

# A BILAYER PROJECT OPTIMIZATION METHOD FOR TRANSPORTATION INFRASTRUCTURE MANAGEMENT SYSTEM

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## ABSTRACT

With limit of budget and time, transportation infrastructure maintenance project decision was needed. Optimization is very important for project decision in the Transportation Infrastructure Management System (TIMS) , due to its multi objectives and factors. However, it has not been widely used in TIMS due to poor performance of conventional optimization models in calculation speed and practical application. Therefore, finding a way to improve performance of optimization models, a novel bilayer project optimization model according to the process of decision-making in transportation management, including budget allocation and project distribution is proposed in this paper. Moreover, Mix of Dynamic Programming (DP) and Genetic Algorithm (GA) were applied to obtain an effective solution. The findings indicated that, this new optimization method can provide a satisfactory and reasonable network-level maintenance schedule for transportation infrastructure. Also maintenance agencies could decide routine management by this model.

**Keywords:** Bilayer Project Optimization, Transportation Infrastructure Management System, Network-level Maintenance Schedule, Mix Algorithm of Dynamic Programming and Genetic

## 1. INTRODUCTION

Transportation Infrastructure Management System (TIMS) is a comprehensive transportation system, correspondingly covers many subsystems, among which Pavement Management System (PMS) and Bridge Management System (BMS) are the most important ones. Project optimization is a key element in the process of decision-making for the infrastructure management. Project optimization Hegazy, 1999) refers to finding an optimal maintenance strategy with maximized benefit through arranging pavement maintenance reasonably in terms of time and space in

the planning period. Most of existing research efforts on project optimization of TIMS focused on PMS.

Since decision supporting system was introduced into the second generation of PMS, project optimization has been paid much more attention by pavement researchers and management agencies. Currently, there are mainly two categories of project optimization methods for network-level pavement management system, namely prioritization method and mathematical optimization (Bandara and Gunaratne, 2001; Fwa et al, 1988). Prioritization method is to carry out project selection based on some principles pre-screened, and then to determine the maintenance strategy for each year in the planning period. In 1992, Haas et al (1992) summarized the characteristics of different prioritization methods, among which the two most popular methods are based on infrastructure performance parameters and economic analysis parameters.

According to different managerial preferences of road administrators and agencies, Decision Support System of Shanghai (PMDSSS) in China has developed eight different prioritization principles taking into account either performance parameters or economic analysis parameters or both, with different combinations of traffic volume, pavement damage condition, riding quality, structural capability and economic indicators. The principles greatly help policy makers to formulate large or medium maintenance plans and long-term rehabilitation strategies in the planning years. However, the tradeoff between the maintenance strategy and the time has not been included in the prioritization method, which leads to huge disparity between the calculated result and the actual optimal solution. Therefore, many researchers have been instead focusing on the mathematical optimization, which refers to considering each project in the planning period, the possible maintenance plan and the implementation schedule through mathematical calculations.

While mathematical optimization can produce the optimal calculation results, the large numbers of factors to be considered, huge data processing, and barely satisfactory calculation speed greatly limit its practical application. In order to apply mathematic optimization to project optimization, the key point is to find a model or algorithm which can save computing resources as well as meeting the practical needs.

Compared to the existing research studies, the main contributions of this paper are: firstly, the project optimization was separated into two independent and interrelated processes, namely budgets allocation and project distribution, and a new bilayer model was developed. Secondly, the technique of Dynamic Programming (DP) and Genetic Algorithm (GA) were applied to solve the model and yield an effective solution. Finally, the new programming method was verified to be effective through the case study in Shanghai, and the poor calculation speed and the practical application limitations of conventional methods are improved.

