

From	To	Frequency of Loaded Trains per Week
Wendover	Cheyenne	27
Alliance	Northport	27
Alliance	Northport	16
Alliance	Topeka	460
Denver	Colorado Springs	30
Colo. Springs	Pueblo	30
Pueblo	Trinidad	18
Trinidad	Amarillo	18
Amarillo	Bowie	3
Topeka	Wichita	212
Wichita	Bowie	212

As explained in Chapter II, the optimality conditions for complimentary slackness for all arcs (ij) are:

$$c_{ij} + \pi_i - \pi_j > 0 \text{ implies } f_{ij} = L_{ij} \quad (11)$$

$$c_{ij} + \pi_i - \pi_j < 0 \text{ implies } f_{ij} = F_{ij} \quad (12)$$

$$c_{ij} + \pi_i - \pi_j = 0 \text{ implies } L_{ij} \leq f_{ij} \leq F_{ij} \quad (13)$$

where c_{ij} = unit transportation cost from i to j

f_{ij} = flow from i to j

F_{ij} = upper bound on arc i, j

L_{ij} = Lower bound on arc i, j

π_i = Dual variable for conservation of flow on node i

π_j = Dual variable for conservation of flow on node j

Let us assume a flow of f_{ab} on a specific arc (a, b) in the network. Under optimality conditions,

$$c_{ab} + \pi_a - \pi_b > 0$$

will imply $f_{ab} = L_{ab}$.

The flows in the network will not be altered so long as

$$c_{ab} > -\pi_a + \pi_b$$

In other words, c_{ab} can be decreased to $(-\pi_a + \pi_b + \Delta)$ where Δ is a small positive quantity without affecting any flow in the network.

If the cost on a specific arc (a,b) is increased, the flow on that arc is decreased, but because flow has already reached the lower bound, the cost can be increased infinitely without affecting the flows in the network.

Hence bounds on c_{ab} for the arc (a,b) is

$$(-\pi_a + \pi_b) < c_{ab} < \infty$$

Similarly,

$$c_{ab} + \pi_a - \pi_b < 0$$

$$\text{implies } f_{ab} = F_{ab}$$

c_{ab} can be increased to $(-\pi_a + \pi_b - \Delta)$ without affecting any flow in the network.

Effect on decreasing cost on the arc (a, b) is an increase of flow through (a, b), but because the flow has already reached to upper bound, the cost can be decreased to zero without affecting any flow through the network.

Hence bounds on c_{ab} for the arc (a,b) is

$$0 \leq c_{ab} < (-\pi_a + \pi_b)$$

The third condition for optimality is

$$c_{ij} + \pi_i - \pi_j = 0 \text{ implying } L_{ij} \leq f_{ij} \leq F_{ij}$$

Because of the equality constraint the above tactics are not applicable here. Instead, two new problems are formulated to establish the sensitivity range of the cost.

Assume the flow on arc (a, b) is f_{ab} and

$$L_{ab} < f_{ab} < F_{ab}$$

A new problem is devised such that the new lower bound on arc (a, b) is

$$L'_{ab} = f_{ab} + \Delta$$

The solution of the problem will result in a new flow on arc (a, b) such as

$$f'_{ab} = L'_{ab} = f_{ab} + \Delta$$

The new complimentary slackness will show

$$c_{ab} + \pi'_a - \pi'_b > 0$$

where π'_a and π'_b are new dual variables and new lowest bound on the cost is

$$-\pi'_a + \pi'_b < c_{ab}$$

Similarly a second new problem is devised with a new upper bound on the arc (a, b) as

$$F''_{ab} = f_{ab} - \Delta$$

The solution of the problem will change the flows in the network and new flow on arc (a, b) will be

$$f''_{ab} = F''_{ab} = f_{ab} - \Delta$$

The new complimentary slackness will show

$$c_{ab} + \pi''_a - \pi''_b < 0$$

where π''_a and π''_b are dual variables of the second new problem.

The new upper bound on the cost is

$$c_{ab} < -\pi''_a + \pi''_b$$

In the original problem because

$$f''_{ab} < f_{ab} < f'_{ab}$$

The sensitivity on cost c_{ab} will also lie within the cost regions of the two new problems, or

$$-\pi'_a + \pi'_b < c_{ab} < -\pi''_a + \pi''_b$$

This method is not a generalized method and may not be successful when the solution is non-unique.

The two most important routes or arcs in the original network of Scenario 1 are Alliance-Topeka route or arc (3,14) and Denver-Colorado Springs route, or arc (6,8). Sensitivity on cost has been tested on these two arcs separately when the flow is in between the lower and upper bounds (Case 2).

Sensitivity on Arc (3,14)

The scenario 1, Case 2 problem has the lower and upper bounds and cost on arc (3,14) as

$L_{3,14} = 0$ unit trains/week

$F_{3,14} = 500$ unit trains/week

$c_{3,14} = 40650$ dollars/unit train

The flow by solving the original problem with an upper bound on Denver-Colorado Springs arc as 70 is

$$f_{3,14} = 95$$

A new problem is developed with an upper bound on arc (3,14) as 94. The bounds and cost on arc (3,14) are now

$L_{3,14} = 0$ arc now

$F_{3,14} = 94$ unit trains/week

$c_{3,14} = 40,650$ dollars/unit train

By solving the problem the flow on (3,14) is found to bound at 94 trains per week and

$$\pi_3 = 69180$$

$$\pi_{14} = 126,210$$

$$\pi_3 - \pi_{14} = 69180 - 126210 = - 57030$$

$$40,650 + (69,180 - 126,210) < 0 \text{ implying } f_{3,14} = F_{3,14} = 94$$

The flows in the network will remain unaltered and $f_{3,14}$ will be 94 as long as

$$c_{3,14} < 57,030$$

In the second new problem the upper bound on (3,14) is changed to 500 and the lower bound to (95+1) or 96. In the solution of this problem

$$\pi_3 = 4,881$$

$$\pi_{14} = 7,457$$

$$\pi_3 - \pi_{14} = 4,881 - 7,457 = -2,594$$

The lower bound on the cost is 2,594. The sensitivity on the cost on arc (3,14) of the original problem thus becomes

$$2,594 < c_{3,14} < 57,030$$

The low and high ranges in unit transportation cost on the Alliance-Topeka route or arc (3,14) is 37,450 and 44,410 dollars per unit train as shown in Table 6, Chapter III. So the flow in the network will not change even if the cost on the route changes within low and high range.

Similarly for the Denver-Colorado Springs route or arc (6,8) the dual variables of the two new problems are

$$\pi'_6 = 128,170 \qquad c_{68} = 5,740$$

$$\pi'_8 = 117,160$$

$$\pi'_6 - \pi'_8 = 11,010$$

$$5,740 + 11,010 > 0 \text{ implying } f'_{68} = L'_{68}$$

and

$$\pi''_6 = 85,520$$

$$\pi''_8 = 98,290$$

$$\pi''_6 - \pi''_8 = 85,520 - 98,290 = -12,770$$

$$5,740 - 12,770 < 0 \text{ implying } f''_{68} = F''_{68}$$

Thus sensitivity on the cost of transportation through the Denver-Colorado Springs route is

$$0 < c_{68} < 12,770$$

The low and high estimates of cost on this route is 5,040 and 5,980 dollars per unit train.

Conclusions

Based on the present work in this thesis, the following major conclusions have been reached.

(1) For optimum allocation of coal trains from Wyoming, the power plants in Houston, Austin and Corpus Christi area should be supplied through Nebraska-Kansas route and trains to Amarillo, Texas and Colorado power plants should travel through the Foothills route. Coal trains going to the Corpus Christi power plant from Western Colorado also should use the Foothills route.

(2) Under the above allocation the frequency of trains through Littleton, Colorado is one unit train, loaded or empty, for every three and one-half hours or 48 trains per week for Scenario 1 and one unit train for every three hours or 60 trains per week for Scenario 2 and 3. However, the frequency of coal trains through the Alliance-Topeka route is 190 unit trains per week, 424 unit trains per week, and 920 unit trains per week for Scenario 1, 2, and 3, respectively.

(3) Assumptions for Scenario 1 are realistic and will happen by 1985. Scenario 2 will probably materialize by the late eighties or nineties. It is very unlikely that Scenario 3 will be a reality in this century. In this study, Scenario 3 has not been pursued in detail except to show the unbearable pressure on the existing railroad system if Scenario 3 ever materializes.

(4) If the Nebraska-Kansas route through Alliance-Topeka-Wichita is restricted to an upperbound of 84 unit trains per week, maximum number of trains passing through Littleton is 114 per week or one train per one and one-half hour under Scenario 1.

(5) The route alternative to Littleton is the Denver-Limon-Colorado Springs diversion. Wherever the Littleton route is restricted, the frequency of coal trains through Limon increases.

(6) For an increment of every two trains per day through Littleton the decrease in total transportation cost is $7,300 per day. It depends on the decision makers whether it is worth it to divert two extra trains per day away from Littleton at a penalty of $7,300 per day or not. The decision should focus on community acceptance and money saved. The decision of building a viaduct should also depend on the extra savings that can be made by increasing the frequency of trains through Littleton.

(7) The most important route in the network is the Alliance-Topeka route. A savings of $64,347 per day can be maintained under Scenario 1 if that specific route can have an unrestricted capacity. Under such conditions the allocation of coal trains will be optimal

and frequency of coal trains through Littleton will remain considerably less. If money is to be spent to improve any track condition or building viaducts, the Alliance-Topeka route should have the first priority. This is an important decision because the money for highway viaducts is most likely to come from federal grants.

(8) The method to analyze cost sensitivity as devised by the author showed effectively that the range of unit shipment cost on the two important routes covers the low and high limits of cost as defined in Chapter III.

(9) The data used in the study are from the forecasts developed during 1977. However, the recent trend in electricity use shows an unprecedented slow rate of growth. While demand for electricity used to increase by 7 percent annually, it is now growing at less than 3 percent per year. In 1979 total energy use in the nation declined (E. Marshall, 1980). Before the oil embargo of 1973-74, energy use increased each year faster than economic growth. Since then, the trend has reversed, with energy demand growing less rapidly than the economy. This slowing trend in electricity growth has not yet been reflected in the large econometric models, but became quite obvious in the industry (E. Marshall, 1980). In the 1980 convention

of the National Electric Reliability Council (NERC) Michael R. Gent, executive vice president of NERC, confirmed that NERC had recently updated their forecasts to reflect the slower growth in electricity use and concluded that some utilities would be cancelling orders for coal. If the recent trends continue, the demand for coal in markets described in the thesis may decrease in the long run. Though the application of the model is still relevant, the frequency of coal trains through Colorado will decrease and problems may not be so acute.

(10) Recent activities in the Green River and Kemmerer coal fields of southern Wyoming indicate a probable shift in coal supply center from Powder River Basin to southern Wyoming (Keystone, 1980). Though Powder River Basin will still remain the major supplier of coal to the southern and southeastern markets, some of the utilities will consider the southern Wyoming coal for their new developments. Under such assumptions the validity of larger supply scenarios in the thesis is doubtful. The extra coal supplied to the market will follow a different route through Omaha and problems of coal frequency through Colorado will not be so important.

Energy Transport System, Inc. (ETSI) decided to go ahead with Phase II action, detailed design and construction of the coal slurry pipeline from Wyoming to the southeastern market. If built, a major part of the coal supplied to Arkansas and Louisiana will be supplied through the slurry pipeline, thus relieving some of the coal transportation pressure from the railroads (Coal Weekly, 1981). ETSI partners have voted to move ahead into the definitive phase of the pipeline, which would include 1,400 miles of 38-inch diameter pipe running from Powder River Basin to Arkansas (Torrington Telegram, Apr. 4, 1981).

