Transportation and Economic Development: Heuristic Decision Framework for Upgrading Highway Weight Limits

Final Report: Appendix VI
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1. TRANSPORTATION AND ECONOMIC DEVELOPMENT
   Final Report - Executive Summary

2. TRANSPORTATION AND ECONOMIC DEVELOPMENT
   Final Report

3. TRANSPORTATION AND ECONOMIC DEVELOPMENT:
   THE GEOGRAPHICAL LITERATURE
   Final Report - Appendix I

4. TRANSPORTATION AND ECONOMIC DEVELOPMENT:
   TRANSPORTATION AND THE MINNESOTA ECONOMY;
   TRANSPORTATION/ECONOMY LITERATURE
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5. TRANSPORTATION AND ECONOMIC DEVELOPMENT:
   EVALUATING CRITERIA FOR HIGHWAY PROJECT SELECTION
   Final Report - Appendix III

6. TRANSPORTATION AND ECONOMIC DEVELOPMENT:
   THE LINK BETWEEN HIGHWAY INVESTMENT AND ECONOMIC
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8. TRANSPORTATION AND ECONOMIC DEVELOPMENT:
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   SIMULATION OF HIGHWAY INVESTMENT IMPACTS ON
   THE FORESTRY SECTOR IN NORTHEAST MINNESOTA
   Final Report - Appendix VII

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A time series methodology is developed that differentiates the effects of highways on development from the effects of development on highways. This methodology uses pooled time-series and cross-sectional data on highway expenditures and county employment for the 87 Minnesota counties and all 9 economic sectors over the 25-year period 1957-1982 and includes classification of counties based on access, demographic and socioeconomic features. Results from vector autoregressions are tested against modern causality tests of Granger-Sims type. In the wholesale and natural-resource-based service sectors (e.g., tourism), increased highway expenditures result in long-term employment increases. While regionally very substantial, the impacts are distributional, i.e., the statewide impact is negligible. Government role is mostly reactive, increasing funding to counties whose economy is increasing, except in rural areas where government also attempts to stimulate declining economies. Funding decisions are highly sensitive to changes in the economy, especially in rural areas, and (as our evaluation of the Minnesota Department of Transportation [Mn/DOT] project selection process indicates) are primarily influenced by the District recommendation. Further, a new B/C project selection process is developed and tested on highway weight restriction policies in Northeast Minnesota. Both simulation with large I/O model and comparison with actual funding decisions made independently by Mn/DOT indicate agreement with our results. An extensive literature review and 175 references are included.

This report consists of nine separate publications: an executive summary, the final report and seven appendices. The publications are listed on the following page.
TRANSPORTATION AND ECONOMIC DEVELOPMENT:

HEURISTIC DECISION FRAMEWORK FOR UPGRAADING HIGHWAY WEIGHT LIMITS

Final Report - Appendix VI

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This report represents the results of research conducted by the author and does not necessarily reflect the official views or policy of Mn/DOT. This report does not contain a standard or specified technique.
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ABSTRACT

A heuristic decision framework is developed for obtaining a regional road development program that optimizes the net benefits of the projects in that program while meeting a specified budget constraint. Because a regional network serves a considerable number of plants and markets and consists of a large number of links, the benefits resulting from improving a single link are almost never immediately realized. In the case of a program upgrading the highway weight limits, a benefit is realized only when the minimum load limit along a travel route is raised. The heuristic algorithm addresses this special constraint and determines optimal road development plans for various budget levels. While this analysis concentrates in selecting projects that deal with upgrading the weight carrying limits on the state highways, the methodology is also applicable to other types of highway project selection.
I. INTRODUCTION

The method described in this paper was developed as part of a larger research project that seeks to identify the possible interactions between state transportation expenditures and economic development. While the issue of determining the existence and size of these interactions is addressed elsewhere (Stephanedes and Eagle, 1986; Stephanedes, 1988), in this paper we are concerned with the ways expected project benefits and costs (including any economic impacts) can be considered in highway project selection. In particular, we develop a framework for obtaining a road development program that optimizes the net benefits of the projects in that program while meeting a budget constraint. Although we focus our analysis in selecting projects that deal with changing the weight carrying limits on the state highways, our method is formulated in a general manner so that it could be applied to other types of highway project selection.

Because a regional highway network serves a considerable number of plants and markets and consists of a large number of links, the benefits resulting from improving a single link of the network are almost never immediately realized. More specifically, the net benefit impacts are not fully realized until the reactions of shippers and carriers to route improvements have taken place and any economies or cost savings resulting from such changes are worked into pricing structures and production levels such that consumer/producer relationships are affected. Alternatively, the network links could be upgraded in sets so that the lowest construction costs result in the maximum realizable benefits. In the case of weight limits, a benefit is realized only when the minimum load limit along a travel route is raised (where the minimum load limit
along a route is equal to the maximum allowable load on that route), and it is this special feature (constraint) that makes the problem interesting. Because the problem does not seem amenable to an obvious dynamic programming formulation, we developed a heuristic algorithm that determines optimal development plans for various budget levels. The heuristic algorithm is based on complete enumeration, a technique that is appropriate for reasonable-size problems such as the one studied here.