## 2. INTEGER PROGRAMMING FOR PROJECT OPTIMIZATION

Goal of project optimization is to achieve project schedule with max benefit by considering each projects, maintenance strategy, project implementation time and their distribution of time and space, integer express was shown as Equations 1-1, 1-2, 1-3, 1-4 and 1-5.

$$\text{Objective} \quad \max Z = \sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^m X_{ijt} * B_{ijt} \quad (1-1)$$

$$\text{Subject to} \quad \sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^m X_{ijt} * C_{ijt} \leq A \quad (1-2)$$

$$\sum_{j=1}^m X_{ijt} = 1 \quad (i=1,2,\dots,N; t=1,2,\dots,T) \quad (1-3)$$

$$X_{ijt} = \begin{cases} 1 & \text{if treatment } j \text{ is applied in segment } i \text{ in year } t \\ 0 & \text{otherwise} \end{cases} \quad (1-4)$$

$$B_{ijt}, C_{ijt}, A, S_t, V_t > 0 \quad (1-5)$$

Where,

Z is total maintenance benefit;

$B_{ijt}$ 、 $C_{ijt}$  are respectively the benefit and cost caused by implementing treatment j in project i in year t;

A is the total budget in planning period;

T is the length of planning period, normally 5 or 10 years;

N is the amount of total road units;

m is the total number of treatments for each project.

It is necessary to simplify the model in order to calculate conveniently as well as meeting practical needs. Equation 1-1 is transformed to the following form, as equation 1-6.

$$\sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^m X_{ijt} * B_{ijt} = \sum_{i=1}^N \sum_{j=1}^m X_{ij1} * B_{ij1} + \dots + \sum_{i=1}^N \sum_{j=1}^m X_{ijk} * B_{ijk} + \dots + \sum_{i=1}^N \sum_{j=1}^m X_{ijT} * B_{ijT} \quad (1-6)$$

If the expression  $f_t(Y_t) = \sum_{i=1}^N \sum_{j=1}^m X_{ijt} * B_{ijt}$  ( $Y_t$  is the budget of year t) is considered as the

maintenance benefit of year t, then the total maintenance benefit in planning years should equal to the summation of maintenance benefit of each year. Therefore,

$$\sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^m X_{ijt} * B_{ijt} = f_1(Y_1) + \dots + f_t(Y_t) + \dots + f_T(Y_T) = \sum_{t=1}^T f_t(Y_t) \quad (1-7)$$

Where,  $Y_t$  is budget of year  $t$  and  $f_t(Y_t)$  is maintenance benefit of year  $t$ .

It was shown in equation 1-1 and 1-7 that solution of project optimization can be approached with the following steps. The first step is budget optimizing to get the budget allocation in each year in the planning period. The second step is project portfolio (including optimization of project scheme and schedule) to get the optimal benefit maintenance strategy in each year based on the budget allocation of first step. After several iterations of optimization, selection, and comparison through the repetition of above two steps, the optimal maintenance strategy under the optimal budget allocation can be achieved finally. Actually, this method well reflects the actual iterative decision-making process of the government agencies, which is “budget allocation – project arrangement – budget adjustment – project adjustment”. Through this iterative method, project optimization is divided into two relatively simple processes, namely budget optimization and project distribution.

### 3. BILAYER OPTIMIZATION APPROACH

According to the above analysis, project optimization can be divided into two layers. The first one aims at how to allocate budgets. The second one determines maintenance projects in each year based on the budget allocation in the first layer. The first layer is defined as budget allocation model and the second as project distribution model, which build up the bilayer optimization approach.

#### 3.1 Budget Allocation Model

Budget allocation model is, under certain amount of fund, to find a reasonable budget allocation for each year in planning period in order to maximize the benefit of budget. The model focuses on the reasonable way of budget allocation

In the process of allocating budgets, pavement management agencies need to consider not only performance of road network but also budget limits (maximal and minimal budgets for each year are expressed with  $S_t$  and  $V_t$ , respectively). Therefore, the budget allocation model can be designed as follows:

$$\text{Objective} \quad \max \sum_{t=1}^T f_t(Y_t) = f_1(Y_1) + f_2(Y_2) + \dots + f_t(Y_t) + \dots + f_T(Y_T) \quad (2-1)$$

$$\text{Subject to} \quad \sum_{t=1}^T Y_t \leq A \quad (2-2)$$

$$Y_t \leq S_t \quad (t=1, 2 \dots T) \quad (2-3)$$

$$Y_t \geq V_t \quad (t=1, 2 \dots T) \quad (2-4)$$

In fact, there are a large number of maintenance projects in the road network for the planning period, and each project has several treatments. Different treatments bring different maintenance benefit. Therefore, it is necessary to pose some limitations to budget allocation considering that pavement management agencies may utilize fuzzy decision unconsciously in the process of decision making which makes their decision rather reasonable. Firstly, budget change is discontinuous when management agencies are allocating or adjusting budgets, therefore the budget change is set as integer times of the smallest unit. Secondly, maximal maintenance benefit in the planning period under certain budget allocation schedule equals to the summation of maximal benefits in each year.

