OPTIMIZATION OF PAVEMENT MAINTENANCE ACTIVITIES CONSIDERING VEHICLE OPERATING COST

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Abstract. *Under financial and time limitations, it's complicated properly distribute resources to achieve maximal benefit to the society. There are a lot of mathematical tools to solve this kind of problem. Each mathematical approach has advantages and disadvantages, and the key is to utilize mathematic instrument with sense of applicability to the practice. The paper focuses on application of dynamic programming in prioritization road sections which require immediate intervention. Vehicle operating costs used as an important factor in the decision-making process which calculated taking into account roughness index IRI. It was found that the optimal solution corresponds to the importance of highway functional classification.*

Keywords: *Vehicle operating cost, functional classification, dynamic programming.*

I. INTRODUCTION

Transportation infrastructure plays enormous role in economic development of a country. In Uzbekistan, there are 8 000 km railroads, 184 000 km of roads, and 13 900 km of major pipelines. According to the recent report of road agency "Uzavtoyul", over 91% freight and 98% passengers transported by roads. Public roads consists of 42 600 km which include international, state and local roads. Through Central Asia Regional Economic Cooperation Road Investment Program (CAREC) there are 404 km of highways in Uzbekistan were rehabilitated since 2006 (World Bank 2015).

A good example of vicious circle of problems in pavement management can described as a leaky ship metaphor (Lyneis J., 2016, Jose G, 2017). Assuming that a ship has a leak and crew has to bail and the same time sail. But the problem is there are not enough crew to bail and sail at the same time. The same applies to pavement management there is a limited funding and number of candidate road sections for rehabilitation and maintenance is quite large, besides road condition changes over time scale. It means while implementing maintenance and rehabilitation activities on a certain sections of road network, the rest road sections with good condition transition to satisfactory level, road condition with satisfactory level to bad conditions and so on.

In Uzbekistan, annual road expenditure increased from 237 million USD in 2013 to 391 million USD in 2017 which constitutes 40% rise. Lion's share is in construction and repair (and maintenance) of highways, which amounts to a total of 90% spending. Interestingly, there is a trend in the increase in construction spending, which is 64% compared to 48%, but for repair and maintenance of highways has decreased from 24% to 35%. For the same period of time total road network increased 22 km which is not significant, and implies that majority road works were rehabilitation (reconstruction) works (Sodikov J., Kasimkhodjaev B., 2018). In other words, majority highway improvement projects are related to capacity expansion or rehabilitation poor road condition. Since independence in 1991, size of Uzbek road network didn’t change significantly, but road expenditure increased each year due to deferred maintenance and poor management practices. To compare highway spending, for instance in US, total highway spending increased 62.8 percent from 2002 to 2012, averaging 5.0 percent per year (FHWA, 2015). Which implies the problem of increased highway spending faced by not only developed countries but also developing countries. In order to solve this problem dynamic programming approach was utilized by incorporating vehicle operating cost.

II. LITERATURE REVIEW

A number of literature addresses the application of dynamic programing in pavement maintenance optimization. Some researchers proved that dynamic programming can be used to determine optimal strategies (Feighan K., 1988, Mbwana J., 1996, Yoo J., 2008, Medury A., 2013). By using stochastic dynamic programming, authors tried to determine optimal strategies and related mean costs over specified life-cycle periods. They investigated the suitability the effects of deferred maintenance (Feighan K., 1988). If pavement performance can be modeled by a Markov chain (i.e., using Markov transition probabilities), then a Markov decision model can be developed to determine optimal maintenance policies. It is assumed that these transition probabilities are known. Mbwana develops a Markov decision model that determines optimal M&R policies that are related to individual pavement sections or links in a highway network. The model consists of two parts: the long-term (steady-state) model and the short-term (transition) model. These models are linked to provide an overall pavement management strategy (Mbwana J., 1996,). Yoo developed an optimization methodology for determining the most cost-effective maintenance and rehabilitation (M&R) activities for each pavement section in a highway pavement network, along an extended planning horizon. A multi-dimensional 0–1 knapsack problem with M&R strategy-selection and precedence-feasibility constraints is formulated to maximize the total dollar value of benefits associated with the selected pavement improvement activities. The solution approach is a hybrid dynamic programming and branch-and-bound procedure (Yoo J., 2008). Recently, Medury applied the state-of-the-art Markov decision process (MDP)-based optimization approaches in infrastructure management, while optimal for solving budget allocation problems, become internally inconsistent upon introducing network constraints. An ADP framework was proposed, wherein capacity losses due to construction activities are subjected to an agency-defined network capacity threshold. A parametric study is conducted on a stylized network configuration to infer the impact of network-based constraints on the decision-making process (Medury A., 2013).

