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PAPERS

OPTIMAL APPROACH TO PAVEMENT MANAGEMENT PLANNING AT THE PROJECT LEVEL

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Importance as well as difficulty of pavement management planning at the project level lies in pavement rehabilitation timing and selection of rehabilitation methods in order to minimize maintenance and rehabilitation costs during pavement life time. Timing and rehabilitation methods make planning difficult and less reliable due to the actual life of pavement differing from its design life and tending to vary widely for various reasons. This paper proposes an optimal method for pavement management planning based on probabilistic dynamic programming (PDP), which can include uncertainties in a statistical sense. Efficiency and reliability of PDP are demonstrated through example problems.

Key Words : *PMS, dynamic programming, engineering economics*

1. INTRODUCTION

Rapid increase of the nation's highway system in length has taken place during the last thirty some years, while a drastic expansion of traffic volume has caused serious damage to the system[1]. It has become imperative to develop a rational pavement management system which supports highway officials' pursuit of their responsibilities effectively under limited budgets and labor resources. Officials are required to design, construct, maintain and rehabilitate pavements rationally by fully utilizing available funds, although they may be limited[2),3)].

When it comes to constructing a new highway, highway officials have to determine highway design based on optimal criteria, considering not only initial construction cost but costs required for maintenance and rehabilitation during its life time[4]. A similar concept should be applied to existing highways. Constant efforts have to be made to reduce maintenance and rehabilitation costs, while keeping pavement above required levels. At the same time user cost caused by maintenance and rehabilitation work or driving on poorly conditioned highways has to be minimized.

Maintenance Control Index (MCI) in Japan and Present Serviceability Index (PSI) in the U.S. have been developed for maintenance and rehabilitation decision making from the viewpoint of pavement serviceability[5]. However the criteria for rehabilitation standards in Japan have not yet been authorized. Instead the necessity of maintenance and rehabilitation is evaluated by experienced highway managers and engineers based on surveys of pavement surface conditions.

There are two types of pavement management : project level and network level[4]. Pavement management at the project level deals with detailed and technical information related to a specific pavement section. On the other hand pavement management at the network level deals with summary information related to entire highway networks. Project level pavement management is concerned with management decisions based on information that involves more technical and specific matters for individual pavement sections.

Commonly used Pavement Management System (PMS) (hereafter called 'current system') selects the best strategy to minimize the total maintenance cost among all candidate strategies. The best solution is dependent on where to set a minimum serviceability level which requires rehabilitation activities. MCI criterion adopts 4.0 and PSI 2.5. If we include a timing and serviceability level for rehabilitation as design variables, the number of candidates increases enormously, for which the current system either takes too long time or fails to reach the best solution.

The authors presented an optimum decision making procedure for PMS by utilizing Dynamic Programming (DP), from which the following observations are made[6),7)];

1) Total maintenance cost from DP is equal to or less than that of the current system.

2) One can find optimal solutions for when and

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what rehabilitation activities need to be executed.

3) A procedure based on DP can also be applicable to a rehabilitation design of existing pavements.

The main difficulty in solving this problem lies in the discrepancy that design pavement life does not coincide with the servicability life of pavement[8]. The reduction of pavement integrity is subject to wide variability. Hence the deterministic approach may lead to erroneous results.

This paper presents an optimal approach to PMS based on a dynamic programming incorporating probabilistic theory. The optimization theory is referred to as 'Probabilistic Dynamic Programming (PDP)'. Numerical demonstrations are made to confirm that the method is rational and efficient. The results of PDP are compared with those of the current system and DP.

2. LIFE-CYCLE COST[4]

Economic evaluation is essential for any engineering project. The concept of life-cycle cost evaluation was introduced to pavement design in 1970's. The concept of life-cycle cost constitutes a basis of optimal pavement management system. All the costs occurring from the initial planning stage of a facility to the end of its life may be included. Hence, the costs may include research, development, construction, operation, maintenace, rehabilitation and salvage costs over expected operational life of a facility. Accurate information on those ingredients determine a usefulness and overall reliability of the system. Assuming all the information is available, design alternatives can be compared accurately and correctly with each other based on economic evaluations.