$$\sum_{t=1}^T f_t(Y_t) = \max(f_1(Y_1)) + \dots + \max(f_t(Y_t)) + \dots + \max(f_T(Y_T)) = \sum_{t=1}^T \max(f_t(Y_t)) \quad (2-5)$$

### 3.2 Project Distribution

Project distribution model is about how to arrange maintenance projects under given budget allocation schedule ( $Y_1, Y_2, \dots, Y_T$ ) in each year in order to obtain the maximal maintenance benefit. It can be designed as follows:

$$\text{Objective} \quad \sum_{t=1}^T (\max \sum_{i=1}^n \sum_{j=1}^m (X_{ijt} B_{ijt})) \quad (3-1)$$

$$\text{Subject to} \quad \sum_{i=1}^n \sum_{j=1}^m (X_{ijt} C_{ijt}) \leq Y_t \quad (t=1, 2, \dots, T) \quad (3-2)$$

$$\sum_{j=1}^m X_{ijt} \leq 1 \quad (i=1, 2, \dots, n; t=1, 2, \dots, T) \quad (3-3)$$

$$X_{ijt} = 0 \text{ or } 1$$

Where,

$n$  is the total amount of projects in road network;

$m$  is the total amount of treatments for each project;

Boolean variable  $X_{ijt} = 1$  (or 0) means treatment  $j$  is applied (or not) to project  $i$  in year  $t$ .

### 3.3 Relation between Budget Allocation Model and Project Distribution Model

The results of the budget allocation model and the project distribution model are interactional. At first, annual budget will be provided through the budget allocation model. Then, the maximal maintenance benefit and project schedule will be constructed through the project distribution model according to the result of the first model, and then a feedback will be offered to the first model to judge whether the solution is the best or not. If not, the budget allocation model will optimize again and

produce a new array of budgets in each year, then the corresponding total maintenance benefit and maintenance schedule will be obtained through the project distribution model. Through iterations of the two models, the optimal strategy will be obtained in the planning years.

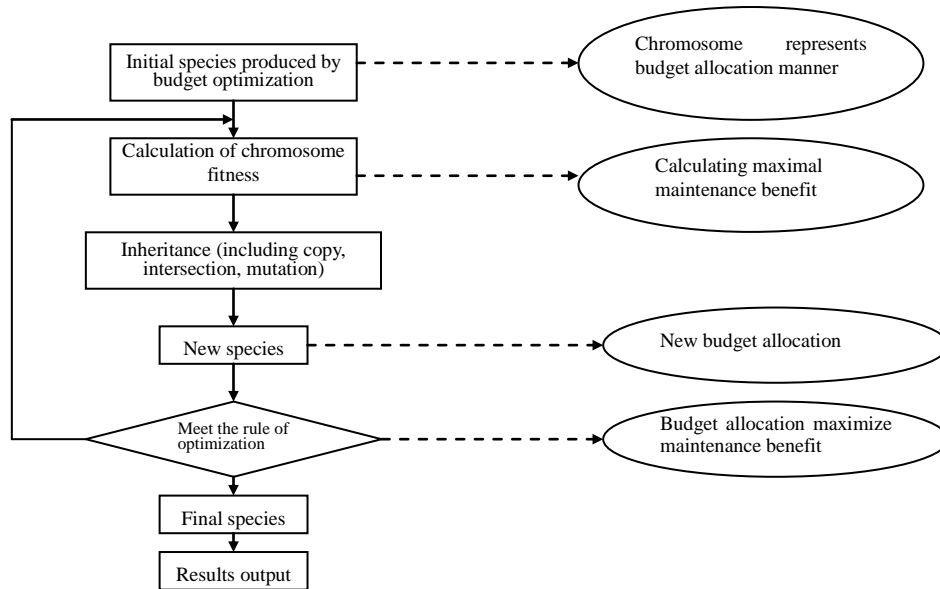
#### **4. SOLUTION OF THIS BILAYER OPTIMIZATION**