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APPENDIX A

REQUIREMENTS OF FUEL IN COAL EQUIVALENT FOR INDIVIDUAL UTILITY COMPANIES

Requirements of fuel in Coal Equivalent (in thousands of tons) for Individual Utility Companies, Source and Proposed Railroads for 1976 and 1985 (for Western coal only).

NEBRASKA

Fremont Department of Utilities

Destination	Fremont
Source	Hanna, Wyoming
Railroad	Union Pacific

	1976	1985
Coal	99	253
Rest	42	4

Nebraska Public Power District

Destination	Northport
Source	North Powder River Basin
Railroad	Burlington Northern

	1976	1985
Coal	576	5400
Rest	2061	2713

Omaha Public Power District

Destination	Omaha
Source	North Powder River Basin
Route	Burlington Northern

	1976	1985
Coal	1376	3462
Rest	101	148

KANSAS

Kansas Power and Light Co.

Destination	Kansas City, Kansas
Source	Syoming
Route	Union Pacific, Burlington northern, Atchinson Topeka and Santa Fe

	1976	1985
Coal	1817	15,101
Rest	4553	2,340

OKLAHOMA

Public Service Company of Oklahoma

Destination	Tulsa
Source	North Powder River
Route	Burlington Northern, and Atchinson Topeka and Santa Fe

	1976	1985
Coal	0	3516
Rest	8927	9787

TEXAS

City of Austin Water, Light and Power

Destination	Austin
Source	Powder River Basin
Route	Burlington Northern

	1976	1985
Coal	0	1620
Rest	1630	800

Central Power and Light Company

Destination	Corpus Christi
Source	Northwest Colorado
Route	Rio Grande and Denver and Burlington Northern

	1976	1985
Coal	0	1600
Rest	487	6715

Lower Colorado River Authority, Austin

Destination	Austin
Source	Powder River Basin
Route	Burlington Northern

	1976	1985
Coal	0	6000

Southwestern Public Service, Amarillo

Destination	Amarillo, Tx
Source	Powder River
Route	Burlington Northern

	1976	1985
Coal	689	4300
Rest	4083	3115

Houston Lighting and Power Company

Destination	Houston
Source	Powder River Basin
Route	Burlington Northern

	1985
Coal	10,069
Rest	24,540

Texas Power and Light Company, Dallas

	1985
Texas Lignite	52,872

City Public Service Board of San Antonio

Destination	San Antonio
Source	Powder River Basin
Route	Burlington Northern

	1985
Coal	3000
Rest	2073

ARKANSAS

Arkansas Power and Light, Little Rock

Destination	Little Rock
Source	Powder River Basin
Route	Burlington Northern, Union Pacific and Atchinson Topeka and Santa Fe

	1985
Coal	7,465
Rest	3,650

LOUISIANA

Central Louisiana Electric Co.

Destination	
Source	Powder River Basin
Route	Burlington Northern, Union Pacific and Atchinson Topeka and Santa Fe

	1976	1985
Coal		1750
Rest		3280

Louisiana Power and Light Co.

Destination	
Source	Powder River Basin
	Burlington Northern, Union Pacific and Atchinson Topeka and Santa Fe

	1976	1985
Coal		1935
Rest		8033

Southwestern Electric Power Co.

Destination		
Source	Powder River Basin	
Route	Burlington Northern, Union Pacific and Atchinson Topeka and Santa Fe	
	1976	1985
Coal		8298
Rest		2576

COLORADO

Public Service Company of Colorado

Destination	Pueblo	
Source	Powder River Basin	
Route	Burlington Northern	
	1976	1985
Coal		6185

APPENDIX B

DESCRIPTION OF THE ROUTES

APPENDIX B

Description of Rail Routes

In this report speed specified on a track is used to define bottleneck of that specific track. In the flat and unrestricted land the loaded trains generally attain a speed of 45 mph. The speed falls near communities, steep gradient or poor track conditions. Track passing through communities with unmanned crossings generally allows a speed of 10 to 20 mph. If the community is provided with an overbridge or a tunnel, the speed could be increased. Sharp curves, poor tracks or steep gradients may control the speed anywhere from 10 to 45 mph. In this report three speed limits have been considered: 15, 30, and 45 mph.

Hence a train may run at 15, 30, or 45 mph on a route depending upon the condition of the track. Bottlenecks occur because of poor track, difficult terrain, and increased density of habitation. Along such sections the speed from a normal of 45 mph may decrease to 30 or 15 mph. This increases length of time required for a one way trip and labor and fuel costs. It has been shown that unit transportation cost for unit coal trains increases with the increase of bottlenecks (Michel Rieber and S.L. Loo, 1970). A bottleneck is defined in this study as equivalent percentage of track that is restricted to 15 mph. That is, if 10 percent of track is posted at 15 mph, and the rest is at 45 mph, the bottleneck of the track is 10 percent. Considering the time required to travel the same distance, 20 percent of the track posted at 30 mph is equivalent to one-fourth of 20 percent or 5 percent of the track at 15 mph, as explained below.

Let x = percentage of track at 30 mph.

y = equivalent percentage of track at 15 mph. Rest of the track in both the cases is at 45 mph.

T = time required to travel 100 miles

then

$$T = \frac{(100-x)}{45} + \frac{x}{30} = \frac{(100-y)}{45} + \frac{y}{15}$$

$$\text{or } 1.5x - x = 3y - y$$

$$\text{or } \frac{x}{y} = 4$$

Consequently, the track with 20 percent length posted at 30 mph has a 5 percent bottleneck.

For every route from source to sink, the total distance in miles and lengths with speed restriction of 15 and 30 mph have been compiled. Distance with 15 mph speed expressed as a percentage of the total is calculated. The same is calculated for 30 mph speed restrictions. The sum of percentage with 15 mph and one-fourth of percentage with 30 mph is the bottleneck on the track. A track with 10 percent distance at 15 mph and 20 percent distance at 30 mph has a bottleneck of 15 percent.

The details of alternative routes for unit coal train movements are discussed in this appendix. Each community is described as to the number of crossings, proximity of housing from the track, city limit, existence of yard, etc. Speed restriction for each township is given. This varies generally between ten and twenty miles per hour. For unit coal trains maximum speed under normal conditions are prescribed to 45 mph. At the junction stations and large yards, speed is generally restricted to 30 mph. Some small towns which have little significance on the train movement are not described.

Data has been collected from various sources. In Colorado most of the data is collected personally from the areas. Operating time tables from the railroads supplied the timings between the station to the other and sometimes speed limits within city limits. Personal interviews helped in finding the standard procedures followed by the coal trains in yards, etc. City descriptions are gathered from city maps, railroad company files, geological survey reports and U.S. topographic quadrangle maps.

A summary of routes with total distance and length with speed restrictions is illustrated in Table B-1 and the details of routes are described in the rest of the Appendix.

Table B-1

Speed Restriction on Specific Routes

Route	Total Distance	Distance with 15 mph	Distance with 30 mph
Wendover to Cheyenne	120	10.0	
Wendover to Northport	102	5.5	
Alliance to Northport	34		
Northport to Denver	219	14.5	
Cheyenne to Denver			
Rt. 1	120	17.0	
Rt. 2	121	9.0	
Rt. 3	95	8.0	
Denver to Colo. Springs	72	9.0	14.0
Denver to Limon	90		
Limon to Colo. Springs	78		
Colo. Springs to Pueblo	44	2.0	
Pueblo to Trinidad	94	15.0	40.0
Pueblo to La Junta	64	6.0	
La Junta to Trinidad	82		
Trinidad to Amarillo	253	10.5	80.0
Amarillo to Bowie	268	9.0	
Alliance to Lincoln	363	9.5	
Lincoln-Fairbury-Topeka	172	12.5	40.0
Limon-Salina-Topeka	483	21.0	37.0

Table B-1 (contd.)

Route	Total Distance	Distance with 15 mph	Distance with 30 mph
Topeka to Wichita	155	15.0	4.0
La Junta-Hutchinson-Wichita	383	24.5	30.0
Wichita to Amarillo	348	27.5	
Wichita to Enid to Bowie	303	17.5	

Wendover to Cheyenne

Colorado and Southern runs south from Wendover to Cheyenne. South of Wendover there is about 3 miles of double track. The track runs through mountainous terrain with ups and downs. Gradients are not steep to pose any problem. There are three tunnels within 7 miles of track. Main highways cross over the tunnel. Last part of the journey is slow climbing but grade is nowhere more than one percent. On the way a total of 10 miles are speed restricted.

Wheatland is a small city on the way. The track traverses through east part of the city. Very little residential area is there on the eastern part except the airport. The main street to airport is at grade but no restriction on speed.

Cheyenne is on the east side of the C&S track going to Denver. The track comes from the west and turns south on the boundary of the city, thus avoiding the city completely. There is no interruption due to C&S line. Cheyenne is a main junction for Union Pacific which crosses the city from west to east.

Wendover to Northport

Just outside Wendover, Colorado and Southern splits. One goes south to Cheyenne. Another goes to Northport, Nebraska.

Guernesey is a small town on the south side of the BN track. There is no interruption.

Chugwater is traversed by BN on the south east quadrant. There is minor residential areas on the other side of the track. One street is at grade but no interruption.

Fort Laramie is on the south of Guernesey. It is on the north of the track. The track descends smoothly to Chugwater.

Lingle is a small town traversed by the track on the southwest corner. There is no interruptions due to trains.

Torrington is traversed by the track on the southwest corner. Part of the residential areas is on the other side of the track. Two mainstreets to the city and also connecting the highway 26, which runs parallel to the track, is at grade. Four minor streets are also crossing at grade. The speed is restricted for about one mile span.

Morrill is a small city north of the line. Highway 226 passes through the town and crosses the track at grade. There is no interruption due to rail traffic.

Mitchel is traversed by BW on the southern part of the town. Some residential areas and the fairground are on the other side of the track. There are three at grade crossings including the highway 29. About one and one-half mile of span is interrupted.

Scottsbluff is interrupted by the BN track for about 2 miles. The track passes through the city on the southwest quadrant. The main street is grade separated. But there are four more at grade crossings. The residential areas are quite near to the lines.

Minatare is a small town on the north of the track. Highway 26 runs parallel to the track on the north of it. There is no interruption.

Bayard is on the east of Minatare on the north side of the track. There is no interruption because of the trains.

Northport is a small town near which the eastbound C&S back joins with north/south track running from Alliance to Brush. About one mile through the yard the speed is restricted.

Alliance to Northport

The C&S track climbs from Alliance to Northport. The only town Angora on the way is quite small. There are no speed restrictions along the track.

Northport to Denver via Brush and Fort Morgan

Currently Burlington Northern moves unit coal trains from North Powder River and Fort Union basins to Texas through Alliance, Nebraska via Sterling and Brush to Denver. A new track from Gillette to Orin, Wyo. is being built to shorten the route.

Wendover to Cheyenne

Colorado and Southern runs south from Wendover to Cheyenne. South of Wendover there is about 3 miles of double track. The track runs through mountainous terrain with ups and downs. Gradients are not steep to pose any problem. There are three tunnels within 7 miles of track. Main highways cross over the tunnel. Last part of the journey is slow climbing but grade is nowhere more than one percent. On the way a total of 10 miles are speed restricted.

Wheatland is a small city on the way. The track traverses through east part of the city. Very little residential area is there on the eastern part except the airport. The main street to airport is at grade but no restriction on speed.

Cheyenne is on the east side of the C&S track going to Denver. The track comes from the west and turns south on the boundary of the city, thus avoiding the city completely. There is no interruption due to C&S line. Cheyenne is a main junction for Union Pacific which crosses the city from west to east.

Wendover to Northport

Just outside Wendover, Colorado and Southern splits. One goes south to Cheyenne. Another goes to Northport, Nebraska.