The above mentioned research works do not take into account the role of the highway functional classification, as well as the importance of vehicle operating costs when making a decision to optimize highway spending.

III. METHODOLOGY

Dynamic programing is used in optimization complex problems which require step by step decision making. Foundation of dynamic programing was laid out by R. Bellman in 1940. Decision making in pavement maintenance is a complicated problem which road section should be treated first, a section with the worst road condition, or road section which would beneficial to locals, or expand the road network, while taking into consideration of financial resources limitation. Additionally, time plays an important role, while performing maintenance and rehabilitation (M&R) activities which may take from several days to years to complete. There are limitations such as time, finance, and network size. In other words, road agency is able to fix a certain part of road network due to financial and time restriction.

The paper investigates prioritization of maintenance and rehabilitation (M&R) activities by utilizing dynamic programming which takes into account vehicle operating cost.

Dynamic programming solves complex problems by dividing it into several small problems and step by step finding minimum or maximum of function. Maximization function can be described as follows:

$$R(x_1, x_2, \dots, x_N) = g_1(x_1) + g_2(x_2) + \cdots g_N(x_N) \quad (1.1)$$

Over the region $x_i \geq 0, \sum_{i=1}^{N} x_i = x,$ N – may assume any integer. Maximum of $R(x_1, x_2, \dots, x_N)$ over the designated region depends upon x and N, sequence function $\{f_N(x)\}$, defined for $N = 1,2, \dots, x \geq 0$, as follows:

$$f_N(x) = \max_{\{x_i\}} R(x_1, x_2, \dots, x_N), \quad (1.2)$$

Where $x_i \geq 0$ и $\sum_{i=1}^{N} x_i = x$.

The function $f_N(x)$ is then the optimal return from an allocation of the quantity of resources x to N activities. Under $f_N(0) = 0, N = 1, 2, \dots$, if $g_i(0) = 0$ for any i then $f_1(x) = g_i(x)$ for $x \geq 0$. Optimal return remaining quantity of resources $x - x_N\ to\ N - 1$ activities, by definition $f_{N-1}(x - x_N)$ initial allocation of $x_N\ to\ the\ Nth$ activity results in total return of $g_N(x_N) + f_{N-1}(x - x_N)$ from the N-activity processes. An optimal choice of x_N, is obviously one which maximizes this function. Basic functional equation:

$$f_N(x) = \max_{0 \leq x_N \leq x} |g_N(x_N) + f_{N-1}(x - x_N)| \quad (1.3)$$

for $N = 2, 3, \dots, x \geq 0$.

An optimal policy has the property that whatever the initial state and initial decisions are, the remaining decisions must constitute an optimal policy with regard to the state resulting from first decision (Bellman R., 1962).

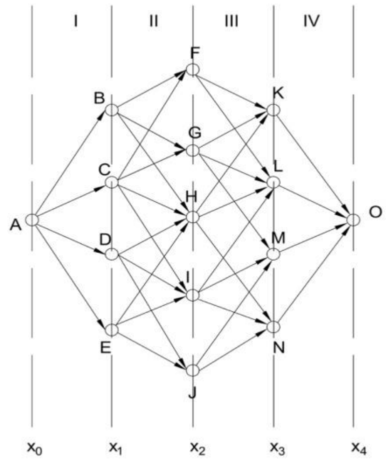

Fig 2. *Schematic representation road sections*

Let's consider an example of prioritization of road-repair works by using of dynamic programming. To solve this problem, an example of the construction of highways was adapted, the purpose of which was to minimize the cost of construction. Instead of construction cost, vehicle operating cost is applied, and the goal is to find road section with the maximum vehicle operating cost. Vehicle operating costs for roads of Uzbekistan are calculated by Sodikov J., 2018, and they adjusted (multiplied) by highway functional classification weight coefficients (Silyanov V., 2017). Figure 2 represents 35 homogeneously sectioned road segments.

