Table 6. Total network time (TSUMM) and total network distance (TLINK) versus trade-off factor.

Program	Factor	TSUMM	TLINK
BUILDER		1418.4	261.8
PLANET1	0.0	1418.4	259.5
PLANET1	0.2	1418.7	257.3
PLANET1	0.6	1421.0	249.5
PLANET1	1.0	1425.4	245.4
PLANET1	3.0	1432.1	241.7
PLANET1	5.0	1439.6	237.5
PLANET1	10.0	1481.0	228.9
PLANET1	15.0	1489.9	228.3
PLANET1	100.0	1558.2	226.0
PLANET1	999.9	1803.2	224.4
MINSPAN		1803.2	224.4
MINTREE		1929.9	215.6

imum spanning tree algorithm to determine the best network they can. PLANET1 and PLANET2 do this with very reasonable computation times. The computational times on Oregon State University's CDC Cyber 73 computer, for the network in Figure 9 were approximately 2.4 s for PLANF1 (PLANF1 generates the input file for PLANET1) and 1.4 s for PLANET1. For a similar network that has three links of different classes between each pair of nodes, the computation times for PLANET2 were approximately 10 s for PLANF2 (PLANF2 generates the input file for PLANET2) and 4 s for PLANET2.

PLANET1 should be used when the information about the network is limited. PLANET2 should be used if (a) the actual construction, maintenance, and operating costs are available; (b) different roadway classes are to be used; or (c) the demands for the individual activities are used. Some additions to PLANET1 and PLANET2 that may be possible are to

1. Divide the traffic into different vehicle classes,
2. Determine which links should be closed and which should be open at a lower class when they are not in the tree, and
3. Take roadway capacities into consideration.

These are some of the additions that should be considered in the future development of PLANET1 and PLANET2.

These two programs make it possible for the analyst or decisionmaker to analyze and evaluate the trade-offs in construction and maintenance cost as convenience is increased, that is as travel time or operating costs are reduced. Since many activities with varying objectives must be served by a forest road network, the transportation planning task is complex. Computerized techniques that indicate the trade-offs between networks identified according to differing criteria assist the decisionmaker in identifying the appropriate roadway arterial, collector, and local systems.

REFERENCES

1. Forest Service Manual. U.S. Forest Service, U.S. Department of Agriculture, 1976.
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Analyzing Transportation Networks for Rural Development

EDWARD C. SULLIVAN

This paper describes a new version of the Timber Transport Model, which is a comprehensive route analysis and network optimization computer program developed to support land management planning in rural forest areas. The technique is generally applicable to transportation economic analysis in any rural setting and involves the transportation of resources or agricultural commodities in a many-to-few shipping pattern. The overall capabilities and problem size limits of the program are described. Program features are illustrated through a simple example. The technique is compared with the classical transshipment problem, with which it has certain features in common. The mathematical formulations used in the program are also presented.

This paper describes the Timber Transport Model, a comprehensive network analysis computer program created to support national forest transportation and lane management planning. A previous version of this program has existed for a number of years and has been used in the selection of capital investments, maintenance levels, and, in some cases, network rehabilitation priorities following slides, floods, and other transportation emergencies (1,2). The current version contains several operational simplifications and enhancements, in many cases suggested by users throughout the country.

This technique was developed under sponsorship of

the U.S. Forest Service, and consequently contains features intended to facilitate analysis of timber haul. However, it is suited to a wide range of rural transport planning situations--in particular, the analysis of penetration road networks in developing regions.

The problems to which the Timber Transport Model is suited have the following characteristics:

1. Network investment and management decisions are based primarily on service to resource-based commerce, such as agriculture, mining, or (as in the national forests) logging;
2. Transport needs are predominantly many-to-few in character, such as in farm-to-market or forest-to-mill transport;
3. Commercial transport needs are multicommodity in nature in that different market locations may exist for different goods;
4. Transportation planning, although attempting to serve numerous objectives and users, is dominated by considerations of economic and financial feasibility and market advantage; and
5. Engineering economic analysis considers the

total benefits and costs associated with the transportation system; that is, the analysis extends to benefits and costs in construction, maintenance, and user operations (user costs and benefits are usually the largest components).

Classical network analysis involves the systematic exploration of alternative routes and tallying their costs, traffic, and other consequences. Network analysis is used in planning through its application to both land use and transportation network alternatives. The Timber Transport Model provides a convenient computerized way to perform classical network analysis in fairly large real-world networks. In addition, it provides the option of network optimization, based on either cost minimization or present worth maximization. As desired, network optimization can be performed for a static situation or for multiple time periods with discounting.

Like its predecessor, the new version of the Timber Transport Model is specifically designed to place the capabilities of computerized network analysis, traffic estimation, and mathematical programming into the hands of field personnel that have relatively little specialized training in planning methods, quantitative analysis, or economics. Intended users are staff engineers and planners at field offices located throughout the country.