The track from Northport runs southward and enters Colorado near Peetz. Grades are gradually descending to Sterling. At Sterling BN trains for Denver operate over UP tracks for 23 miles to Union. Then with a gradual ascent of not more than .5 percent it reaches Brush. Over the 87 miles from Brush to Denver the gradient increases slightly to .6 percent.

There is a mixture of signalling system. Though this was not a mainline, the maximum speed is authorized to 55 mph on the open land.

Bridgeport is on the northside of the track. The track runs north to south and near the city turns SE. Two highways 26 and 88 cross the track at grades, but as there is no residential area on the southside of the track there are no interruptions due to trains.

Dalton is a small community on the east side of the track.

Gurley is traversed by the track on the central part. There are three crossings at grade. In about a stretch of half a mile, the speed in restricted.

Sidney is a junction town for BN and UP. The track enters the city from north and turns west cutting through the southern part of the city. There is one grade separated main street and three at grade crossings. About one and a half mile is interrupted.

Lorenzo is a small town on the west side of the track. The rail lines run parallel to highway 19 and 113. There is one at grade crossing to highways from the city.

Sterling is a fairly large city. BN passes along eastern/ southeastern edge of the city, paralleling Colo. U.S. highway 138 in the northern section of the city and Colo. 6 is in the southern section. All city facilities are located west of the corridor of track and highway. Southeast of the rail line is predominantly industrial. Three minor streets cross the track at grade. Both highway 6 and 176 are grade separated. Community interruption is not serious though speed is restricted to about 1 1/2 miles.

Atwood is a small community about 7 miles south of Sterling. Highway 63 connecting 176 crosses the track at grade. But there is no interruption.

Brush is mainly located on the north of the rail line. There are some scattered rural residential units on the other side of the track. In the central section of the city the line passes along the southern edge of the central business district, crossing the main street at grade. This main street connects some residential developments. The speed is restricted in this part for about 2 miles.

Fort Morgan also is developed mainly on the north of the BN track. Highway 34 and 176 runs parallel to the track on the northern side. There are three main streets connecting the southern part of the city to highways and central business district crosses the line at grade. Two residential areas are near the track. The train movement interrupts normal traffic flow and speed is restricted for about two miles.

Southwest of Fort Morgan the BN track follows U.S. 176 passing through rural communities and open land. Two small cities Kennesburg and Hudson are on the way. There are no major interruptions. After that the main line enters Adams County and the Denver Metropolitan area.

In the southern section, the line passes adjacent to an industrial area between 88th and 96th avenues. South of 88th avenue, the line passes through a residential area. The general area is deteriorated because of the existence of the rail lines. Farther south near 76th and 70th avenues, the line passes through a mixed neighborhood of industrial and residential areas. There are several major intersections at grade streets. The whole of the area is disrupted due to train traffic. The speed is restricted for about five miles. There are some grade separated crossings on U.S. Highway 85 and 270 and Brighton Boulevard.

Cheyenne to Denver

There are three major routes from Cheyenne to Denver.

Route 1 is the Colorado and Southern mainline through the cities of Fort Collins, Loveland, Berthoud, Longmont, Boulder, Louisville, Broomfield, and Westminster.

The route encounters moderate ascending and descending grade-like waves. There are two segments of 1.7 percent gradient of a total of 5 miles near Berthoud pass. Speed is restricted here below 15 mph. Though there are a number of curvatures, these pose no problems.

Authorized speed for unit trains is 45 mph except near the townships where it is restricted below 15 mph. There are three passing tracks more than one mile long. Because of an inadequacy of passing tracks and centralized signal systems, the maximum number of trains allowed on this route is four per day.

The area north of Fort Collins is a rural area. There is only one major highway crossing at grade in the vicinity of a small farm community of Wellington.

Fort Collins is the northernmost major city on route 1. The track divides the downtown area and also the University of Colorado. Residential areas are distributed on both sides of the track.

There are 19 at-grade crossings within the city localities. The required maximum train speed is 15 mph. Total restricted length of the track is about 3 miles.

Loveland is about 13 miles south of Fort Collins. The city is divided in two by the track through central business district. Residential areas are growing in both east and west sides of the track. The U.S. 34 is grade separated with the rail-lines and serves as the major artery of the town. There are 10 at-grade crossings. The speed limit is restricted below 15 mph for 2 miles through the city.

Berthoud is a small community on Colorado Highway 287, south of Loveland. The track bisects the township into east and west segments. Highway 287 and two other streets cross the track at-grade. The line passes within one block of the main commercial street. The speed limit is 15 mph for a length of 1 1/2 mile.

Longmont is south of Berthoud. The track runs north/south through the northeast section and then on a northeast/southeast axis through the southern section of the city. The east side is predominantly residential and the south side is industrial. All eighteen crossings are at grade. The speed limit is below 15 mph for two miles.

Boulder is only peripherally affected by the track, which passes through the northeastern part of the city. The area is primarily industrial with open lands. Four minor streets cross the track at grade.

Lafayette and Louisville are two small communities on the track. The track passes through the outskirts of the cities without much interruption.

Broomfield is crossed by C&S track at the southwestern corner. It is mainly an industrial area. The major street access is grade separated. The service roads are at-grade. The southern stretch of the track passes adjacent to a mixture of light industrial and older residential houses. The area is isolated from the city by U.S. highway 36. Speed limit is restricted to 15 mph for span of 1 1/2 miles.

Westminster is on the northern suburban fringe of Denver. The track bisects the city along northwest/southeast axis. Residential areas occur on both sides of the city. Westminster has nine rail crossings, of which eight are at-grade. Sheridan boulevard is grade separated. The speed is restricted to 20 mph for a two mile stretch.

Route 2 uses the Union Pacific's Fort Collins and Dent branch lines between Fort Collins and Denver. Though this is a branch line, this can be used for unit trains with little upgrading work. The advantage of the route is that it has no major township on the way. This does not have any major steep grades or bad curves. The signal system is not centralized. It follows route two from Cheyenne to Fort Collins. Then continues along U.P. alignment to the southeast.

It passes through four small communities between Fort Collins and Northglenn: Miliken, Firestone, Frederick, and Dacono.

Route two enters the developed portion of the Denver Metropolitan area through the cities of Northglenn and Thornton.

Northglenn is in the western edge of the track. It does not affect the city directly. As it passes through Northglenn, the northern section of the line traverses the eastern edge of a residential neighborhood. The 120th Ave., 112th Ave., and 104th Aven provide access to the city at grade crossings. Speed is restricted for two miles.

Thornton has developed in the shape of a reverse "C" with U.P. tracks running through the city on a north-south axis separating the city into three sections. Thus community life is heavily interrupted by the trains. The line crosses nine city streets at grade, including the important exit of 88th ave. About a stretch of 4 miles is speed restricted.

Route 3 extends from Cheyenne through the agricultural areas of Weld and Adams counties into the developed portion of Denver. The line is owned by the Union Pacific.

North of Greeley the line passes through four small communities: Nun, Pierce, Ault, and Eaton.

Greeley is the largest city on U.P. track. The rail line traverses the city on a north-south axis along the eastern edge of the city. The commercial and industrial area is located mainly on the west side. Some development in east side is quite far from the line. With the exception of U.S. 34 all east-west streets are crossing at grade. There are five of them in total. A stretch of 3 miles is speed restricted.

South of Greeley two small towns, Gilcrest and Platteville, have developed west of the track.

Fort Lupton is on the west side of the track. Land used adjacent to the track is mainly industrial. In the southern section the railroad passes immediately adjacent to the central business district, but there is little interruption to the community life.

Brighton is divided into two parts by the Union Pacific rail line. The track separates the major residential area lying east of the track from the central business district. There are seven at-grade crossings. Three of these crossings are major east-west arterials, providing access to and from U.S. 85. A stretch of about 3 miles are speed restricted. South of Brighton the route parallels Colorado 85 through an agricultural area and then enters into the industrial areas. South of 88th Ave. the line passes through a residential area for a distance of about one-quarter mile.

The line crosses 12 roads at grade between the incorporated areas of Brighton and Commerce City including six major streets for access to northern portion of the Denver Metropolitan area.

Commerce City is developed mainly on the east of the track. U.S. 6 and 85 are grade separated which serves the city. There are residential developments along the track. Speed is restricted within city limits for four miles.

Denver to Colorado Springs

Alternative route 1 enters Denver from northwest approximately one-half mile west of highway 25. The land use is predominantly commercial. The major arterials crossing the lines are grade separated.

Alternative routes 2, 3, and 4 enter Denver from Commerce City. Alternatives 2 and 3 pass through residential areas south of U.S. 70. Route 4 (from Brush) bypasses this area. Areas are mainly industrial with few streets crossing the track at-grade. There is very little interruption due to rail lines north of the city.

Approximately one-half mile north of Denver Central Business District all of the lines join in one general corridor, continuing in this relationship throughout the remainder of the metropolitan area. The track passes adjacent to the Auroria Higher Education center and a large parking area is built to buffer the campus from the track.

With the exception of the Mississippi Ave., Louisiana Ave., and Santa Fe-Kalamath system crossings, all arterial roadways are grade separated. The community along the line in these areas are largely uninterrupted by train movements. Though no speed limit is posted, the trains slow down in the Denver area for about a span of 3 miles due to high density cross points.

From Denver the railroad makes an ascent at a rate ranging from 1 percent to 1.4 percent for four miles. This grade presents a modest problem to the heavy unit trains, but is being overcome for C&S trains by the use of remotely controlled locomotives placed toward the rear of the train. Speed is restricted to 30 mph. Then the track makes a steady descent to Pueblo.

Curvature on the track poses little problem. Maximum authorized speed is 45 mph to Palmer Lake and 25 mph between Palmer Lake and Rosell (10 miles).

The control system is mainly centralized. Capacity of the track is high enough to handle the required number of coal trains.

Englewood is traversed by the rail line on a north-south axis separating the northwest quarter of the city from the rest. The land use is mainly industrial with some commercial. Near West Hampden, (U.S. 285), there are major commercial activities around Cinderella City. Hampden Ave. has a grade separated crossing over the rail corridor and the activities are not interrupted by the train movements. There are five at-grade crossings, four of which are major streets - Dartmouth, Kenyon, Quincey, and Belleview. Theses are busy streets for office-goers. A stretch of about two miles is speed restricted.

Littleton is situated south of Englewood. The track divides the city into east and west sections. Residential and commercial areas are in both parts of the city. The track passes along the eastern edge of the central business district. It crosses the major eastwest access to the city, Littleton Boulevard, at grade. There is significant development in the east of the track including civic centers and county governmental and court complexes. There are no grade separated crossings in Littleton which makes the train movement very critical. The major north-south street, Prince Street, also crosses the line at-grade. About 3 miles is speed restricted.

Castle Rock is divided in two by the D&RGW main line and continues through basically open and rural areas of El Paso county.

Colorado Springs is separated with one-third in the west and two-thirds in the east. The track runs parallel to U.S. I-25 for most of the area. Around the corridor there are open space and industrial development. There are eight grade separated crossings excluding the main highway around the city. Train movements are almost unnoticed in the communities.

At the northern boundary of the city there is a nearly developed residential area adjacent to the line. About one mile of the stretch is speed restricted.

Central business district lies east of the track and has no effect due to trains. The south end of CGD has low income housing. There are about eight crossings at-grade with potential problems. At present there are minor effects.

Security and Widefield are two Colorado Springs suburbs in the south. Both the cities have developed on the east of the track. There is one grade separated crossing leading to U.S. I-25 near Widefield. Main street leading to Security is at grade.

Colorado Springs to Pueblo

About 36 miles south of Colorado Springs, at Bragdon, the D&RGW and AT&SF main lines split, before entering the Pueblo corporate boundaries.

