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A PROCEDURE FOR OPTIMALLY ROUTING OVERSIZED/OVERWEIGHT VEHICLES ON A HIGHWAY NETWORK

by

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ABSTRACT

The State of Colorado annually receives in excess of 70,000 requests for permits of oversized and/or overweight vehicles for travel in the State. Of this number, roughly 150 are so excessive in weight that they must receive a special analysis to assure that they will not jeopardize the structural integrity of the state highway system. With the expected massive increase of energy production activities in the state, the above numbers can be expected to increase dramatically. Movements of mobile homes to house new residents to Colorado's western slope as well as routings of large scale mining equipment and construction items, will need to be handled in an efficient and expedient manner. To this end the herein documented computerized procedure for optimally routing oversized/overweight vehicles was developed.

The computerized process, which includes the use of a shortest path network algorithm, will (1) provide routings very quickly, (2) be able to assure no constraining size or weight variables are violated, (3) achieve an optimal or near optimal routing, and (4) remove, to the extent possible, the probability of human error inherent in a complex manual process.

There are roughly 2000 structures (bridges, underpasses, interchanges, etc.) that are a part of the 9200 mile state highway system in Colorado. Each of these structures has design characteristics (width, height, load carrying capabilities) that potentially limit the

size and weight of a vehicle passing over or under the structure. In addition, there exist naturally occuring physical constraints as well as social, political, and safety constraints that must be considered.

For this project the state highway system will be modeled as a network, with links representing segments of state highways, and nodes placed at the intersection of state highways and at other likely trip origin or destination points. A key element of the study is the assignment of capacity constraints related to size and weight characteristics to each of the links in the network. This will be done by examining all structures and other features on each highway segment and assigning to the link the most limiting factor in each category from all structures along the segment. The link then, in effect, reflects the weakest link in each of a number of separate chains. This guarantees that if an individual vehicle does not exceed any of the "link constraints", neither then can it exceed the associated constraints of the individual structures.

The procedure documented in this report represents the first known application of computer technology to the oversized/overweight vehicle permitting process, and a number of other potential applications are discussed as well. The procedure also takes a somewhat unique approach in the designation of eligible arcs to be operated upon by the shortest path finding algorithm. Implementation of the procedure was recently enhanced by the granting of $18,000 in research funds by the Colorado Highway Department Research Council.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

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INTRODUCTION/PROBLEM STATEMENT

In order to protect the structural integrity of the highway system in Colorado, state statutes and federal regulations establish limitations on the weight and size of vehicles legally traversing the system without special permits. These limits are necessary since highways are designed to withstand only certain loadings and to accommodate certain sized vehicles as deemed appropriate for the individual facilities.

During 1979, the State of Colorado issued more than 70,000 special use permits of which roughly one-third were for overweight vehicles, one-third for oversized vehicles, and one-third for vehicles both oversized and overweight. It is anticipated that in the near term there will be a significant increase in the number of oversized/overweight vehicles in the state, due largely to expected energy development activities in addition to demands placed by normal growth. For example, mobile homes comprise a large percentage of the oversize component, and it is considered likely that there will be a great demand for additional mobile homes in northwestern Colorado to accomodate the expected rapid development of that area. Also, mining activities in this as well as other areas of the state will require large, bulky construction and operating equipment that will need to be transported over portions of the state highway system.

The currently effective legal limits on Colorado state highways are:

Gross Weight (Interstate)	80,000 lbs.
Gross Weight (Non-interstate)	85,000 lbs.
Maximum Weight on any one axle	20,000 lbs.
Maximum Height	13 ft. 6 in.
Maximum Width	8 ft.
Maximum Length (Single Unit)	35 ft.
Maximum Length (Combination)	70 ft.

Maximum legal weights for which no permit is required are also calculated by the following formulas:

For Interstate highways

$$W = 500 \left(\frac{LN}{N-1} + 12N + 36\right)$$

For non-Interstate highways

$$W = 1000 (L + 40)$$

Where:

W = gross weight in pounds (vehicle + load)
L = distance between first and last axle in feet
N = number of axles

It is obvious from these equations that the length of the vehicle and its number of axles are very important factors in determining the effect it imparts on the highway system.

Any vehicle with associated characteristics in excess of the above limits is required by law to obtain a special use permit prior to operating on the system. Of the total permit requests received each year, roughly 150 are for loads so excessive in weight that special analyses are required, as detailed in later sections of this report.

It should be noted that, except for isolated cases, permits are not issued for oversize/overweight vehicles if that vehicle or load can be reasonably separated into loads or vehicles which do not exceed statutory weight restrictions. The permit issuing system currently employed by Colorado is entirely manual (except that the permits are transmitted to remote locations via telex machine). The purpose of this paper is to explain, justify, and detail a permit issuing process which the author feels is a significant improvement over the current method.

THE PERMITTING PROCESS: EXISTING AND PROPOSED

Existing Situation:

The permitting procedure currently used by the Colorado Department of Highways is basically a manual process. The process is initiated upon receipt of a permit request, usually over the telephone but occasionally on a drop-in basis. The following information is obtained from the trucking concern:

- Desired trip origin and destination
- Gross weight
- Number of axles
- Distance from first to last axle
- Overall length
- Height
- Width
- Administrative data including licenses, dates of travel, number of trips, and cargo

Personnel from the permit office then do a quick check to determine if the vehicle in question is so excessively heavy as to require a more in-depth analysis by the Department's Staff Bridge Branch. This check consists of comparing the subject vehicle's gross weight, number of axles, and distance from first to last axle against a "table of allowable gross weights" by number of axles and axle distance. This table appears to be quite liberal; for example, a six axle combination truck with a 57 foot distance from the first to the last axle is not considered to be excessively heavy unless its gross weight is greater than 155,000 pounds, a figure nearly twice the legal limit.

Assuming the subject vehicle did not violate the "table of allowable gross weights", permit office personnel then define a routing for the vehicle based largely on "personal knowledge" of the system and its constraints as well as information on the trucker's desired routing. In the majority of the cases, personal knowledge is adequate in that size characteristics are generally consistent among vehicle types and will rarely pose constraints to travel, and gross weight constraints will have been previously checked. In those cases where size constraints will potentially play a role in the routing, the permit office contacts individual district offices for additional information as needed, prior to approving a routing for the vehicle.

A permit form is then typed and transmitted via telex to locations appropriate for pick-up.

In the event the subject vehicle was found to be excessive in weight, i.e. it "failed" the table of allowable gross weights, additional information is solicited from the trucking concern regarding individual axle loadings and spacings. All data are then transmitted to the Staff Bridge Branch for an investigation of the live load moment and live load shear effects the vehicle would impose on structures along the eventually approved routing.

The currently utilized procedure is a very time consuming, complex manual process that is subject to the probability of human error. The basic approach is to begin the investigation at the trip origin and to manually examine routings in the desired general direction on a piecemeal basis. Using a Department of Highways report, the "Field Log of Structures", an engineer will investigate the lowest rated structure by category (timber, concrete, steel, etc.) within a non-rigorously defined highway segment. The objective then is to string together a series of "segments" that will represent a "reasonable" routing for the vehicle which hopefully will not violate the live load moment or shear capacities of any of the structures along the chosen path. It is not unusual for such an analysis to consume up to three man days time for the longer trips, this at the expense of the disruption of normally scheduled activities of the Bridge Branch. Upon determination of a reasonable routing, the Branch notifies the permit office, details the routing, and the permit is issued. It should be noted that regardless of the staff expenses incurred in defining a routing, the trucking concern pays only the standard permit issue fee of five dollars.

The complexity of the process and the amount of time required by the Bridge Branch no doubt play a large role in the liberal nature of the "table of allowable gross weights", which of course determines the number of requests to be analyzed by the Branch.

Proposed Process:

This paper describes a computerized process, portions of which have been developed and tested, which will (1) provide routings very quickly; (2) be able to assure that no constraining size or weight variables are violated; (3) achieve an optimal or near optimal routing rather than just a reasonable one; and (4) remove, to the extent possible, the probability of error inherent in a complex manual process. More specific detail on the computer software is contained in following sections of this report.

Basically the proposed process for the permit office is as follows:

Step	Operation
1	Receive request/Obtain data
2	Enter data into computer
3	Check against "table of allowable gross weights"
4	If unacceptable, send to Bridge Branch with additional data
5	If acceptable, eliminate highway links from the network on the basis of height, width, length, and gross weight constraints (gross weights checked only on "posted" links), or others as designated (could include "political constraints)
6	Run shortest path algorithm on remaining links (the allowable network)
7	Store truck characteristics and routing in storage file
8	Output routing instructions and permit
9	Transmit permit with approved routing to trucking concern

The data categories would be identical with those currently taken, except additional information would be requested on the type of vehicle (single unit, combination, mobile home, etc.). It should be noted that for similar load and vehicle characteristics requests (e.g. mobile homes), the "allowable network" will only need to be derived once between necessary updates to the network.

Steps 1, 2, 4, and 9 would be handled by personnel from the permit office, while the remaining steps (3, 5, 6, 7, and 8) would be handled internally by the computer. This would result in increased efficiency in the permitting process which would allow for (1) a reduction in the staff necessary to handle the volume of requests under the present system; (2) enhanced accuracy and optimality of the approved route; and (3) a reduction in the response time, although this currently is not a serious problem.

The proposed new process for Bridge Branch handling of the roughly 150 excessively heavy vehicle permit requests is as follows:

Step	Operation
1	Obtain data including axle loadings and spacings
2	Enter data into computer
3	Re-check against "table of allowable gross weights"
4	If acceptable, return to permit office
5	If unacceptable, eliminate links and determine shortest path as detailed in steps 5 and 6 of the permit office process
6	Compute acceptable operating ratings (a measure of an individual structure's load carrying capability) for subject load
7	Identify all "un-ticked" structures along shortest path that have operating ratings lower than that allowed. If none, go to step 13
8	Individually check these structures for moment and shear effects starting with the lowest operating rating
9	If a structure is acceptable for the subject load, "tick" it and continue checking structures

10 If a structure is unacceptable for the subject load, eliminate the associated link from the network

11 Re-run shortest path algorithm

12 Go to step 7

13 The shortest accpetable path has been found. Transmit information to the permit office for data storage and permit issuance

Steps 1, 2, 4, and 13 would be handled by personnel from the Staff Bridge Branch while the remaining steps would be handled internally by the computer.

Independent of the scope of this paper, however, as an integral part of the proposed process for the Bridge Branch, is the computerization of the calculations of live load moment and live load shear effects. Currently these operations are manual, resulting in time delays, loss of accuracy over that expected on a computer, necessary shortcuts in analysis to reduce the volume of work, and often less than optimal routings. Work is being conducted to computerize these operations for incorporation into the overall process. Until such time as this work is available, the Bridge Branch process outlined above, utilizing an interaction of computer (eligible network definition and determination of shortest paths) and manual (calculation of moment and shear effects) techniques, represents a significant improvement over the current methodology.

The following section of this paper discusses in depth the basic elements of the computer software necessary and appropriate to develop the permit issuing capabilities described herein.