Our purpose here is twofold: to introduce the capabilities of the Timber Transport Model, and to show how transportation planning can be included in rural development planning. This is accomplished in two sections, the first of which describes the program, and the second of which documents an example application. The paper presents a brief discussion of implementation and transferability considerations and concludes with the mathematical program formulations used in optimization.

PROGRAM DESCRIPTION

The Timber Transport Model contains three principal capabilities:

1. Route analysis for network alternatives, which includes finding best and several next-best routes in a network on the basis of minimum operating cost, minimum travel time, or minimum travel distance;
2. Traffic assignment, which determines link traffic volumes associated with any selected set of travel routes; and
3. Network optimization, which determines the most economic combination of routes and link changes to achieve either minimum cost or maximum present worth (revenues minus transport costs).

Table 1 contains a summary of the particular features within each of the three principal model capabilities. Size limitations of problems that can be solved are listed in the table below.

Item	Must Not Exceed
Links	1000
Nodes	1400
Origins	100
Destinations	15
Best and next-best routes generated per origin	10
Time periods for discounting	7
Capital investment projects, integer 0-1 variables	99
Link volume capacities	50

The Timber Transport Model incorporates routines for data input and verification, network editing, minimum path and next-best-path estimation, traffic assignment, and mixed-integer mathematical programming.

EXAMPLE PROBLEMS

Three simple examples are used to illustrate several features of the Timber Transport Model. The first demonstrates the route-finding capability of the program, which is a necessary first pass in order to provide input to other steps. The second example demonstrates a traffic assignment. The third shows what is involved in finding the least-cost combination of capital investment alternatives for a rural transportation network to be used in a 20-year program of logging. These examples are simplified versions of the types of problems to which the model is applied in national forests throughout the United States. Although problems of this simplicity would never be solved by computer, because manual solutions are preferable for such simple problems, they are used here because representative real-world examples are too lengthy for useful illustration.

Figure 1 illustrates the existing road network in the hypothetical forest region that is the subject of our example. Each road section is crudely described in terms of its grade, quality of alignment, length, and surface type. This information is the basis for a network representation of the system, contained in Figure 2. Link geometry, condition, and surface type are used to define a link class. Unit costs ($/km) and average running speeds for different vehicles and load conditions are then associated with each class and provide a convenient method to establish costs and travel times for all network links without having to code this information separately for each link. Since many different

Table 1. Summary of model features.

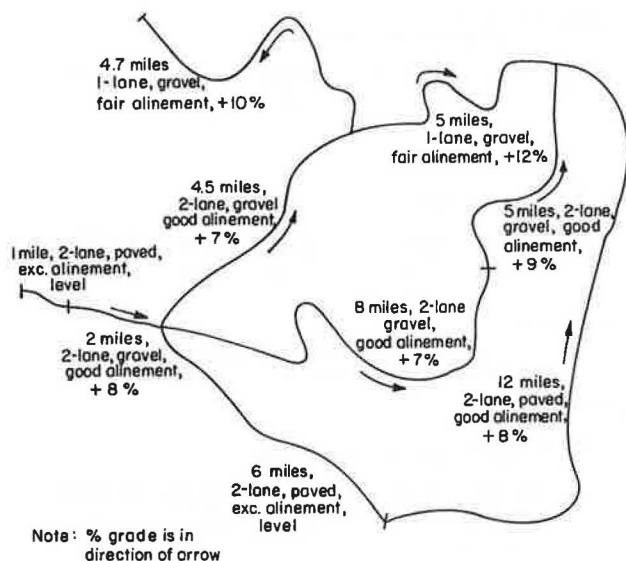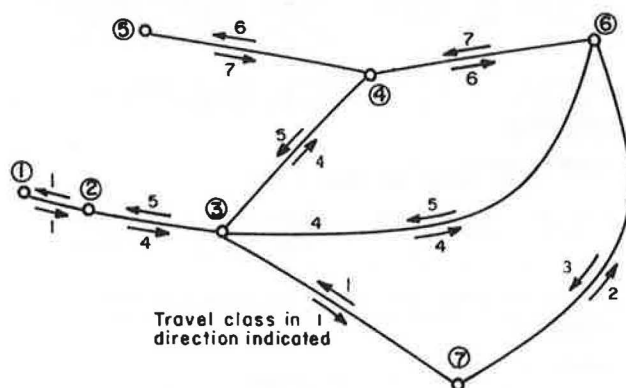| Capability	Feature	Capability	Feature
Route analysis	Finds shortest routes based on travel cost, distance, or travel time Finds shortest and up to nine next shortest routes Permits selected commodities to be shipped to a specified subset of destinations Permits shortest routes to include intermediate stops for repackaging or processing Permits direct input of user-added routes	Optimization	Selects network investment projects from up to 99 alternatives that span up to seven time periods Projects are selected either to minimize the sum of capital and operating costs or to maximize product revenues minus capital and operating costs Model can select the optimal time periods in which to ship commodities Constraints may be imposed on shipment quantities, link traffic, and total capital investment in any time period Origin productivities may vary among time periods
Assignment	Accommodates both all-or-nothing and multipath traffic assignment Output includes traffic in vehicles and volumes of commodities Traffic output is separate for different time periods		

Figure 1. Example road system.

