Infrastructure Management System: Case Study of the Finnish National Road Administration

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The Finish National Road Administration has used its network-level pavement management system, the Highway Investment Programming System (HIPS), as a decision support tool since 1989. However, this system is capable of addressing strategic questions concerning paved roads only; it is not capable of addressing questions concerning bridges, for example. A new idea has been to review the existing pavement management system (HIPS) and take the basic features of the Finnish Bridge Management Systems and to modify and couple these two systems into one system, the infrastructure management system (IMS), to optimize simultaneously bridge and pavement maintenance and rehabilitation under the same budget and other constraints. The development of the first version of IMS appeared to be rather successful. The first results show that it is possible to allocate monies between pavements and bridges by using the minimization of social costs as an objective function. Compared with the short-term allocation procedure in HIPS, the influence of traffic volume is stronger in IMS. The system can be modified further. This means that other parts of the infrastructure, like power transmission lines, can be incorporated into the analysis.

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As such the system considers comprehensively all of the main expenditure items associated with the networks under consideration, that is, bridges and the pavements, in this case, of road networks. Furthermore, the system incorporates discounted cash flow techniques, so that investment efficiency indicators can be estimated for each investment alternative associated with a prespecified level of budgetary availability.

The contents of the case study were

- Modification of the six submodels in HIPS to be used for both the pavements and the bridges, three for each structure;
- Estimation and calculation of the current condition data, deterioration models, and agency and user cost data;
- Modification of the existing software for simultaneous runs of bridges and pavements; and
- Revision of optimization procedures and incorporation of rate of return and other investment efficiency indicators for comparison of alternatives.

This case study was completed by the end of July 1993. At a later stage it is expected that the case study would be integrated into the training program of EDINU of the World Bank.

INFRASTRUCTURE MANAGEMENT SYSTEM

This section describes version 1.0 of the IMS, which was developed for FinnRA by Statistical Computing Ltd., InfraMan Ltd., and Viasys Ltd. IMS is a modified version of the Finnish network-level pavement management system, HIPS, which was developed in cooperation with Cambridge Systematics, Inc., of Cambridge, Massachusetts. (Highway Investment Programming System: User's Manual for Version 1.0 Finnish National Roads Administration, Unpublished, 1989.)

The purpose of the system is to optimize pavement and bridge rehabilitation policies and the allocation of funding among pavement and bridges. The model covers general classes of rehabilitation actions from general patching to total reconstruction. Because it is a strict network-level model, the system analyzes road policies at an aggregate level, considering only subnetworks of roads or bridges.

The system is based on Markov dynamic program, which categorizes pavements into 135 condition states and eight actions and bridges into 81 states and five actions and represents deterioration as the probability of making transitions among all possible pairs of condition states over 1 year. An agency cost model estimates the cost of each possible action, and a user cost model evaluates the costs for road users in terms of travel time, fuel consumption, and vehicle depreciation and for bridges in costs of diverted traffic because of weight restrictions.

Separate models are available for six models: three traffic volume classes for pavements and three for bridges. The Markov model and standard economic efficiency indicators optimize budget allocations within each of these six models, and a benefit-cost procedure optimizes the funding among them.

System Description

The structure of the IMS is shown in Figure 1.

Two classifications of analysis are provided to address the resource allocation policy questions of interest to the Ministry of Finance, the Ministry of Transport, and the Highway Administration. These are the