Each road section has three parameters such as IRI roughness index, (m/km),vehicle operating cost (VOC, US dollar per vehicle km), and highway functional classification (HFC). Table 1 shows the road sections, road condition in terms of IRI, highway functional classification (A - Arterial road, C - Collector road, L - Local road), and vehicle operating cost which calculated taking into account highway functional classification and road conditions. Vehicle operating cost calculation made using software HDM 4 – RUE [World Bank, Road User Effect].

Table 1. *Road section characteristics*

Road section	IRI, m/km	HFC	VOC	Road section	IRI, m/km	HFC	VOC	Road section	IRI, m/km	HFC	VOC
AB	2	A	13.68	DJ	4	A	14.25	IL	3	L	3.81
AC	4	C	7.08	EH	5	L	4.16	IM	7	C	7.81
AD	3	L	3.81	EI	5	C	7.34	IN	3	C	6.86
AE	7	C	7.81	EJ	4	A	14.25	JM	3	L	3.81
BF	3	C	6.86	FK	3	L	3.81	JN	4	L	3.98
BG	5	A	14.71	FL	4	C	7.08	KO	5	A	14.71
BH	4	L	3.98	GK	5	A	14.71	LO	3	C	6.86
CF	5	L	4.16	GL	3	L	3.81	MO	4	A	14.25
CG	3	A	13.74	GM	2	A	13.68	NO	5	L	4.16
CH	3	L	3.81	HK	6	L	4.35				
CI	4	L	3.98	HL	3	A	13.74				
DH	5	A	14.71	HM	2	A	13.68				
DI	3	C	6.86	HN	4	C	7.08				

The goal is to find a road section with maximum vehicle operating costs from A to O (fig. 2), which road sections should be repaired in the first place.

General vehicle operating costs are:

$$F(x_0, x_1, x_2, x_3, x_4) = v_I(x_0, x_1) + v_{II}(x_1, x_2) + v_{III}(x_2, x_3) + v_{IV}(x_3, x_4) \quad (1.4)$$

Step 1. Find maximum of function $\mathrm{f_I(x_1)}$ on sections from I to points B, C, D and E (1.5):

$$\mathrm{f_I(B) = v_I(A, B) = 13.68}$$

$$\mathrm{f_I(C) = v_I(A, C) = 7.08}$$

$$\mathrm{f_I(D) = v_I(A, D) = 3.81}$$

$$\mathrm{f_I(E) = v_I(A, E) = 7.81}$$

Step 2. Find maximum of function $\mathrm{f_{I,II}(x_2)}$ on sections from II to points F, G, H, I and J (1.6):

$$\mathrm{f_{I,II}(F) = \max_{x_1=B,C,D,E}[f_I(x_1) + v_{II}(x_1, F)],}$$

$$\mathrm{f_{I,II}(G) = \max_{x_1=B,C,D,E}[f_I(x_1) + v_{II}(x_1, G)],}$$

$$\mathrm{f_{I,II}(H) = \max_{x_1=B,C,D,E}[f_I(x_1) + v_{II}(x_1, H)],}$$

$$\mathrm{f_{I,II}(I) = \max_{x_1=B,C,D,E}[f_I(x_1) + v_{II}(x_1, I)],}$$

$$\mathrm{f_{I,II}(J) = \max_{x_1=B,C,D,E}[f_I(x_1) + v_{II}(x_1, J)],}$$

These equations are obtained from the optimization theorem for each optimal path from A to F, G, H, I and J, where vehicle operating costs are maximum. Figure 2 shows that for $\mathrm{x_1}$ and the values of B, C, D, and E, we find the functions in 1.6 (when the vertices are not connected, the value is taken -∞):

$$f_{I,II}(F) = \max\left[\underbrace{13.68 + 6.86}_{x_1=B}, \underbrace{7.08 + 4.16}_{x_1=C}, \underbrace{3.81 - \infty}_{x_1=D}, \underbrace{7.81 - \infty}_{x_1=E}\right] = 20.54, \quad with\ x_1 = B$$

$$f_{I,II}(G) = \max\left[\underbrace{13.68 + 14.71}_{x_1=B}, \underbrace{7.08 + 13.74}_{x_1=C}, \underbrace{3.81 - \infty}_{x_1=D}, \underbrace{7.81 - \infty}_{x_1=E}\right] = 28.39, \quad with\ x_1 = B$$