4.7 miles
1-lane, gravel,
fair alinement, +10%

5 miles,
1-lane, gravel,
fair alinement, +12%

4.5 miles,
2-lane, gravel
good alinement,
+7%

5 miles, 2-lane,
gravel, good
alinement,
+9%

1 mile, 2-lane, paved,
exc. alinement,
level

2 miles,
2-lane, gravel,
good alinement,
+8%

8 miles, 2-lane
gravel,
good alinement,
+7%

12 miles,
2-lane, paved,
good alinement,
+8%

6 miles,
2-lane, paved,
exc. alinement,
level

Note: % grade is in
direction of arrow

Figure 2. Example road system with node numbers and link travel classes assigned.

Travel class in 1
direction indicated

links commonly have similar physical characteristics, and therefore fall into the same class, this method reduces the labor involved in network coding substantially.

Travel speeds and vehicle operating costs associated with the different link classes may be obtained from a variety of published sources. Most current users of the model use U.S. Forest Service-compiled cost data for logging trucks (3). The agency periodically publishes unit costs for logging trucks that correspond to a system of 320 standard link classes that are considered to be appropriate for conditions typical of the U.S. national forests (4). For developing countries and applications other than logging, it would be appropriate to use cost data from other sources, such as data gathered by the British Road Research Laboratory in Kenya and more recently by the World Bank and the Brazilian government in Brazil (5,6).

Route Analysis

In order to perform route analysis the origin nodes, destination nodes, unit costs, travel times, estimates of the quantities to be shipped from each origin node, and the average truckload must be specified. One must also specify how routes are to

be selected, for example, the three best routes computed on the basis of minimum travel cost.

Figure 3 shows the model output in the case of the example; where nodes 4, 5, and 6 are origin nodes that ship, respectively, 6, 12, and 5 million board ft annually. (The average load is 5000 board ft/truck.) Node 1 is specified as the destination. In this run, the model evaluates the three shortest routes on the basis of cost, followed by the three shortest routes on the basis of travel time. Although these are identical in this case, they are not always so.

Traffic Assignment

Figure 4 shows the result of using the model to perform an all-or-nothing traffic assignment by using the least-cost routes determined previously. To produce this result, it is necessary to specify, for each origin, the proportion of its shipment that uses each route. Through such specifications, a tally of the traffic consequences of, for example, routing half of a shipment one way, half another is simple.

At this stage, it would be possible to introduce any other routes for evaluation and use in traffic assignment. This is accomplished by listing the nodes through which a route reaches a destination from its origin. This is not illustrated in the example.

Optimization

Figure 5 illustrates how the model is used to solve network optimization problems. The first step involves creation of a network that contains links that are identified as investment projects; that is, portions of the network that can be used for traffic only if an associated capital cost is incurred. Projects are specified by means of network updates. The revised network, which contains projects, is then subjected to route analysis by following the method illustrated in Figure 3. The result is a collection of alternative travel routes, some of which use projects, others not. At this stage, it is essential to confirm that the available routes contain all significant combinations of implementing and not implementing the projects under consideration.

Once route analysis is complete for the network that contains the candidate investment projects, economic optimization can begin. The result of using the model to compute the overall least-cost network and routing pattern for the specified quantity of timber appears in Figure 5. In this example the optimization problem is defined for three time periods. For each period, maximum and minimum limits are imposed on the total amount to be shipped.

To illustrate a form of sensitivity analysis, Figure 5 shows how the origin volumes and capital costs of projects can be changed at optimization time. The model determines which combination of projects, routes, and shipments from the various origins produces the overall least-cost solution. In this simple example, the result is intuitive--to defer the most-expensive shipments as long as possible, subject to satisfaction of the minimum constraints of shipping 3 million board ft in each of the early time periods. The result is that investment project 1 is economically justified in that the associated savings in user cost exceed the size of the investment.