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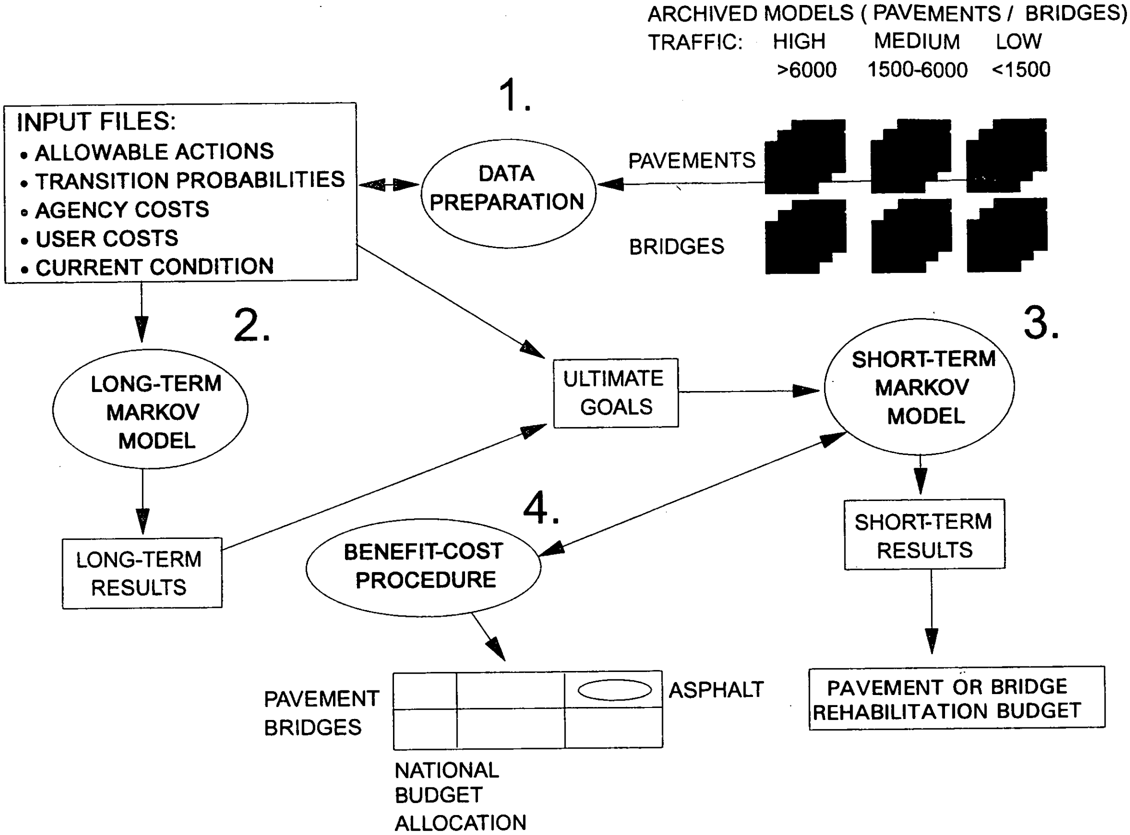


FIGURE 1 Structure of IMS.

- *Structure type level,* pavements or bridges. Each structure type has its own set of condition variables and actions to be modeled.
- *Traffic volume class level,* which affects the rate of deterioration of pavements and bridges as well as the level of user costs associated with pavement condition and diverted traffic costs.
- *Long-term model,* which analyzes possible long-term goals and tries to find a policy that minimizes social costs (the sum of user and agency costs) and that is sustainable indefinitely in the future. The long-term model is not tied to the current condition of the network and imposes no requirements on the specific year in which it should be achieved.
- *Short-term model,* whose first goal is to find the quickest means of achieving the optimal network condition level and whose second goal is to minimize the social costs incurred in the short-term period between the present and the time when the long-term goals are achieved.

As indicated in Figure 1 the flow of activities in using the IMS starts at a very abstract level and ends at a more concrete level. The long-term level defines goals broadly and at some undetermined time in the future; this then proceeds to the short-term level, which is more concrete because it is explicitly tied to the current observed condition of the road or bridge network.