DESCRIPTION OF COMPUTER INPUTS, SOFTWARE, AND OUTPUTS

The total process of permit issuance and the associated structure (or other constraint) evaluation is a complex meld of human and computer functions. Human aspects include the necessary institutional arrangements for effective interaction with "the machine" as well as sensitivity analyses on the reasonableness and meaning of the results generated. The procedure outlined in this paper was purposefully designed to permit a maximum amount of flexibility, keyed by human/ computer interaction.

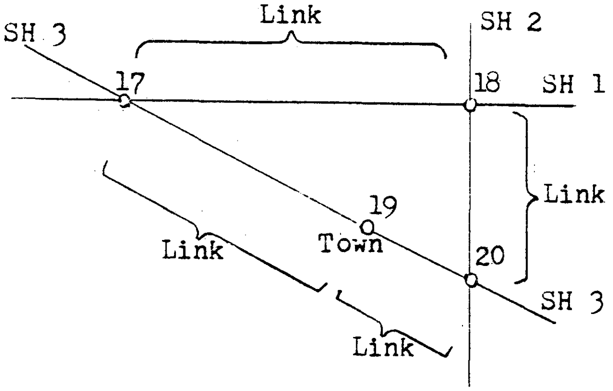
At the same time, one of the primary objectives of this study is to improve the efficiency and accuracy of the permitting operation by removing the human element from the optimum route selection process, Few would argue that such a process is more suited to a computer's capabilities than those of a human.

This section of the report describes three separate computer processes which together comprise the proposed permitting operation package. The first process discussed involves the coding of the State Highway System for input to the computer as a constrained, costed network. It should be noted that the network will basically be limited to the State highway system, since those are the only routes over which the State has jurisdiction. The second process described is appropriate to permit office operations while the third process relates to necessary Bridge Branch activities.

Network Definition and Coding

The network eventually operated on by the path finding algorithm will be a series of directed arcs (one direction only) defined by origin node (I)--destination node (J) pairs. The arcs will also reflect constraints to travel along that arc, an upper bound, a lower bound, and a measure of impedance. Each arc will represent one directional travel along a state highway segment or link. Thus for each highway link there will be two associate "arcs", one in each direction. In general these arc pairs will be identical except for orientation. Non-identical arc pairs will likely be found when they represent segments of divided highways (such as the Interstate highways).

Highway links will generally be defined as state highway segments between the separate intersections of that state highway with one or more other state highways. An example of appropriate link designations follows:



The link on state highway 1 between the intersections with SH 3 (at node 17) and SH 2 (at node 18) will be represented in the network by arcs (17, 18) and (18, 17).

Normally, if a town is of significant size there will be an intersection of state highways within the town. In the example, node 19 was added to represent a town where state highways do not intersect. In general, nodes should be added as necessary to represent likely origins or destinations of oversize/overweight vehicles. Of course, by adding node 19 there are now two links between 17 and 20 or a total of four arcs: (17, 19), (19, 17), (19, 20), and (20, 19). A network representing the State of Colorado would be comprised of roughly 1000 links (2000 arcs) and 750 nodes.

The format under which the links that comprise the highway system will be coded is as follows:

Columns 1-4 - Link number

Col. 5-7 - I node

Col. 8-10 - J node

Col. 11 - 1 if one directional link; 2 if two directional link--the number 2 will act as a switch to create two arcs, identical except for orientation. Divided highway segments must be coded as individual links with a "1" in column 11.

Col. 12-16 - Milepost number at the I node (X 100)

Col. 17-21 - Milepost number at the J node (X 100)

Col. 22-24 - Factor_1 for terrain type (Index 100 = flat)

Col. 25-27 - Factor_2 for speed (or other) (Index 100 = 55 MPH)

Note: The value of impedance against which the shortest path will be built is calculated (by a utility program) for each link as follows:

$$\underbrace{\frac{\left|\text{"I" node milepost - "J" node milepost}\right|}{100}}_{\text{Absolute distance from I to J}} \text{ X } \frac{(\text{Factor}_1)}{100} \text{ X } \frac{(\text{Factor}_2)}{100}$$

Col. 28-31 - Height (XXYY) where XX = feet; YY = inches

Col. 32-35 - Width (XXYY) where XX = feet; YY = inches

Col. 36-40 - Length (XXXYY) where XXX = feet; YY = inches

Note: The above three data items will be converted strictly to inches by a utility program.

Col. 41-42 - Posted weight in tons for Colorado Truck No. 1

Col. 43-44 - Posted weight in tons for Colorado Truck No. 2

Col. 45-46 - Posted weight in tons for Colorado Truck No. 3

Note: The above three data items will be converted to pounds by a utility program. The truck numbers reflect vehicle types.

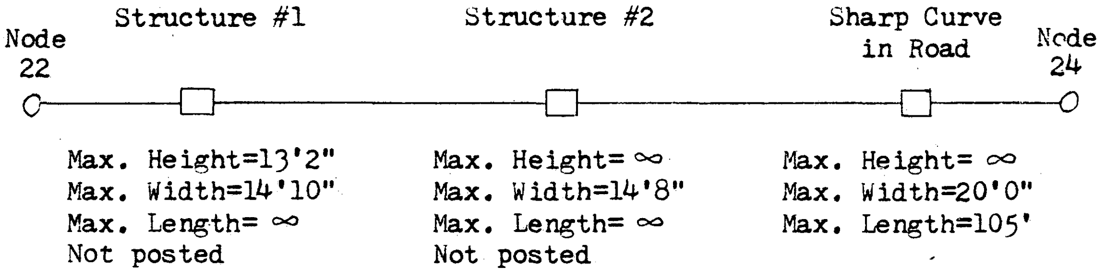
Col. 47-60 - Description of the highway link to be used for identification and for printing the routing on the permit form

Examples: ' S ON I 25 '
'NE ON US 285'

Note: A separate utility program described under the permit office operations will reverse the orientation of this description (N for S; SW for NE) as well as reversing the orientation of the I & J nodes, thereby creating arcs from links.

Col. 61-80 and additional cards as needed - In seven column groups (XXXXXYY) where XXXXX = the structure number and YY is the operating rating for that structure. This information will be coded for every structure along the link.

The values coded under the height, width, length, and posted weight categories for each link represent the most limiting value in each category for all structures along the link. Limiting values due to natural or political constraints will also be entered as appropriate. For example:



Link (22, 24) would be coded to reflect constraining variables of height = 13'2", width = 14'8", and length = 105'0". Since there are no posted structures along the link, Colorado Truck #1, #2, and #3 categories would be coded as 99.

The majority of the needed data items for coding are conveniently listed in the Department of Highways publication, "Field Log of Structures". The only areas for which outside references will be necessary are in (1) obtaining operating ratings for the individual structures and (2) establishing non-structurally related constraints.

Upon completion of the coding, the link file will be operated upon by a yet to be developed utility program. This simple program will have four functions: first, to calculate link impedance as described previously in the section on coding format; second, to convert from feet and inches to strictly inches in columns 28-31, 32-35, and 36-40; third, to convert from tons to pounds in columns 41-42, 43-44, and 45-46; and fourth, to copy the remainder of the file intact, along with the converted data items onto a file to be referred to as the "Link File".

Software Related to Permit Office Operations

This section of the report details the computer program package for handling the 70,000 or so requests for permits received annually by the permit offices. The section is broken down into 28 numbered units, each describing a particular element of the overall process as outlined on the Permit Office Operation Flow Chart, Plate 1.

1) The computer will read the following data items input by the terminal operator (personnel from the permit office). Inputting of the data will take place in direct conjunction with receipt of the permit request, whether by phone or in person.

Data Item	Description
A	Trip origin
B	Trip destination
C	Vehicle type (single unit, combination, mobile home, etc.)
D	Gross weight of vehicle and load
E	Number of axles
F	Distance from first to last axle
G	Height of vehicle
H	Width of vehicle

Data Item	Description (continued)
I	Length of vehicle
X	General administrative information

All of the above items are currently required except for vehicle type. A subroutine to allow for the efficient interfacing of operator with machine for inputting the data will be developed in later stages of the project.

2) Check against the "table of allowable weights". A previous chapter in this report described the utility of the table of allowable weights. Operationally this is accomplished by determining the maximum gross weight "X" which is allowable due to the combination of data items C, E, and F.

3) Having determined the maximum associated value "X", the gross weight of the subject vehicle (D) is compared with "X".

4) If D is greater than "X", the vehicle is considered to be so excessive in weight as to require a thorough analysis by the Bridge Branch, as detailed in the following section of this report. In order to conduct this analysis, additional data on individual axle loadings and axle spacings is required from the trucking concern. The updated data and the permit request are forwarded to the Bridge Branch.

5) If D is less than or equal to "X", the analysis can be handled by the permit office. Thus the analysis is begun by the computer accessing

the link file.

6-10) The descriptions of these operations have been combined since they are within a single loop. Each link in the link file is individually read and given an upper bound = 1, and a lower bound = 0. Then the link height is compared with the vehicle height (G); the link width with the vehicle width (H); the link length with the vehicle length (I); and as appropriate a "posted" link's allowable gross weight by truck type is compared with vehicle characteristics C and D. If the link constraints are not exceeded by the vehicle in question, the next link is read until all links have been evaluated. If one or more of the link constraints are violated by the subject load, the upper bound for that link is set equal to zero, thus effectively eliminating that link from the network, and the next link is evaluated.

11) After all links have been thus evaluated and eliminated as necessary, a network of eligible links remains.

12) A utility program will then operate on this network to convert from links to arcs using the switch coded in column 11 of the link data. If there is a "2" in column 11, two arcs will be created from the link, one a duplicate of the current link, and the other a duplicate in all respects except orientation (i.e. the "I" and "J" node numbers will be switched and the written description of the link will be modified). If there is a "1" in column 11, there will be a one-to one correspondence between the link and its associated arc.

13) After application of the utility program, a network of eligible arcs will result.

14) At this point the trip origin and destination information is entered. In essence a "circulation arc" is imposed on the network which forces unitary flow from the <u>destination</u> to the <u>origin</u> (at zero cost). In order to provide for "conservation of flow", a basic principle behind network analyses, a path will be found between the origin and destination (as long as such flow is feasible). And, in fact, the out-of-kilter algorithm to be used will select the minimum impedance path from origin to destination. The "circulation arc" then has the following characteristics: "I" node = trip destination (B); "J" node = trip origin (A); upper bound = 1; lower bound = 1 (this forces the flow); and impedance = 0.

15) If the user wishes, this step offers the opportunity to set the upper bound on any arc equal to zero. This has the effect of prohibiting travel along that arc and could be used in the event of road closures, avoidance of congested arcs, constraints due to certain types of loads such as hazardous materials, etc. The highway link containing the Eisenhower Memorial Tunnel would be a likely candidate for this kind of treatment. The option of resetting the upper bound equal to one is also available.

16) Similarly, this step offers the user the opportunity to set the lower bound on any arc equal to one. This has the effect of forcing

travel along that arc and could be used for routings with multiple distribution points.

17-24) The description of these operations has been combined since together they form the shortest path finding package. The out-of-kilter algorithm developed by D. R. Fulkerson has been selected as the shortest path finding technique most usable for this problem.