We apply our analysis to transportation benefit and cost data from the forest industries and the highway system in northeast Minnesota. In this application, changes in weight restrictions, in the direction of upgrading and expanding year-round 10-ton state routes, are expected to affect the transport cost per mile and the direct yearly benefits. For instance, assuming constant demand and supply between origins and destinations, the direct benefits depend on the number of trips saved, the transportation unit cost, the length of trips and the annual time period in which the benefits occur. If the shipping patterns of forest industry products remain consistent with previous shipping patterns and the number of shipments is not reduced by the closing of forest plants, then the impact of upgrading a forest product route may be significant.

Given a set of benefit and cost criteria, we may be able to estimate the impacts resulting from upgrading a highway network. However, the challenge is to employ the results of such an impact analysis in order to establish and execute a systematic process that will then lead to the optimal distribution of the available funds to the network. Before outlining the methodology we developed to aid the project selection and assure an optimal fund distribution in a road network, we present a background and review of the subject and other major project selection studies.
II. BACKGROUND

"The demand for highway improvements is increasing much more rapidly than funds are becoming available. Consequently, all jurisdictions in a state feel cheated; [...] Perhaps the best that could be hoped for is that everyone would feel equally cheated." (NCHRP, 1981). Decisions on when, where, and what type of improvements to make are some of the most important tasks faced by transportation agencies at all levels of government. But before decisions can be made, adequate criteria and standards representing the efficiency, effectiveness and equity aspects of a project need to be established. Techniques are, then, required to assist in the evaluation of options for decision-making. Also needed are methodologies to set priorities in programming of projects in a limited financial environment (TRB, 1980).

Substantial work exists in the literature regarding the criteria employed and the nature of the highway programming process in the various states (NCHRP, 1978; TRB, 1980; NCHRP, 1981). Highway cost allocation methods (Bisson et al., 1985; Markow and Wong, 1983; FHWA, 1982) and maintenance programs (State of Minnesota, 1985) have also been described in detail. Computer-based methods (TRB, 1980) and technical procedures have been introduced, but also criticized. For instance, such procedures often take so long to apply that funding decisions must be made without the benefit of those procedures (NCHRP, 1981); yet existing benefit-cost investment rules have been found naive and the need for more-sophisticated rules has been identified (Gomez-Ibanez and O'Keefe, 1985). A major criticism of the recent U.S. highway cost allocation approach (FHWA, 1982) is that it is based on expenditures, not costs. Any expenditures that are incurred in a particular year are allocated to the traffic of that year, even
though the benefits arising from the investments are realized over a long period. Such an approach neglects the indivisibilities that are necessarily involved in the provision of highway infrastructure and the resultant excess of capacity and cost (Bisson et al., 1985). A similar problem arises in upgrading a road network by raising weight limits; in such a case, we can realize a benefit only when a whole travel route is upgraded. In this paper, we consider this nonlinear problem and present alternative methods for addressing it.

A small number of highway investment programming studies have developed highway programming methods based on estimated costs and benefits to highway users (e.g., operating costs, travel time) and nonusers (e.g., governmental costs). Typically these are combinatorial optimization methods such as linear and dynamic programming, branch and bound techniques, etc. Bergendahl (1969), for instance, employed a combination of linear and dynamic programming to determine the optimal size and time for investments in new highway links in southern Sweden. He decomposed the problem into a set of network problems, where each network represented the road system in different phases of development. The road network was assumed fixed in 5-year periods and investments could be undertaken only at these time intervals. The optimal investment between periods was determined by minimizing current operating cost, where link cost was a convex monotone increasing function of traffic flow.

The Dutch Integral Transportation Study (Steenbrink, 1974) devised a method for minimizing the investments and user costs in the Dutch network from 1970 to 2000. To minimize computation time, the method decomposed the original problem into smaller networks, optimized through linear programming. These results were used in the master problem with a stepwise capacity-restraint assignment according to a least marginal objective function and a descriptive route choice.
model, and led to the minimization of a social cost objective function.

A third example of an investment programming method is the Highway Investment Analysis Package (Gruver et al., 1976), which uses microeconomic theory to analyze individual roadway sections and limited networks of sections specified by their physical, traffic and operational characteristics. It is composed of four computer modules which do not guarantee a globally optimal solution but produce efficient solutions satisfying all constraints.