$$f_{I,II}(H) = \max\left[\underbrace{13.68 + 3.98}_{x_1=B}, \underbrace{7.08 + 3.81}_{x_1=C}, \underbrace{3.81 + 14.71}_{x_1=D}, \underbrace{7.81 + 4.16}_{x_1=E}\right] = 18.52, \quad with\ x_1 = D$$

$$f_{I,II}(I) = \max\left[\underbrace{13.68 - \infty}_{x_1=B}, \underbrace{7.08 + 3.98}_{x_1=C}, \underbrace{3.81 + 6.86}_{x_1=D}, \underbrace{7.81 + 7.34}_{x_1=E}\right] = 15.15, \quad with\ x_1 = E$$

$$f_{I,II}(J) = \max\left[\underbrace{13.68 - \infty}_{x_1=B}, \underbrace{7.08 - \infty}_{x_1=C}, \underbrace{3.81 + 14.25}_{x_1=D}, \underbrace{7.81 + 14.25}_{x_1=E}\right] = 22.06, \quad with\ x_1 = E$$

Consequently, for segments I and II together, the maximum costs are:

ABF	if we stop at	F:	costs 20.54
ABG	if we stop at	G:	costs 28.39
ADH	if we stop at	H:	costs 18.52
AEI	if we stop at	I:	costs 15.15
AEJ	if we stop at	J:	costs 22.06

Step 3. By analogy of the calculations in the first and second steps, we will compile the functions maximizing VOC for the segments I, II, and III (1.7):

$$f_{I,II,III}(K) = \max_{x_2=F,G,H,I,J}\left[f_{I,II}(x_2) + v_{III}(x_2, K)\right],$$

$$f_{I,II,III}(L) = \max_{x_2=F,G,H,I,J}\left[f_{I,II}(x_2) + v_{III}(x_2, L)\right],$$

$$f_{I,II,III}(M) = \max_{x_2=F,G,H,I,J}\left[f_{I,II}(x_2) + v_{III}(x_2, M)\right],$$

$$f_{I,II,III}(N) = \max_{x_2=F,G,H,I,J}\left[f_{I,II}(x_2) + v_{III}(x_2, N)\right].$$

The equations (1.7) are result of the optimality theorem, since the optimal path from A to K, L, M, and N must be formed from the previous road sections from A to F, from A to G, from A to H, from A to I , from A to J for which the costs are maximum.

Substituting values from Table 1 into Equations 1.7, we obtain the following:

$$f_{I,II,III}(K) = \max\left[\underbrace{20.54 + 3.81}_{x_2=F}, \underbrace{28.39 + 14.71}_{x_2=G}, \underbrace{18.52 + 4.35}_{x_2=H}, \underbrace{15.15 - \infty}_{x_2=I}, \underbrace{22.06 - \infty}_{x_2=J}\right] = 43.09,$$
$$with\ x_2 = G$$

$$f_{I,II,III}(L) = \max\left[\underbrace{20.54 + 7.08}_{x_2=F}, \underbrace{28.39 + 3.81}_{x_2=G}, \underbrace{18.52 + 13.74}_{x_2=H}, \underbrace{15.15 + 3.81}_{x_2=I}, \underbrace{22.06 - \infty}_{x_2=J}\right] = 32.25,$$
$$with\ x_2 = H$$

$$f_{I,II,III}(M) = \max\left[\underbrace{20.54 - \infty}_{x_2=F}, \underbrace{28.39 + 13.68}_{x_2=G}, \underbrace{18.52 + 13.68}_{x_2=H}, \underbrace{15.15 + 7.81}_{x_2=I}, \underbrace{22.06 + 3.81}_{x_2=J}\right] = 42.07,$$
$$with\ x_2 = G$$

$$f_{I,II,III}(N) = \max\left[\underbrace{20.54 - \infty}_{x_2=F}, \underbrace{28.39 - \infty}_{x_2=G}, \underbrace{18.52 + 7.08}_{x_2=H}, \underbrace{15.15 + 6.86}_{x_2=I}, \underbrace{22.06 + 3.98}_{x_2=J}\right] = 26.04,$$
$$with\ x_2 = J$$

Therefore, the aggregate maximum costs for segments I, II, and III:

ABGK	if we stop at	K: costs 43.09
ABGL	if we stop at	L: costs 32.25
ADHM	if we stop at	M: costs 42.07
AEIN	if we stop at	N: costs 26.04

