WATER CROSSINGS VERSUS TRANSPORT COST: A NETWORK ANALYSIS CASE STUDY

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ABSTRACT

This study determines the impact of fewer water crossings on hauling and road construction costs in a case study situation, and demonstrates the ease and versatility of network analysis in the planning and analysis of forest roads. Using a fixed grid network and modification of a standard network analysis technique allows the solution of large networks in only a few seconds on a personal computer (486-33MHz). The removal of 15 out of a total of 38 culverts resulted in a haul cost increase of \$20 068 (CAD) for 1.2 million m^3 hauled. However, removal of the first 14 culverts only increased the haul cost by \$5 236. The road construction cost saving from not installing the culverts was estimated to be \$75 000 if all 15 culverts were not installed or \$70 000 if 14 culverts were not installed. The case study indicated that considerable savings are possible through better planning of forest roads, especially with the additional expenses required to mitigate environmental impacts.

Keywords: *network analysis, forest roads, hauling, culverts, environment, water crossings.*

INTRODUCTION

With the implementation of more stringent water crossing guidelines in Ontario [1], field personnel have had the impression that significant increases in hauling costs have occurred. These increases would be due to longer haul distances resulting from cutting off the most direct route out of an area.

To study this problem and to demonstrate the ease with which network analysis can be applied, a case study area was analysed to determine the impact of stricter water crossing guidelines on road construction and hauling costs. The road network was established and the logging occurred in the 17 500 ha test area prior to the implementation of current Ontario water crossing guidelines. The stricter requirements have resulted in increased culvert installation costs and fewer crossings.

The analysis compared the hauling cost for 1.2 million m^3 along the existing network with that which would occur if 15 water crossings out of the total of 38 were not installed. Both individual and cumulative effects of culvert removals were studied. The cost differences were then compared with the cost of the culvert installations under the new guidelines.

METHODS

Case Study Area

For the case study, one base map from the Brightsand Forest Management Unit just north of Thunder Bay (Ontario, Canada) was chosen (Figure 1). The entire map sheet was divided into 100 m by 100 m pixels (1 ha) and each pixel was coded according to whether it contained lake, buffer, forest, burn, swamp, river, stream, cut-over, or road class 1, 2, or 3. If a pixel contained a road, it was coded as road, with priority given to the highest road class. With the other categories, the category making up the majority of the pixel was assigned. Of the 17 500 pixels (125 (east-west) x 140 (north-south)), 179 were road class 1, 370 were road class 2, 1 821 were road class 3, and 4 186 were classed as cut-over. The centre point of each pixel defined a road network node. Pixels where roads crossed streams were also recorded.

The raster data can be generated manually from a map sheet or automatically from a GIS (geographic information system). In this case study, the raster data was manually generated. To avoid a "zig-zag" road pattern effect, the procedure outlined in [2] was followed.

Network Minimization Algorithm

The network minimization algorithm is based on the technique outlined in detail by [3]. In the technique the network data (Figure 2) is arranged into a matrix (Table 1).

"Costs" are determined between the source node and all other nodes in the network incrementally. The "costs" from the source node to all other nodes are then checked repeatedly by comparing the difference in "cost" to each node minus the cost to all

