Effects of Traffic Volume on Optimal Road Condition

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A pavement management system was developed in Finland in the 1980s. This system is used to analyze different maintenance and rehabilitation strategies for the existing paved road network. The optimal road condition is the distribution where the sum of the user and the agency cost is at the minimum. It has also been found that the optimal condition should be better than the current condition. This optimal condition level depends on the traffic volume. Moreover, different budget strategies have been analyzed to find the optimal strategy from the current condition to the optimal condition. The short-term (8-year) budget was beneficial when high- and medium-trafficked roads were analyzed, but on low-volume roads it was not very significant. Benefits gained from the reduced traffic costs are so low that in addition to lower condition requirements, very constrained short-term budgets are sufficient for low-volume road upkeep.

The transportation system in Finland consists of a road network, railroads, and air transportation. The road network is the most important part of this transportation system. The economic structure of Finland is based mainly on forest and metal industries, and the raw materials are transported long distances. In general, distances in Finland are long because of the low population density, especially in the northern parts of the country.

The total length of the public road network in Finland is about 77 000 km. The daily traffic volume on most roads is rather low because of the low population density. Therefore, the proportion of unpaved roads is also relatively large. About 55 percent of the total road network is paved roads, 16 000 km of which are asphalt concrete and about 27 000 km are oil gravel (emulsion gravel), which is the main pavement type on paved low-volume roads.

The road network was constructed mainly during 1950s and 1960s. The design age of the paved road structure has been 15 to 20 years, depending on the pavement type. Since then the volume of traffic, axle loads, and gross weights of heavy vehicles have increased significantly. In the 1980s and 1990s, maintenance and rehabilitation of the existing road network has become an important part of road keeping. One important issue has been how to decide on the optimal service level, the pavement surface condition, and the optimal structural service level.

It is well known that keeping roads in too good or too bad condition is uneconomical. Usually the annual budget level is insufficient, and it is important to decide how to allocate the available funds in the most economical way. In Finland, it has become important to develop a decision support system for managing pavements. The development of the Finnish Pavement Management System (PMS) started in the 1980s. The goal was to develop a management system for both network and project levels.

Today the Finnish PMS includes network-level (HIPS) and project-level (PMS91) systems, as well as the road data bank and the road condition data bank (KURRE). The detailed system is documented elsewhere (*1–6*).

This paper presents examples of how to use the results of the network-level system in finding the optimal level of service (condition) and how it depends on the traffic volume of the road network.

The basic questions in network-level decision making are as follows:

- What is the best condition target for the long term? What is the optimal condition distribution and how much does it cost to keep the network in that condition?
- How large is the gap between the current condition and the target condition and what could be the most economical strategy to move from the current state to the optimal state? Moreover, how can the limited funding available be allocated most effectively among different areas and among different functional road classes?

When these questions were taken into account, it was straightforward to formulate a two-stage network-level management system in such a way that the first stage could answer the first question and the second stage could answer the second question.

In the network-level system, the road network is divided into 12 subnetworks. The lengths and average daily traffic (ADT) volumes of the subnetworks are shown in Table 1.

The basic features of the systems are illustrated in Figures 1A–1D. Figure 1A presents theoretically how the point of minimum costs differs in each subnetwork, that is, in each traffic volume class. The long-term target budget level is taken from the point where the total costs in each subnetwork are at a minimum. High-volume traffic networks need more maintenance actions than low-volume traffic networks.

The condition distribution achieved with different budget levels depends on the budget level, which is illustrated in Figure 1B. The class limits of each condition variable is presented in Table 2. The number of roads in poor condition increases when the budget decreases, and vice versa. The optimum condition distribution is taken from the point (step) where the total costs are then at a minimum.

MODELS

Four different categories of models are built into the HIPS system: the agency cost model, user cost model, deterioration model, and model for the effects of maintenance and rehabilitation actions.

All models are based on four condition variables. The common condition variables for both pavement types [asphalt concrete (AC) and oil gravel (OG)] are roughness (IRI mm/m), bearing capacity (MN/m^2), and defects (m^2/100 m). The fourth condition variable is the AC model rut depth (mm) and the OG model transversal roughness (mm) (see Table 2). The number of condition classes varies from three to five according to the condition variable. The total number of different condition states is $3 \times 5 \times 3 \times 3 = 135$ in AC models and $3 \times 4 \times 3 \times 3 = 108$ in OG models.