The ellipses numbered 2 to 4 in Figure 1 represent the major analytical features of the IMS in the order in which they are normally used. Central to all of these features is the optimization model in Processes 2 and 3 and the economic analysis and resource allocation within and between models in Process 4. All of these models include the following components:

- *Agency cost model,* giving the average costs for eight (five for bridges) general categories of maintenance and rehabilitation, from do nothing to reconstruction.
- *User cost model,* which quantifies in economic terms the increase in travel time, fuel consumption, and vehicle depreciation associated with deteriorated road condition or additional detours associated with weight restrictions on bridges.
- *Deterioration model,* describing the process by which pavements and bridges deteriorate and thereby cause higher user costs. Similarly it also describes the improvements that can be expected after each of the general rehabilitation actions is applied.
- *Economic model,* describing the economic indicators and the process by which decision makers are able to compare various maintenance and rehabilitation strategies.

The following policy questions are addressed in the framework:

- What is the optimal level of expenditure on rehabilitation on the nationwide road and bridge network and within selected subnetworks?
- At funding levels that do not minimize societal costs, what is the optimal allocation of funding among subnetworks, and what is the most cost-effective means of spending the available money: what actions should be applied to what kind of roads or bridges?
- To what extent do budget constraints increase the level of costs borne by road users, and what does this tell decision makers about the importance to society of user costs relative to agency costs?

Many different modeling methodologies have been applied to these questions around the world. None of these methodologies has been proven to be superior to the others. The methodology selected for HIPS (and IMS) was an adaptation of Markov dynamic programming. The attributes that make it attractive are (2) that

- It describes the behaviors of pavements and bridges in a simple manner and fits the decision-making process well at the strategic level; thus, it is suitable for the anticipated training.
- It explicitly recognizes the stochastic nature of pavement and bridge behaviors, and therefore expresses its conclusions in a suitable form.
- The same approach is most obviously useful to other countries and other parts of the infrastructure.

Definition of Pavement and Bridge Condition

Altogether in the pavement (bridge) models there are 135 (108) condition states and 8 (5) action types, for a total of 1,080 (405) states describing each stage. Each state has associated with it an agency cost, a user cost, and a current condition distribution.

For defining an asphalt pavement's condition state the following four major condition variables are used:

- Bearing capacity (five classes, representing ranges of MN/m^2),
- Defects (cracking and patching, three classes, in m^2),
- Rut depth (three classes, in mm), and
- Roughness (three classes, representing ranges of the International Roughness Index).

For bridges there are 81 condition states:

- Superstructure (three classes; good, fair, and poor),
- Substructure (three classes; good, fair, and poor),
- Bearing capacity (three classes; good, fair, and poor), and
- Deck (three classes; good, fair, and poor).

The bearing capacity of a bridge is considered to be the major factor affecting the road user costs of bridges. Other variables also have an influence on the deterioration of other factors.

The maintenance districts have a larger number of standard rehabilitation procedures, but for the purposes of the Markov model they are condensed into several categories, which are for pavements:

- Do nothing (routine maintenance),
- Rut patching,
- General patching,
- Planing,
- Thin overlays,
- Thick overlays,
- Light reconstruction, and
- Heavy reconstruction.

For bridges the categories are

- Do nothing,
- Minor improvements,
- Strengthening,
- Superstructure rehabilitation, and
- Reconstruction.

Optimization

Optimization in IMS is executed in four steps:

1. Long-term optimization,
2. Resource allocation among subnetworks,
3. Short-term optimization, and
4. Optimization by economic indicators.

The first three steps are executed inside the original software, and their definitions can be found in a previous report (2). The fourth step, optimization and money allocation by economic indicators calculated from short-term results, is executed inside separate EXCEL procedures.

To compare policy alternatives some measures that describe the benefits from the policy or the investment are needed. The following standard measures are used (3):

- Net present value (NPV),
- Internal rate of return (IRR),
- First-year benefit (FYB),
- Time to break even (TBE), and
- Marginal revenue of the investment (MRI).

The economic analysis package (Step 4) consists of three EXCEL 4.0 worksheets:

- ECON,
- GAIN, and
- MODEL.