The primary reasons this algorithm was chosen are (1) it operates on directed networks, (2) it operates very efficiently, and (3) it is a well tested and well documented method. Since it is not the intent of this paper to make any advances in the state-of-the-art of shortest path finding algorithms, but rather to propose a new and unique application of an existing algorithm, no attempt will be made to expound upon the theory of the shortest path finding process. If the reader wishes further discussion of the workings of the algorithm, an excellent source is "Operations Research for Immediate Application: A Quick and Dirty Manual" by R.E.D. Woolsey and H.S. Swanson, pps. 100-114. Another excellent reference is "Flows in Networks" by L.R. Ford and D.R. Fulkerson. A listing of the out-of-kilter computer code used for this project is contained in Appendix A. The basic formulation was taken from the Quick and Dirty Manual referenced above.

As a first step to this operation, the network of arcs is reformatted for input into the algorithm. This reformatted network, called the "working network file", is then operated upon by the out-of-kilter algorithm with one of two possible results. The most likely case is that a shortest path has been determined. This path, identified by a series of arcs containing one unit of flow each, defines the routing of minimum impedance from the trip origin to the destination. The other alternative occurs when no feasible solution to the problem exists. This is not a very likely occurance (it may happen infrequently for excessively heavy vehicles), but should it happen to be the case, a listing will be issued of the series of arcs that acted to prohibit flow and the terminal operator will be alerted. At this time special allowances might be made for priority loads (energy product haul or military vehicles) or a non-state highway bypass sought. The upper bound of a selected arc could then be reset equal to one (step 15) which would allow flow through the identified bottleneck, and likely a shortest path could then be determined.

25) This step serves to receive routing information and vehicle data from Staff Bridge Branch that has resulted from their analysis of an excessively heavy load. This information is transmitted to the permit office both for record keeping purposes and to assure that all permits are issued from the appropriate office.

26) The listing of arcs with flow emanating from the shortest path finding process will then be consecutively ordered from trip origin (A) to trip destination (B). Summations will also be made along arcs of the path of the total route distance and the cumulative impedance.

27) Permitted routings and all associated vehicle characteristics

data will be stored and made available for statistical evaluations. This will prove to be very helpful in determining repetitions of overloads on certain structures, and may eventually be used in calculating new factors to be applied to the impedance which would tend to route overloads away from overly utilized structures.

28) The final permit will be printed on a lineprinter for transmission via a telex machine or other distribution as appropriate. The permit will include data items A through I and X (plus J and K for routings approved by Bridge Branch) as well as an exact routing to be followed when traveling in the state. The printed routing will have the format of direction of travel and highway name and number. This will be achieved by utilizing the consecutively ordered arcs and data originally coded in columns 47 through 60 on the link data and carried over onto the arc files (with reverse orientation as warranted). Printing of an arc description will be suppressed if the immediately preceeding arc contains an identical description. The final permit form will be nearly identical to those currently being issued and will include the standard statements of state law as well as general advisory information, conditions to usage, and contractual language.

Software Related to Bridge Branch Operations

This section of the report details the computer program package for handling the roughly 150 requests for approved routings received annually by the Bridge Branch. The section is divided into 39 numbered units, each describing a particular element of the overall process as outlined on the Bridge Branch Operation Flow Chart, Plate 2. Throughout this section there will be a great deal of reference made to the previously detailed permit office operations (the immediately preceeding section) as the link elimination methodology is identical and the shortest path operations are quite similar.

1) Same as PO-1 (step 1 from the permit office operation flow chart) except the following additional data items will be read:

Data Item	Description
J	Individual axle loadings
K	Axle spacings (between axles)

2) Same as PO-2.

3) The gross weight of the subject vehicle (D) is compared with the maximum allowable weight "X". This step is identical to PO-3 except the "yes/no" branching is reversed in orientation.

4) If "D" is less than or equal to "X", the vehicle routing does not need to be examined in depth by the Bridge Branch and the request should be returned to the permit office. Actually, steps 2, 3, and 4 should rarely be necessary but they do serve as a quick and easy check to assure that in fact a structural analysis is called for by the Bridge Branch.

5) If "D" is greater than "X", a Bridge Branch analysis is required and the link file is called up.

6-24) Identical to steps PO-6 through PO-24.

25) The operating ratings (a measure of structural sufficiency) for all structures along the identified shortest path will be consecutively ordered from lowest to highest. The operating rating will carry along with it the structure number for which it applies (OR_X where "X" is the structure number). An artificial OR of maximum value will also be added to the listing for computational purposes.

26) A printed record will be made of the path under investigation and the consecutively ordered operating ratings along that path.

27) The minimum OR_X is identified from the ordered listing.

28-29) The purpose of these steps is to determine a miminum acceptable operating rating for the vehicle in question. In general, as the weight of a vehicle increases, the minimal acceptable operating rating for that vehicle decreases; however, other factors in this relationship include the vehicle's length and number of axles. A table relating these factors will be developed for use by this computer program such that for a particular vehicle request, a minimum acceptable operating rating (AOR) will be determined based on data items C, D, E, and F.

30) A comparison will be made to determine if the lowest remaining operating rating (OR_X) along the current shortest path is acceptable.

31-32) If OR_X is greater than or equal to AOR, the shortest acceptable path has been determined and such information is transmitted to the permit office for permit issuance and record keeping.

33) If OR_X is less than AOR, a determination is made whether or not $Structure_X$ has been previously evaluated for its ability to handle the vehicle in question (has the structure been "ticked").

34) If the structure has been "ticked", the associated OR_X is removed from the listing and the process returns to step 27.

35) If $Structure_X$ has not been "ticked", a subroutine package will be executed to determine the live load moment and live load shear effects of the subject vehicle on the structure. This subroutine package, which has not yet been developed, will utilize data items C, D, E, F, J, and K operating on a separate file of information on each structure in the state. (Note: Until such time that the subroutine package and structure file are compiled, this portion of the process will be handled manually utilizing current methodologies.)

36) An evaluation will be made as to whether or not the subject vehicle "passes" both the live load moment and live load shear tests.

37) If the vehicle violates neither the moment or shear capacities of

the structure, the structure is "ticked" to show that the subject load is acceptable for that structure and the process moves to step 34.

38) However, if the subject vehicle does violate either the live load moment or live load shear capacity of Structure$_x$, the upper bound for the arc(s) containing that structure are set equal to zero. This, of course, has the effect of prohibiting travel by the subject vehicle along the associated highway segment.

39) The working network file is updated to reflect the change and the process is returned to step 20 where the algorithm is rerun on a revised network and a necessarily different shortest path is determined. It should be noted that if a structure has been "ticked", it will continue to carry this designation through all iterations. Thus it will be evaluated for moment and shear effects only once for each subject vehicle.

EXAMPLES/MODEL SENSITIVITY/REFINEMENTS

This chapter of the report presents the results of sample tests made of the program package on a highway system, describes some of the options available to the user to enhance the meaningfulness of the results obtained, and suggests possible refinements or modifications to the process.

In order to test the utility of the program package, a small test network was developed. The area tested was Colorado Planning and Management Region 11 in northwestern Colorado, comprised of Moffat, Rio Blanco, Garfield, and Mesa Counties. This area was chosen (1) because of the anticipated exponential growth in industrialization of the area which will result in a massive increase in the number of oversized/overweight vehicles, and (2) because of the author's familiarity with the area from having participated in the development of the Council of Governments' long range transportation plan for the area.

A majority of the energy products produced in the region will be transported out by rail or pipeline, and that which does move by truck will be of a "divisible" nature, which implies that it can be hauled within legal limits. However, much of the necessary mining equipment and machinery will need to move, at least a portion of their journey, along the highway system; and, in fact, depending upon the emergency nature of the development of the area, some energy product haul may well be made in oversized/overweight loads.

For this test the network was extended beyond the state highway system proper to include very likely destinations of oversized/overweight vehicles. The Piceance Creek Road, a county road, was added to provide access to the oil shale facilities at Tract C_A, Tract C_B, and Superior, and the Parachute Creek Road was added for access to the Colony, Union, and Paraho sites. Figure 1 (on the following page) displays the sample network utilized for northwestern Colorado.

Three separate tests were made of the shortest path finding properties of the program package. In example 1 an oversized vehicle was routed from Utah (on I-70) to the Superior oil shale site. For example 2 the same origin and destination were used except the vehicle was overweight, resulting in a different routing. In example 3 an oversized vehicle is routed from Grand Junction to Craig with intermediate stops in Rifle and Meeker.

Of the total program package described in the Permit Office Operation Flow Chart and the Bridge Branch Operation Flow Chart, the only portions currently operational involve the shortest path finding algorithm. Work is currently underway on the "preprocessor" portions, or that series of steps that prepares the data for the shortest path finding algorithm. The steps comprising the preprocessor are all quite straightforward and basically consist of (1) making comparisons, (2) applying factors, and (3) reformatting. The report writer, upon which work has not begun, is again a relatively straightforward procedure. The crux of the entire process, computationally, is the

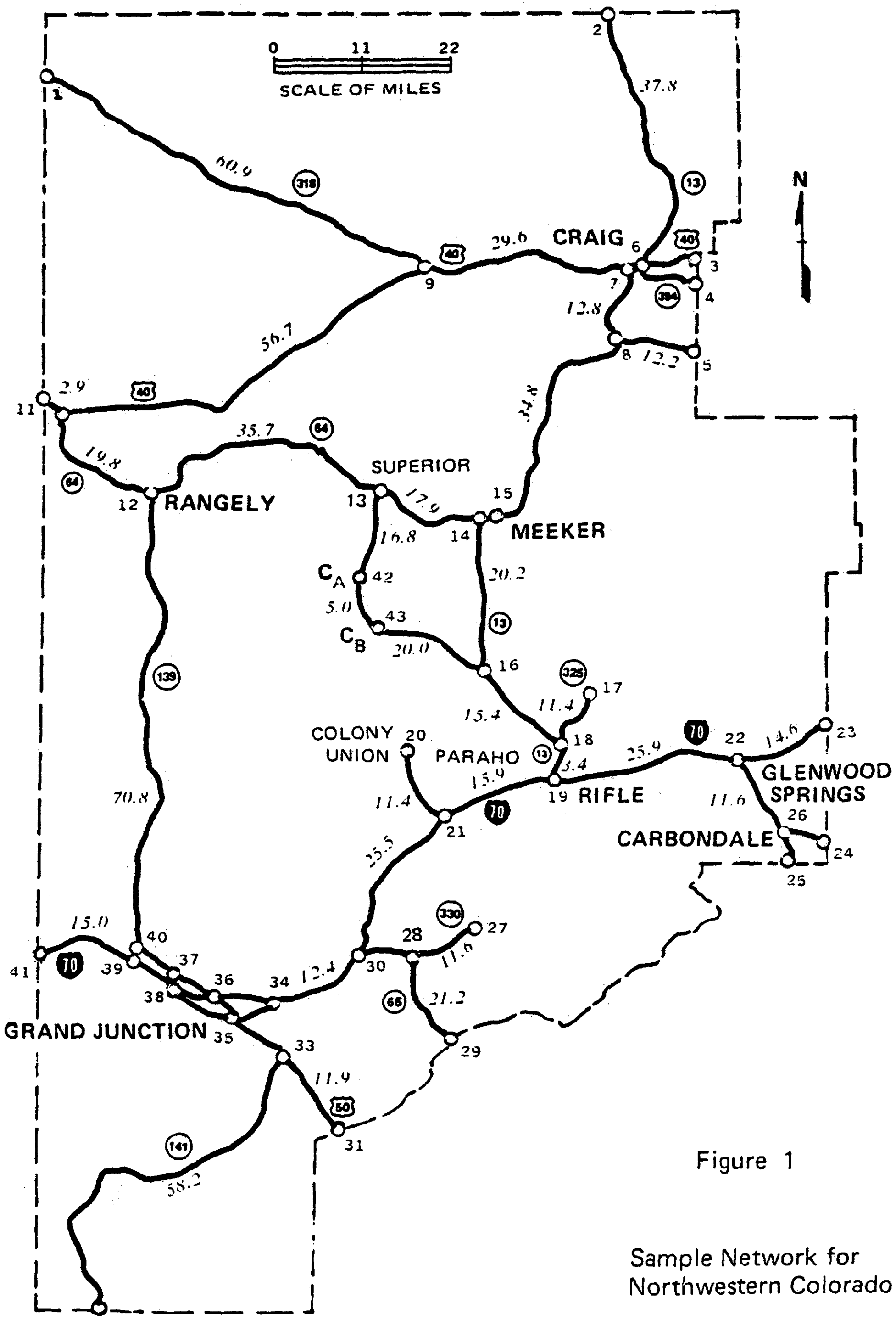


Figure 1

Sample Network for Northwestern Colorado shortest path finding algorithm, examples of which follow.