Several state highway agencies in the U.S. have been using life-cycle cost analysis with reasonable success. Of forty nine noth America agencies responding to a survey, twenty two agencies state a use of some life-cycle cost analysis methods in selecting pavement design alternatives on contrary to nine which do not use life-cycle cost analysis method.

3. COST COMPONENTS[3]

The selection of the proper cost components and the use of reasonably accurate data are important elements of life-cycle cost analysis. There main components of the analysis are as follows,

1) Road administration cost ;
   new construction cost,
   daily maintenance cost,
   rehabilitation cost,
   salvage value,
2) User cost ;
   vehicle running cost,
   discomfort cost,
   delay cost,
3) Non-users cost;
   Social cost (vibration, noise and air pollution etc.)

(1) Road administration cost

Road administration cost implies the cost of constructing and maintaining pavement facilities. The cost includes engineering design and supervision, roadway acquisitions, construction, traffic control devices and all other work necessary to keep pavement in serviceable condition during its operational life. Salvage value at the end of the life is also included.

(2) User cost

User cost refers to the cost which direct road users have to the pay. This cost includes vehicle running cost, delay cost caused by traffic congestion or detours during maintenance or rehabilitation, and discomfort and vehicle damage cost while driving on poorly conditioned pavement. Hence the poorer a pavement condition becomes, the more user cost increases.

(3) Non-user cost

Non-user cost is a loss cost due to ground vibration, noise and air pollution which inhabitants along roadway have to bear. In general, as pavement surface condition deteriorate, non-user cost increases.

4. COST MODEL

(1) Pavement cost for analysis

In order to compare PDP with the current system as well as DP decribed in Ref. 5), the following pavement conditions are used in this paper,

1) Length : 500 m
2) Width : 15 m
3) Number of lanes : 4
4) Pavement condition : Newly constructed
5) Analysis period : 30 years
6) Discount rate : 6%
7) Average daily traffic volume per lane : 5 000
8) Ratio of heavy vehicles per lane : 15%
9) Minimum maintenance level (MCI) : 4.0
10) Maximum speed limit : 60 km/hr.
11) Cost items considered in the analysis : Daily maintenance cost, user cost, rehabilitation cost, delay cost, salvage values.

The following classification is made in our analysis. Daily maintenance cost and user cost are included in maintenance, whereas delay cost and rehabilitation cost are included in rehabilitation. Salvage value is the worth remaining at the end of the analysis period.

(2) Serviceability (MCI) Estimation Model[5)]

Good evaluation of pavement condition not only at present but in the future is a key to develop an optimum PMS. The serviceability model available today in Japan is MCI which has been established by the Ministry of Construction. The following expressions are used for new, overlaid and surface treated pavements[5)],

For new pavement :

$$MCI = 10.1 - 0.41a - 0.18\times10^{-3}b - 0.10\times10^{-1}C \quad \cdots\cdots (1)$$

or overlaid pavement :

$$MCI = 9.7 - 0.42a - 0.27\times10^{-3}b - 0.45\times10^{-1}c \quad \cdots\cdots (2)$$

For surface treated pavement :

$$MCI = 10.2 - 0.71a - 0.44\times10^{-3}b - 0.28\times10^{-1}c \quad \cdots\cdots (3)$$

where a=Time in servic (year),

b=Average daily traffic volume per lane,

c=Ratio of heavy traffic volume (%)

The above three equations are used to obtain the number of years it takes for MCI to drop to 4.0 depending on whether the pavement is new overlaid or surface treated. The years are as follows:

new pavement : 14 years,
overlay : 10 years,
surface treatment : 6 years

Hence, it is here in assumed that design lives of new construction, overlay, surface treatment are 14, 10, and 6 years respectively.

(3) Daily Maintenance Cost

The maintenance cost varies according to pavement condition. If pavement is in poor condition, maintenance costs more, whereas if it in good condition, it costs less. Summary information for maintenance cost used in our analysis is given in **Table 1**.