Figures 2A and 2C contain examples of pavement deterioration and maintenance action effects on pavement condition distribution. Figures 2A and 2B show the probabilities of the best and the worst roughness and defects in two bearing capacity classes when the initial condition state is the best condition state and no maintenance actions are applied. These figures show how the probability of the best condition classes decreases and the probability of the worst classes increases during the time and how the bearing capacity affects the deterioration.

An example of how maintenance actions influence deterioration is given in Figure 2C. If we assume that the maintenance actions are always made in the worst condition (defects), we can see how they affect the

TABLE 1 Length and ADT of Subnetworks

Length km /ADT	Asphalt Concrete Pavement			Oil Gravel Pavement *)		
	Traffic Volume			Traffic Volume		
Region	High	Medium	Low	High	Medium	Low
North	602/10027	3791/2906	2278/1024	2763/1198	6406/534	8199/201
South	1970/11577	5171/3133	2903/896	1869/1210	4458/540	3858/223
Total km	2572	8962	5181	4631	10864	12057

*)The binder of oil gravel pavement is bituminous oil.

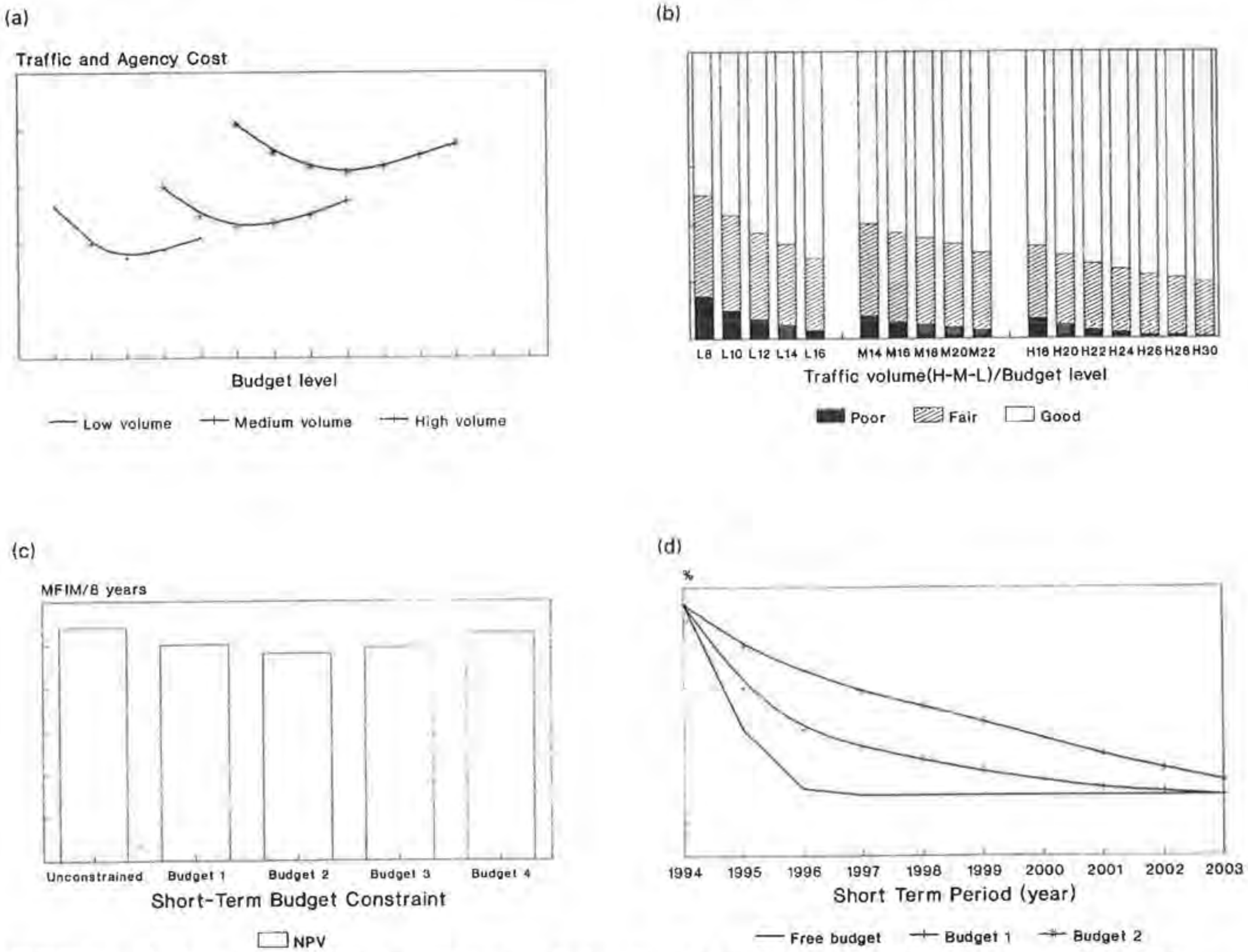


FIGURE 1 Total costs and condition versus long-term budget levels: (*a*) total costs versus long-term budget, (*b*) condition distribution versus budget level, (*c*) net present value, (*d*) poor condition progression versus budget.

probabilities of the best and the worst conditions. Maintenance Action 3 is planing and/or remix and Maintenance Action 5 is a thick asphalt overlay (2 in.).

The effect of both maintenance actions on the probability of the worst condition class is quite similar. But Maintenance Action 5 is better than 3 because the probability of the best condition class is better when using Maintenance Action 5.

RESULTS

Optimal Long-Term Budgets and Condition in Different ADT Classes

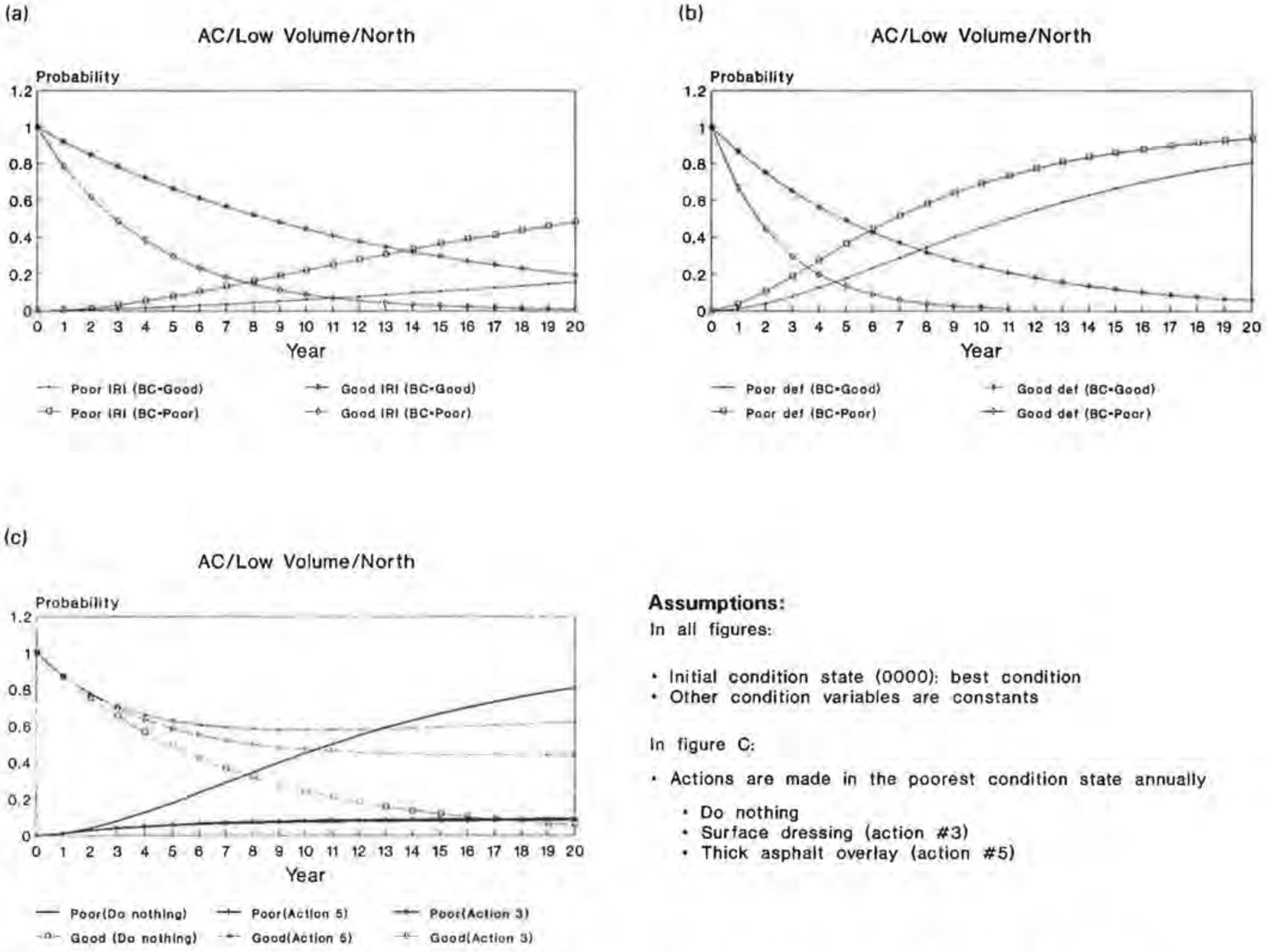
The primary results of the long-term analysis are (a) the long-term optimal budgets for maintenance and rehabilitation actions for each subnetwork and (b) the optimal condition distributions of different condition variables.