The key to apply the mathematic optimization method into practice is to find a reasonable solving method which ensures certain accuracy and meets practical requirements. In the objective function of equation 2-1, it is difficult to be expressed for  $f_i(Y_i)$  by explicit functions, which causes difficulty in effectively solving it with normal algorithm. Given that Genetic Algorithm (GA) is able to search the global optimal solution in a complicated space while its objective functions are not necessary to be explicit functions, GA is chosen to solve the budget allocation model 2-1.

In budget allocation model, decision (maintenance strategy) of each stage (planning year) is the function of pavement network condition given by the decision of last stage. That is, each stage will influence the next stage through the network condition resulted from the different treatment strategy. Therefore, under given budget allocation ( $Y_1, Y_2, \dots, Y_T$ ), the formulation of pavement network maintenance strategy in planning years is a multi-stage problem in which all stages have mutual connections, namely a classic dynamic programming problem. Therefore, the method of dynamic programming is employed to solve the projects distribution model 3-1.

##### **4.1 GA for Budget Allocation Model**

Before the calculation with GA, some parameters including length of chromosome, species group scale, intersection rate, and mutation rate have to be set in advance according to the scale of pavement network, length of planning period, and budget. Then, the budget allocation model can be solved in the following process, as shown in Figure 1.



**Figure 1. Calculation process of budget allocation with GA**

- (1) Initial species: each chromosome in the species represents a budget allocation mode.
- (2) Fitness function: the fitness function of chromosome is derived from the maximal maintenance benefit under a budget allocation mode. The function is computed using the project allocation model.
- (3) Genetic manipulation of chromosome: through the genetic manipulation of chromosome, the budget allocation with superior maintenance benefit can be inherited, and those inferior ones will be eliminated.
- (4) Termination of iteration: certain iteration times can be set as the termination condition of GA.

Among above calculation process, fitness function of chromosomes which are not subject to the budget constraints can be limited by penalty function, or given a very small fitness value. The chromosome with the biggest fitness value was obtained by GA and the corresponding budget allocation manner was the final solution of the budget allocation model.

#### 4.2 DP for Project Distribution Model

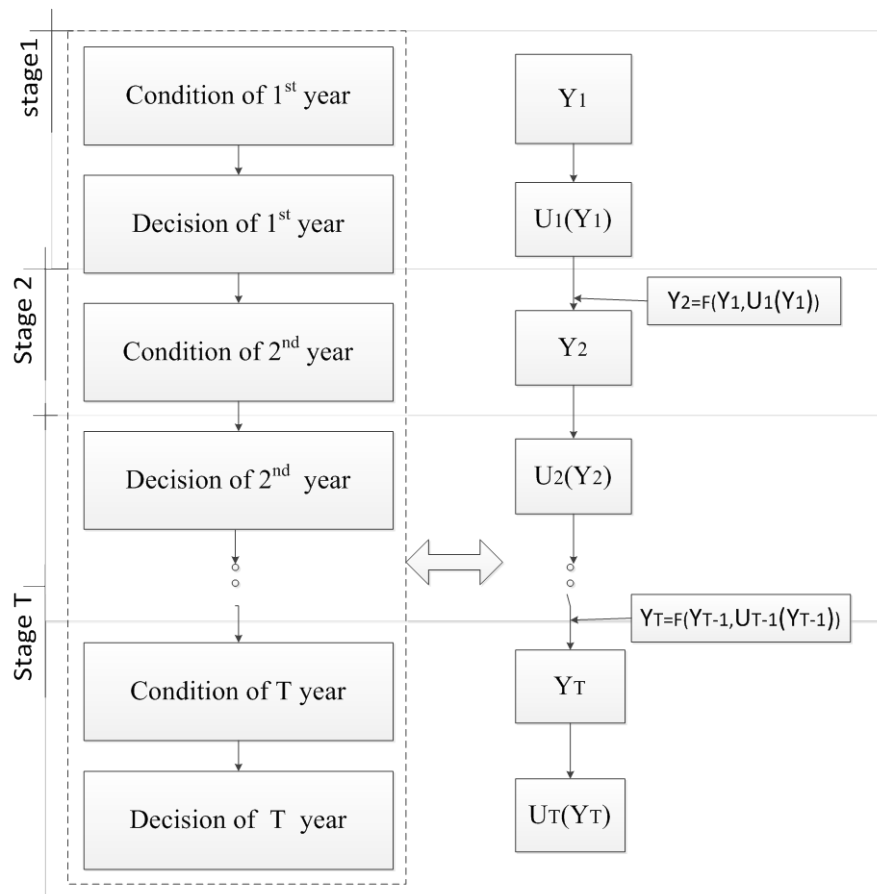
Project distribution model is mainly used to arrange project implementation in each year under a given optimization result of budget allocation. The output results should include a list of maintenance projects in each planning year. Meanwhile, through the project distribution model, the fitness value can be achieved for the above mentioned chromosome, which can serve as the basis of calculation for further optimization.