For the purposes of these examples the work of the preprocessor, preparing the network for input to the algorithm, will be done manually. Similarly, there will be a narrative interpretation of the results, in lieu of the report writer. The examples further assume that no in depth analysis will be required by the Bridge Branch for the subject loads.

In the first example, a request is received for a slightly oversized vehicle with an origin at the Utah border on I-70 (node 41) and the destination being the proposed Superior oil shale facility (node 13). For this subject request it is assumed that none of the constraining link features are violated (Step PO-7) and thus the vehicle is operating on an unconstrained network. In fact, this will likely be the case for many of the actual permit requests received. Also, since the vehicle was only oversized, it will pass the check against the table of allowable weights. The links are converted to arcs (PO-12), the circulation arc (<u>from</u> 13 <u>to</u> 41) is inserted (PO-14), and the data reformatted into the working network file (PO 17-18). The working network file is then operated upon by the out-of-kilter algorithm (Appendix A) and the shortest path is determined. The computer printout of results for this example problem is contained in Appendix B.

This printout shows that there are 43 nodes and 99 arcs. "I" (from) and "J" (to) define directionally the nodes at each end of an arc. The value under the "flow" column indicates if the arc is a part of the shortest path (1 = yes, 0 = no). "Cost" refers to distance in miles times 10. For these examples speed and terrain factors are not applied. "HI" and "LO" refer to the arc's upper and lower bound, respectively. The final arc listed, number 99, is the circulation arc. For it the upper and lower bounds are both set equal to one and the cost equals zero. It is this arc, from 13 to 41, that demands flow between 41 and 13 and the algorithm assures that this flow will follow the shortest possible path. The "PI" values for each node are related to the dual solution of the problem and are not utilized at the present time. Neither is the information listed at the bottom of the printout on the number of breakthroughs and non-breakthroughs.

In the listing of arc information, data shown for I, J, cost, hi, and lo is merely a reflection of the input data, while information in the flow column represents the real output of the algorithm. For the particular example at hand, it can be seen that the following arcs have flow and thus are a part of the shortest path: (12, 13), (40, 12), (39, 40), and (41, 39). The circulation arc (13, 41) also contains one unit of flow, but this is disregarded since it was added to the network solely to identify the trip origin and destination and to force flow between them.

One of the duties of the report writer is to consecutively order the links from origin to destination, which for this example would result in: (41, 39), (39, 40), (40, 12), and (12, 13). The minimum path described by this series of arcs is also shown in Appendix B.

The distance along this path is equal to the sum of the distances along each arc or: 35.7 + 70.8 + 1.3 + 15.0 = 122.8 miles. It is obvious by scanning the arc information that, except for the circulation arc, the upper bound of all arcs equals one, and all lower bounds are equal to zero. This, of course, represents an unconstrained network. In each of the two following examples, this is not the case as the algorithm is tested on networks with constraints.

In order to test some of the sensitivity of the model, the second example (Appendix C) is designed so that the origin and destination are the same as in the first example, however, the permit request is for an overweight vehicle. The vehicle is not so excessive in weight that it fails the "table of allowable weights", but it is too heavy to tolerate travel over posted bridges. Therefore, by steps PO-7d and 8, the upper bounds for all links containing posted bridges are set equal to zero. As reflected in the arc listing in Appendix C, the associated arcs are: (1, 9), (9, 1), (4, 6), (6, 4), (12, 40), (40, 12), (37, 40), and (40, 37).

With the exception of the upper bounds of the above arcs being set equal to zero, the network is identical to that used in the first example (including the circulation arc). Yet, with the constrained network a very different routing occurs. The consecutively ordered arcs with flow are: (41, 39), (39, 38), (38, 36), (36, 34), (34, 30), (30, 21), (21, 19), (19, 18), (18, 16), (16, 14), and (14, 13) which cover a total distance of 147.4 miles. This is to be compared with 122.8 miles between the same two endpoints but on an unconstrained network. A graphical display of the new constrained shortest path is also contained in Appendix C.

The third example shows the results of forcing the routing through designated arcs by setting the lower bounds of these arcs equal to one. Assume an oversized vehicle trip is to be made from Grand Junction (Node 35) to Craig (Node 6) with intermediate stops in Rifle and Meeker. In the probable direction of travel the lower bound of an arc connecting with node 19 (Rifle) is set equal to one. In this case arc (19, 18) is chosen. In a like fashion the lower bound of arc (14, 15) is set equal to one to force the routing through Meeker.

This methodology has some deficiencies in that probable arcs and directions of travel must be predetermined. More accuracy may be possible by introducing a second node and a connecting dummy link to, in effect, capacitate certain nodes. However, this action is not recommended until proven necessary through more vigorous testing since it would increase the size of the network and thus the cost of operating on it. A secondary purpose of the "dummy link and node" concept is to act as a surrogate for congestion at the node. An impedance could be assigned to the link which may make other routes more attractive.

The results of the third example problem are given in Appendix D. Note that the lower bounds for arcs (14, 15) and (19, 18) are set equal to one and that these arcs are a part of the consecutively ordered arcs comprising the shortest path: (35, 34), (34, 30), (30, 21), (21, 19), (19, 18), (18, 16), (16, 14), (14, 15), (15, 8), (8, 7), and (7, 6). The cumulative distance along these arcs is 150.9 miles, a figure confirmed by Department of Highways mileage tables. Appendix D also contains a figure graphically displaying the results of this test.

By working with the model and monitoring the effects of small changes in the variables, the user can learn a great deal about the sensitivity of the model and better understand the workings of the highway system as a whole. In order to check the reasonableness of a particular routing, the user would be well advised to rerun the algorithm on a totally unconstrained system. This could be accomplished by inputting artificially low truck characteristics (weight = 0, width = 0, etc.). By comparing the results of this run with the initial routing, the user is bound to obtain a greater understanding of the system.

Another possibility involving multiple passes through the network would be to find all paths within a given percentage (say 5%) of the total distance (or impedance) of the shortest allowable path. The assumption here is that all paths within that range represent viable alternatives to the shortest path that for undetermined reasons may be more favorable to the state or the trucking concern. To achieve alternative shortest paths, it will be necessary to set the upper bounds equal to zero for one or more of the arcs on the existing shortest path. The decisions on which arcs to select are left to the judgement and desires of the user.

A multiple pass may also be made through the network to effect a "loosening" of the constraints. In Colorado special priority is given to military and energy related movements. While most of the physical constraints are indeed binding, the weight related constraints are less rigid. Thus, artificially lowered vehicle weights could be assumed for such a movement which may well result in a more acceptable routing.

One very important aspect of this model is that for vehicles with identical or very similar characteristics (e.g. mobile homes), the network of eligible arcs will be identical for all requests. Thus, by storing this information after it is first generated and referring to it each time a similar request is made, a large number of time consuming, duplicative steps can be avoided.

As the development and testing of this methodology proceeds, a number of refinements or minor modifications may need to be made. This section of the report details certain of the refinements which have been foreseen as necessary, depending upon the results of more thorough testing and actual applications of the model.

One area of concern is the problem of a desired origin or destination interior to a link (i.e. not at a node). If a potentially constraining feature separates the trip endpoint from a node, a problem exists. Naturally, if there are many requests for this trip endpoint, a node can be added to handle the problem. The currently proposed solution is that a computer interactive approach be taken. The operator will first determine if the link in question poses any constraints to the subject vehicle. If it does not, the nearest node in the most likely direction of travel is chosen as the trip origin or destination as appropriate. If the link does pose a constraint, it will be checked manually to determine if travel along the link on either side of the trip endpoint is feasible. If travel is feasible, it will be so routed. If not, a permit cannot be issued without special exception.

A potential refinement would be to computerize the above process. However, it appears to be a relatively difficult thing to do and may not be cost effective depending upon the number of occurrences. Thus, a decision on this item should be delayed pending more thorough testing.

Another problem that will need to be examined in greater depth occurs when there is no feasible solution to the shortest path. An answer to this problem is pertinent since it will identify those arcs which are acting to prohibit the flow (the minimum cut in the vernacular). Two possible solutions are being considered. First, a more in depth study of the dual solution to the out-of-kilter algorithm to determine if the information isn't "easily" available; and second, the application of a simple, labeling algorithm specifically designed to produce the minimum cut.

One item of particular interest in the further testing of the program package will be the performance of the out-of-kilter algorithm (OKA). The OKA was selected as appropriate for this project because: (1) research indicated it to be quite efficient on a relatively small network (2000 arcs and 750 nodes for all of Colorado); (2) the model was easily available and well documented; and (3) the author had previous experience working with the OKA. However, during the course of the study, the efficiency of the OKA on the full scale network will be evaluated and other shortest path finding techniques may be considered.

There are also two operational questions that will need to be addressed. The first involves the development of a procedure for maintaining and updating the data files. Over time the constraining features of a link will change as old structures are replaced by new, as structures are widened, or as other features or political constraints change. When a roadway receives an overlay, it can have an effect on the distance between that roadway and the bottom of a structure passing overhead. Also the gross weight of an overlay on a bridge affects the load carrying capability of that structure. Thus, it is crucial to the success of the entire project that accurate, up to date information be available to the computer package.

The second operational question involves the appropriate computer system to operate upon and the associated hardware requirements. Options include purchase of a micro computer (data storage may be a problem), time sharing on the Highway Department's mini computer, or time sharing on the large computer at Colorado University under an existing agreement. All options would require terminals and a line printer in the central permit office. Another concern is for a back-up system or procedure in the event the computer is not operational.

OBSERVATIONS ON THE STATE-OF-THE-ART OF COMPUTER APPLICATIONS TO THE PERMITTING PROCESS

While in the initial investigative stages of research for this project, one of the first issues addressed concerned the possible existence and application of a computerized technique for issuing oversized/overweight vehicle permits. The feeling was that by its very nature (extremely data intensive and a routine checking procedure) the permitting process fairly cried out for computerization. Yet all investigations indicated that at the present time no other state had a computerized system operational nor was there any indication that any of the states were planning for one.