Figure 3 shows how the total costs (traffic costs and agency costs) depend on the annual long-term budget in *markkan* (FIM) per kilometer per year. Because the deterioration, maintenance costs, and traffic volumes of each subnetwork are different, the optimal long-term budget level varies respectively. When the annual budget level is too low, the condition distribution is worse, and the traffic costs increase. On the other hand, when the budget level is too high, the condition distribution improves but the traffic costs do not decrease and the total costs increase. The optimal budget level (and the condition level) is found at a point where the total costs are minimized.

Figure 3A shows the cost-budget lines of low-volume asphalt concrete networks and the high-volume (ADT > 800) oil gravel networks. The budget level for high-

TABLE 2 Classification of Condition Variables

Variable	Class	AC low	OG high	OG Med	OG Low
Roughness IRI (mm/m)	Good	> - 1,5	> = 2	> = 2	> = 2
	Fair	1,6-3,5	2,1-3,5	2,1-3,5	2,1-3,5
	Poor	>3,5	>3,5	>3,5	>3,5
Bearing Capacity (MN/m²)	BC0	>230	>200	>200	>185
	BC1	201-230	140-200	140-200	130-185
	BC2	171-200	125-139	125-139	120-129
	BC3	141-170	<125	<125	<120
	BC4	< = 140	-	-	-
Defects (m²/100m)	Good	< = 25	< = 25	< = 25	< = 25
	Fair	26-60	26-60	26-60	26-60
	Poor	>60	>60	>60	>60
Rutting or transf.roug (mm)	Good	< = 12	< = 5	< = 6	< = 5
	Fair	13-19	6-12	6-12	6-12
	Poor	>19	>19	>12	>12



Assumptions:

In all figures:

- Initial condition state (0000): best condition
- Other condition variables are constants

In figure C:

- Actions are made in the poorest condition state annually
  - Do nothing
  - Surface dressing (action #3)
  - Thick asphalt overlay (action #5)

FIGURE 2 Pavement probabilistic behavior: (*a*) roughness versus bearing capacity, (*b*) defects versus bearing capacity, (*c*) defect progression with maintenance actions.