DISCUSSION OF RESULTS

This approach to network analysis is significantly

Figure 3. Output for route-finding example.

```
PLEASE GIVE OUTPUT TO    ED SULLIVAN
*** OUTPUT FROM ASCII FORTRAN TIMBER MODEL ***
YOUR INPUT CRITERIA FILE NAME IS    CRIT1.
YOUR INPUT LINK FILE NAME IS    LINKS.
YOUR UPDATED LINK FILE NAME IS
YOUR OUTPUT TRAFFIC FILE NAME IS    TRAF1.
YOUR MESSAGE FILE NAME IS    MESS1.
YOUR DOCUMENT FILE NAME IS    DOC1.
@XQT ITS*BBTIMBER.TIMBRIIX
TRANSPORTATION TIMBER MODEL PROGRAM

DATA   RUN

NMIL =  1, NMKT =  1, NSAL =   3
NPATHS =  2, TRUCK LOADING = 5.000

MILLS-
MILL DESCRIPTION                    NODE  MIN-VOL  MAX-VOL
                              S001    1   NONE  UNLIMITED

MARKETS-

                              S001    1
```

MARGINAL LOG HAUL COSTS –

FOR KTYP =	1	2	3	4	5	6	7
UP TO DISTANCE= 100.000–...328	.139	.428	.236	.469	.264	.600	.
FROM 100.000 TO 200.000–...328	.139	.428	.236	.469	.264	.600	.
BEYOND DISTANCE= 200.000–...328	.139	.428	.236	.469	.264	.600	.

MARGINAL LUMBER HAUL COSTS –

FOR KTYP =	1	2	3	4	5	6	7
UP TO DISTANCE= 100.000–...328	.139	.428	.236	.469	.264	.600	.
FROM 100.000 TO 200.000–...328	.139	.428	.236	.469	.264	.600	.
BEYOND DISTANCE= 200.000–...328	.139	.428	.236	.469	.264	.600	.

```
NEW LINK CLASS SPEEDS UP TO CLASS   7

55.00 27.00 48.00 27.00 42.00 17.00 20.00

PATH CRITERIA - COST TIME


NO UPDATES

SALES-
```

SALE NODE	SALE DESCRIPTION	ROAD MILE POST	SALE CODE	VOL- UME	TRUCK LOAD	NO.OF TRUCKS	B	ALLOWED MILL DESTINATIONS
6			T001	5000.	5.	1000		S001
5			T002	12000.	5.	2400		S001
4			T003	6000.	5.	1200		S001

```
**************

GENERATED ROUTE NO.    1
          1ST SHORTEST PATH  BASED ON COST
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TOT COST	ASSOCIATED DISTANCE	ASSOCIATED TIME
6	1	1	3.495	12.500	25.377
PATH/	6–	4–	3–	2–	1–

```
**************

GENERATED ROUTE NO.    2
          2ND SHORTEST PATH  BASED ON COST
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TOT COST	ASSOCIATED DISTANCE	ASSOCIATED TIME
6	1	1	4.099	16.000	22.520
PATH/	6–	3–	2–	1–	

```
$$$$$$$$$$$$$$
**************

GENERATED ROUTE NO.    3
          1ST SHORTEST PATH  BASED ON COST
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TOT COST	ASSOCIATED DISTANCE	ASSOCIATED TIME
5	1	1	3.397	12.200	24.477
PATH/	5–	4–	3–	2–	1–

```
**************

GENERATED ROUTE NO.    4
          2ND SHORTEST PATH  BASED ON COST
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TOT COST	ASSOCIATED DISTANCE	ASSOCIATED TIME
5	1	1	8.641	25.700	54.267
PATH/	5–	4–	6–	3–	2–	1–

```
$$$$$$$$$$$$$$
**************
```

Figure 3. Continued.

```
GENERATED ROUTE NO.    5
          1ST SHORTEST PATH  BASED ON COST
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TOT COST	ASSOCIATED DISTANCE	ASSOCIATED TIME
4	1	1	1.855	7.500	10.377
PATH/	4–	3–	2–	1–	

```
**************

GENERATED ROUTE NO.    6
          2ND SHORTEST PATH  BASED ON COST
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TOT COST	ASSOCIATED DISTANCE	ASSOCIATED TIME
4	1	1	7.099	21.000	40.167
PATH/	4–	6–	3–	2–	1–

```
$$$$$$$$$$$$$$

LEAST COST PATH TOTAL UNDISCOUNTED COST FOR VOLUME
     23000.00 FROM   3 SALE NODES = $            .00

**************

GENERATED ROUTE NO.    7
          1ST SHORTEST PATH  BASED ON TIME
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TIME	ASSOCIATED DISTANCE	ASSOCIATED COST
6	1	1	22.520	16.000	4.099
PATH/	6–	3–	2–	1–	

```
**WARNING** IDENTICAL TOTAL COST AND SALE ORIGIN AS PREVIOUSLY
GENERATED PATH.   IT WAS NOT WRITTEN ONTO YOUR TRAFFIC FILE
**************

GENERATED ROUTE NO.    8
          2ND SHORTEST PATH  BASED ON TIME
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TIME	ASSOCIATED DISTANCE	ASSOCIATED COST
6	1	1	25.377	12.500	3.495
PATH/	6–	4–	3–	2–	1–

```
**WARNING** IDENTICAL TOTAL COST AND SALE ORIGIN AS PREVIOUSLY
GENERATED PATH.   IT WAS NOT WRITTEN ONTO YOUR TRAFFIC FILE
$$$$$$$$$$$$$$
**************

GENERATED ROUTE NO.    9
          1ST SHORTEST PATH  BASED ON TIME
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TIME	ASSOCIATED DISTANCE	ASSOCIATED COST
5	1	1	24.477	12.200	3.397
PATH/	5–	4–	3–	2–	1–