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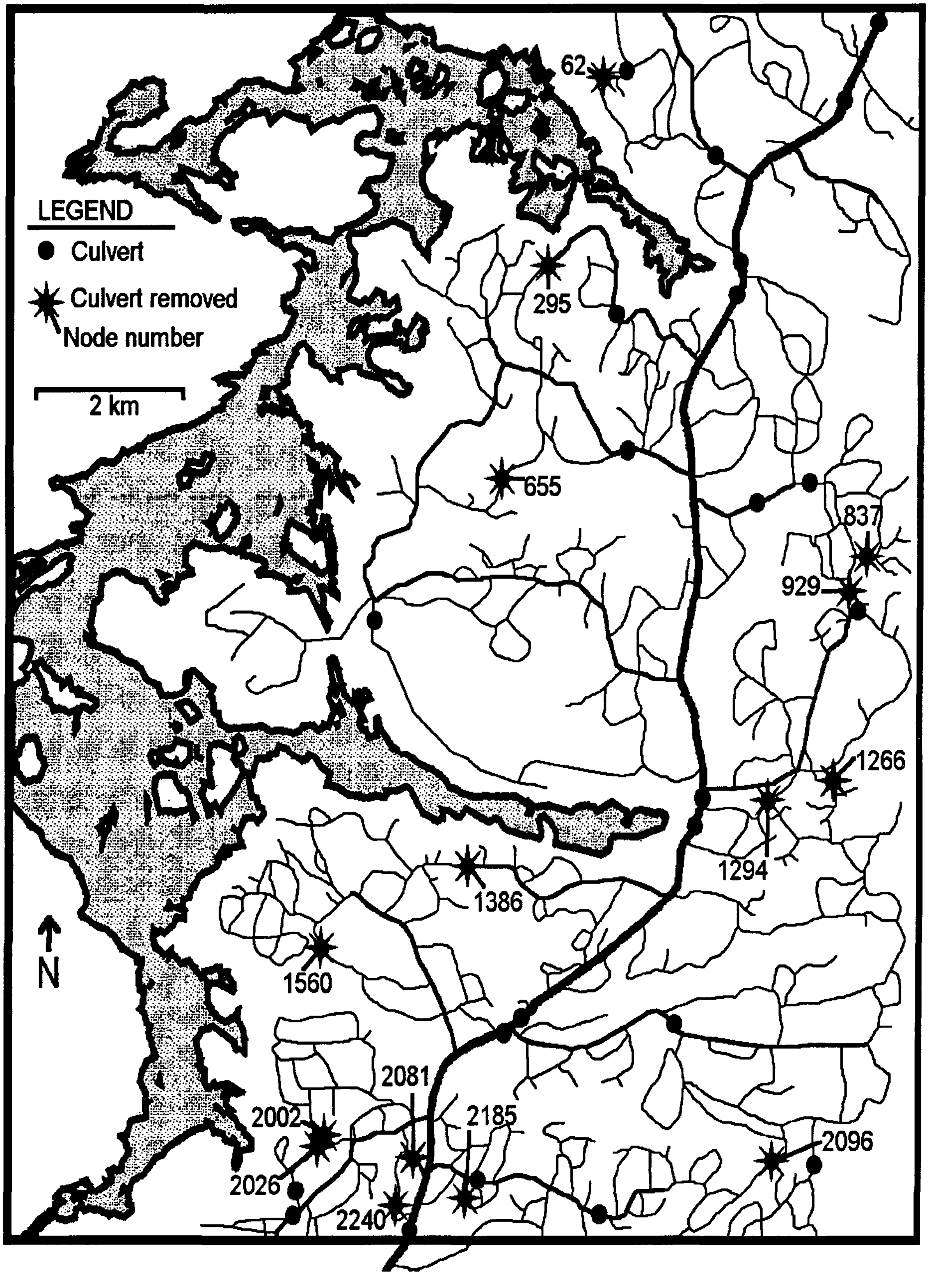

Figure 1. Road network and culvert location map for case study area.

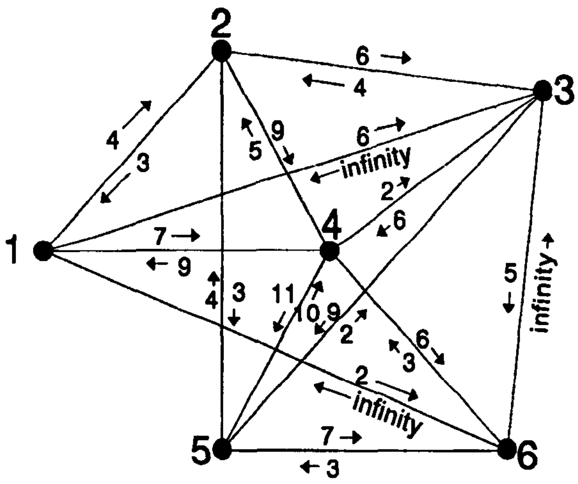

Figure 2. Example of an asymmetric network.