As discussed above, the determination of maintenance strategy of pavement network in each stage is a multi-stage decision making problem in which each stage is interactional. The process have following characters: at the beginning of each stage, optimal decision of each stage is only related to road network condition, but not related to the decision of the previous stage in which the road network condition is

known. The combination of optimal decision in each stage is the best strategy for the planning period. In the other hand, the process of decision making is a multi-stage chain in which each stage does not influence the following stages. Therefore, the dynamic programming is a powerful tool to solve this kind of problem.

#### 4.2.1 Calculation Process of DP

According to the characteristics of DP and project distribution model, the process of DP in project distribution can be described as the following Figure 2.



**Figure 2. DP process of projects distribution model**

It was shown in Figure 2 that the whole planning period of T years can be divided into T stages. Vector  $Y_t = (\text{pavement network condition in year } t, \text{ budget of year } t)$  represents initial condition of each stage. The decision can be made according to  $U_t(Y_t) = U_t(\text{pavement network condition in year } t, \text{ budget of year } t)$ . Finally the maximal maintenance benefit, benefit in this stage, can be calculated based on the  $U_t(Y_t)$  and the condition transition function  $Y_{t+1} = F(Y_t, U_t(Y_t))$ .



#### 4.2.2 Calculation of Maximal Maintenance Benefit [Determination of Ut(Yt)]

Calculation model of maximal maintenance benefit  $U_t(Y_t)$  in each year can be devised as follows:

$$\max \sum_{i=1}^n \sum_{j=1}^m (x_{ij} b_{ij}) \quad (5-1)$$

$$\text{s.t. } \sum_{i=1}^n \sum_{j=1}^m (x_{ij} C_{ij}) \leq y \quad (5-2)$$

$$\sum_{j=1}^m x_{ij} \leq 1 \quad (5-3)$$

$$x_{ij} = 0 \text{ or } 1$$

Where,

$n$  is the number of projects;

$m$  is the number of treatments for each project;

$y$  is the total maintenance budget;

$X_{ij}=1$  (or 0) means treatment  $j$  is selected (or not) in project  $i$ .

Following is a recursion equation built up by the DP method, in which there are 3 treatments for each project. The cost of each treatment is defined as integer and described from small to large as  $w_{i1}$ ,  $w_{i2}$ , and  $w_{i3}$ . At the same time, the corresponding benefit is  $v_{i1}$ ,  $v_{i2}$ , and  $v_{i3}$ , respectively.

$$f(i,m) = \begin{cases} f(i+1,m) & 0 < m < w_{i1} \\ \max(f(i+1,m), f(i+1, m-w_{i1}) + v_{i1}) & w_{i1} < m < w_{i2} \\ \max(f(i+1,m), f(i+1, m-w_{i1}) + v_{i1}, f(i+1, m-w_{i2}) + v_{i2}) & w_{i2} < m < w_{i3} \\ \max(f(i+1,m), f(i+1, m-w_{i1}) + v_{i1}, f(i+1, m-w_{i2}) + v_{i2}, f(i+1, m-w_{i3}) + v_{i3}) & m > w_{i3} \end{cases}$$

(5-4)

Then constraints can be formulated as follows:

$$f(n,m) = \begin{cases} 0 & m < w_{n1} \\ v_{n1} & w_{n2} < m < w_{n1} \\ \max(v_{n1}, v_{n2}) & w_{n2} < m < w_{n3} \\ \max(v_{n1}, v_{n2}, v_{n3}) & m > w_{n3} \end{cases}$$

(5-5)

The function of  $f(i, m)$  can be solved through the backward deduce method and the optimal solution for each stage can be achieved through the backtracking method.