The most profitable policy for each model is calculated in ECON. The module GAIN compares policies with a chosen discount rate. The last program, MODEL, is used in the allocation of monies between the models.

The first program, ECON, does the calculations needed in the choice of the most profitable policy (Figure 2). The first row contains the name of the model (Pavement High, . . . , Bridge Low). The second row contains the names of the policies (max 1 + 5, do nothing, and five other policies, usually different budget constraints) to be considered. The first column contains the results from the reference policy in terms of social costs. The next five columns contain the results from the other policies. The reference policy should usually be the do-nothing policy, but other reference policies can be used as well.

The result represented by the first value gives the social costs from each policy except the reference policy. If the curve is decreasing the condition of the item in that row is improving in 8 years, and vice versa. IRR is the largest discount rate for which each policy is profitable. The second value shows the gain of each policy when it is subtracted from the reference policy. Normally, the gain is negative in one or two of the first years when the investments are started but becomes positive later. The total gain from the policies can be compared by using NPV, which is the discounted value of the investment during the 8-year investment period.

The second program, GAIN, compares policies with a chosen discount rate in terms of profit per dollar. The GAIN worksheet is shown in Figure 3.

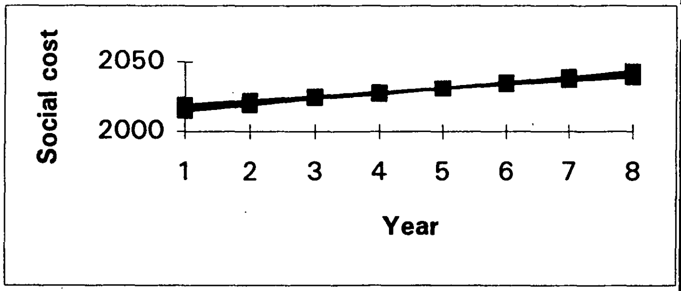
The results in the first table give user cost reduction, agency cost reduction, and social cost reduction during the total 8-year period.

Pavement medium			*social cost*		
pm0	pm15	pm14	pm13	pm12	pm11
2005	2019	2018	2017	2016	2015
2013	2022	2020	2020	2019	2019
2021	2025	2025	2024	2024	2024
2030	2028	2028	2027	2027	2028
2040	2031	2031	2031	2031	2031
2050	2034	2034	2034	2035	2035
2060	2037	2037	2037	2038	2039
2070	2039	2040	2040	2041	2043

Data aquisition

1. Select database file from Window menu.
2. In the database, select policy/policies .
3. Click right button. Select copy.
4. Select ECON.XLS from the Window menu.
5. Select cell A2-F2. (A2 for the reference policy)
6. Click right button. Select paste.
7. Name data set in cell A1.

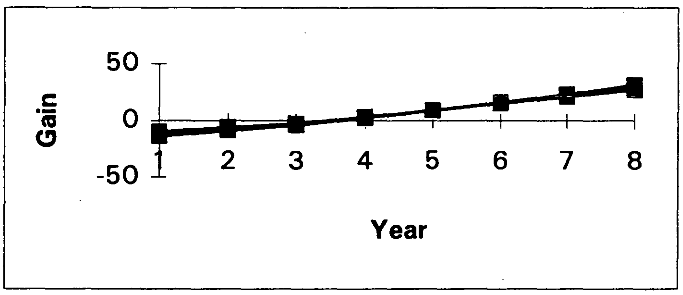
Order of symbols in curves is as follows:
b. square, square, b. diamond, diamond, triangle



The first figure gives social costs from each policy excepting the reference policy.

IRR	24%	26%	29%	31%	31%

IRR gives the largest discount rate for which the investment is profitable.