In arriving at this conclusion the following resources were explored. A U.S. Department of Transportation report to the Congress entitled "Overweight Vehicle Penalties and Permits - An Inventory of State Practices" went into great depth in describing the current permitting procedures of all the states. A careful examination of this rather lengthy document revealed absolutely no reference to the existence anywhere of the application of computerized techniques in issuing permits. This finding was confirmed by Mr. John D. Hibbs, Chief of Traffic Performance and Programs in the Federal Highway Administration's Office of Traffic Operations in Washington, D. C. Through personal contacts with local experts (both at the Federal and State level) in the field of oversized/overweight vehicles, again the consensus was that this was likely the first proposal for the computerization of the process. In addition to the aforementioned report to Congress, two National Cooperative Highway Research Program reports were examined: Number 68 - Motor Vehicle Size and Weight Regulations, Enforcement, and Permit Operations, April 1980; and Number 198 - State Laws and Regulations on Truck Size and Weight, February 1979. The purpose of reviewing these documents was twofold, first to achieve a greater understanding and awareness of the many ramifications of the permitting process, and secondly, to further explore the existence of a computerized technique. Regarding the second purpose, again there was no evidence that a computerized process is operational.

It should be noted that much of the author's knowledge of the permitting process was the result of time spent observing operations at the Department's central permit office as well as extensive discussions with the Staff Maintenance Superintendent (in charge of all permit applications), the branch manager of the Staff Bridge Branch, other personnel from the Bridge Branch, and personnel from the Colorado State Patrol.

The second major area of research involved the investigation of the current state-of-the-art of shortest path algorithms. The primary focus of this investigation was to determine the availability of a shortest path network algorithm that would operate on multiple upper bounds on a link. Had such an algorithm existed it would then have been possible to have the algorithm operate directly on the multicapacitated network rather than utilizing a preprocessor to eliminate links which fail one or more constraints. In searching for such an algorithm, personal contacts were made with professors from both the Colorado School of Mines and the University of Colorado, and an article entitled "A Computational Analysis of Alternative Algorithms and Labeling Techniques for Finding Shortest Path Trees" by Dial, Glover, Karney, and Klingman was reviewed.

The search provided no indication of the existence of such an algorithm, which, in the final analysis may be just as well. It is very likely that had such an algorithm existed it would have been very expensive to use relative to one (such as the out-of-kilter) which operates on a single upper bound. This consideration takes on a great deal of importance when one is dealing with more than 70,000 separate applications each year. The added expense of utilizing a preprocessor which merely makes comparisons to eliminate arcs is thought to be relatively minor. Another consideration, mentioned previously in this paper, is that the out-of-kilter algorithm is a well documented and often utilized algorithm which lends added credence to its utilization here. In this regard, reference was made to an article by D. R. Fulkerson entitled "An Out-of-Kilter Method for Minimal - Cost Flow Problems".

The third major area of research involved investigation into other similar applications of shortest path finding techniques. The primary resources for this work were Peter A. Steenbrink's book, "Optimization of Transport Networks", and a rather extensive file of articles on network applications to transportation related problems. This file was collected by Mr. Dipak Sengupta, a doctoral candidate at the Colorado School of Mines, and represents a fairly comprehensive coverage of the current literature. Neither of these sources described applications remotely similar to the gist of this paper.

The literature search did reveal a very similar theoretical methodology developed by Shiva K. Pant and Frederick J. Wegmann, as documented in the February 1973 issue of the American Society of Civil Engineers Journal of Transportation Engineering, pages 151-166. However, the emphasis in this approach is the development of a strategy to minimize user costs in situations where a trucking concern is financially penalized depending upon 1) the degree its vehicle is overweight, and 2) the number of miles the vehicle travels in the state. As mentioned previously, Colorado has a flat $5.00 permit fee regardless of the size or weight of the vehicle. Additionally, many of the basic analytical assumptions made by Pant and Wegmann are quite different than those incorporated in the herein documented permitting procedure.

There are a number of areas of potential further research with regard to this project. Empirical studies could be conducted to determine relative values for the speed and terrain factors which play a role in determining link impedances. Also a factor should be developed which is sensitive to load repetitions on marginally sound structures.

CONCLUSIONS

The preceding narrative describes in depth a procedure whereby the oversized/overweight vehicles permitting process can be effectively and efficiently computerized in Colorado. There is every reason to suspect that the procedure could be equally well utilized in the other states as well as in some of the larger metropolitan areas in the country.

The procedure is really quite straight forward and easy to understand which should greatly ease its eventual implementation. Evidence that the procedure will eventually be used in Colorado was strengthened recently by the announcement that the Colorado Highway Department Research Council had designated this proposal as its top priority project for funding. Accordingly, approximately $18,000 (the full amount requested) will be allocated for doing this project including (1) coding of the entire state highway system, (2) writing of the preprocessor, the structural analysis subroutine, and the report writer, and (3) in depth testing of the program package.

Some of the major benefits to be derived by the implementation of this system are as follows:

1) Quicker response to requests for excessively overweight vehicles. It is expected that a number of energy development vehicles will fall in this category.

2) More efficient handling of all requests.

3) Reduced probability of human error.

4) Because the procedure would be computerized, it would be practical to reduce the criteria in the "table of allowable gross weights" as well as to test more structures for live load moment and live load shear effects. By taking these two actions, the structural integrity of the highway system would be protected to a greater degree.

5) Statistics on permitted routings would be easily available. These would be useful both to assist the Department in reporting permitting operations to the Federal Highway Administration for certification purposes, and to allow the Department to monitor oversized/overweight routings on particularly sensitive state highway segments.

6) Personnel cost savings on the order of $50,000 per year.

The costs associated with these benefits are as follows:

1) Short term confusion and general inefficiency associated with the replacement of a familiar system by a modified procedure, especially when the modification is as severe as that proposed herein.

2) Equipment costs. These are one-time costs but could vary widely depending upon institutional arrangements. The equipment costs will likely run between $1500 for two terminals and a line printer to $4000 for a micro computer with disc drive capabilities.

3) Training of the personnel should be a minor expenditure.

4) Computer time costs. Again, depending upon the institutional arrangements, these costs could be a determining factor in the eventual hardware solution. One possibility being discussed would be to have the computer charges added on to the basic $5.00 permit fee.

Since the inception of this project, three other potential uses for the process and/or the data base have been identified. The Colorado State Patrol has expressed considerable interest in the possibility of using this system or something very similar for the routing of trucks carrying hazardous materials through the state. After a cursory examination of the problem and the needs of the State Patrol, it seems quite likely that something can and will be worked out.

Other potential uses relate to problems encountered by the Staff Bridge Branch. The Branch occasionally receives requests concerning 1) the maximum permissible gross weight of a vehicle traveling a good path between two given points, and 2) data to assist a trucking concern in designing a vehicle (total length, number of axles, axle spacings, axle loadings) which will be allowed to travel over as much of the state highway system as possible. The solution to both of these problems would be helped greatly by utilizing the program package and data base.

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APPENDIX A

Computer code listing of the Out-of-Kilter Algorithm

Source: Operations Research for Immediate Application: A Quick and Dirty Manual" by R.E.D. Woolsey and H.S. Swanson, pps. 115-117.

```
C******PATHS1.FOR****  SHORTEST PATH ALGO (OUT-OF-KILTER)
      IMPLICIT INTEGER (A-Z)
      DIMENSION COST(100)
      DIMENSION I(100),J(100),HI(100),LO(100),FLOW(100),PI(100)
      LOGICAL INFES
  100 FORMAT(I2,I3)
  105 FORMAT(I2,I3,2I2,I4)
  110 FORMAT(8I2)
  115 FORMAT(//,'1NUMBER OF NODES = ',I5,/,' NUMBER OF ARCS  = ',I5,///,
     15X,' ARC      I     J    FLOW   COST    HI     LO',//,
     2(7X,I2,5X,I2,4X,I2,6X,I1,5X,I3,2(5X,I1)))
      READ(1,100) NODES,ARCS
          DO 5 M=1,ARCS
      READ(1,105) I(M),J(M),HI(M),LO(M),COST(M)
    5     FLOW(M)=0
          DO 10 M=1,NODES
   10     PI(M)=0
 6666 CONTINUE
      CALL NETFLO(NODES,ARCS,I,J,COST,HI,LO,FLOW,PI,INFES,IBT,NBT)
      IF(.NOT.INFES) WRITE(4,120)
      WRITE(4,115)NODES,ARCS,(M,I(M),J(M),FLOW(M),COST(M),HI(M),
     1LO(M),M=1,ARCS)
      WRITE(4,130)  (M,PI(M),M=1,NODES)
      WRITE(4,500)  IBT,NBT
  120 FORMAT(///,' SOLUTION INFEASIBLE',//)
  130 FORMAT(///,' NODE    PI(NODE)',/,(1X,I4,2X,I10))
  500 FORMAT(/,5X,' THE NUMBER OF BREAKTHROUGHS IS ',I6,//,5X,' THE NUMB
     1ER OF NONBREAKTHROUGHS IS ',I6,//)
 3838 CONTINUE
      STOP
      END
      SUBROUTINE NETFLO(NODES,ARCS,I,J,COST,HI,LO,FLOW,PI,INFES,IBT,NBT)
      IMPLICIT INTEGER (A-Z)
      DIMENSION I(100),J(100),COST(100),HI(100),LO(100),NB(100)
      DIMENSION FLOW(100),PI(100),NA(100)
      LOGICAL INFES
C   CHECK FEASIBILITY OF FORMULATION
      INFES=.TRUE.
          DO 10 A=1,ARCS
   10     IF(LO(A).GT.HI(A)) GO TO 39
C    SET INF TO MAX AVAILABLE INTERGER
   16 INF=999999
      AOK=0
      IBT=0
      NBT=0
```

```
C   ***** IBT IS A COUNTER ON NUMBER OF BREAKTHROUGHS ****
C   **** NBT IS A COUNTER ON NUMBER OF NONBREAKTHROUGHS ***
C   FIND OUT OF KILTER ARC
    20      DO 21 A=1,ARCS
            IA=I(A)
            JA=J(A)
            C=COST(A)+PI(IA)-PI(JA)
       IF((FLOW(A).LT.LO(A)).OR.(C.LT.0.AND.FLOW(A).LT.HI(A))) GO TO 22
    21 IF((FLOW(A).GT.HI(A)).OR.(C.GT.0.AND.FLOW(A).GT.LO(A))) GO TO 23
C    NO REMAINING OUT OF KILTER ARCS
       GO TO 38
    22 SRC=J(A)
       SNK=I(A)
       E=+1
       GO TO 24
    23 SRC=I(A)
       SNK=J(A)
       E=-1
       GO TO 24
C    ATTEMPT TO BRING OUT OF KILTER ARCS INTO KILTER
    24 IF((A.EQ.AOK).AND.(NA(SRC).NE.0)) GO TO 25
       AOK=A
          DO 26 N=1,NODES
          NA(N)=0
          NB(N)=0
       NA(SRC)=IABS(SNK)*E
    26 NB(SRC)=IABS(AOK)*E
    25 COK=C
    27 LAB=0
          DO 30 A=1,ARCS
       JA=J(A)
       IA=I(A)
       IF((NA(IA).EQ.0.AND.NA(JA).EQ.0).OR.(NA(IA).NE.0.AND.NA(JA).NE.0)
      1) GO TO 30
       C=COST(A)+PI(IA)-PI(JA)
       IF(NA(IA).EQ.0) GO TO 28
       IF(FLOW(A).GE.HI(A).OR.(FLOW(A).GE.LO(A).AND.C.GT.0)) GO TO 30
       NA(JA)=I(A)
       NB(JA)= A
       GO TO 29
    28 IF(FLOW(A).LE.LO(A).OR.(FLOW(A).LE.HI(A).AND.C.LT.0)) GO TO 30
       IA=I(A)
       NA(IA)=-J(A)
       NB(IA)=-A
    29 LAB = 1
C    NODE LABELED, TEST FOR BREAKTHROUGH
       IF(NA(SNK).NE.0) GO TO 33
    30 CONTINUE
C   NO BREAKTHROUGH
       IF(LAB.NE.0) GO TO 27
       NBT=NBT+1
```

```
C  DETERMINE CHANGE TO PI VECTOR
      DEL=INF
         DO 31 A=1,ARCS
         JA=J(A)
         IA=I(A)
      IF((NA(IA).EQ.0.AND.NA(JA).EQ.0).OR.(NA(IA).NE.0.AND.NA(JA).NE.0))
     1GO TO 31
      C=COST(A)+PI(IA)-PI(JA)
      IF(NA(JA).EQ.0.AND.FLOW(A).LT.HI(A))  DEL= MIN0(DEL,C)
      IF(NA(JA).NE.0.AND.FLOW(A).GT.LO(A))  DEL= MIN0(DEL,-C)
   31 CONTINUE
      IF(DEL.EQ.INF.AND.(FLOW(AOK).EQ.HI(AOK).OR.FLOW(AOK).EQ.LO(AOK)))
     1DEL=IABS(COK)
      IF(DEL.EQ.INF)  GO TO 39
C  EXIT, NO FEASIBLE FLOW PATTERN
C  CHANGE PI VECTOR BY COMPUTED DEL
         DO 32 N=1,NODES
   32 IF(NA(N).EQ.0)PI(N)=PI(N)+DEL
C  FIND ANOTHER OUT OF KILTER ARC
      GO TO 20
C  BREAKTHROUGH, COMPUTE INCREMENTAL FLOW
   33 EPS=INF
      IBT=IBT+1
      NI=SRC
   34 NJ=IABS(NA(NI))
      A=IABS(NB(NI))
      C=COST(A)-ISIGN(IABS(PI(NI)-PI(NJ)),NB(NI))
      IF(NB(NI).LT.0)  GO TO 35
      IF(C.GT.0.AND.FLOW(A).LT.LO(A))  EPS=MIN0(EPS,LO(A)-FLOW(A))
      IF(C.LE.0.AND.FLOW(A).LT.HI(A))  EPS=MIN0(EPS,HI(A)-FLOW(A))
      GO TO 36
   35 IF(C.LT.0.AND.FLOW(A).GT.HI(A))  EPS=MIN0(EPS,FLOW(A)-HI(A))
      IF(C.GE.0.AND.FLOW(A).GT.LO(A))  EPS=MIN0(EPS,FLOW(A)-LO(A))
   36 NI=NJ
      IF(NI.NE.SRC)  GO TO 34
C  CHANGE FLOW VECTOR BY COMPUTED EPS
   37 NJ=IABS(NA(NI))
      A=IABS(NB(NI))
      FLOW(A)=FLOW(A)+ISIGN(EPS,NB(NI))
      NI=NJ
      IF(NI.NE.SRC)  GO TO 37
C  FIND ANOTHER OUT OF KILTER ARC
      AOK=0
      GO TO 20
   39 INFES=.FALSE.
   38 CONTINUE
      RETURN
      END
```