The D&RGW traverses Pueblo on a north-south axis closely paralleling U.S. I-25. The land use is mainly industrial and commercial. The area to the east of the line along Fountain Creek is designated as a park. Because of the location of rail line with respect to the creek and highway, it has no effect on the community of Fountain. The major arterials tying the two sections of the city together have grade-separated crossings.

The Santa Fe line enters Pueblo in the northwestern part traversing diagonally the central section of the community. There are some scattered residential areas and the State Hospital long the track. There is one street grade-separated and one at grade. Very little disruption affects the community. A total of 2 miles is speed restricted.

Pueblo to Trinidad

From Pueblo the track separates out to two directions. The Santa Fe turns to Oklahoma and Texas through La Junta, Colorado and Southern resumes straight to Walsenburg along with Denver and Rio Grande Western. From Walsenburg D&RGW turns toward Alamosa and C&S proceeds southward to Trinidad and Amarillo, Texas.

Route 1: From Pueblo to Walsenburg RGW and C&S continue their operations to form a double track. From Pueblo the line climbs to Walsenburg with a grade of about one percent. Curves are frequent. There are no signals. The track is in poor condition. The maximum authorized speed for this 53 mile stretch is 30 mph.

The 38-mile track from Walsenburg to Trinidad is first ascending and then descending. Curves are frequent but not serious. A 40-mile per hour speed is authorized along this track. Centralized signalling system is provided.

The track from Pueblo runs parallel to U.S. I-25. Communities on both sides of the track are joined by grade separate streets. At the southern edge of the city the line passes directly adjacent to CF&F Corp. plant.

Between Pueblo and Walsenburg the track traverses mainly the range land.

Walsenburg is a small city cut by the tracks in the eastern section. Near the center D&RGW and C&S are joined. The southeastern quadrant is separated from the rest of the city by two tracks. The track crosses the main residential area and passes along the central business district. There are six railroad crossings, none of which are grade separated. A total of about one mile is speed restricted.

Trinidad is the southernmost city of Colorado. The track traverses the city in the shape of a "C" entering from the southeast and changing eastward at the center. Along the track are mainly industrial areas. East of the downtown are, it passes through a residential area. There are five at-grade crossings in this area. The community is not greatly disrupted. The speed is restricted to 15 mph for about one mile through the yard.

Route 2: The Santa Fe runs eastward from Pueblo to La Junta. At La Junta it again separates out in two directions. One goes towards Oklahoma and Kansas and the other comes back to Trinidad. The route is steadily descending and ascending. Grade is not too steep, less than one percent. Signalling is through centralized system. A maximum allowable speed is 45 mph.

East of Pueblo there are two small towns of Fowler and Manzanola in the lower Arkansas Valley. Both of the towns have developed on one side of the track. There is no interruption due to train traffic. Avondale is a junction station for AT&SF and MP. The yard is about one mile long where speed is restricted. There is little interruption to the community life.

Rocky Ford is bisected by the track along a northwest-southeast axis. Important areas and residential communities are on both sides of the track. There are eight at-grade crossings in the city. About two miles is speed restricted.

La Junta is situated basically south of the track. There are no interruptions in community life due to trains. Speed is restricted for about two miles.

On the La Junta/Trinidad route, the signalling system is not sophisticated and passing tracks are limited, so the number of trains per day are restricted.

Alliance to Lincoln

The Burlington Northern mainline runs east through the plains of Nebraska to Lincoln. The track has a southeast direction from Thedford to Rowenna. The line is gradually descending towards east in favor of the load except at places where there is a wavy topography like near Grand Island.

The track is well maintained and suitable for unit trains. Signalling system is adequate and there are a number of passing tracks more than one mile long. Capacity is well beyond the expected number of trains.

Immediately leaving Alliance to the south, the BN mainline bifurcates. One line goes southward to Brush and Denver, and the other eastward to Lincoln. It crosses three small towns of Antioch, Lakeside, and Bingham. These are mainly rural communities. There is very little interruption due to increased train traffic.

Ansley is traversed by BN mainline on the western part of the city. There is some rual development of the other side of the city. There are three crossings at grade. The train movement is not restricted.

Anselmo is traversed by the track at the center of the city. There is residential development on either side of the track. The two parts are connected through three crossings at grade. The speed is restricted for about one mile.

Broken Bow is also traversed through the center of the town. The community activities are on the north part of the town. The track runs East/West. There are four streets crossing the track at grade and speed is restricted for about two miles.

Ansley is on the eastern side of the track. There are some residential areas on the other side, but they are mainly rural. There is no major interruption due to train traffic.

Mason City is on the south side of the track and there are no residential areas adjacent to the track. There are two streets crossing at grade to connect rural communities on the other side of the track, but there is no interruption due to these roads. Highway 2 runs parallel to the track on the same side of the town.

Litchfield is a small town north of the main line. Highway 2 runs parallel to the line on the south side of it. Only one street from the city to the highway crosses the track at grade.

Hazard is also a small town north of the track and highway 2 runs south of the track. The highway connection crosses the track at grade.

Rowena is situated on the south side of the BN line. Highway 2 is on the same side. There is no interruption due to train traffic.

After leaving Rowena the track again runs eastward on the south bank of the South Loup river. It passes parallel to highway 2 on the south side. It runs through two small rural townships of Abbott and Phillips. The land is mainly agricultural and flat.

Aurora is traversed by the BN mainline in the west of the town, which then runs along the southern part. The main business area is on the northern part of the city, but there are some residential areas and highway 14 is on the south of the track. There are five streets crossing the line at grade. Total restriction is for two miles.

Garland is a small town cut in two by the track along east/west axis. There are two at-grade crossings. Speed is restricted for about half a mile.

Lincoln is a very important junction for the BN lines. Rail lines converge from all the four corners to the yard on the west of the city. The suburbs of the city extend beyond the track. Residential areas have developed along the track. There are some industrial barriers between the time and houses. Eight streets including highway 34 cross the track at grade. The traffic is interrupted by the train movement. Speed is restricted through the town for about four miles.

Lincoln to Fairbury

Chicago Rock Island and Pacific railroad line connects Lincoln to Fairbury. There are a number of small towns on the way. The track runs on flat land. Though it is not maintained as an important mainline and the signalling system is not sophisticated, the unit trains can move on this short distance connection. On the route from Lincoln to Topeka for about 40 miles, the speed is restricted to 40 mph.

Martell is a small town west of the track. There is some residential development on the east connected with the west by three at-grade crossings. Speed is restricted for about half a mile.

Hallan is traversed by the track through the center of the town. There are three at-grade crossings and interruption occurs for about one mile.

The CRI&P track crosses BN tracks about one mile southeast of the city of Dewitt with restricted speed. Plymouth is a small town on the line without any interruption.

Jansen is on the north of the track. Highway 136 is also on the southside of the track.

Fairbury is on the north of the track. The rail line makes a U-shape with the town at the bottom of the U. There are some residential areas on the southwest quadrant. There are ten streets crossing the track at grade. Highway 8 is grade separated. Speed is restricted for about two miles near the town.

Fairbury to Topeka

The Union Pacific railroads handle the mainlines from Fairbury to Topeka. It is primarily run in flat land with high density communities.

Hanover is the junction town for BN and UP. The main yard is on the west side of the city. UP track runs through the south part. Residential areas are on both sides quite adjacent to the track. Connecting streets including highway 15E are at grade. There are six such streets. Speed is restricted to about two miles.

Herkimer is on the north side of the track. There is a rural development on the other side of the track. The connection to US 36 is at grade. There are no major interruptions.

Marysville is traversed by the UP mainline on the west central part of the town. Nine streets including the main street cross the track at grade. The interruption is for about two miles.

Frankfort is the junction for UP and MP on the southern boundary of the town. Some residential areas are on the other side of the track including highway 9. All the connecting streets are at grade. There are four of such streets. Speed is restricted for about one mile.

Duluth and Onaga are two small towns north of the track. There are no interruptions.

Silver Lake is about ten miles west of Topeka on the northern bank of the Kansas River. The main track runs on the northern boundary. There is speed restriction within the city limits for one mile.

Topeka is a junction town for CRI&P and UP railroads. The yard is on the northern boundary of the town. The UP track runs on an east/west axis separating northern Topeka from the main town. The track runs along the northern bank of the Kansas river which is a natural barrier between the two parts of the town. There are four grade separated crossings over the track and the river. No interruption is assumed. Speed is restricted in the yard for about three miles.

Topeka to Herrington

Chicago Rock Island and Pacific railroads run from Topeka to Herrington. The rail-line ascends gradually to Herrington.

Maple Hill is a small community north of the track. Highway 30 crosses the track at grade near the town. There are no major interruptions.

Alma is five miles west of the town of McFarland. CRI&P passes southeast of the town and joins with UP. There are residential developments on the other side of the track. Three streets and also a highway cross the track at grade. Speed is restricted for about a mile.

White City is a small town before Herrington. The raillines pass on the west side of the city. Though there are two streets at grade, there is no interruption due to train traffic.

Herrington is a fairly large town. The railroad bisects the city into two. There are five crossings at grade with a total of about three miles of restricted speed to 15 mph.

Herrington to Wichita

The same line continues from Herrington to Wichita.

Lost Springs is a small town west of CRI&P track. There is a connecting street leading to Highway 56, east of the track. There is no interruption. Speed is restricted at the crossing of AT&SF at 30 mph for two miles.

Lincolnville is on the east side of the track. Highway 77 is also on the same side of the track. There are three at-grade crossings to connect the rural communities on the other side of the track.

Marion is on the east side of CRI&P tracks. This is a junction also for Atchinson, Topeka, and Santa Fe. There are some residential areas on the other side of the track. There are four streets crossing the track at grade and speed is restricted for about a one-mile span.

Whitewater is a small town east of the track. There is no interruption to the community due to train traffic.

Ketchi is a bedroom community for the city of Wichita.

It is situated on the west of the track on the same side with Wichita, so there is no interruption.

Wichita is an important junction station for the Chicago Rock Island & Pacific, Atchinson, Topeka & Santa Fe, and Missouri Pacific railroads. CRI&P enters the city from the north and MP crosses through the west central region. Though the main arterial, Broadway Ave., is grade separated, about thirty street crossings are at grade. Residential areas have developed along the track without any major barrier. Communities are interrupted due to train traffic. Speed is restricted below 15 mph for about ten miles.

Limon to Salina to Topeka

The Union Pacific railroads connect Limon to Herrington. It is a main line and well maintained with a mixed signalling system. On the central part of Kansas, it follows a mountainous terrain. Near Carneiro and again at Elmo, the track experiences a sharp wavey topography. Speed is restricted along these two regions to below 30 mph for about 25 miles. Other than that the track has a gradual descent to Herrington.

Most of the area traversed by the track is open and rural lands, interspaced by small towns. Population in these towns is not large enough and there is little community interference due to heavy train traffic.

The rail line enters Kansas near the town of Cheyenne Wells. Between Limon and the Kansas border, there are some insignificant rural townships such as Clifford, Wild Horse, Kit Carson, etc. These are all agriculturally based with little traffic movements.

Winona is on the north side of the track. Highway 40 runs on the other side of the track. The connection to the highway crosses the track at grade. There is little interruption due to train traffic.

Monument is on the south of the track and so is highway 40. No interruption is due to train traffic.

Oakley is the junction station for the railroads. Speed is restricted for about one mile.

Wakeney is divided in two parts along an east/west axis by the UP mainline. There is a barrier due to open land between houses and the track. There is one at-grade crossing and speed restriction occurs for one mile.

Ellis is traversed by the UP line through the center along an east/west axis. There are residential areas close to both sides of the track. Highway 40 runs parallel to the track. Six connections between the two sections of the city are at grade. Speed is restricted for about one mile.

Hays is also cut by the UP main line on an east/west axis. There are residential areas on both sides and the central business district is on the north. Eight streets including the main streets cross the track at grade. Because of the proximity of the housing to the track, speed is restricted for about four miles.