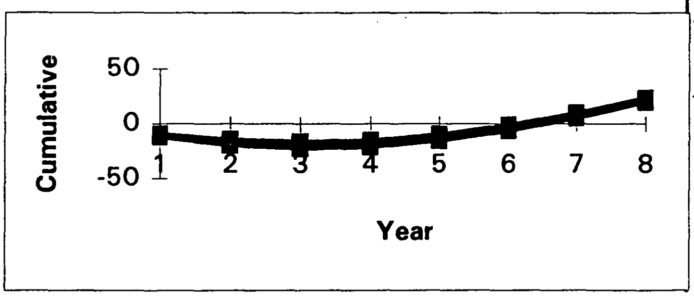
The second figure shows the gain when substracted from the reference policy.

Calculation of the Net Present Value

Write the discount rate in the cell A41. It can be changed when necessary.

10					
NPV	19	21	24	24	22

NPV gives the net value of each policy with given discount rate.



The third figure gives the year, when each policy becomes profitable when compared to the reference policy.

FIGURE 2 ECON module.

In the case in which social cost reduction is negative, agency costs are larger than the gain of the user, and the investment is therefore unprofitable. The first figure gives social cost reduction as a function of agency cost in 8 years for all alternatives used in the analysis.

The second table gives the first-year agency cost (per kilometer) for each policy and the marginal social cost reduction for each policy. The marginal cost is the gain from the last dollar invested in the policy. The second figure gives marginal gain as a function of the first-year agency cost.

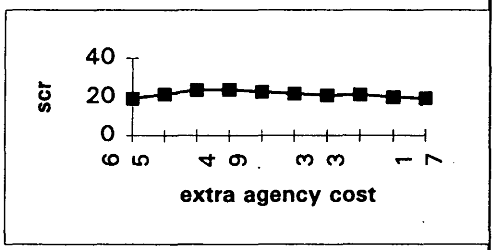
The third program, MODEL, is used in the allocation of monies between the models. The worksheet is shown in Figure 4.

The worksheet consists of the results of the GAIN program for three pavement models and three bridge models. For each model,

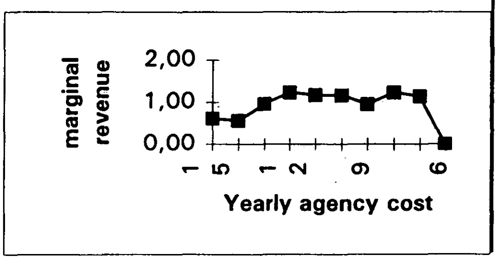
Pavement medium			*social cost*		
pm0	pm15	pm14	pm13	pm12	pm11
2005	2019	2018	2017	2016	2015
2013	2022	2020	2020	2019	2019
2021	2025	2025	2024	2024	2024
2030	2028	2028	2027	2027	2028
2040	2031	2031	2031	2031	2031
2050	2034	2034	2034	2035	2035
2060	2037	2037	2037	2038	2039
2070	2039	2040	2040	2041	2043

Pavement medium			*agency cost*		
pm0	pm15	pm14	pm13	pm12	pm11
1	15	14	13	12	11
2	15	14	13	12	11
2	15	14	13	12	11
3	15	14	13	12	11
3	15	14	13	12	11
4	15	14	13	12	11
4	15	14	13	12	11
5	15	14	13	12	11

10					
agency	65	60	55	49	44
scr	19	21	24	24	22



agency	15	14	13	12	11
marginal	0,61	0,56	0,96	1,23	1,17



Data aquisition

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2. In the database select policy/policies .
3. Click right button. Select copy.
4. Select GAIN.XLS from the Window menu.
5. Select cell A2-F2. (A2 for the reference policy)
6. Click right button. Select paste.
7. Name data set in cell A1.

Order of symbols in curves is as follows:
b. square, square, b. diamond, diamond, triangle

Ten different policies may be compared though only five are shown at a time.

Social and agency costs can also be read simultaneously.

Setting the discount rate

Can be changed when necessary.

Table gives user cost reduction, agency cost and social cost reduction for each policy.

The first figure gives social cost reduction as a function of agency cost in eight years.