Further, Schnuerer (1984) studied the optimization of road investments in the province of Salzburg, Austria, based on travel times and using a dynamic programming model. He examined costs of road improvements, arising from different terrain conditions, and travel times, resulting from alternative speed-design standards that vary within each link of a route. While the links of a route differ in their construction cost/design-speed functions, he assumes a convex monotone increasing function between costs and design-speed to be valid for all the links. Frequently, however, a link belongs to several routes and, therefore, the reconstruction requirements for that link are determined by several standards (e.g., routes of 50 and 60 miles speed limit), a problem the author does not indicate how he addressed.

Combinatorial optimization methods, such as the ones reviewed above, could in principle be used to also address the problem under study, i.e., optimization of road investments. In particular, investments for upgrading and expanding year-round 10-ton state routes should be optimized on economic criteria determined by the needs of an economy, e.g., the Arrowhead region of Northeast Minnesota. But these economic criteria could also reflect social factors. For example, a highway improvement could take place even if the benefit in terms of dollars is small, as long as the revitalization of a disadvantaged section in
the region is significant in terms of employment or stabilization of its declining towns.

The realized economic benefits of road investments are quantified through the transportation cost reductions. However, the benefits vary among the industries of an economic sector because the method of transportation cost payments varies from one industry to another. In the forest industry, for instance, an examination of alternative payment structures is necessary because changes in factors affecting the transportation cost determine different schemes of benefits for the shippers and the freight carrying companies. Some shippers pay the freight carriers a flat rate for the movement of their products. Others, contracting with independent truckers, pay (a) by the loaded miles, (b) by the running mile or (c) by the loaded miles with an additional hourly rate for time spent at the truck terminal. Shippers who lease trucks pay according to a lease agreement. In the first payment alternative, transportation cost reductions are a benefit to the carriers, while in the rest of cases the benefits are enjoyed to a larger extent by the shippers.

In the next section, a heuristic procedure is developed to solve the problem of combining the maximum realizable economic benefits, resulting from the alleviation of weight restrictions or other road improvements, with the minimal incurred construction costs, expended for the upgrading of the network links. To be sure, both benefits and costs are amortized over the time horizon appropriate for each project. The principles of the heuristic optimization procedure are elucidated with an example.
III. PROBLEM AND METHOD

In this section, we develop a method for obtaining a road development program that optimizes project net benefits under a budget constraint. As in every combinatorial optimization problem, the current problem can in principle be solved by "exact" techniques, i.e., tree search, branch and bound, etc. But these techniques frequently require computation times that grow faster than polynomially with the size of the problem and get out of control with excessively large problems. While most of the combinatorial optimization problems can also be transformed into integer programming models, the disadvantage of that approach is that the mathematical techniques for treating such models are generally inefficient (Muller-Merbach, 1976) -- although certain efficient heuristic techniques (e.g., Lagrangian relaxation heuristics) have been suggested (for a detailed review of the literature see, e.g., Crowder et al., 1983; Magnanti and Wong, 1984.)

When "exact" mathematical techniques or integer programming models are inefficient in solving the problem, there are two ways to overcome the dilemma. Either the problem has to be modified, by relaxing the elements causing the algorithmic difficulties, or heuristic procedures must replace the exact mathematical techniques. It is usually advantageous to leave the problem unchanged and develop heuristic procedures, i.e., "systematic" procedures that are precisely defined and, therefore, can be programmed for a computer.

In the problem under study, "exact" techniques, e.g., linear or dynamic programming, are not applicable, since the principle of optimality does not hold. This is evident since, first, minimization of total construction costs and maximization of benefit/cost ratios or net benefits may dictate the
upgrading of different routes depending on the proposed road construction sequence and, second, different budget constraints should be considered in predicting what is optimum in the process of road investments.

Apart from the linear and dynamic programming methods, no practicable conventional procedure minimizes road improvement costs in a complete road network while considering all possible route combinations simultaneously. Such a simultaneous optimization could not be tackled because of the large number of decision variables and constraints. Thus, in this analysis, a technique is developed so that the best solution can be determined in a stepwise procedure.

While the realizable benefits of each upgraded link depend on the load category of other links, costs are independent and are used to decompose the problem into subproblems along the cost dimension. We then identify "mutually exclusive projects", with respect to the construction costs, i.e., projects with costs that do not incur the need of any further expenditures and exclude the upgrading of any different project(s).

In this analysis, a "project" is the upgrading of path-link(s) which allow the establishment of a better load category for an entire path and the realization of benefits. Projects leading to only unrealizable benefits are discarded, so that the final list only contains an implicit enumeration of all projects which have realizable benefits. Unrealized benefits of a complete project are not weighted in this implicit enumeration procedure.
IV. MODEL DEVELOPMENT

IV.1 Road network representation

Three characteristics of the road network are of interest, i.e., (i) the nature of the network, (ii) the load carrying type for each arc (road), and (iii) the length of each arc. This information may be represented in a matrix $P$ of size $N \times N$, where $N$ denotes the number of nodes in the network. The element $a_{ij}$ in cell $(i,j)$ of matrix $P$ is zero, wherever nodes $i$ and $j$ in the network are not directly connected. For a pair of nodes $i$ and $j$ which are directly connected, the element $a_{ij}$ is represented by a pair of numbers, the first number $k$ giving the weight carrying type, and the second number $\ell$ giving the length of the arc $(ij)$ -- See Table 1.