Step 4. Finally we compute f as maximal function $F(x_0, x_1, x_2, x_3, x_4)$:

$$f = \max_{x_3=K,L,M,N}\left[f_{I,II,III}(x_3) + v_{IV}(x_4, O)\right].$$

$$f = \max\left[\underbrace{43.09 + 14.71}_{x_3=K}, \underbrace{32.25 + 6.86}_{x_3=L}, \underbrace{42.07 + 14.25}_{x_3=M}, \underbrace{26.04 + 4.06}_{x_3=N}\right] = 57.80, \qquad with\ x_3 = K$$

Calculations showed that the most expensive path is A → B → G → K → O of $ 57.80 per vehicle-km. Since vehicle operating cost make up the bulk of the costs of road users and it plays an important role in decision making. A number of literature utilizes vehicle operating cost as primary factor in pavement management (Zaniewski J., 1982, Cheser A., 1987, Chatti K., 2012).

Sensitivity analysis carried out to verify how model reacts to new data. To verify the behavior of the optimization model, input data such as highway functional classification have been modified. The first model implied that all roads, that is, 35 road sections are arterial roads, the second model considers all sections of the collector roads, and the third model, where all sections are local roads, and general model which is explained above mentioned example. For the convenience of solving dynamic programming equations, a program was created in MS Excel.

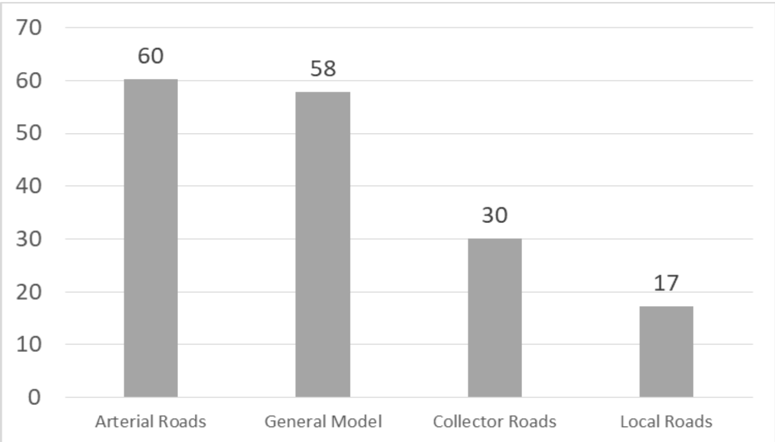

Fig 3. *Change in vehicle operating cost across models (USD per vehicle km)*

As can be seen from Figure 3, vehicle operating costs are reduced according to the highway functional classification from $ 60 per vehicle-km in arterial, 30 in collector roads, and 17 in local roads. The general model is close to the arterial model, because the solution A → B → G → K → O consists of the following sections AB, BG, GK, and KO which in turn are arterial road sections. Consequently, the optimization model using dynamic programming solved the problem adequately with assigning the priority to highway functional classification:

1.Arterial roads;

2.Collector roads;

3.Local roads.

The objective was to find the maximum vehicle operating costs, depending on the road condition (IRI, m / km). The application of dynamic programming allows you to identify the most important road sections that require immediate intervention, that is, with limited financial resources to get the maximum benefit for society as a whole.

IV. CONCLUSION

Under financial and time limitations, it's complicated properly distribute resources to achieve maximal benefit to the society. There are a lot of mathematical tools to solve this kind of problem. Each mathematical approach has advantages and disadvantages, and the key is to utilize mathematic instrument with sense of applicability to the practice. In developing countries, lack of advanced road data collection systems, tools and software to manage road assets force highway engineers practice old paper based approach fix the worst first based on spring and autumn visual survey. The paper offered simplified approach to prioritize road sections which need to be fixed depending on highway functional classification and road condition IRI (m/km) .

Application of dynamic programming proved that optimization at project level is well suited when vehicle operating cost calculated for each road section and adjusted by highway functional classification weight coefficients. Besides, sensitivity analysis showed that changing input values according to three scenarios such as arterial, collector and local models total vehicle operating cost varies according to importance of road section. Proposed approach offers prioritization with minimal road data such as road condition IRI, highway functional classification and vehicle operating cost. Future research would focus on multi-year planning and optimization taking into account probability state of road sections.

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