Table gives first year agency cost for each policy and marginal social cost reduction (gain from last dollar invested) for each policy.

The second figure gives marginal gain as a function of first year's agency cost.

FIGURE 3 GAIN module.

data consist of total unit agency costs (per kilometer or unit bridge) and marginal cost reduction (user gain from the last dollar invested) with three policies. The central column is the one with which calculations are carried out. On the left and right sides are alternative policies. The cells show the total agency cost (i.e., the total budget of the model). It is the unit agency cost multiplied by the volume (kilometers or unit of bridges). The cell labeled "1st year" at the bottom gives the total budget of all models, its marginal cost reduction, and its average cost reduction, that is, the average cost reduction for each dollar invested.

CASE EXAMPLE

The following example shows the practical results of the IMS for the main road network in Finland.

Introduction

FinnRA is responsible for its main road network, comprising 12 000 km of roads and 4,000 bridges. For this IMS analysis the

Pavement	23	*high*	
39	38		37
1,24	1,07		0,80
Pavement	45	*medium*	
13	12		11
0,96	1,23		1,17
Pavement	14	*low*	
7	6		
0,58	0,00		0,00
Bridges	37	*high*	
45	40		39
0,74	1,22		0,61
Bridges	10	*medium*	
12	11		10
0,83	1,05		0,94
Bridges	2	*low*	
6	5		
0,62	0,00		

Resource allocation between models

The yellow column contains the current allocation of resources between the six models. The yellow cells contain the first year total agency cost for each model together with their sum. Below each yellow cell we have the unit agency cost and below that the marginal user cost reduction in eight years , i.e. the user gain from the last dollar invested for each model and for the total investment. The total average denotes the average user cost reduction for all dollars invested in all of the models.

Changing resource allocation.

1. Choose one of the models by moving the cursor on one of the green or yellow cells of the model. Click left button.
2. Use either button in the bottom of the sheet to decrease or increase resources in the model.
3. Wait until calculations are updated.

1st year	132	*agency*
total	1,25	*marginal*
total	1,68	*average*

FIGURE 4 MODEL module.

infrastructure is divided into three subnetworks according to the average daily traffic (ADT). There are thus six models, three for roads and three for bridges. The size of this infrastructure is as follows:

	>6,000 (high)	1,500–6,000 (medium)	<1,500 (low)
Roads (km)	2,179	5,852	3,887
Unit bridges (no.)	932	938	392

The main problem that FinnRA has in maintaining these structures is the allocation of money for these models under certain multicriteria goals, such as minimal allowable condition and budgetary constraints. The investment period is arbitrarily taken as 8 years.

The budget for the total network is expected to be about 210.000 units of money [1 unit = 1,000 (FIM) Finnish marks (US$1 = about 4.7 FIM)]. The minimum constraint for each model equals 5 units of money per 1 km or 1 unit bridge. This constraint ensures the lowest feasible traffic conditions. This differs from the do-nothing policy, in which only routine maintenance is carried out.

The current condition of the network to be analyzed is given in Table 1 (in marginal distributions, class 0 is the best class).

Other data used in this analysis are retrieved from HIPS (*4*) and the Finnish Bridge Management System (*5,6*).

As an example, the Pavement Medium model is used.

For the economic analysis of the Pavement Medium model, the results from several IMS runs are collected in the data base beforehand. First policies with five different budget constraints ranging from 11 to 15 are compared. The first sheet (Figure 2) shows the basic results from the ECON program. The first figure shows that there is only a slight difference in the costs of these policies. This is because in each policy only minor reparations are made. The IRRs of the policies are also near each other ranging from 24 to 31 percent. In almost every case they will be profitable. According to IRR, Policies pm12 and pm11 have the highest IRRs (31 percent), showing that they are the least sensitive to the discount rate. The second figure shows the gain from each policy when compared with the do-nothing policy (pm0). Again the results for all policies are similar. With a discount rate 10 percent the net present value is largest (24) for Policies pm12 and pm13, indicating that in such a case these are the most profitable ones. The last figure shows that each policy pays the investment back in about 6 years.