## 5. CASE STUDY

The model and algorithm are tested and verified through a case study with the data collected from asphalt pavements of 12 districts in Shanghai in 2004. The planning period lasts 10 years, the total number of sections surveyed is 867, the total road length is 238 km, and the total area is 3 093 293 m<sup>2</sup>.

(1) Parameters of funds are provided as follows:

- (a) Total budget: 160 million RMB
- (b) Minimum investment for each year: 13 million RMB
- (c) Maximum investment for each year: 17 million RMB
- (d) The step change of investment for each year: 100 000 RMB

(2) Parameters of GA are provided as follows:

- (a) Reproduction rate: 0.7
- (b) Mutation rate: 0.05
- (c) Crossover rate: 0.3

The calculation software was programmed with Microsoft Visual Basic 6.0. The model proposed and developed in this paper (hereafter referred to as “new method”) was compared with current pavement maintenance method (hereafter referred to as “conventional method”), in which maintenance would be conducted once the PCI was lower than 75, currently adopted by pavement management agencies in Shanghai. The calculation results were listed in Table 1 and Table 2.

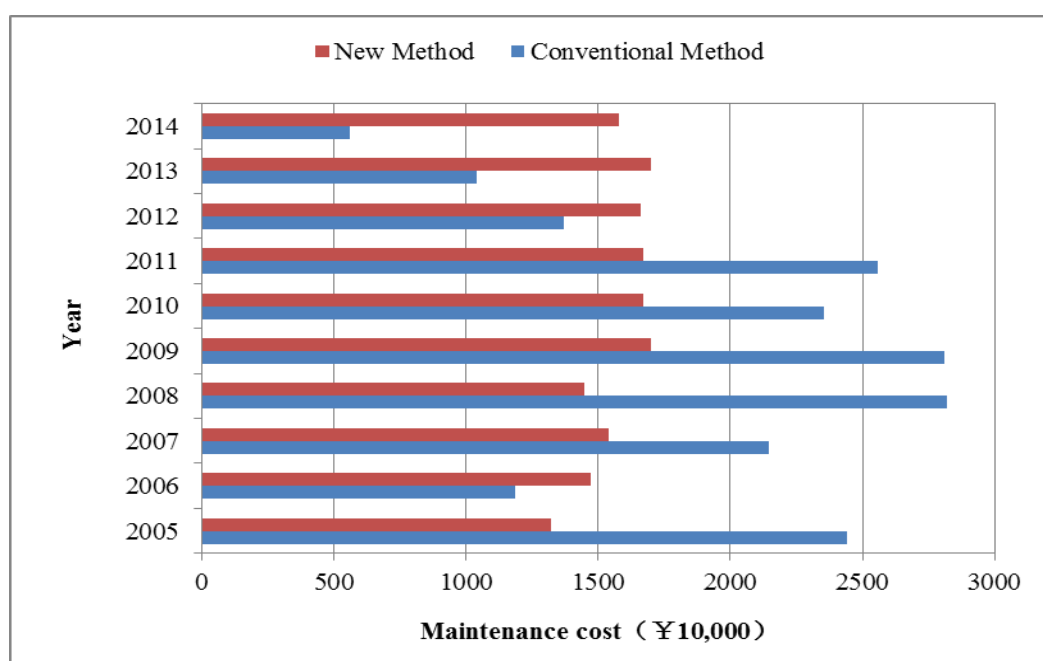