```
**WARNING** IDENTICAL TOTAL COST AND SALE ORIGIN AS PREVIOUSLY
GENERATED PATH.   IT WAS NOT WRITTEN ONTO YOUR TRAFFIC FILE
**************

GENERATED ROUTE NO.   10
          2ND SHORTEST PATH  BASED ON TIME
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TIME	ASSOCIATED DISTANCE	ASSOCIATED COST
5	1	1	54.267	25.700	8.641
PATH/	5–	4–	6–	3–	2–	1–

```
**WARNING** IDENTICAL TOTAL COST AND SALE ORIGIN AS PREVIOUSLY
GENERATED PATH.   IT WAS NOT WRITTEN ONTO YOUR TRAFFIC FILE
$$$$$$$$$$$$$$
**************

GENERATED ROUTE NO.   11
          1ST SHORTEST PATH  BASED ON TIME
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TIME	ASSOCIATED DISTANCE	ASSOCIATED COST
4	1	1	10.377	7.500	1.855
PATH/	4–	3–	2–	1–	

```
**WARNING** IDENTICAL TOTAL COST AND SALE ORIGIN AS PREVIOUSLY
GENERATED PATH.   IT WAS NOT WRITTEN ONTO YOUR TRAFFIC FILE
**************

GENERATED ROUTE NO.   12
          2ND SHORTEST PATH  BASED ON TIME
```

TIMBER SALE NODE	MILL NODE	APPRAISAL NODE	MINIMUM TIME	ASSOCIATED DISTANCE	ASSOCIATED COST
4	1	1	40.167	21.000	7.099
PATH/	4–	6–	3–	2–	1–

```
**WARNING** IDENTICAL TOTAL COST AND SALE ORIGIN AS PREVIOUSLY
GENERATED PATH.   IT WAS NOT WRITTEN ONTO YOUR TRAFFIC FILE
$$$$$$$$$$$$$$

LEAST TIME PATH TOTAL UNDISCOUNTED COST FOR VOLUME
     23000.00 FROM   3 SALE NODES = $            .00

THE FOLLOWING ROUTES (IDENTIFIED BY ROUTE NUMBER)
WERE NOT ADDED TO YOUR TRAFFIC FILE BECAUSE THEY WERE
EITHER DUPLICATE PATHS OR PATHS THAT USED PROJECT LINKS
WITHOUT COMMON TIME PERIOD AVAILABILITY
    7    8    9   10   11   12
```

Figure 4. Output for traffic-assignment example.

```
PLEASE GIVE OUTPUT TO   ED SULLIVAN
*** OUTPUT FROM ASCII FORTRAN TIMBER MODEL ***
YOUR INPUT CRITERIA FILE NAME IS   CRIT2.
YOUR INPUT LINK FILE NAME IS   LINKS.
YOUR INPUT TRAFFIC FILE NAME IS   TRAF1.
YOUR MESSAGE FILE NAME IS   MESS2.
YOUR DOCUMENT FILE NAME IS   DOC2.
@XQT ITS*BBTIMBER.TIMBRIIX
TRANSPORTATION TIMBER MODEL PROGRAM

PICK  RUN

SALES-
SALE  SALE DESCRIPTION    ROAD MILE  SALE VOL-   TRUCK NO.OF  B  ALLOWED MILL
NODE                      POST CODE   UME  LOAD TRUCKS          DESTINATIONS
  6                            T001 5000.   5.  1000            S001
  5                            T002 12000.  5.  2400            S001
  4                            T003 6000.   5.  1200            S001

USER SELECTED PATHS
       GENERATED    SALE  NEXT BEST  MINIMUM PATH  PERCENTAGE OF
      ROUTE NUMBER  NODE  PATH NO.    CRITERION    VOLUME ALLOWED
                                                     OVER PATH
            1        6        1          COST         100.00
            3        5        1          COST         100.00
            6        4        2          COST         100.00
NO USER DEFINED PATHS INCLUDED
```

Figure 5. Output for least-cost network and routing pattern.