Table 1. Adjacent Arc Matrix representing the network

<table>
<thead>
<tr>
<th>NODES</th>
<th>1</th>
<th>2</th>
<th>...</th>
<th>j</th>
<th>...</th>
<th>N</th>
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<td>NODES</td>
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[A non-zero entry appears only where nodes $i$ and $j$ are connected by a direct arc. $k$ is weight carrying type, e.g., 9-ton, and $\ell$ is length of arc $(i,j)$.]
IV.2 Customer's route demand matrix

We initially concentrate on a single commodity served by the network and define the demand matrix for this commodity while suppressing the index for the commodity. Our final purpose is, of course, to compute the total net benefits realizable from the upgrading of the network over all commodities. Once the scheme for computing benefit for one commodity is laid out, the benefit over all commodities can be computed easily by summing the benefit over all individual commodities.

Let \((i_s, j_s)\) denote the pair of source and sink nodes for customer \(s\), where the index for the commodity is suppressed. Let \(d(i_s, j_s)\) denote the annual demand in tons for customer \(s\) from source node \(i_s\) to sink node \(j_s\). The demand \(d(i_s, j_s)\) and routing information for each customer \(s\) is given in Table 2. The

<table>
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<th>(s)</th>
<th>(i_s)</th>
<th>(j_s)</th>
<th>EL</th>
<th>E2</th>
<th>E3</th>
<th>F1</th>
<th>F2</th>
<th>G9</th>
<th>(d(i_s, j_s))</th>
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<td>1</td>
<td>3</td>
<td>7</td>
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Table 2. Matrix of source-sink pairs, routing and demand data
first column of the table, labelled $s$, indicates the customer number and the second column, labelled $(i_s, j_s)$, indicates the source and sink node pairs for each customer. The middle section includes the routing information; each row represents a route from a source node to a sink node. Each arc is coded according to existing weight restrictions, e.g., 'E' stands for 9-ton roads operated as 10-ton in the three winter months etc. A 'one' under an arc implies that this arc is involved in the route from $i_s$ to $j_s$ and a 'zero' entry implies the arc is not involved. We may list more than one route for each source-sink pair, assigning a separate line for each route.

For each source-sink pair, the last column indicates the annual demand in tons from node $i_s$ to node $j_s$. As upgrading of the arcs proceeds, it is very likely that some customers may change from their current routes to different routes. To provide for this possibility, all routes which can potentially become optimal routes are listed a priori.

IV.3 Route Capacity

The special feature of the transportation network is that the weight limit on a route is determined by the minimum value of the weight limits of the arc involved in that route. Benefits from upgrading weight limits of various arcs are, therefore, realized only if these improvements lead to the raising of the minimum value of the weight limits on complete routes. Two maintenance policy alternatives are considered regarding the route capacity of the network.
(a) Arc\((i,j)\) is upgraded from its current type \(k_{ij}\) to a new type \(k'_{ij}\), where \(k' > k_{ij}\).

(b) Arc\((i,j)\) of current type \(k_{ij}\) is used without improvement for loads of type \(k'_{ij}\). This would lead to a reduced expected life and an increase in the maintenance costs.

Further, let 
\[
c(i,j,k,R) = \text{Present worth of the sum of the initial costs for upgrading arc\((i,j)\) from load type } k \text{ to load type } R, \text{ and the maintenance costs over a planning horizon of } T \text{ years.}
\]
\[
e(i,j,k,R) = \text{Present worth of the increased maintenance costs incurred over a planning horizon of } T \text{ years when arc\((i,j)\) of load type } k \text{ is used for load type } R, \text{ where } k' > k.
\]

For every arc with current load type \(k\), a decision has to be made, i.e., (a) should it be improved and, if so, to what new category \(k'\), or (b) should it be used for higher loads without improvement.

IV.4 Decision variables and mathematical formulation

Let 
\[
X(i,j,k,R) = \begin{cases} 
1, \text{ if arc}(i,j) \text{ is upgraded from type } k \text{ to } k' \\
0, \text{ otherwise}
\end{cases}
\]

\[
Y(i,j,k,R) = \begin{cases} 
1, \text{ if arc}(i,j) \text{ of type } k \text{ is used for loads of type } k' \\
0, \text{ otherwise}
\end{cases}
\]
Then, for every arc \( (i, j) \), find \( X(i, j, k, K) \), \( Y(i, j, k, K) \) which maximize the total net benefit \( Z \) summed over all \( s \) customers and all \( p \) commodities:

\[
\max_Z = \sum_{p, s} b_p(i_s, j_s, m, n) \quad (1)
\]

where the term \( b_p(i_s, j_s, m, n) \) denotes the net benefit realized for customers of product \( p \) as a result of raising the minimum weight limit from \( m \) to \( n \) on the route from \( i_s \) to \( j_s \).