APPENDIX B

Sample problem number 1. Unconstrained flow between Utah (Node 41) and the Superior Oil Shale site (Node 13)

(Note: ** denotes arcs with flow.)

```
NUMBER OF NODES =     43
NUMBER OF ARCS  =     99

     ARC         I         J      FLOW      COST       HI        LO

       1         1         9         0       609        1         0
       2         9         1         0       609        1         0
       3         2         6         0       378        1         0
       4         6         2         0       378        1         0
       5         3         6         0        69        1         0
       6         6         3         0        69        1         0
       7         4         6         0        93        1         0
       8         6         4         0        93        1         0
       9         5         8         0       122        1         0
      10         8         5         0       122        1         0
      11         6         7         0        14        1         0
      12         7         6         0        14        1         0
      13         7         8         0       128        1         0
      14         8         7         0       128        1         0
      15         7         9         0       296        1         0
      16         9         7         0       296        1         0
      17         8        15         0       348        1         0
      18        15         8         0       348        1         0
      19         9        10         0       567        1         0
      20        10         9         0       567        1         0
      21        10        11         0        29        1         0
      22        11        10         0        29        1         0
      23        10        12         0       198        1         0
      24        12        10         0       198        1         0
      25        12        13         1 **    357        1         0
      26        13        12         0       357        1         0
      27        12        40         0       708        1         0
      28        40        12         1 **    708        1         0
      29        13        14         0       179        1         0
      30        14        13         0       179        1         0
      31        13        42         0       168        1         0
      32        42        13         0       168        1         0
      33        14        15         0        21        1         0
      34        15        14         0        21        1         0
      35        14        16         0       202        1         0
      36        16        14         0       202        1         0
      37        16        18         0       154        1         0
      38        18        16         0       154        1         0
      39        16        43         0       200        1         0
      40        43        16         0       200        1         0
      41        17        18         0       114        1         0
      42        18        17         0       114        1         0
      43        18        19         0        34        1         0
      44        19        18         0        34        1         0
      45        19        21         0       159        1         0
      46        21        19         0       159        1         0
```

47	19	22	0	259	1	0
48	22	19	0	259	1	0
49	20	21	0	114	1	0
50	21	20	0	114	1	0
51	21	30	0	255	1	0
52	30	21	0	255	1	0
53	22	23	0	146	1	0
54	23	22	0	146	1	0
55	22	26	0	116	1	0
56	26	22	0	116	1	0
57	24	26	0	60	1	0
58	26	24	0	60	1	0
59	25	26	0	38	1	0
60	26	25	0	38	1	0
61	27	28	0	116	1	0
62	28	27	0	116	1	0
63	28	29	0	212	1	0
64	29	28	0	212	1	0
65	28	30	0	103	1	0
66	30	28	0	103	1	0
67	30	34	0	124	1	0
68	34	30	0	124	1	0
69	31	33	0	119	1	0
70	33	31	0	119	1	0
71	32	33	0	582	1	0
72	33	32	0	582	1	0
73	33	35	0	86	1	0
74	35	33	0	86	1	0
75	34	35	0	70	1	0
76	35	34	0	70	1	0
77	34	36	0	110	1	0
78	36	34	0	110	1	0
79	35	36	0	60	1	0
80	36	35	0	60	1	0
81	35	38	0	140	1	0
82	38	35	0	140	1	0
83	36	37	0	60	1	0
84	37	36	0	60	1	0
85	36	38	0	62	1	0
86	38	36	0	62	1	0
87	37	38	0	4	1	0
88	38	37	0	4	1	0
89	37	40	0	50	1	0
90	40	37	0	50	1	0
91	38	39	0	45	1	0
92	39	38	0	45	1	0
93	39	40	1 **	13	1	0
94	40	39	0	13	1	0
95	39	41	0	150	1	0
96	41	39	1 **	150	1	0
97	42	43	0	50	1	0
98	43	42	0	50	1	0
99	13	41	1	0	1	1

```
NODE      PI(NODE)
   1         1228
   2         1228
   3         1228
   4         1228
   5         1228
   6         1228
   7         1228
   8         1228
   9         1228
  10         1069
  11         1098
  12          871
  13         1228
  14         1228
  15         1228
  16         1093
  17         1053
  18          939
  19          905
  20          860
  21          746
  22         1164
  23         1228
  24         1228
  25         1228
  26         1228
  27          710
  28          594
  29          806
  30          491
  31          522
  32          985
  33          403
  34          367
  35          317
  36          257
  37          199
  38          195
  39          150
  40          163
  41            0
  42         1228
  43         1228

      THE NUMBER OF BREAKTHROUGHS IS        1

      THE NUMBER OF NONBREAKTHROUGHS IS       25

STOP
```

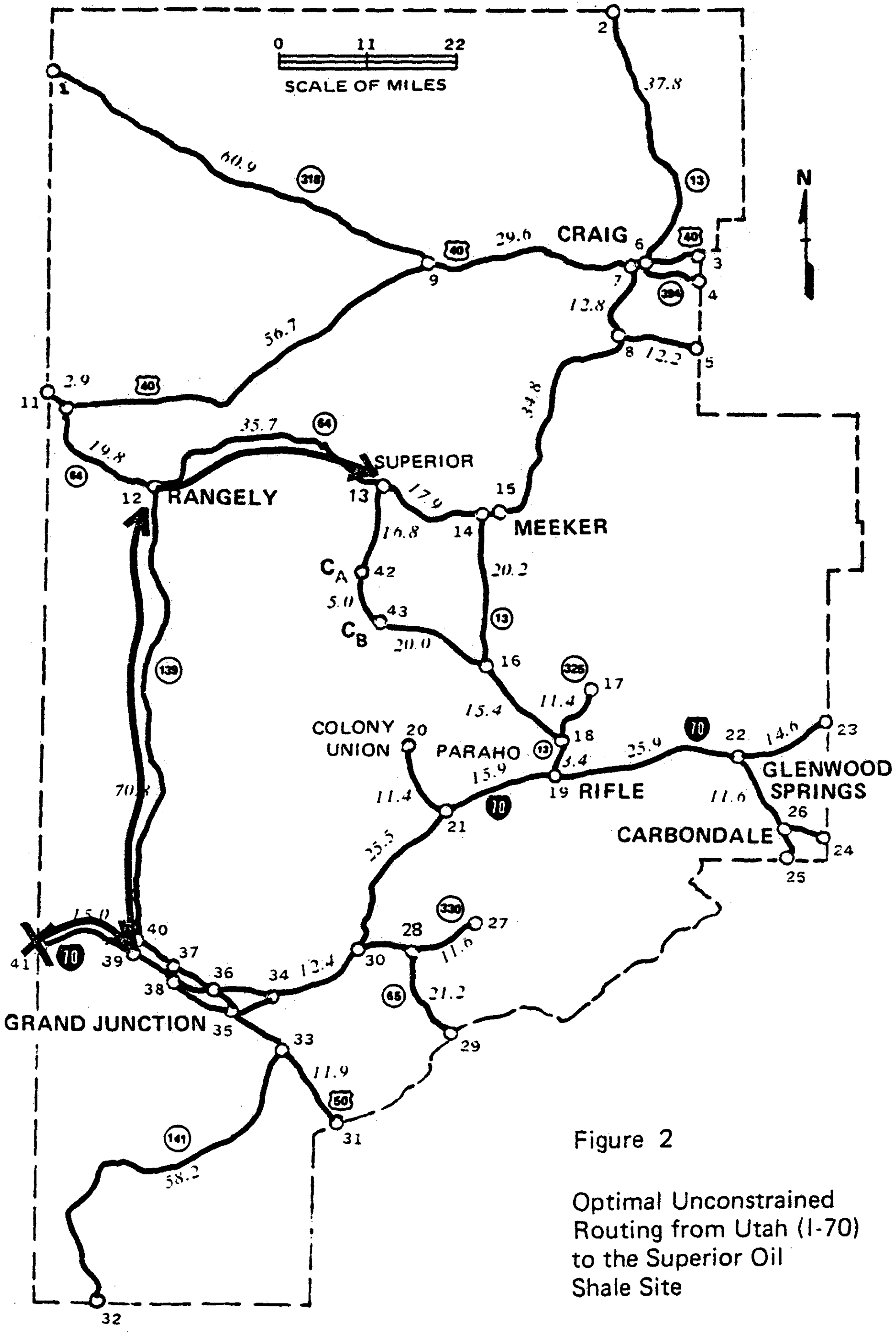


Figure 2

Optimal Unconstrained Routing from Utah (I-70) to the Superior Oil Shale Site

APPENDIX C

Sample problem number 2. Constrained flow (no travel allowed on "posted" links) between Utah (Node 41) and the Superior Oil Shale site (Node 13)