```
PLEASE GIVE OUTPUT TO   ED SULLIVAN
*** OUTPUT FROM ASCII FORTRAN TIMBER MODEL ***
YOUR INPUT CRITERIA FILE NAME IS   CRIT4.
YOUR INPUT LINK FILE NAME IS   LINKS.
YOUR INPUT TRAFFIC FILE NAME IS   TRAF3.
YOUR WORKING MATRIX FILE NAME IS   MAT4.
YOUR MESSAGE FILE NAME IS   MESS4.
YOUR DOCUMENT FILE NAME IS   DOC4.
@XQT ITS*BBTIMBER.TIMBRIIX
TRANSPORTATION TIMBER MODEL PROGRAM

OPT3  RUN

SALES-
SALE  SALE DESCRIPTION    ROAD MILE  SALE VOL-   TRUCK NO.OF  B  ALLOWED MILL
NODE                      POST CODE   UME  LOAD TRUCKS          DESTINATIONS
  6                            T001 5000.   5.  1000            S001
  5                            T002 12000.  5.  2400            S001
  4                            T003 6000.   5.  1200            S001

3 PERIODS
   INTEREST RATE = .03
   PROJECT COSTS OCCUR  .10 THROUGH PERIOD
   HAUL COSTS AND PROFITS OCCUR  .50 THROUGH PERIOD

NUMBER OF LINES OF TIME PERIOD SALE VOLUMES =   0

  PERIOD 1 BEGINS YEAR  0 ENDS YEAR  1
  PROJECT YEAR SET TO  0 HAUL YEAR SET TO  1
  PROJECT COST DISCOUNT FACTOR 1.0000 HAUL DISCOUNT FACTOR .9709

  PERIOD 2 BEGINS YEAR  1 ENDS YEAR  6
  PROJECT YEAR SET TO  1 HAUL YEAR SET TO  4
  PROJECT COST DISCOUNT FACTOR .9709 HAUL DISCOUNT FACTOR .8885

  PERIOD 3 BEGINS YEAR  6 ENDS YEAR 10
  PROJECT YEAR SET TO  6 HAUL YEAR SET TO  8
  PROJECT COST DISCOUNT FACTOR .8375 HAUL DISCOUNT FACTOR .7894

    CHANGES IN PROJECT DATA
    PROJECT   UNDISC. COST BEGINS  ENDS
       1        50000.     1       3
       2         1300.     1       3

TOTAL FOREST HARVEST CONSTRAINTS
TIME MINIMUM MAXIMUM
PER. VOLUME  VOLUME
* 1  3000.0 23000.0 VALUES ASSUMED*
* 2  3000.0 23000.0 VALUES ASSUMED*
* 3  3000.0 23000.0 VALUES ASSUMED*
NO USER ADDED PATHS GIVEN


**CHOSEN PATHS**


GENERATED ROUTE NO.   2
    PATH NODES      6-    4-    3-    2-    1-
TIME          TRUCK- UNIT
PER. VOLUME   LOADS  COST TOTAL COST
----  ------  ------- ----- ----------
 3    5000.   1000   3.50   17475.
                   ( 2.76)( 13795.)
ALL TIME PERIODS COMBINED:
      5000.   1000   3.50   17475.
                          ( 13795.)
```

Figure 4. Continued.

```
TRAFFIC ASSIGNMENT FOR LOADED TRUCKS

    FROM     TO      TIMBER      ASSOCIATED
    NODE    NODE     TRAFFIC       VOLUME


     2       1        4600        23000.0
     3       2        4600        23000.0
     4       3        3400        17000.0
     4       6        1200         5000.0
     5       4        2400        12000.0
     6       3        1200         6000.0
     6       4        1000         5000.0

TOTAL UNDISCOUNTED HAUL COST ON ASSIGNED PATHS = $      100830.50
```

Figure 5. Continued

```
GENERATED ROUTE NO.   7
    PATH NODES      5-    4-    3-    2-    1-
TIME          TRUCK- UNIT
PER. VOLUME   LOADS  COST TOTAL COST
----  ------  ------- ----- ----------
 3   12000.   2400   3.40   40760.
                   ( 2.68)( 32177.)
ALL TIME PERIODS COMBINED:
     12000.   2400   3.40   40760.
                          ( 32177.)


GENERATED ROUTE NO.  12
    PATH NODES      4-    3-    2-    1-
TIME          TRUCK- UNIT
PER. VOLUME   LOADS  COST TOTAL COST
----  ------  ------- ----- ----------
 1    3000.    600   1.86    5565.
                   ( 1.80)(  5403.)
 2    3000.    600   1.86    5565.
                   ( 1.65)(  4945.)
ALL TIME PERIODS COMBINED:
      6000.   1200   1.86   11131.
                          ( 10348.)

FOR VOLUME  23000.00 TOTAL COST = $   69366.50   DISCOUNTED = $   56319.86

SALE TIME PERIOD HARVEST VOLUMES IN OPTIMAL SOLUTION
SALE NODE TOTAL VOLUME FOR   VOLUMES HARVESTED DURING TIME PERIOD:
          ALL TIME PERIODS   1      2      3
    6        5000.           0.   0. 5000.
    5       12000.           0.   0.12000.
    4        6000.        3000. 3000.    0.