The above optimization is subject to the following constraints:

\[
\sum_{(i, j) \in R > k} \left[ \sum_{R > k} c(i, j, k, \bar{K}) X(i, j, k, \bar{K}) + \sum_{R > k} e(i, j, k, \bar{K}) Y(i, j, k, \bar{K}) \right] \leq W \quad (2)
\]

where \( W \) = the present worth of the total available budget over the planning horizon of \( T \) years

\[
\sum_{R > k} [X(i, j, k, \bar{K}) + Y(i, j, k, \bar{K})] \leq 1 \quad \text{for every } (i, j) \quad (3)
\]

In equation (1), \( m \) and \( n \) define the present and the new load limits for route \( (i_s, j_s) \) and these are equal to the minimum values of \( k \) and \( \bar{K} \), respectively, for the arcs \( (i, j) \) involved in the route \( (i_s, j_s) \). Therefore, a benefit is realized only when the minimum load limit on a route is raised from \( m \) to \( n \).
The above problem does not seem amenable to an obvious dynamic programming formulation, i.e., one based on Bellman's principle of optimality. According to that principle, if we allocate a specific amount of a resource to a given activity, say activity \( i \), we have a chance of obtaining an overall optimal return only if the remaining amount of the available resource is allocated in an optimal fashion among the remaining activities. The principle does not hold in our case since, e.g., the set of transportation projects that is the optimal solution for a large budget does not necessarily contain (as a subset) the optimal solution project set of a smaller budget.

Since we cannot employ the principle of optimality to eliminate a feasible solution of our problem, we may use a branch and bound or other programming technique or an enumerative approach. We have not considered branch and bound since our network is of a size for which the enumerative approach is quite adequate. A solution algorithm that is essentially of an enumerative type is developed in the next section.

V. SOLUTION ALGORITHM

The algorithm for obtaining optimal highway development (e.g., upgrading) plans at any available budget \( W \) is based on complete enumeration, a reasonable strategy when the size of the problem is not too large. The algorithm follows three basic steps:

**Step 1.** Generate a set \( U \) of all feasible combinations of elemental projects, coded by highway arc. Arrange these projects in a monotonic increasing order based on their cost.
Step 2. From set $U$, generate a set $V$ that indicates all the feasible breakpoints on the budget axis (see Fig. 1).

Step 3. For any given budget $W$, select the set of projects which maximizes total net benefit. Repeat for all breakpoints on the budget axis.

We note that we begin by ordering the projects based on cost (step 1) merely to facilitate the subsequent search for feasible budget breakpoints (step 2.) Project selection then proceeds based on any acceptable criterion such as net benefit or B/C. In this analysis an elemental project is defined as the upgrading of a route from node $i$ to node $j$ that allows the establishment of a better load category for the entire route $(i,j)$. Further, the set $U$ of all feasible project combinations includes upgrading combinations that lead to the same final outcome but are accomplished in a different sequence. For instance, a 9-ton road may be upgraded to 10-ton directly; alternatively (and this would be considered a different project in $U$), the 9-ton road may be partially improved at first, to 10-ton for 10 months. To be sure, the cost of upgrading a highway in steps is higher than making the complete improvement at once.

After a project is selected for completion, the cost of all arcs belonging to that project is set equal to zero and the costs of all remaining projects are updated. For those projects that include arcs that are common to those of the selected project, the cost decreases; for all others, the cost remains the same.

The nature of the relationship between the total optimal benefit $Z$ and the available budget $W$ is illustrated in Figure 1. In general, the set $U$ initially may contain one or more small projects, the completion (upgrading) of which leads to immediate completion (upgrading) of one or more complete routes. If
such projects are present in U, the curve of Fig. 1a begins with a B/C ratio greater than one. If, on the other hand, no such project exists in U initially, the rate of accumulation of the total benefit $Z$ is slow and the curve begins below the breakeven ($B/C = 1$) line as Fig. 1b indicates. As more arcs are completed, the benefit accumulation rate accelerates and the curve of Fig. 1b may again cross the breakeven line as it enters a range where $B/C > 1$ at some stage (point D). Towards the end, when most important routes in the network have been upgraded, the rate of increase of $Z$ slows down again.