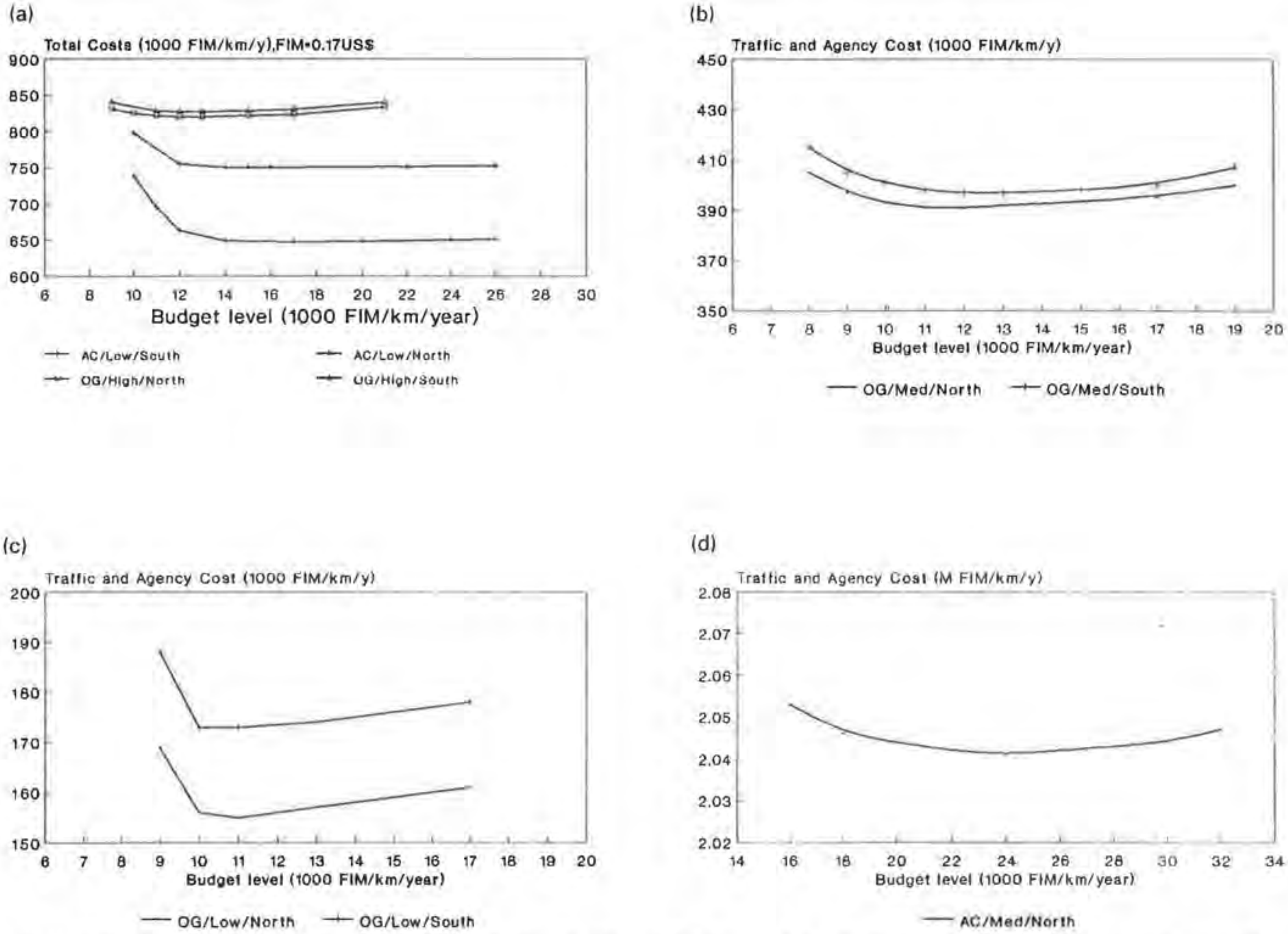


FIGURE 3 Total annual cost versus long-term budget levels: (*a*) AC/low and OG/high, (*b*) oil gravel/medium traffic, (*c*) oil gravel/low traffic, (*d*) AC/medium traffic.

TABLE 3 Agency and Total Costs at Steady State (Long-Term Optimum)

Subnetwork Pavement/ Type/Volume/Area	Agency costs at steady state (FIM/km/year)	Total costs at steady state (FIM/km/year)
AC/Med/North	24,000	2,041,000
AC/Med/South	34,000	2,252,000
AC/Low/North	15,000	750,000
AC/Low/South	17,000	647,000
OG/High/North	12,000	820,000
OG/High/South	12,000	828,000
OG/Med/North	11,630	391,000
OG/Med/South	12,000	397,000
OG/Low/North	11,100	155,000
OG/Low/South	10,900	173,000

volume oil gravel roads is 12 000 FIM/km/year to keep the condition sustainably steady. The total costs are about 830,000 FIM/km/year. If the annual budget level decreases below 10,000 FIM/km, the condition deteriorates and the traffic costs and total costs will increase. Moreover, the same figure shows that in asphalt concrete subnetworks, the total costs are less than in OG networks because there is less ADT. The optimal long-term budgets are, however, higher than OG budgets (15,000 to 17,000 FIM/km/year). Two reasons for higher optimal budget levels in low-volume AC networks are design standards (e.g., pavement type and width) and higher maintenance costs.

The optimal long-term budget levels in each subnetwork in Figure 3 appear in Table 3. These expected optimal budget levels imply expected optimal condition distributions. The situation in the northern region of Finland is presented in Figure 4. The situation in the southern region is similar. The primary result is that in most subnetworks the optimal condition distribution is better than the current condition distribution (Figure 5 *top*).