Shown in Figure 3 are the basic results from the GAIN program for each of the policies. The results show that the NPV of 24 is achieved for Policy pm13 with an agency cost of 55 and for Policy pm12 with an agency cost of 49. When these two policies are further considered, the marginal revenue of Policy pm13 equals 0.96, showing that the gain from the last dollar invested after Policy pm12 is only 96 cents and the extra investment is, therefore, unprofitable. Thus, the Policy pm12 is chosen as the optimal one; policies with larger agency costs have smaller payoffs in terms of social costs, and they are in both respects less profitable. When the same analysis is performed for all models, the optimal policies are as listed in Table 2.

The total of these is about 227 million FIM, which is greater than the expected budget. Hence it is not possible to keep all models in the economic optimum, and the budgets of some of them must be decreased. This kind of tuning is carried out by using the MODEL program. As a rule the budget of the model with the smallest marginal cost reduction is reduced. It often happens that several models have marginal cost reductions of the same size. In such a case the decision maker may use his or her expertise and reduce the budget of some other model, too. In this way it is possible to take into account details that are important, even though they are not included in the models (Table 3). As can be seen in Table 3 the investment level depends heavily on the traffic volume. Low-volume roads and bridges get only a minimal fraction of the budget.

TABLE 1 Current Condition of Network To Be Analyzed

		pavement high	pavement medium	pavement low
Roughness	T0	45.0	41.8	31.7
	T1	52.0	54.1	60.2
	T2	3.0	4.1	8.1
Bearing Capacity	K0	71.8	80.6	68.2
	K1	6.8	5.5	13.2
	K2	7.3	5.6	6.7
	K3	4.5	2.9	4.9
	K4	9.6	5.4	7.0
Defects	V0	95.9	86.1	77.5
	V1	3.5	11.3	17.1
	V2	0.6	2.6	5.4
Rutting	U0	94.1	97.9	98.5
	U1	3.4	1.7	1.0
	U2	2.5	0.4	0.5

		bridges high	bridges medium	bridges low
Substructure	A0	23.4	21.9	38.2
	A1	70.0	75.4	57.6
	A2	6.6	10.7	4.2
Super-structure	S0	24.0	20.9	30.6
	S1	75.1	75.8	64.8
	S2	0.9	3.3	4.6
Deck	D0	34.7	29.7	41.2
	D1	65.3	69.5	54.7
	D2	0.0	0.8	4.0
Bearing capacity	B1	98.6	99.1	99.5
	B2	1.4	0.9	0.5
	B3	0.0	0.0	0.0

TABLE 2 Costs of Various Models

model	kFIM/km	total (1000 FIM)
pavement high	39	84.981
pavement medium	12	70.224
pavement low	6	23.322
	kFIM/ub	
bridges high	36	33.552
bridges medium	14	13.132
bridges low	5	1.960
TOTAL		227.171

TABLE 3 Adjusted Costs of Various Models

model	kFIM/km	total (1000 FIM)
pavement high	38	82.802
pavement medium	10	58.520
pavement low	6	23.322
	kFIM/ub	
bridges high	35	32.620
bridges medium	11	10.318
bridges low	5	1.960
TOTAL		209.542

CONCLUSIONS

Described in this paper is the IMS developed for FinnRA and the World Bank. This system is a network-level management system that optimizes pavement and bridge maintenance policies under the same budgetary constraints.

The development of the first version of IMS appeared to be rather successful. The first results show that it is possible to allocate monies between pavement and bridges by using the minimization of social costs as an objective function. Compared with the short-term allocation procedure in HIPS, the influence of traffic volume is stronger in IMS.

The system can be modified further. This means that other parts of the infrastructure, like power transmission lines, can be incorporated into the analysis.

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