(4) User Cost

It is assumed that user cost starts increasing when MCI drops below 7.5 in this paper. The cost is adopted from an FHWA report on 'Vehicle Operating Costs, Fuel Consumption and Pavement Type and Condition Factors'. The cost also depends on pavement condition and differs between light and heavy vehicles. The following relationships between user cost and MCI are used for the analysis[5)].

For light vehicles at 60 km/hr:

$$UC = (12.125M^2 - 189.999M + 734.190)\times4.173 \quad \cdots\cdots (4)$$

For heavy vehicles at 60 km/hr:

$$UC = (37.677M^2 - 560.504M + 2\,085.490)\times0.73 \quad \cdots\cdots (5)$$

where UC : User cost, M=MCI

By using Eqs.(1) through (5) with simple computation, both maintenance cost and user cost are summarized in **Talbe 2**.

Table 1 Daily Maintenance Cost

MCI	Maintenance Cost(yen/m2)
10.0 - 9.0	27
9.0 - 8.0	44
8.0 -7.0	62
7.0 -6.0	79
6.0 - 5.0	96
5.0 - 4.0	13
4.0 - 3.0	130

(5) Rehabilitation Cost

In the 41 st Technical and Research Meeting of Ministry of Construction, it is reported that construction cost per unit area of pavement is,

Reconstruction	15 020 (yen/m²)
Overlay	4 749 (yen/m²)
Surface Treatment	1 976 (yen/m²)

(6) Delay Cost

Delay cost due to traffic congestion and the use of an alternate road depends on duration of rehabilitation. Duration depends on area of rehabilitation. The assumed area to be rehabilitated per day is 1 390 m² for both overlay and surface treatment[5)]. Hence the area and duration for this analysis problem become,

$$Area = length\times width = 500\times15 = 7\,500 \quad (m^2) \quad \cdots\cdots (6)$$

$$Duration = total\ area\ for\ rehabilitation/the\ area\ of\ rehabilitation\ per\ day = 7\,500/1\,390 = 5.4 \quad (days) \cdots (7)$$

Ref.5) evaluates delay during rehabilitation work as one minute for a four lane road with user cost of 31 yen/min for a light vehicle and 46 yen/min for a heavy vehicle. Assuming 50% of total traffic volume suffers the delay caused by rehabilitation work, the delay cost may be computed as follows,

$$Delay\ cost = delay\ in\ minutes\times[31\times(1-heavy\ vehicle\ ratio)+46\times heavy\ vehicle\ ratio]\times daily\ traffic\ volume\times delayed\ traffic\ volume\ in\ percentage\times duration\ of\ rehabilitation\ in\ days$$

$$= 1\times[31\times(1-0.15)+46\times0.15]\times2\,000\times0.5\times5.4$$

$$= 1\,795\,500 \quad (yen) \cdots\cdots (8)$$

When converted to the cost per unit area, it becomes 240 yen/m². Similarly, the delay cost due to reconstruction work can be estimated as 2 675

Table 2 Analyzed Data

Year in Service	New Construction			Overlay			Surface Treatment		
	MCI	MC	UC	MCI	MC	UC	MCI	MC	UC
1	9.2	27	0	7.7	62	0	7.6	62	0
2	8.8	44	0	7.3	62	14	6.9	79	50
3	8.4	44	0	6.8	79	62	6.2	79	150
4	7.9	62	0	6.4	79	132	5.5	96	375
5	7.5	62	8	6.0	79	224	4.7	11	698
6	7.0	62	39	5.6	96	342	4.0	113	1068
7	6.6	79	94	5.2	96	485			
8	6.2	79	175	4.7	113	698			
9	5.8	96	270	4.3	113	896			
10	5.4	96	410	3.9	130	1120			
11	5.0	96	565						
12	4.5	113	764						
13	4.1	113	1005						
14	3.7	130	1241						

Note: MC= Maintenance cost, UC= User Cost

yen/m^2.