Table 1. An example of asymmetric, cyclic network data arranged in a matrix.

		To Node					
		1	2	3	4	5	6
From Node	1	999	4	6	7	999	2
	2	3	999	6	9	3	999
	3	999	4	999	2	9	5
	4	9	5	6	999	11	6
	5	999	4	2	10	999	7
	6	999	999	999	3	3	999

directly connected nodes, to the "cost" of connecting the two nodes. If the difference is less than or equal to the cost of connecting the two nodes, no shorter route can be found between the two nodes and the next node is checked. If the above condition is not met, a new "minimum cost" is calculated to the adjacent node by adding the cost of connecting the two nodes to the "minimum cost" of the node used in the check. The above process is repeated until no changes in "minimum cost" are made.

The solution of small problems using the above technique with the data in matrix form is quite efficient. However, with large networks the technique becomes limited, due to huge memory requirements and excessive processing time. For example, the 2 370 road nodes analysed in the case study would require a matrix 2 370 x 2 370 in size (5 616 900 addresses).

In the above case, the majority of the matrix would be unfeasible arcs between nodes. In a fixed grid network, each road node can only be connected up to a maximum of four other road nodes. In this case the actual number of data addresses required is a maximum of 9 480. The same technique can be used in road locating; however, impediment values would be required to all eight surrounding nodes.

The fixed structure of the grid permits modification of the algorithm presented by [3], so only arcs between adjacent pixels are analysed. In this way only four nodes are tested for solution improvement at each iteration instead of all 2 370. This allows the solution of the problem on a personal computer (PC) in only a few seconds instead of days if all addresses were searched. The data form is presented in Table 2. If a node is not connected to four other nodes, dummy arcs back to itself at a very high impediment are set so that each node has four records.

Table 2. Examples of the data form used in the solution of the large network problem.

Node Number		From Node road class	To Node road class	Distance, m
From	To			
1	2	3	3	100
1	1	999	999	999
1	1	999	999	999
1	1	999	999	999
...	...	...	...	...
2370	2357	3	3	100
2370	2370	999	999	999
2370	2370	999	999	999
2370	2370	999	999	999

The overall "program engine" for the algorithm is only 40 program lines. However, if a path is desired between the source node and a destination node, another 20 lines is required.

An additional data file containing the node number for each road pixel is required for output of the data in a pixel map format. In this way the minimum hauling times from the source node to all other road nodes in the network can be saved in the same format as the map data for the area.

HAULING TIME AND COST ANALYSIS

The empty and loaded driving speeds on the three road classes are presented in Table 3. The cost to operate a haul truck, including driver and fringes, was set at $85/h (all dollars are CAD). The average haul truck load size was 55 m^3 and the average volume removed per hectare for the area was 185 m^3 (i.e. 3.36 loads per pixel cut). In total, 6 556 ha were cut, yielding a total of 1 212 785 m^3 or 22 051 truck loads of wood.

Table 3. Haul truck driving speeds by road class.

Road Class	Speed (km/h)	
	Loaded	Unloaded
1	55	60
2	21	24
3	9	10

The total hauling cost from the area was calculated by flowing the wood from each pixel cut, including the road node itself, to the nearest road pixel (based on straight-line distance). The number of pixels assigned to each road pixel was multiplied by the number of truck loads per pixel and hauling time (both empty and loaded driving times). The times required for hauling from all pixels were then summed as the total hauling time required to transport all wood from the area.