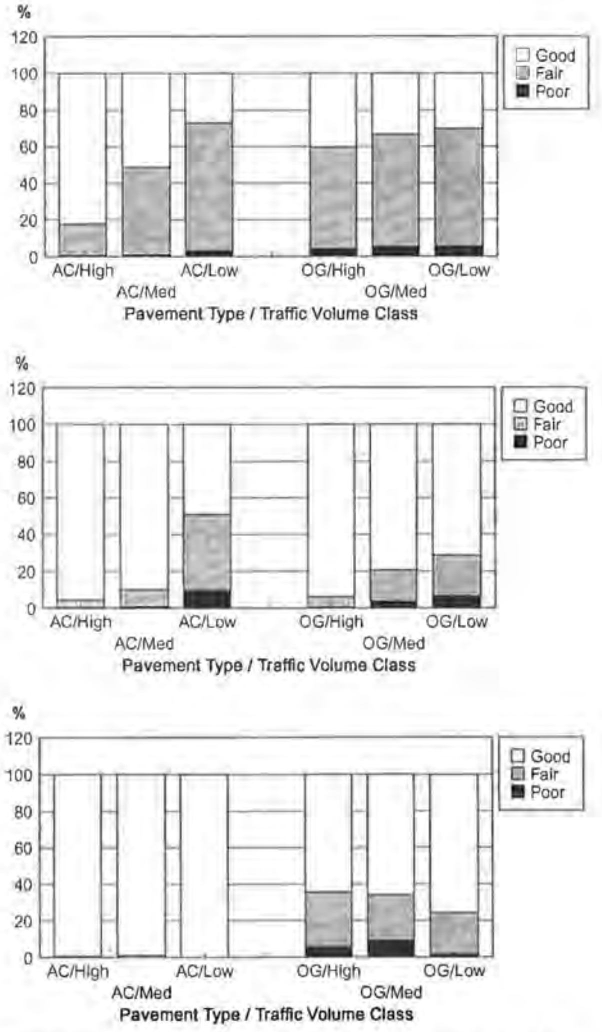


FIGURE 4 Optimal condition distributions (north subnetworks): (*top*) optimal roughness, (*middle*) optimal defects, (*bottom*) optimal bearing capacity.

According to these results, the structural condition (bearing capacity) of asphalt concrete roads should be in the highest bearing capacity class. In oil gravel networks the distribution is different. The proportion of the highest bearing capacity class should be about 70 percent.

These results vary among the subnetworks and are not completely comparable because of the different bearing capacity class limits among the networks. From these figures we can, however, see how the distributions vary according to the traffic volume class and that the condition is better when the traffic volume is higher.

According to these results, roughness and defects should be mostly in the medium (fair) or the best (good) condition class. However, the most important class in practical road keeping is the poorest class (see Table 4).

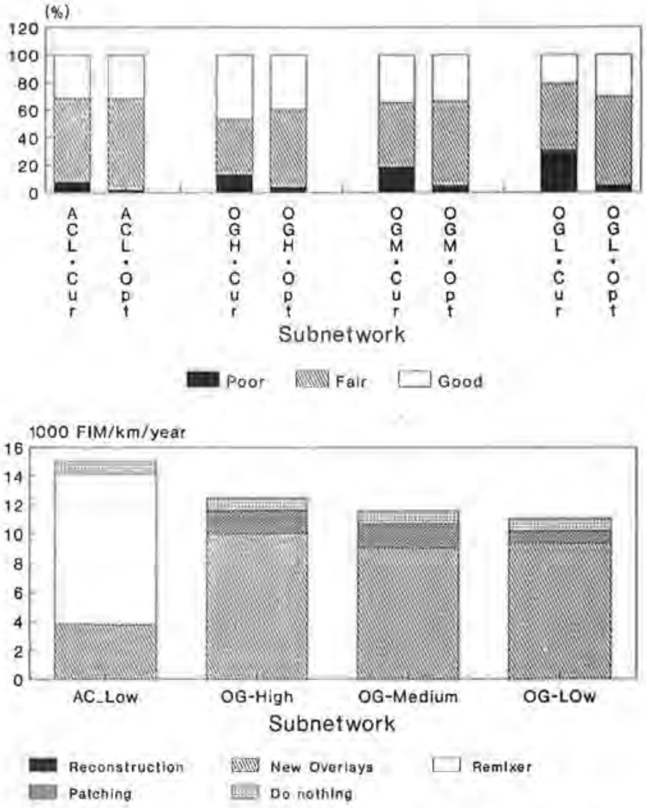


FIGURE 5 Example of long-term results: (*top*) current and optimal condition, (*bottom*) optimal long-term policy.