Victoria is a small town mainly north of the track. There is some rural development on the other side of the track, but little interruption is due to train traffic.

Walker is traversed on the southwest corner by the UP mainline. The residential area on the other side of the track is quite small. There is one at-grade crossing.

Gorhma is a small town cut by the UP track on the east/west axis. There are residential developments on both sides of the track. There are three streets crossing at the grade.

Russell is mainly on the south of the track. Though the business district is on the south, about one-third of the total population comes from the northern section. There are four at-grade crossings including highway 281. Speed is restricted for one and a half miles.

Black Wolf is also cut by the UP track on an east/west axis. Highway 40 runs parallel on the south side of the track. There are four at-grade crossings, and speed is restricted for about one and a half miles.

Ellsworth is traversed by the track on the southern part of the town. U.S. Highway 40 runs on the northern part of town. There is a large residential area on the south of the track and seven streets cross the track at grade. Speed is restricted for about one and one-half mile.

Kanopolis is the next junction station with the Missouri Pacific railroads. The large yard is in the heart of the town. Several roads cross the track at grade. Speed is restricted for about three miles.

Brookville is a small town on the north side of the track and also highway 40. There is about one and a half mile speed restriction.

Salina is a large junction station for the Union Pacific and the Missouri Pacific railroads. From Salina onward, the track is owned by MP. There is a large residential area on the north of the track and the central business district is on the south. Highway 40 which runs north/south is grade separated. There are six main at-grade crossings. There is no barrier between the track and the housing. Along three miles, which span the community, are interruptions due to train traffic.

Solomon is cut by UP track on the southern part of the city. There is a playground adjacent to the yard. The yard is one and a half miles long. There are four at-grade crossings and about one mile is restricted to 15 mph.

Abilene is situated on the north side of the track. The yard is two miles long and there are four minor crossings. The speed is restricted to 35 mph for 8 miles. Chapman is a small township situated on the north side of the track. There is no speed restriction in the area.

Junction City is a junction station on the UP route. The main route goes to Topeka. The city is on the west side of the track. Highway 40 crosses the track over the bridge. There is no speed restriction in the area.

Ogden is a small town with a two mile long passing zone for the trains. There is no restriction of speed.

Manhattan, on the north side of the track, has a ball park adjacent to the track. There is no grade crossing but speed is restricted to 35 mph for four miles.

Wamego and Belvue are two small towns with no restrictions to speed on the track.

St. Mary's is a fairly large size city situated on the north side of the track. Highway 24 runs parallel to the track on the south side and connected with the city through an overbridge. The speed is restricted to 15 mph for one mile.

Rossville is a small town divided in two halves by the track. There are two on-grade crossings but no speed restriction.

Silver Lake is a small town south of the track.

La Junta to Hutchinson to Wichita

Atchinson, Topeka, and Santa Fe railroad connects La Junta with Wichita. The rail-lines traverse through flat lands of south Kansas. This main line is suitable for running unit coal trains. The signalling system is adequate along the way. The land is mainly agricultural and there are several rural communities on both sides of the track.

La Junta is situated on the southern side of the line. Highway 50 serves as a barrier between the residential developments and the rail-line. There is no interruption due to train traffic, but speed is restricted for two miles in the yard.

Las Animas is a small town on the north of the track. There is no development near the track and no interruption.

Granada is traversed by the track on east/west axis through the central region. Central business district is on the south and a major residential area is on the north. There are two crossings at grade and speed is restricted for about one mile.

Holly is a rural community on the border between Colorado and Kansas. The rail-lines run through open fields and there are little interruptions due to train traffic.

Syracuse is the first town on the track in Kansas. The line runs on the southern boundary of the town. Houses are at a distance from the track. Highway 270 crosses the track at grade.

Kendall is a small community on the north side of the track along with Highway 40.

Lakin is traversed by the main line from NE to SW through the center of the city. There are developments close to the track. Two sections of the city are connected by four streets crossing at grade. Speed is restricted for about one and a half miles.

Deerfield is a small community. There is no impact due to train traffic.

Garden City is traversed by the track through the southern part of the city. About one-third of the development is on the other side of the track. The main highway (156) and the central business district are in the north. Four streets including the main connection to the highway cross the track at grade. Speed is restricted for three miles.

Pierceville is a small town on the south side of the track. There are some rural developments on the north. No major interruption is anticipated.

After leaving Pierceville near Charleston, the rail-lines pass through a mountainous topography. The speed is restricted below 30 mph for about 30 miles.

Ingalls is on the northeast of the track. Highway 50 runs parallel to the track on the same side. Though there are some rural communities on the other side of the track, there are no major interruptions.

Cimmaron is on the north side of the track. There are residential areas on both sides. Highway 40 runs parallel to the track on the northern section. Five crossings including highway 23 are at grade. Speed is restricted for about one mile.

Dodge City is the most important city in this region. The track runs through the southern section of the city. U.S. 50 runs along the north. Four main streets, including Highway 56 cross the track at grade. On both sides residential housings are quite close to rail-lines. Speed is restricted for about three miles.

After Dodge City, the rail-lines pass two small townships of Spearville and Offerle.

Kinsley is a fairly populated city. The track runs southwest/northeast parallel to Highway 56. Highway 50 is grade separated on the southwest boundary of the city. All other four crossings are at grade. Speed is restricted about two miles.

Lewis, Belpre, Macksville, and Stafford are small rural communities developed mainly on one side of the track. They pose no problems for heavy train traffic.

Sylvia is situated on the southern side of the track. But there are residential areas on the northern section too. Highway 50 crosses the track at grade about half a mile east of the city. There are two at-grade crossings and the interruption is for about one mile.

Pleuna is a small community on the southern side of the track. There is no interruption.

The track passes through two more rural communities of Abbyville and Partridge without interruption before it enters the junction of Hutchinson.

Hutchinson is an important junction for AT&SF and CRI&P. The track passes through southcentral area of the city. Near the western boundary there is grade separated Highway 50. Hutchinson is a scattered community with suburbs extending east and west. There are 13 at-grade crossings and the speed is restricted for about five miles.

Burton is cut on east/west axis by the main line. There is an open land left as a barrier between housing development and the track. Two streets cross the track at grade. Speed is restricted for about one mile.

Newton is also a junction for MP and AT&SF. The large yard is on the southwest boundary of the city. The track enters the city at the southwest corner and leaves through the northeast. There are four streets including Highway 81 crossing the track at grade. Speed is restricted for three miles due to proximity of the housing.

Wedgewick is traversed by the main line through the eastern part of the city. Residential developments are on both sides of the track. There are three at-grade crossings. Interruption occurs for about one mile.

After Sedgewick the track enters the junction city of Wichita.

Wichita to Enid to Bowie, Texas

Atchinson, Topeka, and Santa Fe Railroad runs south from Wichita through Oklahoma and joins with eastbound Burlington Northern at Bowie, Texas. The topography basically has gradual descent to south and without much vegetation. The rail-lines run straight without many curves. AT&SF bypasses Oklahoma City in the east of it and there are no big townships on the way.

On the southern-bound line CRI&P pass through suburbs of Wichita, Glenville, and Haysville. Highway 235 is grade separated at Derby. All along the track for about five miles the residential areas have been developed. Community life is disrupted by train traffic.

Caldwell is situated on the east side of the track. Residential housings are very near to the track without much barrier. Speed is restricted for about one mile.

Wellington is on the border of Kansas and Oklahoma. The rail-lines separate the western third of the city from the rest. The two sections are connected by a grade separated crossing of Highway 160. No major interruption is anticipated.

Medford is developed as two rectangles connected at the corner. The track runs northeast-southwest through that corner. There is no housing near the track and only one crossing at grade. For about half a mile the speed is restricted.

Pond Creek is on the east of the track. The central business district is on the east side but there are residential developments on the west. Four streets including highway 60 are crossing the track at grade. Speed is restricted for about one and a half miles.

Kremlin is shielded from the rail-lines by the industrial areas. There is no major interruption.

Enid is traversed by the track along a northeast/southwest axis. The town has developed along the track and is quite disrupted by the train traffic. Ten streets including highway 15 cross the track at grade. Speed is restricted for about two and a half miles.

Dover is a small rural community where Highway 81 crosses the track along a grade separated overpass.

Kingfisher is situated on the west side of the track. There are some residential areas on the other side. Highway 81 runs parallel to the track on the west. The main connection, state highway 33, crosses the track at grade and also the other five streets. Speed is restricted for about one mile.

Highway I-84 crosses the rail-lines through an overpass south of Kingfisher near the small community of Okarche.

El Reno is traversed by the track through the western part of the city. A large residential area is on the other side of the track. There are four crossings at grade and speed is restricted for about two miles.

Union City is a small rural community on the west of the track. Open land serves as a barrier between the track and residential developments. Highway 152 crosses the track at grade to connect with Highway I-81 which runs parallel to the track on the other side. Speed is restricted for about half a mile.

Minco is situated on the west of the track. There is a rural development on the other side of the track. The main road runs parallel to the track and serves as a barrier from the track. Highway 81 is grade separated about one mile north of the town.

Chickasha is a large junction south of Minco. The main line passes through the east side of the town. The industrial development serves as a barrier between the town and the track. Highway 92 is grade separated and serves as the main arterial between the two parts of the city. Only one street is at grade. There is very little interruption due to train traffic. Speed is restricted for one and a half miles in the yard.

Duncan comes after two small rural communities of Rush Springs and Marlow. CRI&P rail-lines cut the town on a north/south axis. Both the sections are equally developed. Highway 7 is grade separated and serves as the main arterial. There is little barrier between housing and track. Speed is restricted for about two miles.

Commanche is situated east of the track. Highway 53 and another two streets cross at grade to connect the development on the other side. Speed is restricted for about one mile. Highway 81 is grade separated about six miles south of the city.

Terral is on the Texas border. Highway 81 runs parallel to the track on the east side. There are no interruptions due to train traffic.

At Bowie CRI&P lines join with Denver and Fort Worth (BN) railroads and proceed towards Fort Worth and Dallas.

Trinidad to Amarillo to Bowie to Fort Worth

Fort Worth and Denver railroads run from Trinidad to Fort Worth. This is a subsidiary of Burlington Northern Railroad Company. The main lines cross the Colorado border near the small town of Trinchere and enter into the rugged country of northeastern New Mexico. The track follows a serpentine route through mountainous terrains of Alps Mesa, Royce Mountain, and Mountain Dora, east of Sierra Grande. For about 60 miles the speed is restricted to below 30 mph. Grades are more than 2 percent at places. There are some small towns on the way like Folsom and Des Moines.

Clayton is situated more than halfway to the Texas border. The lines come down to a better terrain before the town and cut through the western part of the town. About one-third of the development is on the other side of the track. The residential areas are quite near the main lines. There are three crossings at grade including Highway 56. Speed is restricted for about two miles.

Highway 84 runs parallel to the track all the way from the Colorado Border. It crosses the lines through an overpass half a mile north of the town.

Texline North is the border town between New Mexico and Texas situated on the northern side of the track. Highway 87 runs parallel to the lines on the same side. A barrier from the track is maintained by road and open land. There is little interruption due to trains.

Near the Texas boundary, the BN lines join with CRI&P rail-lines at Dalhart junction. After Dalhart the track again enters a mountainous terrain and follows the valley. The grade on the way is never too steep. The curvatures are moderate. For a total span of 20 miles near the regions of Boden and Wolf Mountain, the speed is restricted below 30 mph.

Amarillo is cut by the track through an east/west axis. On both sides of the track there are residential and business areas. Two main arterials are grade separated. The industrial areas are mainly on the north and serve as a barrier. There are seven at-grade crossings including a highway. On the west side of the town, a large lake acts as a natural barrier. At other areas the housing is close to the rail-lines. Speed is restricted for about two miles.