CULVERT REMOVAL ANALYSIS

A total of 38 culverts at streams/rivers were located in the study area. Of the 21 culverts on tertiary roads, 15 were identified for removal where alternative transport routes were available (Figure 1). None of the nine culverts on primary roads or eight culverts on secondary roads were removed. In this way no area was cut off. Additional culverts could have been removed but would have resulted in restricted access to areas or relocation of roads, both of which were beyond the scope of this case study.

In the first phase of the analysis, roads were cut at individual culvert locations, and the network analysis and total hauling time programs run. In the second phase of the analysis, culverts were removed progressively to obtain a cumulative effect. The culverts which had the least impact in the first phase were removed first and culverts with progressively greater effect were subsequently removed. Similarly, the total transport time and cost for each run were determined.

Water crossings are a major source of sedimentation in streams and can result in serious disturbance to or destruction of the stream bed. The water crossing guidelines [1] strive to minimize and mitigate these impacts. With the implementation of the guidelines there has been a major increase in culvert installation and rehabilitation cost, and a decrease in the number of culverts installed . Based on discussions with the Forest Management Agreement (FMA) holder, the average culvert installation and rehabilitation cost was set at $5 000 per culvert.

RESULTS AND DISCUSSION

With a PC-486-33MHz, the time required to read and process the data, and output the solution was less than one minute. The actual processing time for solution of the 2 370 node network problem was only five seconds. For a 10 000 node problem the processing time is less than 1 minute. The total computing time required for all the analyses was less than two hours; i.e. incremental and cumulative removal of culverts, and calculation of total hauling times. However, a great deal of time was spent getting the information into a form usable by the network analysis algorithm. The time required can be greatly reduced by producing the network data directly from a GIS.

Figure 3 presents both the individual and cumulative effects of culvert removals on total transport times. Figure 4 presents the change in hauling cost for both the individual and cumulative effects. As can be seen, 13 culverts could be removed with a total increase in hauling cost of less than $5 000 for the 1.2 million m^3 hauled (i.e. less than the cost of installing one culvert). Only one culvert, located at road node 1 266, had a major impact of increasing hauling costs ($14 832). The hauling cost increase with the removal of all 15 culverts was $20 068, while for the first 14 it was $5 236.

The current total cost of culvert installation was estimated to be $75 000, while for 14 culverts it would be $70 000. It was assumed that the reduction in road building on both sides of the culvert (i.e. 600 m) would offset any cost increases in building turnarounds and road widenings for truck passing. There would be no additional costs for off-road transport, since landings are not usually placed beside streams or rivers. There could possibly be a slight additional increase in hauling costs with culvert removals from road loops since haul trucks may have to wait to allow others to pass.