(Note: ** denotes arcs with flow.)

```
NUMBER OF NODES =     43
NUMBER OF ARCS  =     99

   ARC        I        J      FLOW      COST       HI        LO

     1        1        9       0        609        0         0
     2        9        1       0        609        0         0
     3        2        6       0        378        1         0
     4        6        2       0        378        1         0
     5        3        6       0         69        1         0
     6        6        3       0         69        1         0
     7        4        6       0         93        0         0
     8        6        4       0         93        0         0
     9        5        8       0        122        1         0
    10        8        5       0        122        1         0
    11        6        7       0         14        1         0
    12        7        6       0         14        1         0
    13        7        8       0        128        1         0
    14        8        7       0        128        1         0
    15        7        9       0        296        1         0
    16        9        7       0        296        1         0
    17        8       15       0        348        1         0
    18       15        8       0        348        1         0
    19        9       10       0        567        1         0
    20       10        9       0        567        1         0
    21       10       11       0         29        1         0
    22       11       10       0         29        1         0
    23       10       12       0        198        1         0
    24       12       10       0        198        1         0
    25       12       13       0        357        1         0
    26       13       12       0        357        1         0
    27       12       40       0        708        0         0
    28       40       12       0        708        0         0
    29       13       14       0        179        1         0
    30       14       13       1 **     179        1         0
    31       13       42       0        168        1         0
    32       42       13       0        168        1         0
    33       14       15       0         21        1         0
    34       15       14       0         21        1         0
    35       14       16       0        202        1         0
    36       16       14       1 **     202        1         0
    37       16       18       0        154        1         0
    38       18       16       1        154        1         0
    39       16       43       0        200        1         0
    40       43       16       0        200        1         0
    41       17       18       0        114        1         0
    42       18       17       0        114        1         0
    43       18       19       0         34        1         0
    44       19       18       1 **      34        1         0
    45       19       21       0        159        1         0
    46       21       19       1 **     159        1         0
```

```
 47      19      22        0       259       1       0
 48      22      19        0       259       1       0
 49      20      21        0       114       1       0
 50      21      20        0       114       1       0
 51      21      30        0       255       1       0
 52      30      21        1**     255       1       0
 53      22      23        0       146       1       0
 54      23      22        0       146       1       0
 55      22      26        0       116       1       0
 56      26      22        0       116       1       0
 57      24      26        0        60       1       0
 58      26      24        0        60       1       0
 59      25      26        0        38       1       0
 60      26      25        0        38       1       0
 61      27      28        0       116       1       0
 62      28      27        0       116       1       0
 63      28      29        0       212       1       0
 64      29      28        0       212       1       0
 65      28      30        0       103       1       0
 66      30      28        0       103       1       0
 67      30      34        0       124       1       0
 68      34      30        1 **    124       1       0
 69      31      33        0       119       1       0
 70      33      31        0       119       1       0
 71      32      33        0       582       1       0
 72      33      32        0       582       1       0
 73      33      35        0        86       1       0
 74      35      33        0        86       1       0
 75      34      35        0        70       1       0
 76      35      34        0        70       1       0
 77      34      36        0       110       1       0
 78      36      34        1 **    110       1       0
 79      35      36        0        60       1       0
 80      36      35        0        60       1       0
 81      35      38        0       140       1       0
 82      38      35        0       140       1       0
 83      36      37        0        60       1       0
 84      37      36        0        60       1       0
 85      36      38        0        62       1       0
 86      38      36        1 **     62       1       0
 87      37      38        0         4       1       0
 88      38      37        0         4       1       0
 89      37      40        0        50       0       0
 90      40      37        0        50       0       0
 91      38      39        0        45       1       0
 92      39      38        1 **     45       1       0
 93      39      40        0        13       1       0
 94      40      39        0        13       1       0
 95      39      41        0       150       1       0
 96      41      39        1 **    150       1       0
 97      42      43        0        50       1       0
 98      43      42        0        50       1       0
 99      13      41        1         0       1       1
```

```
NODE     PI(NODE)
   1         1474
   2         1474
   3         1474
   4         1474
   5         1474
   6         1474
   7         1474
   8         1474
   9         1474
  10         1474
  11         1474
  12         1474
  13         1474
  14         1295
  15         1316
  16         1093
  17         1053
  18          939
  19          905
  20          860
  21          746
  22         1164
  23         1310
  24         1340
  25         1318
  26         1280
  27          710
  28          594
  29          806
  30          491
  31          522
  32          985
  33          403
  34          367
  35          317
  36          257
  37          199
  38          195
  39          150
  40          163
  41            0
  42         1343
  43         1293

    THE NUMBER OF BREAKTHROUGHS IS         1

    THE NUMBER OF NONBREAKTHROUGHS IS      30

STOP
```

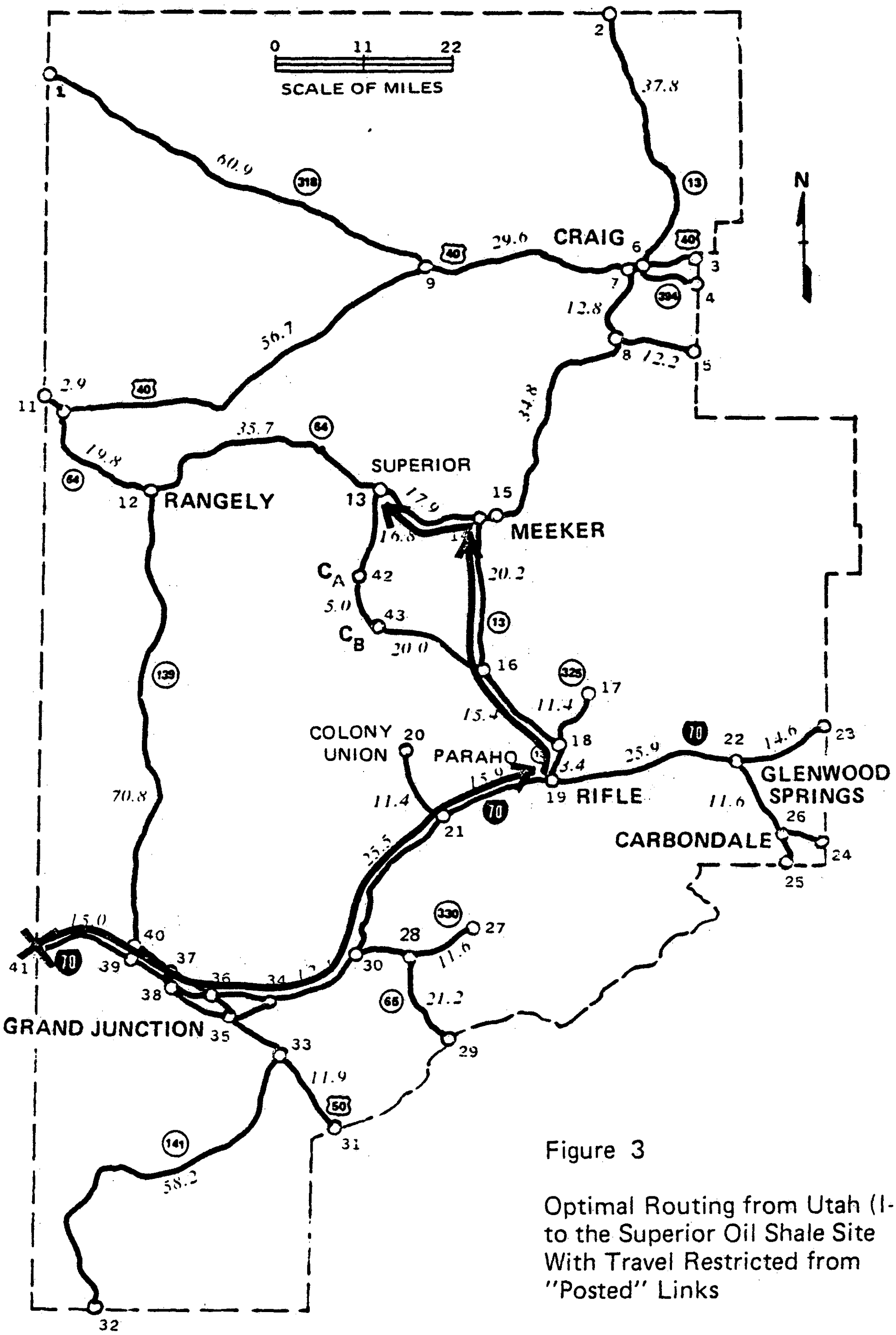


Figure 3

Optimal Routing from Utah (I-70) to the Superior Oil Shale Site With Travel Restricted from "Posted" Links

APPENDIX D

Sample problem number 3. Constrained flow (travel forced through the towns of Rifle and Meeker) between Grand Junction (Node 35) and Craig (Node 6)