Pullman is a ranch community. Highway 287 runs parallel to track in north, then crosses the lines in an overpass near the settlement.

Clarenden is traversed by the track through the north west quadrant. Three streets and highway 70 which connect I-287 on the south cross the track at grade. There is no barrier between the houses and the track. Speed is restricted for about one mile.

Childress is cut by a track on an east/west axis through the center. There are three streets at grade and speed restriction is for about one mile.

Kirkland is a small town on the southside of the track. There are some residential developments on the north of the track. Three streets including the main connection to highway 287 are at-grade crossings. Speed is restricted for one mile.

Electra is traversed by the track from northwest corner to southeast corner. Highway is parallel to the lines on the NE side. The development is along the track. All the four crossings are at grade. There is about one and a half miles restricted due to train traffic.

APPENDIX C

SENSITIVITY ANALYSIS ON TRANSPORTATION COST

APPENDIX C

Sensitivity Analysis on Transportation Cost

To check the results on sensitivity analysis on transportation costs on arcs (6,8) and (3,14), costs on these arcs are increased with increments and results are tallied. The following two tables C-1 and C-2 show the results.

Table C-1

Results of Incremental Cost on Arc (6,8)

Arc	Arc Cost $	Arc Flow
6,8	0	21
	10,000	21
	12,700	21
	12,800	0

So lower limit of the cost is zero and upper limit is between $12,700 and $12,800. Range established by the method in the text is:

$$0 < \text{Cost} < 12{,}770$$

Table C-2

Results of Incremental Cost on Arc (3,14)

Arc	Arc Cost $	Arc Flow
3,14	10,000	104
	25,000	104
	25,900	104
	25,950	95
	50,000	95
	57,000	95
	58,000	52
	65,000	14

So lower limit of the cost on arc (3,14) is between \$25,900 and \$25,950 and upper limit is between \$57,000 and \$58,000.

Range established by the model is:

$$25,940 < \text{Cost} < 57,030$$

APPENDIX D

ALTERNATIVE APPROACHES TO NETWORK SOLUTION

Appendix D

Alternative Approaches to Network Solution

To establish the uniqueness of the solution of the problem described in the thesis, three other alternative methods of solution were used. They are:

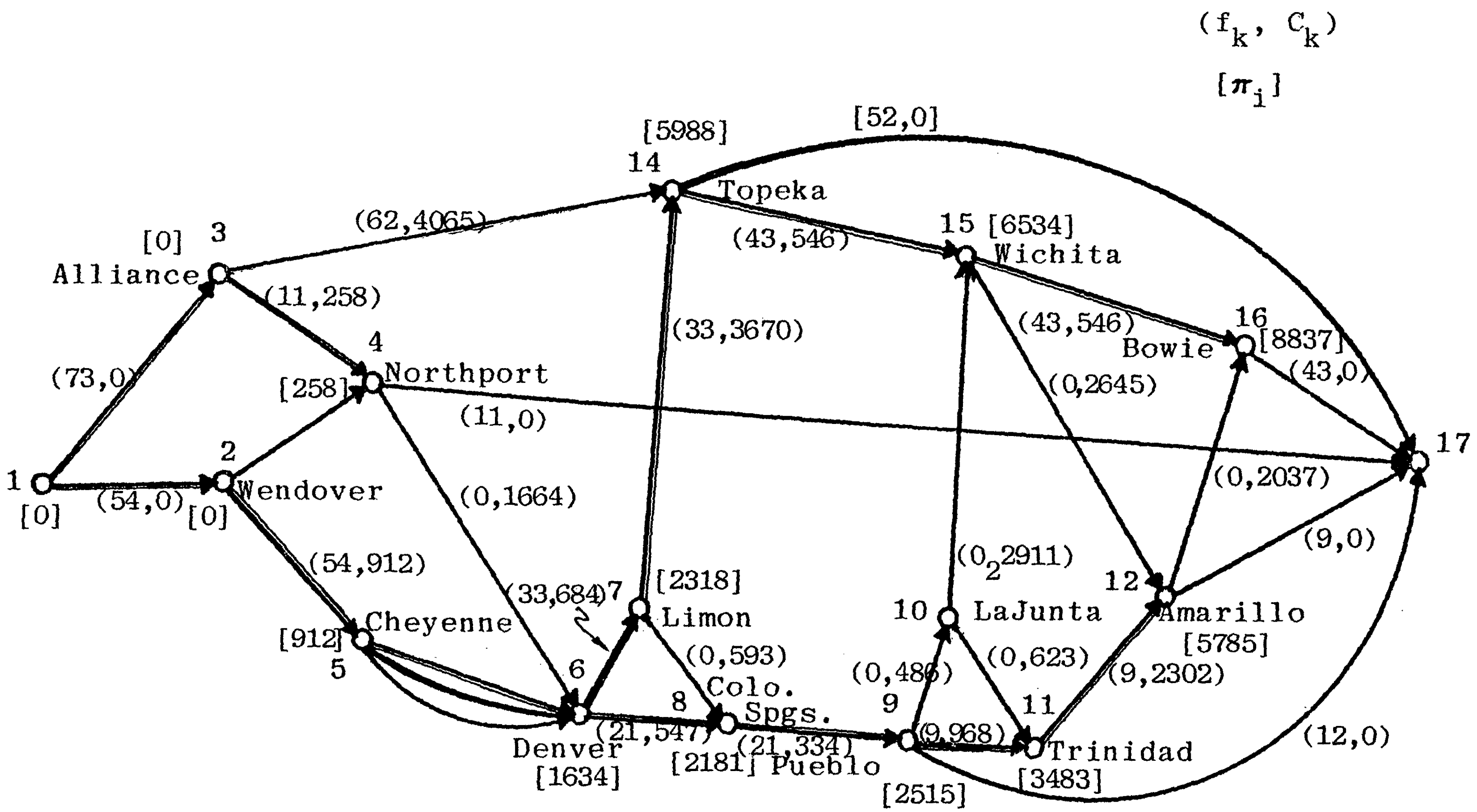
a) Basic Primal Method
b) Nonbasic Primal Method
c) Dual Node Infeasible Method

The algorithms used here are described in "Network Flow Programming" by Paul A. Jensen and J. Wesley Barnes.

The original railroad network (Fig. C-1) as described in the text was the model on which the algorithms were applied. For simplicity, the three coal trains running from Denver to Amarillo were not considered. The model as in Scenario 1, Case 1 with upper bound of 62 trains on arc 3,14 (Alliance-Topeka) and 84 trains on all other arcs was used for all the cases. Demands, costs and other parameters were described as required in the algorithms.

Basic Primal Algorithm

The basic primal algorithm has five principal steps:



Negative $d_{12,16} = -1,015$

Figure C-1: Network with the Basis Tree

a) Establish a basis tree in the network by solving a maximum flow problem. Maxflow problem takes help of changing the flow in an augmenting path.

b) Select a nonbasic arc that violates any of the complimentary slackness conditions. Call this an entering arc $K_E(i_E,j_E)$.

c) Determine the cycle composed of basic arcs and the entering arc on which the flow must be changed in order to bring K_E into the basis. Find the maximum flow change possible. Either the entering arc or some basic arc will leave the basis. Call this the leaving arc $K_L(i_L,j_L)$.

d) Modify the basis tree so that K_E enters and K_L leaves. If K_E and K_L are the same arc, no change is necessary.

e) Modify the node potential so that:

$$\pi_i + C_k = \pi_j \quad \text{for arc } k(i,j) \in M_T$$

where π_i, π_j are the node potentials.

C_k is the cost of arc $k(i,j)$.

M_T is the collection of arcs at terminal.

Figure C-1 illustrates the railroad network. Cost (C_k) and fixed external flow (F_k) are shown along the respective arcs. Arcs (1,2) and (1,3) are unbounded in flows with zero cost and arc (3,14) has an upper bound of 62. All other arcs have 84 as upper bound.

To find the maxflow to satisfy the external fixed flows, flows in all the arcs are put to zero. Find a path from source (S) to sink (T) through admissible arcs and increase the flow.

Source S	Path S→T	Upper Bound	External Flow	Maximum Flow	Remaining External Flow
1	1,3,14	62	52	52	0
1	1,3,14,15,16	10	43	10	33
1	1,3,4	84	11	11	0
1	1,2,5,6,8,9	84	12	12	0
1	1,2,5,6,8,9,11,12	72	9	9	0
1	1,2,5,6,7,14,15,16	63	33	33	0

All the external flows are satisfied, so a basis tree is formed as shown in the table. Initial flows are shown in Fig. C-1 along the arc.

Initialize $\pi_1 = 0$

Find $\pi_j = \pi_i + C_k$ such that arc (i,j) is in the basis. Consider both forward and mirror arcs.

Node	π_i
1	0
2	0
3	0
4	258
5	912
6	1,634
7	2,318
8	2,181
9	2,815
11	3,483
12	5,785
14	5,988
15	6,534
16	8,837

Find the negative d_k on any nonbasic arc. Arc 12,16 is such an arc.

$$d_{12,16} = -1,015$$

Find the cycle which contains the arc 12,6 with basic arcs. Such a cycle is:

12,16,15,14,7,6,8,9,11,12.

Arc	Forward Flow	Mirror Flow	Maximum Change	New Flow
12,16	0	0		33
16,15		-43	+33	-10
15,14		-43	33	-10
14,7		-33	33	0
7,6		-33	33	0
6,8	21		33	54
8,9	21		33	54
9,11	9		33	42
11,12	9		33	42

The new basis tree is shown in Figure C-2. Find the new node potentials.

Node	π_i
1	0
2	0
3	0
4	258
5	912
6	1,634
8	2,181
9	2,515
11	3,483
12	5,785
16	7,822
15	5,519
14	4,973

The d_k's calculated for each nonbasic arc from the new node potentials are the following:

Arc	d_k
2,4	517
6,4	3,040
7,14	10,15
7,8	730
9,10	0
10,11	141
10,15	393
15,12	2,381
14,3	908

All d_k's are positive, so optimum solution has been reached. The flows are as follows:

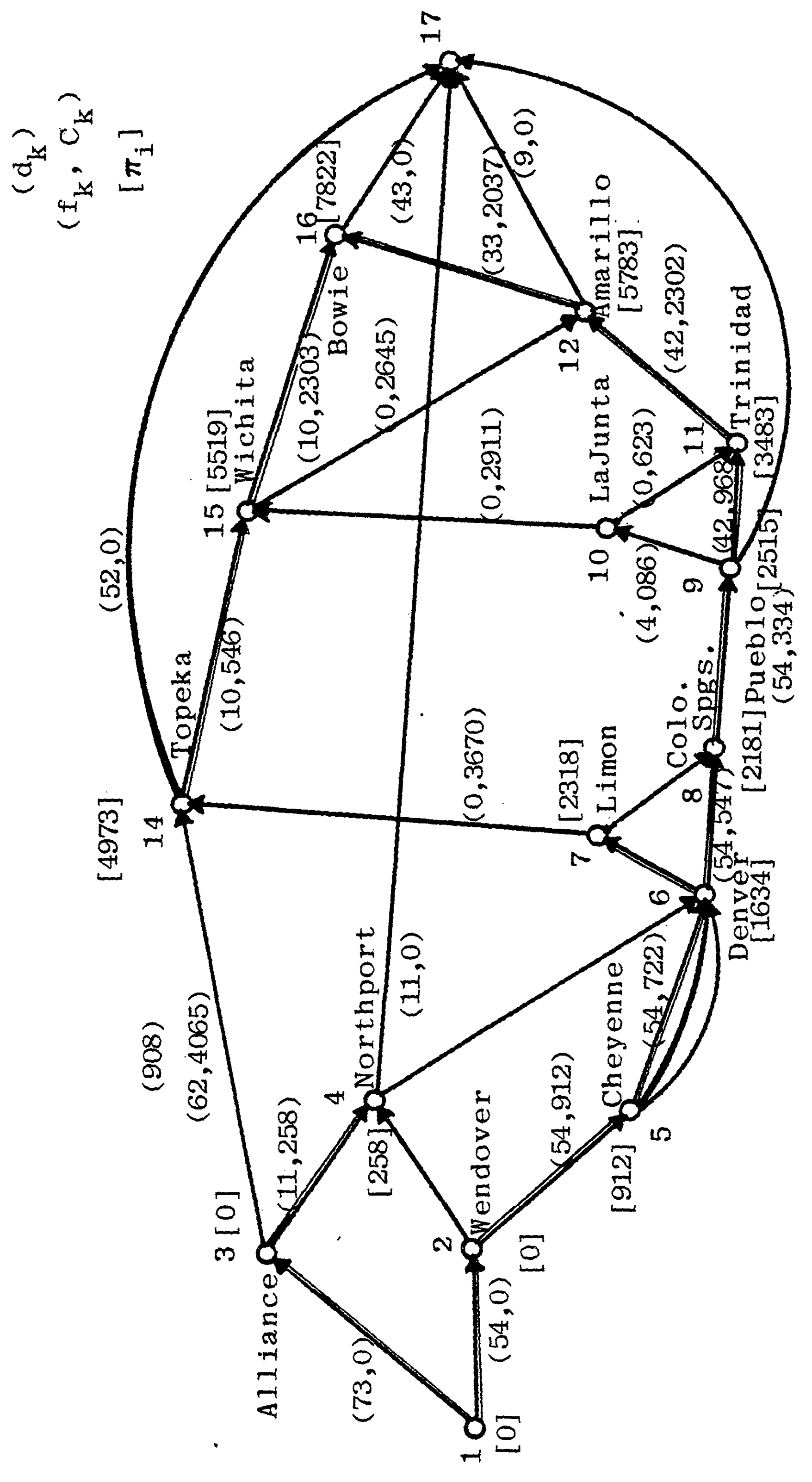


Figure C-2: Network with Basis Tree

Arc	Flow
1,2	54
1,3	73
3,4	11
2,5	54
5,6	54
6,8	54
8,9	54
9,11	42
11,12	42
12,16	33
3,14	62
14,15	10
15,16	10

The results are the same as the results obtained by OKA.

Nonbasic Primal Method

The steps are as follows:

a) Find a primal feasible solution using MAXFLO algorithm.

b) Find node potentials through basic arcs and d_k's for all the nodes and arcs:

$$d_k = \pi_i + C_k - \pi_j$$

c) Find a cycle with negative cost in the marginal network using ROOT algorithm. If none exists, stop with optimum solution.

d) Find list of arcs on the negative cycle.

e) Determine the maximum flow change in the cycle that maintains the arc feasibility. Change the flow in the cycle. Go to step (a).

New cost d_k's are calculated from the node potentials and original costs.

Arc i,j	New Cost d_k	Flows
1,3	0	73
1,2	0	54
3,4	0	11
2,4	517	0
2,5	0	54
5,6	0	54
4,6	288	0
6,7	0	33
6,8	0	21
7,8	730	0
8,9	0	21
9,10	0	0
10,11	141	0
9,11	0	9
11,12	0	9
12,16	-1,015	0
10,15	622	0
15,12	3,394	0
3,14	1,923	62
7,14	0	33
14,15	0	43
15,16	0	43

Start with the spanning tree developed with MAXFLO algorithm in Primal Basic method. It is illustrated in Figure C-3.

Calculate all node potentials along the basic arcs.

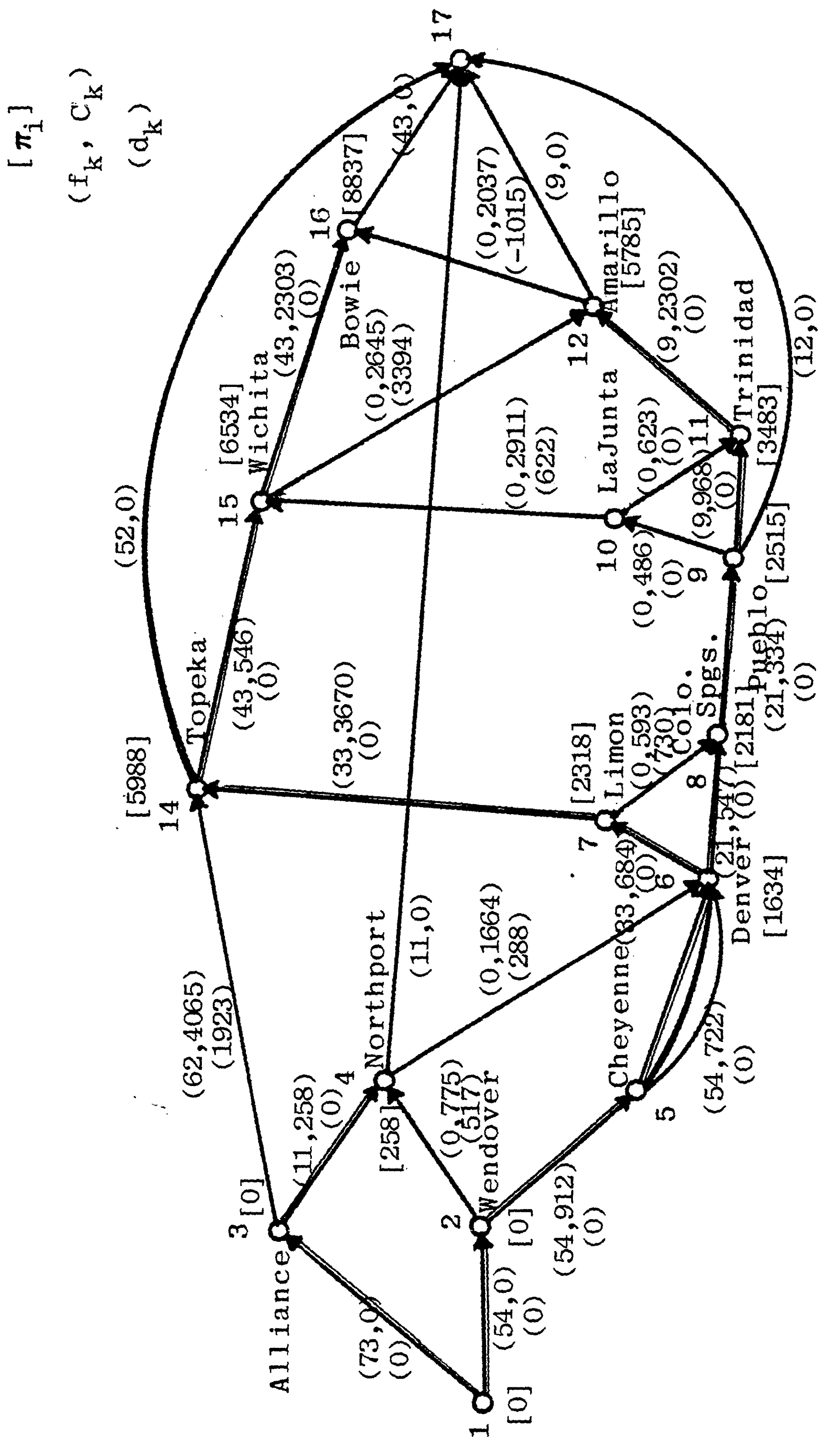


Figure C-3: Network with Flow and Cost

Node i	Potential π_i
1	0
2	0
3	4
4	258
5	912
6	1,634
7	2,318
8	2,181
9	2,515
10	3,001
11	3,483
12	5,785
14	5,988
15	6,534
16	8,837

Select root 6 and find a cycle on 6 following ROOT algorithm. Two branches on spanning tree are (6,8,9,11,12) and (6,7,14,15,16). The cycle is 6,8,9,11,12,16,15,14,7,6. The value of the cycle is (0 + 0 + 0 + 0 - 1,015 - 0 - 0 - 0 - 0) = -1,015. The cycle is negative.

The nonbasic arc comes to basis with a maximum flow change of 33. Change the flow. The new basis tree is shown in Figure C-4.

Node potentials and new costs are calculated. No other negative cycle is found. The optimum solution is reached.

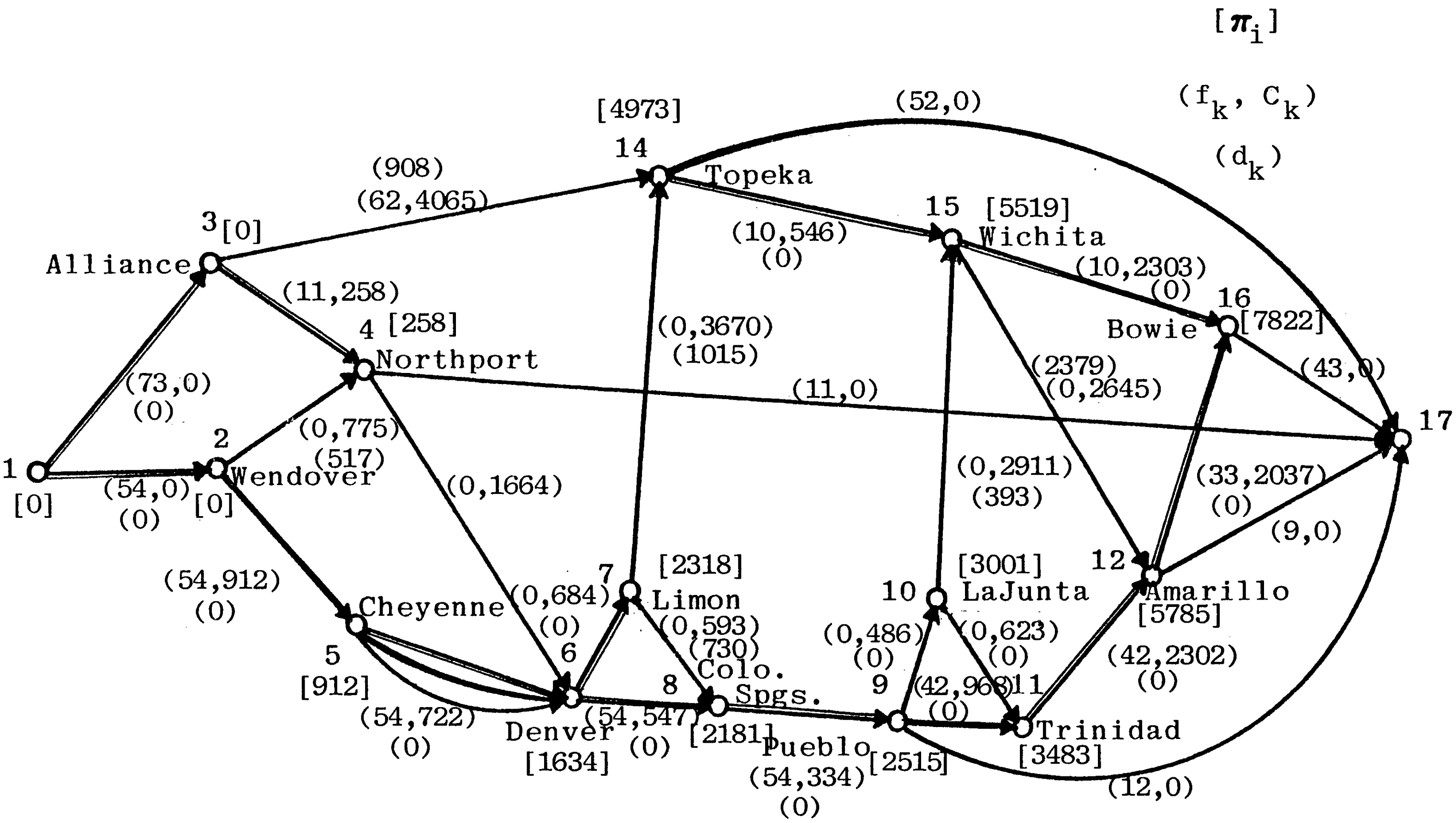


Figure C-4: Network with f_k,C_k and d_k

Node i	Potentials π_i
1	0
2	0
3	0
4	258
5	912
6	1,634
7	2,318
8	2,181
9	2,515
10	3,001
11	3,483
12	5,785
14	4,973
15	5,519
16	7,822

Arc i,j	Flow	New Cost d_k
1,2	54	0
1,3	73	0
2,4	0	517
3,4	11	0
2,5	54	0
5,6	54	0
6,7	0	0
6,8	54	0
8,9	54	0
9,10	0	0
10,11	0	0
10,15	0	393
9,11	42	0
11,12	42	0
12,16	33	0
3,14	62	908
7,14	0	1,015
14,15	10	0
15,16	10	0

The flows are the same as OKA.