PROJECTS IN OPTIMAL SOLUTION
  PROJECT NUMBER  COST   DISCOUNTED COST
                                         FROM    TO
                                         NODE    NODE
       1      $ 50000.  $ 50000.
                                           3       4
                                           4       3


    TOTAL COST FOR  1 PROJECTS  $    50000.
    DISCOUNTED COST $    50000.

    SOLUTION PRESENT WORTH = $  -106320.


TRAFFIC ASSIGNMENT FOR LOADED TRUCK TRIPS
          ALL TIME PERIODS
FROM  TO   TIMBER  ASSOCIATED  TIMBER VOLUME/(TRUCKS) DURING TIME PERIOD:
NODE NODE  TRAFFIC  VOLUME       1        2        3
 2    1     4600    23000.     3000     3000    17000
                            (  600) (  600) (  3400)
 3    2     4600    23000.     3000     3000    17000
                            (  600) (  600) (  3400)
 4    3     4600    23000.     3000     3000    17000
                            (  600) (  600) (  3400)
 5    4     2400    12000.        0        0    12000
                            (    0) (    0) (  2400)
 6    4     1000     5000.        0        0     5000
                            (    0) (    0) (  1000)
```

different from other network optimization approaches found in the literature. This approach has particular strengths and weaknesses compared with other ways of addressing this type of problem, and these warrant discussion.

Perhaps the closest relative to this approach is the classical transshipment problem, discussed in mathematical programming textbooks such as Dantzig (9, chapter 16). The transshipment problem forms the basis for the Integrated Resource Planning Model, which also has been developed for use in U.S. Forest Service land management planning (10). The classical transshipment formulation can easily be extended to a mixed-integer formulation in which links of the network can be used only in conjunction with a lump-sum capital investment, in the manner of the Timber Transport Model. The transshipment problem can also be embellished with multiple time periods and various practical constraints such that the problems that are addressed by the two methods begin to look similar.

The essential difference between a mixed-integer adaptation of the transshipment problem and the Timber Transport Model lies in the explicit analysis of routes. The transshipment problem does not deal with routes explicitly; therefore, the traffic on any link is not able to be traced to a particular origin-destination source. Thus, particularly in solutions that involve link capacity constraints, it is not always clear how particular shipments should be routed in order to achieve the optimal solution, because determination of who is diverted from congested links is, in large networks, somewhat difficult.

On the other hand, the explicit route analysis incorporated in the Timber Transport Model places a burden on the user to be sure that all significant routing possibilities are considered, a burden not encountered in the transshipment formulation. Although this forces users to examine intermediate output carefully and leads to a better intuitive understanding of how the system is operating, there is no question that a substantial level of effort is involved in finding a solution to a large, practical problem.

Another difference in using explicit routes in the analysis is that it allows determination of optima based on other-than-minimum paths. For example, if the second least-cost route for an origin is preferred because the least-cost route is unacceptable due to vehicle size limitations or some other reason, in the Timber Transport Model, the ineligible route may be dropped prior to optimization.

These simple examples are intended to give an introduction to what the model can do, and, intentionally, many features are excluded that are typically used in day to day transportation planning. For example, instead of minimizing project plus user costs, specification would have been possible for market prices for delivered commodities for each origin, and then the optimization could determine whether shipments from all origins are, in fact, economic, in the sense of contributing to the net worth of the solution. Also, a variety of other constraints are available, including budget constraints on expenditures for projects in different time periods.

IMPLEMENTATION CONSIDERATIONS

The Timber Transport Model is programmed in FORTRAN for the Department of Agriculture's Univac 1100 series computer. In this form, the FORTRAN program produces a matrix for the mixed-integer optimization problem; it then solves the problem by using Sperry Univac's Functional Mathematical Programming System. A second version, with smaller problem size capability, exists on the University of California's CDC 6400 computer, for which the mixed integer optimization problem is solved directly by using a FORTRAN subroutine.

The mathematical program formulations used in the optimization are described in the following section. Additional information about the program is available (7). Copies may be obtained from the Systems Unit of the Institute of Transportation Studies, University of California, Berkeley.

OPTIMIZATION METHOD

Cost Minimization

The mixed-integer formulation for minimizing total transportation cost has the following form:

$$\text{Minimize } z = \sum_{ijkt} C_{ijkt} \cdot X_{ijkt} + \sum_{r} D_r \cdot I_r \tag{1}$$

subject to the following constraints:

Each timber node must export a given timber volume after all time periods,

$$\sum_{jkt} \alpha_i \cdot X_{ijkt} = \overline{T}_i \quad \text{for all timber nodes (i) and periods (t)} \tag{2}$$

Each timber node may export up to a given timber volume in each period,

$$\sum_{jk} \alpha_i X_{ijkt} \leq T_{it} \tag{3}$$

Resource use constraints are necessary for cost minimization,

$$\sum_{ijk} \alpha_i X_{ijkt} \geq \overline{V}_t \quad \text{for each time period (t)} \tag{4}$$

Resource conservation constraints are optional to cost minimization,

$$\sum_{ijk} \alpha_i X_{ijkt} \leq V_t \quad \text{for some periods (t)} \tag{5}$$

$$\sum_{ik} \alpha_i X_{ijkt} \leq K_{jt} \quad \text{for all mills (j) and periods (t)} \tag{6}$$

The traffic on certain links during certain time periods is optionally limited,

$$\sum_{ijk} [P_{lt}] \beta_{it} X_{ijkt} \leq F_{lt} \quad \text{for some links (1) and a time period (t)} \tag{7}$$

The timber volume to each mill in each period has an optional lower bound,

$$\sum_{ij} \alpha_i X_{ijkt} \geq \overline{K}_{jt} \quad \text{for all mills (j) and periods (t)} \tag{8}$$

The traffic on certain links during any period is optionally limited,

$$\sum_{ijke} [P_l] \beta_{it} X_{ijkt} \leq F_l \quad \text{for some links (1) and any time period} \tag{9}$$

Certain routes require certain projects to be built,

$$\sum_{ijke} [U_r] X_{ijkt} - h_r I_r \leq 0 \quad \text{for all projects (r)} \tag{10}$$

where

X_{ijkt} = number of truck trips in period t on the kth route that connects timber node i and mill node j; [An optional formulation that includes the variable Y_{ijkt} to represent independently routed return trips is not described. It follows directly from partitioning $\{X_{ijkt}\}$ and $\{C_{ijkt}\}$ into two equivalent

subsets that apply, respectively, to the loaded and unloaded travel direction.]

C_{ijkt} = round trip cost per truck in period t and route ijk;

I_r = -1, if project r is built, 0 otherwise;

D_r = investment cost associated with project r;

$\bar{T}_i$ = timber volume (MBF) that must be exported from node i in all time periods;

T_{it} = timber volume (MBF) exported from node i in period t;

V_t = upper limit on total timber harvested in period t;

$\bar{V}_t$ = lower limit on total timber harvested in period t;

K_{jt} = maximum allowed volume for mill node j in period t;

$\bar{K}_{jt}$ = smallest acceptable timber volume (MBF) for mill j in period t;

$\bar{F}_{\bar{l}}$ = maximum permissible daily (or monthly, etc.) traffic (trucks) on link l during any time periods;

F_{lt} = maximum permissible daily (or monthly, etc.) traffic (trucks) on link l in time period t;

α_l = average truck load (MBF) for timber from node i;

β_{it} = proportion of timber from node i in period t that is transported during the link capacity period;

$\{P_l\}$ = set of routes (ijk) that use link l during any time period;

$\{P_{lt}\}$ = set of routes (ijk) that use link l during any time period;

$\{U_r\}$ = set of routes (ijk) that require project r to be built;

h_r = arbitrary large constant greater than the total number of trucks from all timber nodes in all periods that use project r;

i = particular timber node;

j = particular lumber node;

k = sequence number of a particular route for a given combination of i and j;

t = particular time period;

r = particular investment project; and

l = particular link in the transportation network.

In the formulation, the Xs and Is are unknowns computed by the solution algorithm. All other parameters are known. All costs are automatically discounted prior to use. Project investment costs are the sum of initial outlays plus a discounted stream of maintenance costs incurred in subsequent periods.

Present Worth Maximization

The option to maximize present worth is achieved by modifying the previous mixed-integer program as follows.

The objective function becomes

$$\text{Maximize } Z' = \sum_{it} W_{it} \left(\sum_{jk} X_{ijkt} \right) - \sum_{ijkt} C_{ijkt} X_{ijkt} - \sum_r D_r I_r \qquad (11)$$

Constraint I becomes

$$\sum_{jk} \alpha_i X_{ijkt} \leqslant \bar{T}'_i \quad \text{for all timber nodes, (i) and all periods (t)} \qquad (12)$$

Resource conservation constraints are necessary for present worth

$$\sum_{ijk} \alpha_i X_{ijkt} \leqslant V_t \quad \text{for each period (t)} \qquad (13)$$

Resource use constraints are optional for present worth

$$\sum_{ijk} \alpha_i X_{ijkt} \geqslant \bar{V}_t \quad \text{for some periods (t)} \qquad (14)$$

The program optionally includes budget constraints

$$\sum_r S_r I_r \leqslant B \qquad (15a)$$

or

$$\sum_r S_r I_r \geqslant \bar{B} \qquad (15b)$$

where

W_{it} = present value of timber cut in period t at node i,

T_{it} = volume of timber available for harvest at node i in all time periods,

V_t = upper limit on total timber harvested in period t,

$\bar{V}_t$ = lower limit on total timber harvested in period t,

S_r = budget cost for project r,

B = upper limit on budget funds available, and

$\bar{B}$ = lower limit on budget funds.

All other parameters are as defined in the preceding section.

ACKNOWLEDGMENT

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