(Note: ** denotes arcs with flow.)

```
NUMBER OF NODES =     43
NUMBER OF ARCS  =     99

   ARC        I       J      FLOW     COST      HI       LO

     1        1       9       0        609       1        0
     2        9       1       0        609       1        0
     3        2       6       0        378       1        0
     4        6       2       0        378       1        0
     5        3       6       0         69       1        0
     6        6       3       0         69       1        0
     7        4       6       0         93       1        0
     8        6       4       0         93       1        0
     9        5       8       0        122       1        0
    10        8       5       0        122       1        0
    11        6       7       0         14       1        0
    12        7       6       1 **      14       1        0
    13        7       8       0        128       1        0
    14        8       7       1 **     128       1        0
    15        7       9       0        296       1        0
    16        9       7       0        296       1        0
    17        8      15       0        348       1        0
    18       15       8       1 **     348       1        0
    19        9      10       0        567       1        0
    20       10       9       0        567       1        0
    21       10      11       0         29       1        0
    22       11      10       0         29       1        0
    23       10      12       0        198       1        0
    24       12      10       0        198       1        0
    25       12      13       0        357       1        0
    26       13      12       0        357       1        0
    27       12      40       0        708       1        0
    28       40      12       0        708       1        0
    29       13      14       0        179       1        0
    30       14      13       0        179       1        0
    31       13      42       0        168       1        0
    32       42      13       0        168       1        0
    33       14      15       1 **      21       1        1
    34       15      14       0         21       1        0
    35       14      16       0        202       1        0
    36       16      14       1 **     202       1        0
    37       16      18       0        154       1        0
    38       18      16       1 **     154       1        0
    39       16      43       0        200       1        0
    40       43      16       0        200       1        0
    41       17      18       0        114       1        0
    42       18      17       0        114       1        0
    43       18      19       0         34       1        0
    44       19      18       1 **      34       1        1
    45       19      21       0        159       1        0
    46       21      19       1 **     159       1        0
```

```
47    19    22    0     259   1   0
48    22    19    0     259   1   0
49    20    21    0     114   1   0
50    21    20    0     114   1   0
51    21    30    0     255   1   0
52    30    21    1 **  255   1   0
53    22    23    0     146   1   0
54    23    22    0     146   1   0
55    22    26    0     116   1   0
56    26    22    0     116   1   0
57    24    26    0      60   1   0
58    26    24    0      60   1   0
59    25    26    0      38   1   0
60    26    25    0      38   1   0
61    27    28    0     116   1   0
62    28    27    0     116   1   0
63    28    29    0     212   1   0
64    29    28    0     212   1   0
65    28    30    0     103   1   0
66    30    28    0     103   1   0
67    30    34    0     124   1   0
68    34    30    1 **  124   1   0
69    31    33    0     119   1   0
70    33    31    0     119   1   0
71    32    33    0     582   1   0
72    33    32    0     582   1   0
73    33    35    0      86   1   0
74    35    33    0      86   1   0
75    34    35    0      70   1   0
76    35    34    1 **   70   1   0
77    34    36    0     110   1   0
78    36    34    0     110   1   0
79    35    36    0      60   1   0
80    36    35    0      60   1   0
81    35    38    0     140   1   0
82    38    35    0     140   1   0
83    36    37    0      60   1   0
84    37    36    0      60   1   0
85    36    38    0      62   1   0
86    38    36    0      62   1   0
87    37    38    0       4   1   0
88    38    37    0       4   1   0
89    37    40    0      50   1   0
90    40    37    0      50   1   0
91    38    39    0      45   1   0
92    39    38    0      45   1   0
93    39    40    0      13   1   0
94    40    39    0      13   1   0
95    39    41    0     150   1   0
96    41    39    0     150   1   0
97    42    43    0      50   1   0
98    43    42    0      50   1   0
99     6    35    1       0   1   1
```

```
NODE      PI(NODE)
   1          1454
   2          1454
   3          1454
   4          1454
   5          1434
   6          1454
   7          1440
   8          1312
   9          1454
  10          1131
  11          1160
  12           933
  13          1164
  14           985
  15           964
  16           783
  17           743
  18           629
  19           663
  20           618
  21           504
  22           922
  23          1068
  24          1098
  25          1076
  26          1038
  27           468
  28           352
  29           564
  30           249
  31           260
  32           723
  33           141
  34           125
  35            55
  36           115
  37           175
  38           177
  39           222
  40           225
  41           372
  42          1033
  43           983

     THE NUMBER OF BREAKTHROUGHS IS        3

     THE NUMBER OF NONBREAKTHROUGHS IS      37

STOP
```

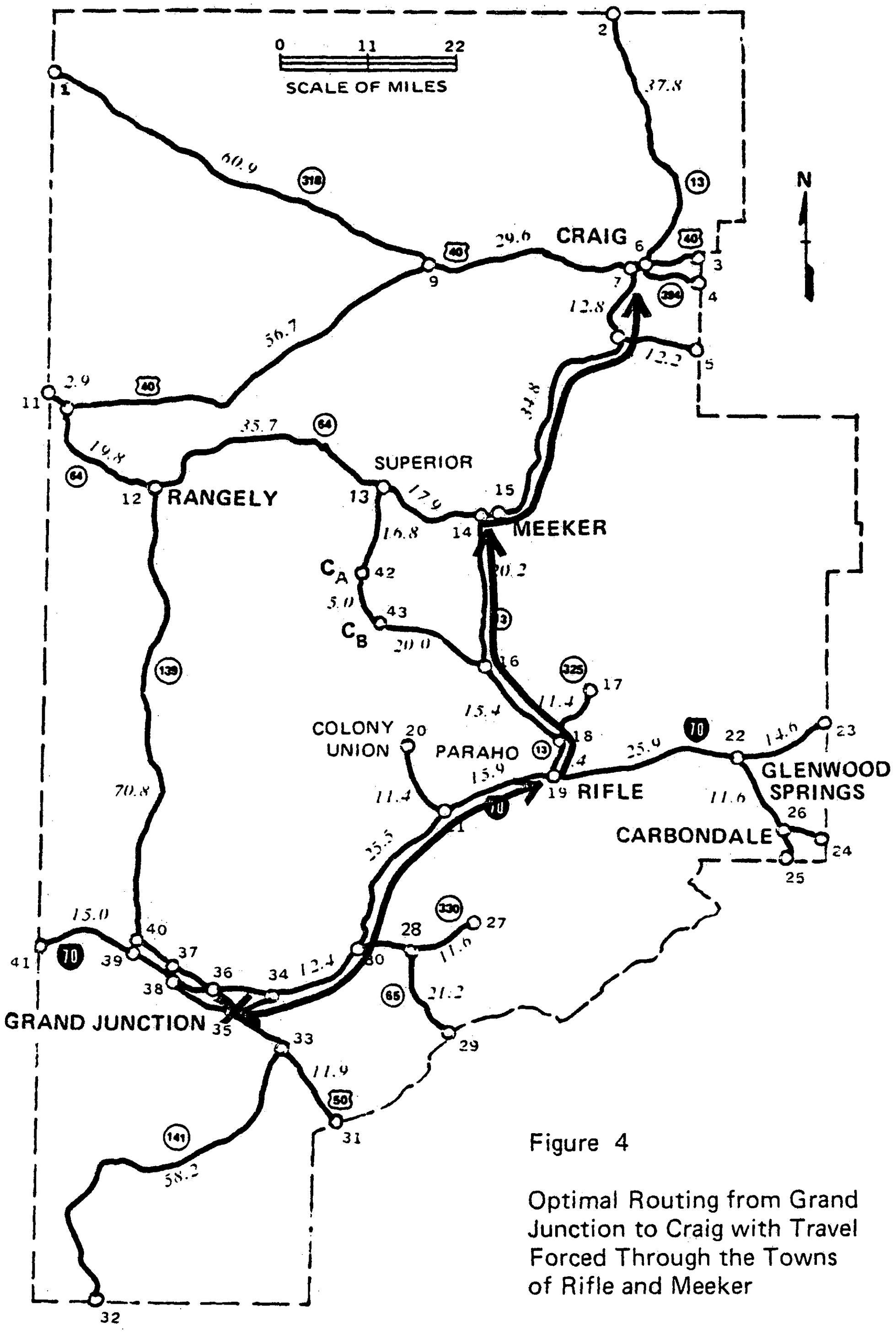


Figure 4

Optimal Routing from Grand Junction to Craig with Travel Forced Through the Towns of Rifle and Meeker

PLATE 1

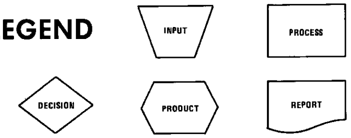
PERMIT OFFICE OPERATION FLOW CHART

WILLIAM W. TODD

T-2323

1980

LEGEND



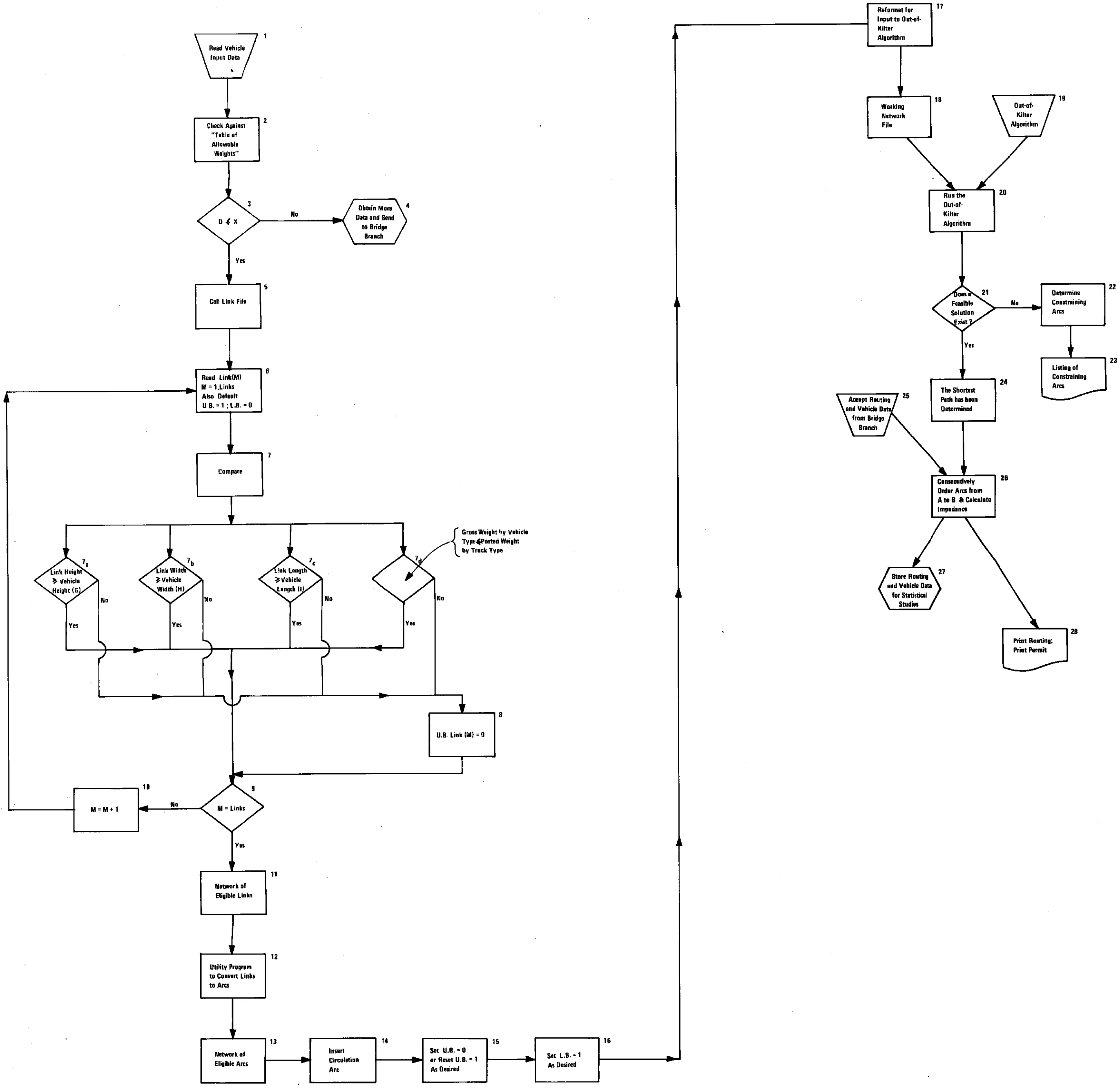


PLATE 2 BRIDGE BRANCH OPERATION FLOW CHART

WILLIAM W. TODD T-2323 1980