(7) **Salvage Value**[4),9)]

Salvage value refers to the remaining worth of pavement at the end of the analysis period. For the sake of simplicity, salvage value is assumed to be derectly related to the time the last rehabilitation occurred and what method was used. The following equation evaluates the salvage value.

$$SV=(1-Y/X)C \qquad (9)$$

where, SV=Salvage value,

X=Expected service life after rehabilitation (year),

Y=Time from the last rehabilitation to the end of the analysis period (year)

C=Cost of the last rehabilitation work.

(8) **Economical Evaluation Method**[4),9)]

Equivalence calculations are necessary for a meaningful comparison of alternative projects. The present worth analysis is a convenient tool for economical evaluation of various alternatives and it is herein utilized. All cash flows during the analysis period have to be converted to the present worth by the following formula.

$$PW=F/(1+i)^N \qquad (10)$$

where PW=Present worth,

F=Cost borne in the Nth years,

i=Discount rate at the minimum attractive return rate.

(9) **Reliability of Serviceability Life**[10),11)]

Design lives of new construction, overlay and surface treatment are assumed to be 14, 10 and 6 years respectively according to **4. (2)**. However their serviceability lives are in general different from the design lives. The service lives tend to vary depending on pavements, even if their design lives are the same. Pavement gradually suffers deterioration to unsatisfactory serviceability. Time span that MCI reaches 4.0 will vary due to uncertainties in traffic volumes, pavement structures and environmental conditions. The time span is called service life. It is assumed that the distribution of life is normal as shown in **Fig.1.** Design lives of new, overlaid and surface treated pavements are standard deviation less than mean service lives of corresponding pavement status.

Failure rate may be given by cumulative probability density when service life equal to design life in **Fig.1.** Hence it is assumed that design lives of new, overlaid and surface treated pavements are standard deviation less than mean service lives of corresponding pavement status[12)]. Two different deterioration models as shown in **Table 3** are considered for the sake of comparison. The two models can be described as,

(Model 1)

New construction:

mean=16 years,
standard deviation=2 years,

Overlay

mean=12 years,
standard deviation=2 years,

Surface treatment

mean=8 years,
standard deviation=2 years,

(Model 2)

New construction:

mean=19 years,
standard deviation=5 years,

Overlay:

Table 3 Failure Rate

Service Year	New Construction Model 1	New Construction Model 2	Overlay	Surface Treatment
1	0	0	0	0
2	0	0	0	0.0013
3	0	0	0	0.0062
4	0	0.0013	0	0.0228
5	0	0.0026	0	0.0668
6	0	0.0043	0.0013	0.1587
7	0	0.0082	0.0062	
8	0	0.0139	0.0228	
9	0	0.0228	0.0668	
10	0.0013	0.0359	0.1587	
11	0.0062	0.0548		
12	0.0228	0.0808		
13	0.0668	0.1151		
14	0.1587	0.1587		

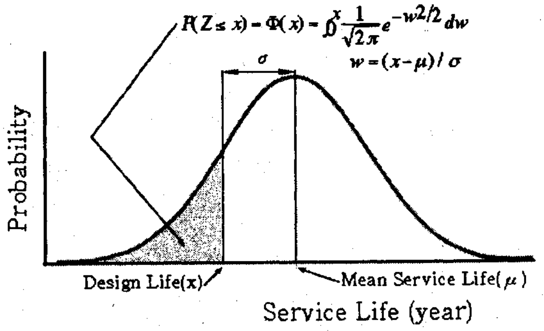

Fig.1 Distribution when MCI=4.0

mean=12 years,
standard deviation=2 years,
Surface treatment,
mean=8 years,
standard deviation=2 years,

The difference of the two models lied in the failure rate of newly constructed pavement. The failure rate for Model 2 is higher than that of Model 1. which implies the performance level of Model 1 is more reliable than that of Model 2.

5. NUMERICAL DEMONSTRATION

Three PMSs called 1) Current System, 2) DP and 3) PDP are described and the results from the three procedures are compared in this section.