![Diagram of total benefit $Z$ as a function of budget $W$.](image)

**Fig. 1a** Beginning with $B/C > 1$  
**Fig. 1b** Beginning with $B/C < 1$

Figure 1. Total optimal benefit as a function of available budget

It should be noted that, when the budget is overly restricted or the highway network is well developed, the B/C curve of Fig. 1 may end as convex, i.e., reaching the breakeven line from below rather than from above; points C or D in Fig. 1 may, then, never be reached. Further, the continuous curve of Fig. 1 should, more accurately, be discrete reflecting the discrete nature of the optimal benefit increments -- see, e.g., the dashed lines in Fig. 1b.
VI. CASE STUDY IN NORTHEAST MINNESOTA

VI.1 Case description

The objective of the case study is to analyze the economic viability of upgrading the spring weight restrictions on the state highways of northeast Minnesota. In particular, the case study focuses on evaluating the network upgrading on the basis of realized net benefits from the paper and waferboard product industries of that region. Benefits would accrue if the network upgrading reduced transportation costs and, thus, made the final production cost of the above forest products more competitive in the nation's markets. These industries could, then, increase the production capacity of their plants and, in time, their export market share in the national and international markets.

While transportation cost is an important factor in the final cost of the voluminous forest products, organized cost and shipment data do not exist or are incomplete. In particular, the difficulties associated with the collection of reliable data and data confidentiality are often cited (Eldridge and Fruin, 1984; ARDC, 1985) as the two major reasons for the lack of complete data. In order to obtain a more complete database on paper and waferboard product shipments, a survey was conducted in northeast Minnesota in 1985. The survey sought information on shipment origins and destinations, cost structure, tonnage, modal split, shipment value, trip duration, etc. for the nine leading woodpulp mills in the area. The paper and waferboard producers belonged to the following companies: Potlatch, Blandin, Northwood Panelboard, Boise Cascade, Superwood, Conwed, Diamond International, and Great Lakes Forest Products. A summary of relevant data from these producers is presented in Tables 3 and 4.
Table 3. Active pulpwood mills and waferboard plants in northeast Minnesota by location and capacity as of 1982

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Capacity (tons/24 hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodpulp Mills</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Producer X</td>
<td>Grand Rapids</td>
<td>300</td>
</tr>
<tr>
<td>Producer Y</td>
<td>International Falls</td>
<td>920</td>
</tr>
<tr>
<td>Producer Z</td>
<td>Cloquet</td>
<td>475</td>
</tr>
<tr>
<td>Producer T</td>
<td>Bemidji</td>
<td>100</td>
</tr>
<tr>
<td>Producer U</td>
<td>Duluth</td>
<td>350</td>
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<tr>
<td>Producer V</td>
<td>Cloquet</td>
<td>50</td>
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<table>
<thead>
<tr>
<th>Waferboard Plants</th>
<th>Capacity (est tons/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Producer A</td>
<td>Grand Rapids</td>
</tr>
<tr>
<td>Producer B</td>
<td>Bemidji</td>
</tr>
<tr>
<td>Producer C</td>
<td>Bemidji</td>
</tr>
<tr>
<td>Producer D</td>
<td>Cook</td>
</tr>
</tbody>
</table>

[ Eldridge and Fruin, 1984]

Table 4. Data summary of forest product producers in NE Minnesota*

<table>
<thead>
<tr>
<th>Company</th>
<th>max distance between plant and market (miles)</th>
<th>max distance between plant and market (miles)</th>
<th>max distance by truck ($/mi)</th>
<th>Shipment size (short tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1800</td>
<td>U</td>
<td>1.2</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>2100</td>
<td>U</td>
<td>1.1-1.4</td>
<td>23</td>
</tr>
<tr>
<td>3</td>
<td>48 states</td>
<td>800</td>
<td>1.2</td>
<td>23</td>
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<tr>
<td>4</td>
<td>48 states</td>
<td>800</td>
<td>1.2</td>
<td>23</td>
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<tr>
<td>5</td>
<td>48 states</td>
<td>U</td>
<td>1.1-1.3</td>
<td>23</td>
</tr>
<tr>
<td>6</td>
<td>48 states</td>
<td>U</td>
<td>1.1-1.2</td>
<td>23</td>
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<tr>
<td>7</td>
<td>700</td>
<td>700</td>
<td>NA</td>
<td>22</td>
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<table>
<thead>
<tr>
<th>Company</th>
<th>max distance between plant and market (miles)</th>
<th>max distance between plant and market (miles)</th>
<th>max distance by truck ($/mi)</th>
<th>Shipment size (short tons)</th>
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<tbody>
<tr>
<td>1</td>
<td>1800</td>
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<td>3</td>
<td>48 states</td>
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<tr>
<td>7</td>
<td>700</td>
<td>700</td>
<td>NA</td>
<td>22</td>
</tr>
</tbody>
</table>

* = for confidentiality purposes, not all producers are listed.
U = unlimited; depends on market conditions and order size.
na = not applicable; mode not used.
NA = not available
In addition to the information summarized in Tables 3 and 4, the responses to our survey indicated that the transportation cost is an important component of the final price of paper and waferboard, especially for shipments outside Minnesota. To be sure, each company has established its own transport policy that may not necessarily include the transport cost explicitly in the final product price. Further, not all companies collect the information on transport cost components (such as travel time and loading cost) in a uniform manner, and a substantial portion of it is based on estimates. In general, the paper market is relatively more stable than the waferboard market; it employs more trains over longer distances, and procurement planning is more long-term. On the other hand, waferboard planning is based on a shorter horizon and involves shorter haul and heavier use of trucks that often determine their own shipment routes.