TABLE 4 Optimal Roughness and Defects Among Northern Subnetworks, Percentage of Poorest Class

	Poor Roughness (%)			Poor Defects (%)		
Pavement type	High traffic	Medium traffic	Low traffic	High traffic	Medium traffic	Low traffic
Asphalt Concrete	0.5	0.9	2.2	0.3	1.1	9.4
Oil Gravel	4.3	5.2	5.6	1.2	3.8	6.6

The optimal number of roads in the poorest roughness class varies between 0.5 and 5.6 percent. In oil gravel roads and in low-volume roads, the percentile is significantly higher than in other roads.

The influence of traffic volume on optimal defect distribution and specially on the poorest defect class is quite clear as well (Table 3). In low-trafficked AC and OG roads, the amount of roads in the poorest defect class is almost 10 percent.

Difference Between Current and Optimal Conditions and Recommended Volumes of Maintenance and Rehabilitation

The difference between the current and the long-term condition distributions is significant. Figure 5 (*top*) shows how the current condition and the optimal condition differ among each OG subnetwork. The current proportion of roads in poor condition classes is large, especially in low-volume networks. The result of total cost optimization suggests that it should be much smaller.

According to the results, the main maintenance action should be either remix (AC networks) or milling and planing (OG networks). In optimal condition, little reconstruction is needed. Maintenance actions could be very light because of a good structural condition level (bearing capacity). (See Figure 5, *bottom*.)

Sensitivity analysis also shows that optimal conditions are rather sensitive to long-term budget levels and to the user cost weight factor, as is shown in Figure 6. Without user costs, the optimal condition level would decrease significantly.

Examples of Strategies Meeting Different Funding Levels

In short-term analysis, the budget constraints are the main tools to make different short-term strategies. So-called unconstrained short-term analysis gives the fastest strategy from the current condition to optimal condition. Unconstrained runs always give unrealistic results because the budgets for the first years are too high. The budget constraints can be set between the unconstrained runs and the budget level of long-term results, which is the minimal realistic budget level (because it is

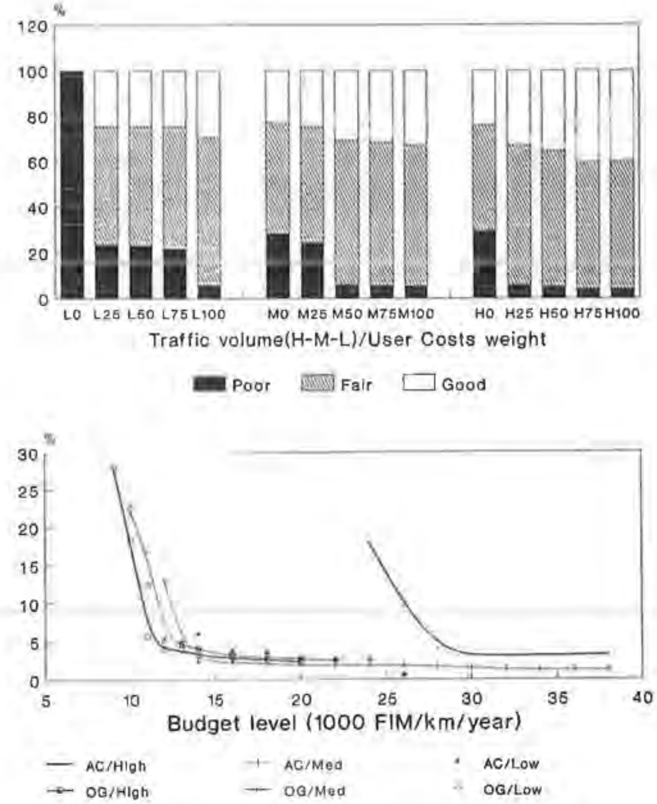


FIGURE 6 Sensitivity analysis of condition distribution: (*top*) condition distribution versus user cost weight, oil gravel roads, northern subnetworks; (*bottom*) poor roughness versus long-term budget, southern subnetworks.

the minimal funding level to maintain the optimal condition).

The short-term funding strategies in this study were as follows:

1. Unconstrained budget levels (to AC and OG subnetworks);
2. Long-term (LT) optimum level;
3. LT level + 50 MFIM/AC and LT + 50 MFIM/OG subnetworks; and
4. LT level + 200 MFIM/AC and LT + 150 MFIM/OG.