Dual Node Infeasible Method

The major steps for this algorithm are as follows:

a) Change the network with one source and one sink.

b) Find the least cost path in the network by finding node potentials in the marginal network.

c) Set all flows to zero.

d) Find shortest path from source to sink.

e) Increase the flow in the path to meet the demand.

From Node i	To Node j	Cost	π_j	Minimum π_j	New Cost d_k
1	2	0	0	0	0
1	3	0	0	0	0
2	4	775	775	258	517
3	4	258	258	258	0
2	5	912	912	912	0
4	6	1,664	1,922	1,634	288
5	6	722	1,634	1,634	0
6	7	684	2,318	2,318	0
6	8	547	2,181	2,181	0
7	8	593	2,911	2,181	730
7	14	3,670	5,988	4,065	1,923
3	14	4,065	4,065	4,065	0
8	9	334	2,515	2,515	0
9	10	486	3,001	3,001	0
9	11	986	3,483	3,483	0
10	11	623	3,624	3,483	141
10	15	2,911	5,912	4,611	1,301
14	15	546	4,611	4,611	0
11	12	2,302	5,785	5,785	0
15	12	2,645	7,256	5,785	1,471
12	16	2,037	7,822	6,914	908
15	16	2,303	6,914	6,914	0

The node potentials are shown in Figure C-5, and the path is shown with a dark line.

Flow is maximized along the shortest path to meet the external flows. The arc flows are as follows:

i	j	Flow
1	2	21
1	3	73
3	4	11
4	17	11
2	5	21
5	6	21
6	8	21
8	9	21
9	17	12
9	11	9
11	12	9
12	17	9
3	14	62
14	17	52
14	15	10
15	16	10
16	17	10

The admissible arcs and the new least cost path is shown in Figure C-6.

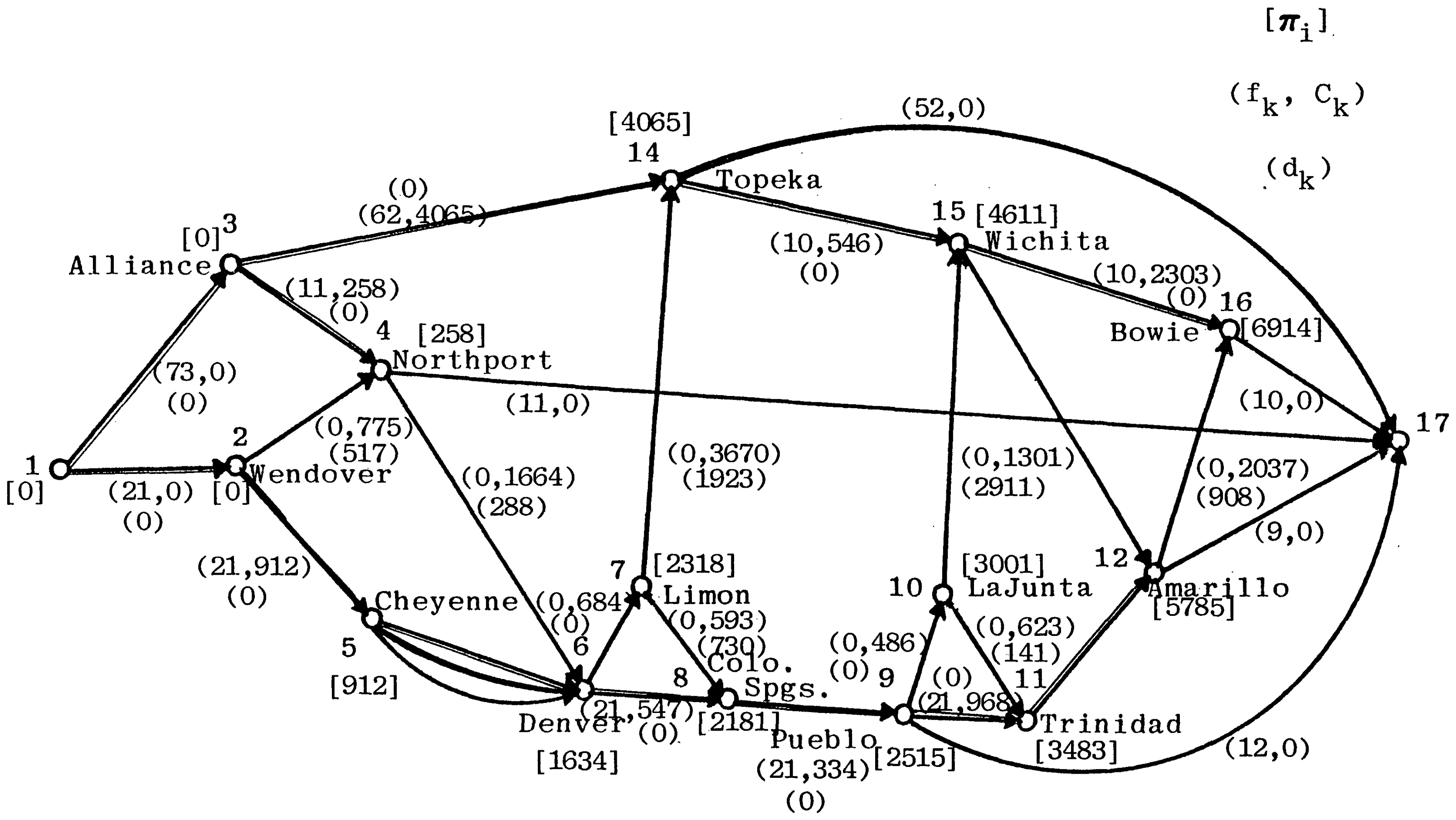


Figure C-5: Network with Maximum Possible Flow

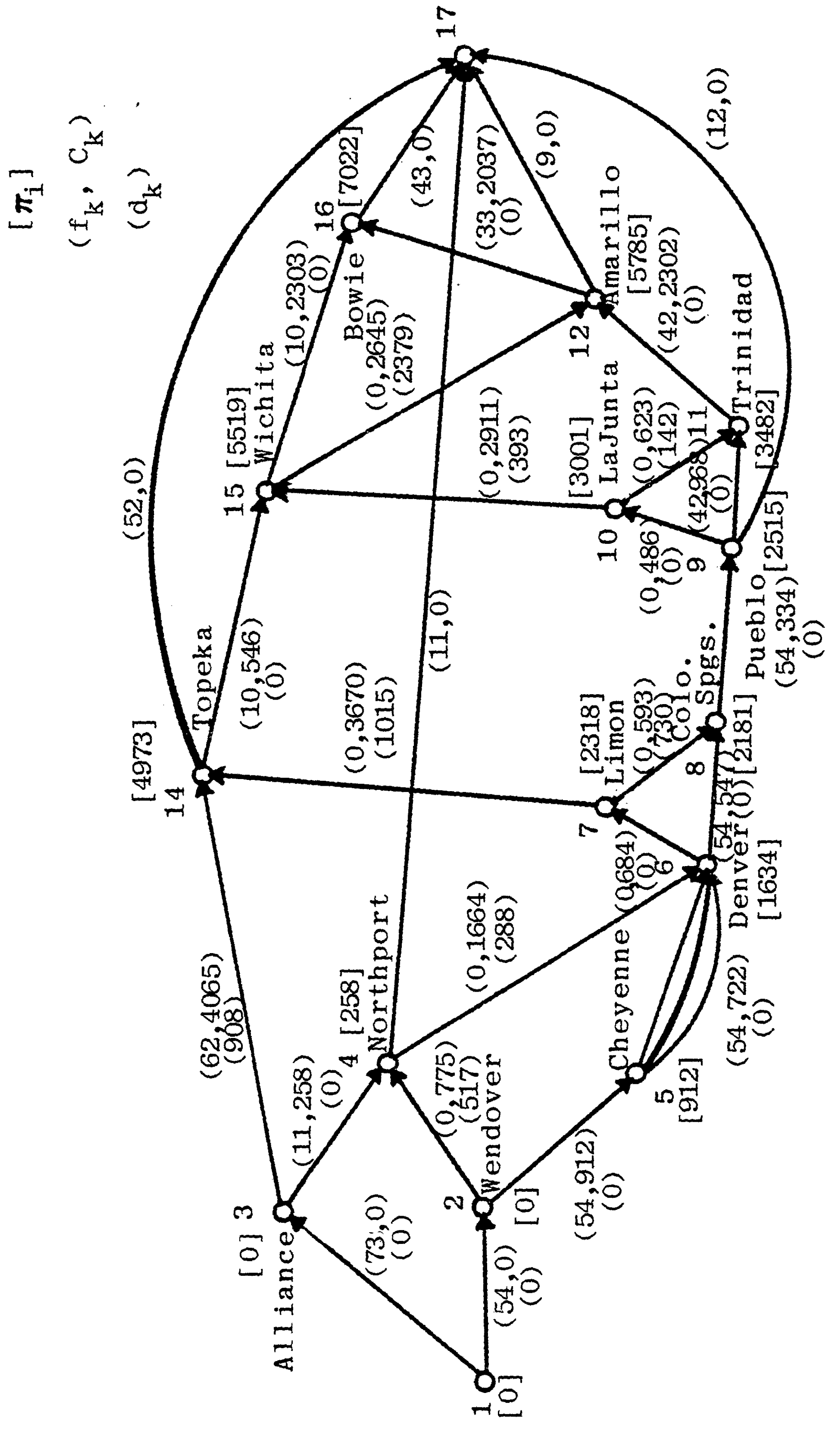


Figure C-6: Network with Optimum Flow

The admissible arcs and the new least cost path is shown in Figure C-6.

From Node i	To Node j	π_j	Minimum $_j$	New Cost d_k
1	2	0	0	0
1	3	0	0	0
3	4	258	258	0
2	4	775	258	517
2	5	912	912	0
5	6	1,634	1,634	0
4	6	1,922	1,634	288
6	7	2,318	2,318	0
6	8	2,181	2,181	0
7	8	2,911	2,181	730
7	14	5,988	4,973	1,015
8	9	2,515	2,515	0
9	10	3,001	3,001	0
10	15	5,912	5,519	393
10	11	3,624	3,482	142
11	12	5,785	5,785	0
14	13	908	0	908
12	16	7,022	7,022	0
16	15	5,519	5,519	0
15	14	4,973	4,973	0
15	12	7,898	5,785	2,379
16	17	7,022	7,022	0

The shortest path in the network is designated as (1,2,5,6,8,9,11,12,16) to satisfy the demand on 16,17. No mirror admissible arc belongs to the shortest path. Maximum flow of 33 is increased and the optimum flow is:

Arc	Flow
1,2	54
1,3	73
3,14	62
14,15	10
15,16	10
3,4	11
2,5	54
5,6	54
6,8	54
8,9	54
9,11	42
11,12	42
12,16	33

This is the same as the OKA results.