(1) Current System

The current system is based on economical decision making in traditional use[13]. Two alternatives are selected for comparison, which are,

Alternative 1 : New Construction-Overlay-Surface Treatment

Alternative 2 : New Construction-Surface Treatment-Overlay

Alternative 1 means that after new construction pavement will be rehabilitated by overlay in the 14 th year and by surface treatment in the 24 th year. Alternative 2 implies that pavement will be rehabilitated by surface treatment in the 14 th year and by overlay in the 20 th year. In these alternatives, the timing of rehabilitation is the year when MCI drops to 4.0. In order to sum up total cost over the analysis period, maintenance and user costs are considered in the year of maintenance, and rehabilitation and user costs are included in the year of rehabilitation. Neither alternative possesses salvage value in the 30 th year. It is possible to consider more alternatives. However they are excluded because their salvage values remain at the end of the analysis period.

(2) Dynamic Programming[14),15)]

DP requires a backward analysis from the end to the beginning of the analysis period to determine optimum maintenance and rehabilitation planning. To obtain total cost, maintenance and user costs are considered in the year of maintenance and in the year of rehabilitation, rehabilitation and user costs are counted. The decision for maintenance or rehabilitation of pavement by using DP is described by the following equation:

$$F_n(i,j) = \min.\{DM : M(i,j) + U(i,j) + F_{n-1}(i,j+1),\ DR : U(i,j) + R(r) + F_{n-1}(r,1)\} \quad (11)$$

where DM=Dicison is maintenance
DR=Decision is rehabilitation
i=Present pavement condition
new construction when $i=1$
overlay when $i=2$
surface treatment $i=3$
r=Rehabilitation method

new construction when $r=1$
overlay when $r=2$
surface treatment $r=3$

j=Years in service since previous new construction or rehabilitation
new construction for $j=1,...,14$
overlay for $j=1,...,10$
surface treatment for $j=1,...,6$

$F_n(i,j)$=Present value of total cost of pavement which is in condition i and in j th year after new construction or rehabilitation with n years remaining in the analysis period.

$M(i,j)$=Present value of maintenance cost of pavement which is in condition i and in j th year after new construction or rehabilitation.

$U(i,j)$=Present value of user cost of pavement which is in condition i and j th year after new construction or rehabilitation.

$R(r)$=Present value of rehabilitation cost and delay cost of r method.

(3) Probabilistic Dynamic Programming[14),15)]

PDP also moves backward from the end to the beginning of the analysis period to compute total cost just like DP. However, contrary to DP, this approach has to consider both the probabilities of maintenance and rehabilitation in addition to user cost every year. The decision to maintain and rehabilitation pavement by PDP will be described by the following equation:

$$EF_n(i,j)=\min.\{DM:P(i,j)[U(i,j)+R(r)+EF_{n-1}(r,1)]+[1-P(i,j)][M(i,j)+U(i,j)+EF_{n-1}(i,j+1)],\ DR:M(r,1)+U(r,1)+R(r)+EF_{n-1}(r,2)\} \quad \cdots\cdots (12)$$

where

$EF_n(i,j)$=Expected present value of total cost of pavement which is in condition i and in j th year after new construction or rehabilitation with n years remaining in the analysis period,

$P(i,j)$=Failure rate of pavement which is in condition i and in j th year after new construction or rehabilitation according to 4.(9).