The priority of the strategies can be based on economical indicators, for example, the rate of return or the net present value of the total costs. The priority can also be based on how the targets for the condition state are achieved.

The results, however, show that the economic indicators of different strategies to maintain low-volume roads differ little. The main target should be to improve the high-volume roads according to the economics of analysis. Improvements on low-volume roads can be allocated in a flexible way, depending on the funding situation.

One example of the effect of the different budget constraints on the distribution of maintenance actions and on the poor condition in the AC low-volume network is shown in Figure 7. As one can see, the differences are small at the end of the period, although the budget levels vary significantly.

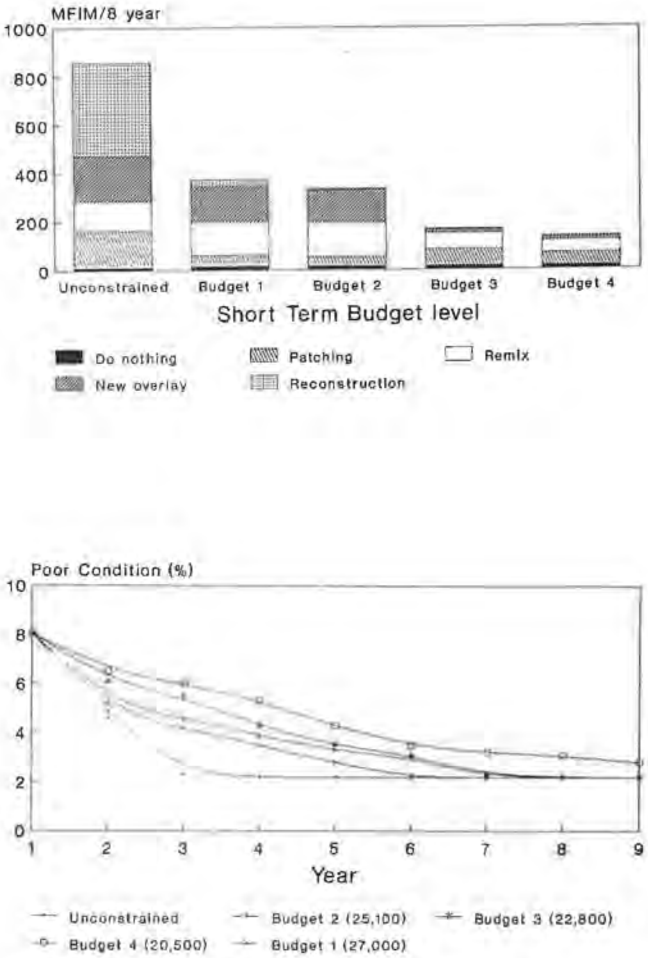


FIGURE 7 Example of short-term results: (*top*) short-term maintenance strategies (AC/low), (*bottom*) condition progression versus budget level (AC/low).

USING RESULTS IN MANAGEMENT BY OBJECTIVES

This type of analysis forms a basis for the strategic planning in the Finnish National Road Administration. The long-term and short-term condition distributions and budget allocations are used when defining the roadkeeping products the road districts should offer for the central administration. In practice, this means that the annual condition requirements are defined by the central administration, and the road districts estimate the costs to maintain the road in the required condition. If the measured condition is not met within the negotiated one, the districts have to pay for depreciation.

Because of the different condition levels in the districts, the application of this procedure is not always straightforward. Those districts that have executed a reasonable road-keeping policy during recent years will get less funding in this product-based system. On the other hand, those districts that have neglected their road network to some degree will now have higher funding levels. Unfortunately, this problem will lead to rather volatile annual budget levels in some districts during the next years. After this transition period, the budgets will become less volatile.

CONCLUSION

An example of the economic analysis of rehabilitation and maintenance of low-volume roads in Finland is presented. The results show that it is still rather difficult to admit that less funding can be allocated to low-volume roads.

The long-term optimization results in the condition of low-volume roads being better than the current condition. However, the results of short-term analysis show that the strategy, which can be used to reach the optimal condition, can be very flexible, that is, the budget level can vary widely due to low economic benefits.

This paper partly reveals that a strictly optimal short-term resource allocation is not easy: if the optimization is based on technical criteria only, the importance of traffic costs is underestimated. The optimization should be based more on pure economical optimization, where more emphasis is put on evaluation of the economical benefits of road keeping (*8*).

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