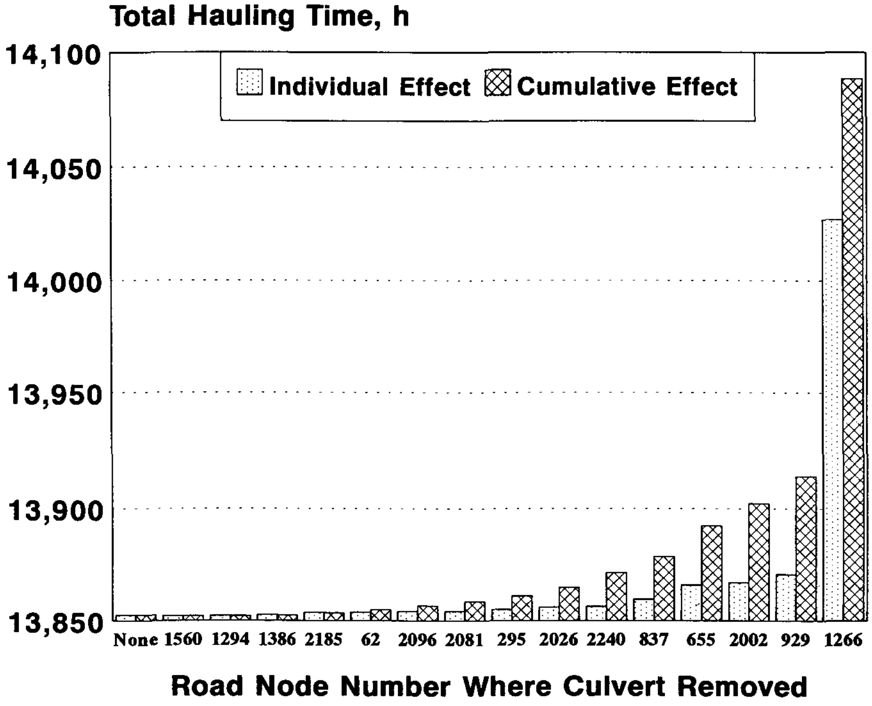

Figure 3. Individual and cumulative effect of culvert removals on total hauling time.

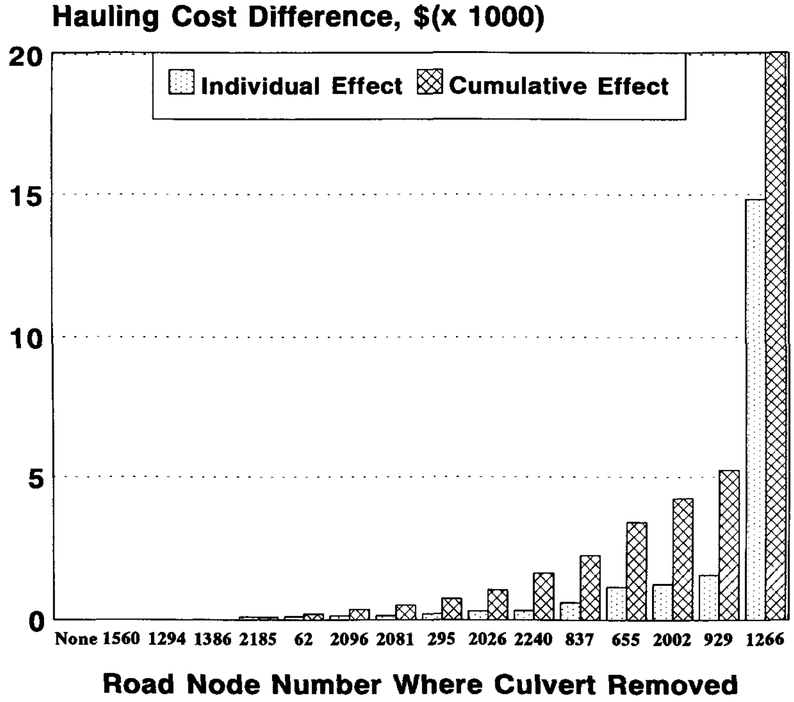

Figure 4. Individual and cumulative effect of culvert removal removals on total hauling costs.

CONCLUSIONS

For the case study area the results showed the general impression held by field personnel -- that stricter water crossing guidelines significantly increase hauling costs -- to be unfounded. For the first 14 culverts removed, the increased hauling cost was \$5 236 for 1.2 million m^3 hauled, while the savings from fewer culvert installations was \$70 000. Removal of the fifteenth culvert resulted in a total haul cost increase of \$20 068, while the saving in culvert installations was \$75 000.

The case study clearly demonstrated how simple the network analysis algorithm is and the utility of the technique in the analysis of changes in road network design. Some simple modifications to the network minimization algorithm presented by [3], allowed by using a fixed grid design, enabled the use of the technique for the solution of large network problems on a PC.

The case study also showed that network analysis techniques are a useful aid in road planning to locate roads and water crossings to minimize environmental impacts, as well as costs.

The case study presented is only one application of network analysis in road location planning and analysis. For example, [4] lists 117 references related to operations research and road planning. In [5], 34 papers were presented on computer supported planning of forest roads. A copy of the program source code is available from the author.

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