No surveyed company disclosed product demand data at the customer, town or city level. As a result all our demand data are at the state level.

We expanded the above database with data related to the principal highways the forest industries use in northeast Minnesota. We used these data, provided by the Minnesota Department of Transportation (MnDOT), to develop the layout of the relevant highway network, illustrated in Figure 2. The MnDOT classifies these highways in three load categories, i.e.,

a) E - category: 9-ton roads operated as 10-ton in the 3 winter months,
b) F - category: 9-ton roads operated as 10-ton for 10 months, and
c) G - category: 10-ton roads year-round.
Figure 2. Principal highways of northeast Minnesota used by forest industries.
Using the above information, we segmented the principal highways of NE Minnesota into links by load category and estimated remaining life -- see Table 5.

Having identified and classified the relevant links, we implemented our algorithm to analyze these highways with the help of a personal computer in Pascal. The computer code accepts the arc length and remaining life of highways, and the number of truckloads between origins and destinations as inputs. The output is a prioritization of the available projects subject to a budget constraint.

The project prioritization results are based on the assumption that the realizable project benefit per truck load is approximately 3 short tons, i.e., the difference between the currently allowed 73820 pounds GVW and the desirable 80000 pounds GVW. No effects were considered that relate to possible truck detouring or plant closing because of road deterioration.

IV.2 Case study results and discussion

Prior to considering the results of this case study, a few comments are in order regarding the relevance of this case to typical project selection/prioritization problems. More specifically, upgrading highway weight limits has been a major issue in the state of Minnesota and the choice of the particular topic is, therefore, timely. The upgrading issue is particularly relevant in the north, where road condition requires extensive improvement.

The issue is also relevant in that part of the state for two additional reasons. First, timber industry is a major user of the roads; that industry carries heavy loads over long distances and is incurring a substantial competitive disadvantage by having to operate trucks below capacity. Therefore,
Table 5. Trunk highways of northeast Minnesota used by forest industries

<table>
<thead>
<tr>
<th>Trunk Highway (TH)</th>
<th>2 Lanes</th>
<th>4 Lanes</th>
<th>Category</th>
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<tbody>
<tr>
<td></td>
<td>Mileage Remaining</td>
<td>Mileage Remaining</td>
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<tr>
<td></td>
<td>Life</td>
<td>Life</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td></td>
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<tr>
<td>J-15</td>
<td>2.65</td>
<td>2.65</td>
<td>F</td>
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<tr>
<td></td>
<td>1.03</td>
<td>1.03</td>
<td>F</td>
</tr>
<tr>
<td>Cleaner</td>
<td>3.75</td>
<td>3.75</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>4.10</td>
<td>4.10</td>
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<tr>
<td>TH 2</td>
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<td>F</td>
</tr>
<tr>
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<tr>
<td>2</td>
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<tr>
<td>Duluth</td>
<td>7.01</td>
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<tr>
<td></td>
<td>6.77</td>
<td>6.77</td>
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<tr>
<td>TH 194</td>
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<tr>
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<tr>
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<tr>
<td></td>
<td>3.25</td>
<td>3.25</td>
<td>E</td>
</tr>
<tr>
<td>International Falls</td>
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<tr>
<td>61</td>
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<td></td>
<td></td>
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<tr>
<td>Duluth</td>
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<td>12.00</td>
<td>G</td>
</tr>
<tr>
<td>Two Harbors</td>
<td>3.55</td>
<td>3.55</td>
<td>E</td>
</tr>
<tr>
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<td>17.77</td>
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<tr>
<td></td>
<td>38.41</td>
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<tr>
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<td>16.14</td>
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<tr>
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<td>17.70</td>
<td>17.70</td>
<td>E</td>
</tr>
<tr>
<td>U.S. Border</td>
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</tbody>
</table>
the industry has been vocal in its requests for road upgrading.

Tourism is the second major user of the roads in the north and could benefit from improved road quality. In particular, previous findings indicate that tourist-related services stand to gain substantially when access is improved. These findings were recently confirmed for Minnesota (Stephanedes, 1988), where it was found that only in non-metropolitan counties that have a strong tourist base do highway improvements have a significant long-term beneficial effect on employment.