When $P(i,j)$ is 0, it is unnecessary for pavements to be rehabilitated. Hence the decision will be made of 'maintenance'. In this case, Equation (12) reduce to Equation (13).

$$EF_n(i,j)=M(i,j)+U(i,j)+EF_{n-1}(i,j+1) \quad \cdots\cdots (13)$$

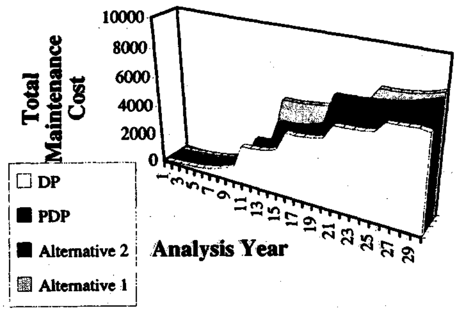

Fig.2 The Total Maintenance Cost

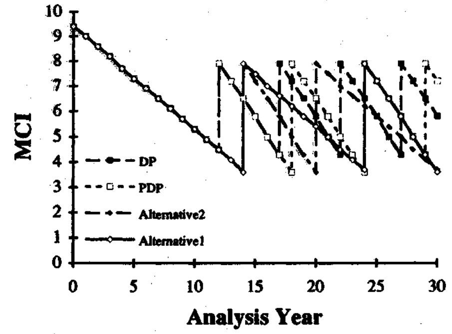

Fig.3 The Expected Transition of MCI

There are two entries in Eq.(12), which are defined as *DM* and *DR*. *DM* implies expected cost when the action of maintenance will be adopted, while *DR* refers to expected cost when that of rehabilitation will be performed. The action corresponding to the minimum cost will be finally taken in the j th year. In this formulation, the timing of rehabilitation for PDP differs from that for DP and the current system when evaluating rehabilitation cost. PDP compute rehabilitation cost at the end of year, while the others do in the beginning of the year. The different timing produces little difference in the cost computation.

(4) Results and Discussions

Increase in total maintenance cost during service year is shown in **Fig.2**. The timing of rehabilitation is also clearly seen in this figure. The figure illustrates that according to the current system the total maintenance cost for Alternative 1 is 8 032 (yen/m^2), while the cost for Alternative 2 is 7 818 (yen/m^2). Hence it may be stated that Alternative 2 is a better strategy than Alternative 1 under present worth analysis. Total maintenance cost for DP results in 6 466 (yen/m^2) and that for PDP is 6 526 (yen/m^2). It is clear that DP and PDP yield better results than the current system does. PDP considers uncertainty in yearly variation on performance level of pavement and, as a result the total cost for

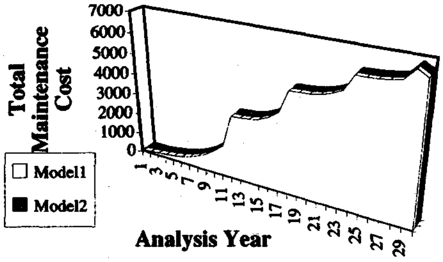

Fig.4 The Total Maintenance Cost between Model 1 and Model 2

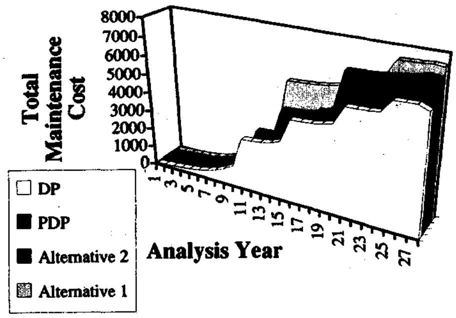

Fig.5 The Total Maintenance Cost Analysis Period : 28 years

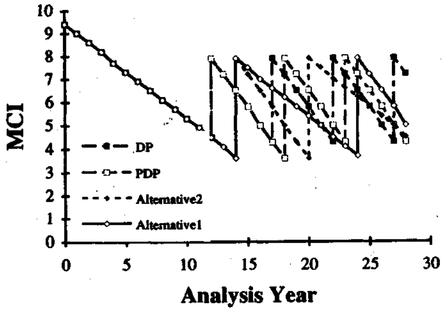

Fig.6 The Expected Transition of MCI Analysis Period : 28 years

PDP becomes higher than that for DP.