**Table 1. Results of new method**

Year	No. of segments to be treated	Length of road to be treated (m)	Area of pavement to be treated (m <sup>2</sup> )	Total maintenance cost (¥10,000)	Average PCI of pavement network	Average PII of pavement network
2005	60	17859	187210	1320	89.6	483649.2
2006	56	17234	223318	1470	88.3	361548
2007	63	17298	221853	1540	87.1	571428.7
2008	81	23026	303050	1450	86.8	888703.5
2009	89	23103	307059	1700	87	782662.4
2010	112	28812	334866	1670	88.3	780185.2
2011	85	22393	310335	1670	88.8	755266.7
2012	80	22567	328590	1660	89.3	675452.1
2013	98	22582	272024	1700	90.6	520031.3
2014	75	22688	319542	1580	91.1	504012.8
Total	799	217562	2807847	15760	88.69	6322940

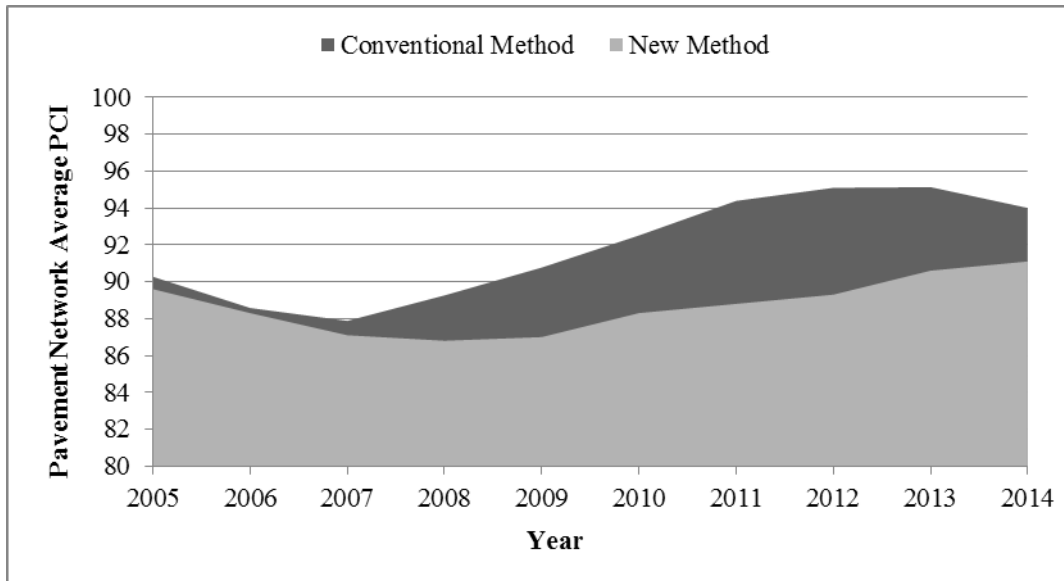
**Table 2. Results of conventional method**

Year	No. of segments to be treated	Length of road to be treated (m)	Area of pavement to be treated (m <sup>2</sup> )	Total maintenance cost (¥10,000)	Average PCI of pavement network	Average PII of pavement network
2005	78	24152	269404	2440	90.27	572719
2006	43	13433	173309	1188	88.58	302004
2007	73	20923	257218	2145	87.88	621756
2008	133	37972	461683	2820	89.26	1131875
2009	121	33224	446845	2810	90.77	962347
2010	118	29992	366621	2356	92.51	749037
2011	115	31383	435860	2559	94.38	864322
2012	79	19932	279639	1370	95.09	551289
2013	63	15851	224198	1039	95.13	340663
2014	34	8620	130474	559	94	150450
Total	857	235482	3045251	19286	91.78	6246469