While we recognize the importance of both the timber industry and tourism to the economy of northeast Minnesota, time limitations allowed us to implement this method with timber movements only. Therefore, the determination of benefits that would result from the upgrading is conservative as it only includes timber-related benefits.

Of all candidate upgrading projects considered, the following were selected in order of priority, based on the selection algorithm (the selected projects are placed on the Minnesota map of Figure 3) and the estimated benefits that would result for the timber industry:

1. TH 33, from I-35 to Cloquet; upgrade to 10-ton road year round.
2. TH 33, from Cloquet to TH 2; and TH 2, from TH 33 to Grand Rapids; to 10-ton year round.
3. TH 53, from Cook to International Falls; to 10-ton for 10 months.
4. TH 2, from Grand Rapids to Bemidji; to 10-ton year round.
5. TH 61, from Two Harbors to U.S. border; to 10-ton for 10 months or year round.
6. TH 33, from TH 2 to TH 53, and TH 53, from TH 33 to International Falls; to 10-ton year round.
load categories

E: 9-ton; 10-ton in 3 winter mos.
F: 9-ton; 10-ton for 10 mos.
G: 10-ton

weight upgrading: E+F, E+G, F+G

project priority rating: 1 (highest) to 7

Fig. 3. Prioritized projects in NE Minnesota
We note that, once selections #1 and #2 from the above set are made, the remaining selections indicate a cumulative benefit/cost ratio that is less than 0.2 and may, thus, not appear attractive at this stage. In fact, only the segment of Trunk Highway 33 (TH 33), connecting Interstate 35 (I-35) with Cloquet (see Figure 3) has a benefit/cost ratio greater than 1 if only timber-related travel is considered.

To be sure, as noted above, this finding is not surprising and does not indicate lack of relevance of the new method. In fact, the low cumulative B/C is partly the result of considering the benefits accruing to only one customer, i.e., the forest industry. When the benefits accruing from the additional economic sectors that stand to benefit from improved access (such as the service sector in relation to tourism) are considered, the B/C's of these projects are expected to improve.

From the above, we note that the project prioritization algorithm was effective in reducing a very large number of possible project combinations to a prioritized project selection of manageable size. Having considered the estimated benefits for only one industry and the upgrading costs, the prioritization conclusively indicated the desired order in which the projects should be undertaken. The prioritization could certainly be extended to consider expected benefits to additional industries.

The above analysis does not consider the opportunity cost of not tending to deteriorating highways in a timely fashion. For instance, roads of low quality are likely to result to truck detours, when an alternative path is available, and higher transportation cost. When the cost crosses a certain threshold, that the industry considers unacceptable, that industry may relocate; similarly, new industry may not be attracted. Further, the analysis does not consider any
rerouting that may take place following partial upgrading of the network. However, the centralized nature of the NE Minnesota network substantially reduces the possibility for such rerouting.

It should be noted that the Minnesota DOT has recently alleviated weight restrictions on TH 2 based on highway engineering criteria (deflection tests) and is considering upgrading TH 33 from I-35 to Cloquet. These decisions, made independently of this analysis, are in substantial agreement with our results.

VII. SUMMARY

A heuristic framework was developed for selecting and prioritizing highway weight-upgrading projects. The method can aid the decision maker identify the most worthwhile projects in terms of benefits to highway users and upgrading costs over the planning horizon.

The analysis evaluates all feasible project combinations. In particular, it considers all individual highway arcs of each project in every order and all combinations of intermediate upgrading possibilities. A special constraint of the problem dictates that a benefit for a path is realized only when the minimum load limit along the whole path is raised.

Without loss of generality, the method was applied to the northeast Minnesota network and evaluated all possible upgrading project combinations relative to a major highway user, i.e., the forest industry. Following the evaluation, the long list of possible project combinations led to the identification of a small set of projects which were prioritized for implementation. It is encouraging to note that, even though the scope of the example application was limited to one user, the results of the prioritization
are in substantial agreement with the upgrading decisions which the Minnesota DOT made independently of this analysis.

While the algorithm leads to a conclusive prioritization of the best project combination selected from an all-inclusive list of feasible projects, it must be used for each major highway user in order to reflect the benefits that would accrue to all users. The algorithm was implemented in a case study that was limited to only one industry, but its extension to additional industries is straightforward as it has been designed to be used in the general case of the highway user.

Ongoing research seeks to include the time element in the above analysis. For instance, it is desirable to identify the time at which each of the reviewed projects may become attractive subject to a planning horizon and annual budget restrictions.

ACKNOWLEDGEMENT

The work described here is the result of research funded by the Minnesota Department of Transportation. The comments made by three anonymous referees and the members of the Committee on Transportation Programming, Planning, and Systems Evaluation of the Transportation Research Board are gratefully acknowledged.
REFERENCES