The expected transition of serviceability level MCI is shown in **Fig.3**. The selected rehabilitation procedure is also readable from the expected serviceability transition after rehabilitation in this figure. When DP and PDP are used, both methods select only surface treatment as rehabilitation activity from the point of view of a minimum total maintenance cost for this given problem. However, the current system is not flexible since it chooses a rehabilitation activity from the alternative only when the serviceability level drops to 4.0. According to the report in the 41 st Technical and Research Meeting of the Japan Ministry of Construction, the total maintenance cost attains a minimum when the pavement is rehabilitated at the serviceability level MCI a little higher than the so called minimum level 4.0. The results of DP and PDP support this observation. The current systme fails to find the best timing and activity for rehabilitation, while DP and PDP select the best strategy among all possible rehabilitation activity. Furthermore, DP and PDP have sufficient flexibility to search a new optimum solution even if a domain of the design conditions fall in the middle of a pavement design life.

Fig.4 shows the total maintenance cost for Model 1 and Model 2 during the analysis period. Model 2 represents a less reliable serviceability level of new pavement as shown in **Fig.1**. The total maintenance cost for Model 2 is 6 566 (yen/m^2), which is higher than that of Model 1 6 526 (yen/m^2), although the timing of rehabilitation and the selected rehabilitation activity is the same for the both models. It may be stated that the total maintenance cost also depends on the reliability of pavement performance level.

Fig.5 illustrates the total maintenance costs for three methods when the analysis period changes from 30 to 28 years. This figure shows PDP results in a little higher cost than does DP. **Fig.6** presents the expected transition of serviceability level for the three methods. The different of the analysis period can be observed on **Fig.5** and **6**, in which the rehabilitation timing of the PDP is required a little earlier than that of DP. That is, uncertainty of serviceability level suggests earlier rehabilitation.

6. CONCLUSION

The PDP approach to project level pavement management has been developed in this paper. By using this method, optimum selection of timing and rehabilitation work has been made on a simple example problem and the results are presented in the form of comparison with the current system and DP method. The following conclusions can be made ;

1) PDP and DP can provide maintenance and rehabilitation planning in which the total maintenance cost becomes equal to or less than that of the current system.

2) The current system determines the timing of rehabilitation only from the performance level. On the other hand PDP and DP select the timing and rehabilitation procedure from the point of view of minimum total maintenance cost during pavement design life. PDP can take an uncertainty of pavement performance level into consideration when making a decision on maintenance and rehabilitation. That is a point on which PDP differs

from DP.

The current system requires the computation of total maintenance cost on all possible alternatives. However it is next to impossible to select all the alternatives. In general it takes an enormouns amount of time before the system finds the optimum alternative.

PDP and DP can be easily used to draw up maintenance and rehabilitation planning for existing pavement. Decision making based on uncertainties in the future will greatly affect economical maintenance and rehabilitation. PDP is the rational and efficient method that possesses a sufficient flexibility to take into account reliability of design life and design environmental conditions.

Through development of nondestructive testing such as FWD, it has become possible to make structural evaluation of pavement in recent years. Hence, it has becomes possible to grasp reliability of its service life not only from surface conditions but also bearing capacity of pavement. PDP will serve as a more rational and efficient tool for pavement management systems.

A relatively simple model used in this paper helps to elucidate the remarkable flexibility the PDP possesses. The simplicity, however, does not hamper generalities required for pavement management systems involve a long range perspective such as the analysis period of 30 years considers in this paper. However, during this period, a drastic change in design environments such as development of new materials and new rehabilitation procedures may occur. The PDP presented in this paper is fully capable of and adaptable to design environmental changes.

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確率動的計画法を用いたプロジェクトレベルでのアスファルト舗装の維持修繕計画

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プロジェクトレベルでの維持修繕計画において，将来発生する維持修繕費用を最小にする最適な修繕時期と修繕工法の選定は重要である．しかしながら，計画段階での新設，修繕寿命とは違い，現実の新設，修繕寿命にはばらつきがある．これのばらつきを考慮しないと維持修繕計画の信頼度は低いものとなる．本論文は，舗装寿命のばらつきを考慮するために確率動的計画法を用い，プロジェクトレベルでの維持修繕計画の有効性に関する考察を行ったものである．