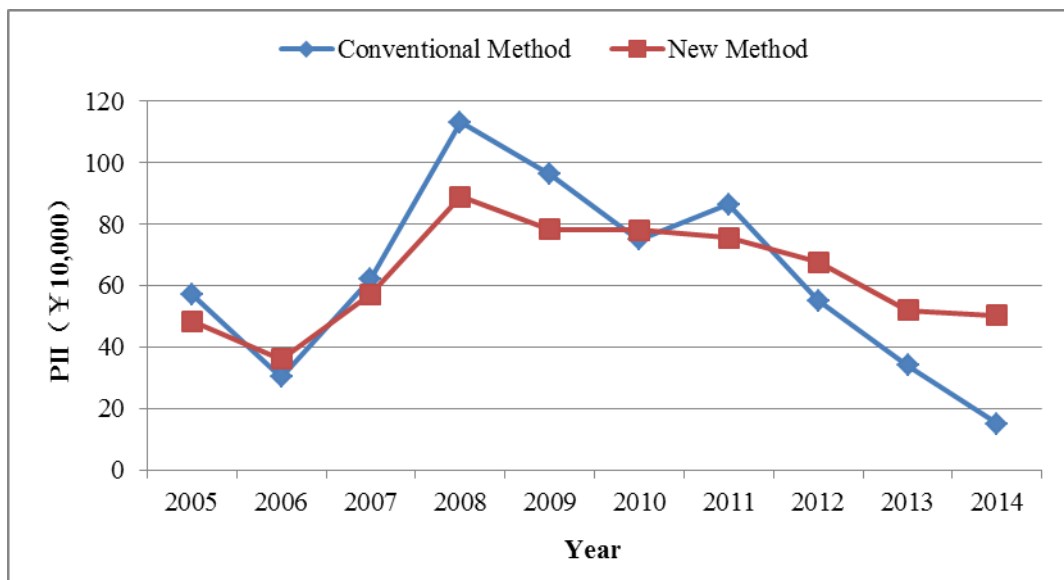
In these tables, maintenance benefit of the pavement network was indicated with PII (Pavement Improvement Index). PII mainly considers restoration of pavement indicators, interval time between two maintenance services, and social impact. Comparison of the data in Table 1 and Table 2 was shown in the following Figure 3 and Figure 4.



**Figure 3. Maintenance cost comparison of road network**



**Figure 4. Average PCI comparison of road network**



**Figure 5. PII comparison**

Based on the case study results, the following observations can be drawn:

- 1) The total maintenance benefit increases (the PII improves from 6246469 to 6322940 after optimization with the new method), while the average PCI of road network in the planning period decreases after adopting the new method. At the same time, the total cost in the planning period is significantly reduced (the total cost decreases from ¥19286 to ¥15760, a drop of 18%). That is, pavement management agencies will achieve better maintenance benefit through spending less resource with the new method.
- 2) As shown in Figure 3, through the conventional method, budget demand in each planning year is significantly different (i.e. the maximal budget demand is ¥28,200,000 in the fourth year, and the minimal demand is ¥5,590,000 in the tenth year. The variance of the investment in each year is up to 2447). That

seriously violates the rule of a stable financial plan of local finance department. Through the new method, the budget of each planning year is well controlled. The difference of each year's budget effectively decreases (i.e. the maximal budget demand is ¥17,000,000 in the fifth and ninth year, and the minimal demand is ¥13,200,000 in the first year. The variance of the investment in each year is lowered down to 387). It well reflects the rule of a stable financial plan of finance department.

- 3) Figure 4 and Figure 5 indicated that PCI and the PII of road network in each year, similar to the maintenance budget, change remarkably when adopting the conventional method. On the contrary, the new method can significantly mitigate the variation of PCI and PII. The variance of PCI decreases from 8.3 to 4.5 and the variance of PII decreases from 928403 to 505346.

In general, pavement management agencies will get more maintenance benefit with fewer funds through the new model. Meanwhile, the amount of investment and the variability of pavement network PCI in each planning year can be effectively controlled to meet the rule of a stable project plan for pavement management agencies. Consequently, the new model and the solving method proposed in this paper are effective and practical for the infrastructure management.

## **6. CONCLUSION**

A proper model and algorithm is very critical for project optimization. To solve the problems of poor calculation speed and practical application limitation of the conventional mathematic method, a bilayer model consisted of the budget allocation model and the project distribution model was developed in this paper. In addition, the model was solved through a mix of dynamic programming and genetic algorithm. Furthermore, it was verified to be effective by practical data in a case study. The findings indicated that, this new optimization method could provide a satisfactory and reasonable maintenance schedule for transportation infrastructure maintenance agencies, whose routine management also can benefit from the newly proposed model.

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