Heuristic Approach for Fund Allocation in Complex Rehabilitation Programs

Tarek HEGAZY, Roozbeh RASHEDI, and Abdelbaset ALI
Department of Civil and Environmental Engineering, University of Waterloo
Waterloo, N2L3G1, Canada

ABSTRACT

Pavements are important assets to the safety and serviceability of road networks. Due to their fast deterioration and stringent municipal budgets, allocating the limited rehabilitation funds becomes a complex task. In this paper, an efficient heuristic approach for fund allocation has been introduced. After prioritizing pavements based on different criteria, such as AADT, pavement IRI, and road type, the proposed heuristic process combines three procedures for determining required amount of funding and the best pavement treatments to use during the planning horizon. To automate the process, it has been programmed within a simplified pavement management system (PMS) for testing and validation on a case study of more than 1200 pavements. Based on the results of various experiments, the proposed method allocated the limited rehabilitation funds efficiently, and selected the most appropriate treatments to use. This method is simple and logical, allows multiple what-if scenarios, and can be used on variety of asset types to improve infrastructure fund allocation.

Keywords: Infrastructure Assets, Rehabilitation, Pavement Management, Heuristic, Fund Allocation, Computer Application.

1. INTRODUCTION

Repair and rehabilitation are important decisions for sustaining the serviceability and safety of the civil infrastructure. Effectively allocating limited rehabilitation funds amongst numerous assets, however, is a large-scale and complex optimization problem that has not been adequately addressed by traditional optimization tools. Improper fun allocation for maintaining pavement networks, for example, results in poor ride quality and consequently impose huge indirect costs to the society, including vehicles wear, traffic congestion, crashes, injuries, and delays.

To help asset managers in the difficult infrastructure management decisions such as the allocation of rehabilitation funds, Infrastructure Management Systems (IMSs) or Asset Management Systems (AMSs) have emerged as a systematic process of maintaining, upgrading and operating physical assets cost effectively [1; 2; 3]. Hudson et al. (1997) defined an infrastructure management system as “the operational package that enables the systematic, coordinated planning and programming of investments or expenditure, design, construction, maintenance, rehabilitation, and renovation, operation, and in-service evaluation of physical facilities” [4]. A generic asset management includes different functions (Figure 1): (a) accurate inspection and condition assessment of all components; (b) predicting future condition deterioration of these components along a planning horizon (e.g., 5 years); (c) identifying repair types and estimating their costs and benefits in terms of condition improvement for each component; and (d) life cycle analysis to decide on which components to be repair, best repair types, and best timings to repair these components, under budgetary and other practical constraint.

A Pavement Management Systems (PMS) is an infrastructure management system that applies specifically to roads (e.g., bottom of Figure 1). Among its main functions is to facilitate the prioritization and fund allocation decisions related to road rehabilitation and repairs [5]. In the literature, various efforts have developed rigorous mechanisms to prioritize pavement candidates for repair purposes based on a single criterion or a multiple criteria. Upon prioritizing the various pavement sections, however, existing mechanisms leave the fund allocation task to the asset manager, assuming that it is just a simple matter of assigning money to top priority items until the budget is exhausted. This assumption, however, is an oversimplification since fund allocation decisions require detailed life cycle cost analysis at both individual pavement level and at the whole network level as well [6; 7]. A good pavement management system (PMS) ideally integrates the above functions properly. First, current condition on pavements in terms of riding quality can be assessed based on different condition indices, such as international roughness index (IRI), pavement quality index (PQI), or surface distress index (SDI) [8].

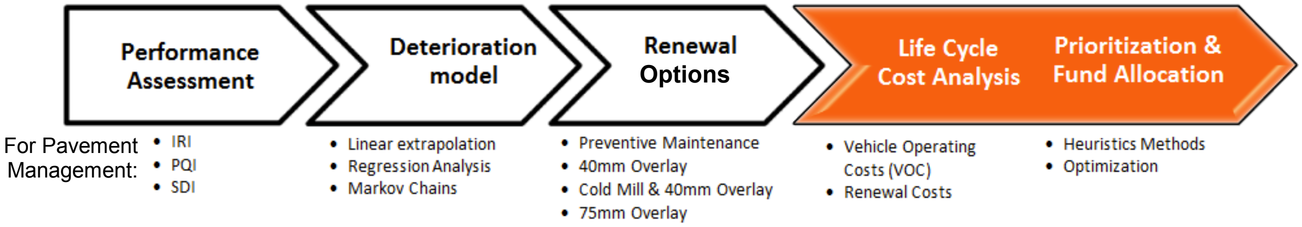


FIGURE 1 Generic pavement management framework.

Next, future pavement conditions for different road types, such as interurban or rural roads, are estimated using different deterioration models, e.g., regression analysis or Markov chains [9; 10]. These models should consider the impact of factors such as annual average daily traffic (AADT) on the future condition of a pavement. In the next step, different repair alternatives (preventive maintenance, cold mill, overlay, micro surfing) need to be evaluated in terms of their costs and improvement effects. Finally, using a life cycle cost analysis (LCCA), the best repair scenarios are selected to maintain a good overall ride quality for the pavement network, cost-effectively. In essence, LCCA considers all the sub-decisions within the planning horizon related to when, and how to repair pavements. To find the best solution by LCCA, a pavement prioritization and fund allocation mechanism needs to be developed. However, when large number of pavements with different deterioration behaviors require repair actions, it is extremely difficult to handle such large-scale and complex combinatorial problem [11]. For instance, consider the case of a small municipality that has 100 pavements sections along a 5-year planning horizon. If three repair alternatives are available (cold mill, 40mm overlay, and 75mm overlay), the possible combination of repair actions is $5^{100\times3}$, which is extremely large and prohibitive.

As an effort towards enhancing asset management capabilities related to fund allocation decisions, this paper proposes a practical and efficient heuristic mechanism for fund allocation. To arrive at a cost-effective solution for large-scale problems, the proposed method incorporates three heuristic procedures and supports fund allocation taken into account road priorities, serviceability requirements, deterioration trends, and budget limits. The proposed methodology has been implemented in a simplified spreadsheet-based PMS and applied on a network of more than 1200 roads. Comments on the performance of the methods are then highlighted.

2. CASE STUDY

The case study is a pavement management investment analysis challenge posted at the 6th International Conference on Managing Pavements (ICMP6). The Challenge was initiated to carry out an analysis and recommend strategies for managing a defined network of interurban and rural roads.

The pavement network is comprised of a total of 1293 road sections spanning 3240 km, covering two road classes, and varying in traffic use, surface age, and condition. The rural roads (R) span most traffic and condition categories. Inter-urban roads (I) are represented on the medium to very highly traffic roads. All pavement sections are located within the same climatic region with consistent sub-soil conditions. Each section has a defined length, width, number of lanes, AADT, soil type, year of construction, base thickness, base material type, most recent treatment, and surface thickness. In addition, surface condition assessments (International Roughness Index, IRI, and others), extent of distresses, and predicted trigger or needs year are specified for all sections. The discount rate for investment analysis is specified as 6%, also increase in vehicle operating costs due to increase in pavement roughness, represented by IRI, and the annual traffic growth rate for the interurban and rural road networks are 2.5 and 1.5%, respectively. Tables 1, 2, and 3 show the annual rate of increase of IRI, the repair costs, and the IRI trigger levels, respectively. Figure 2 also shows the roughness improvements due to different treatments.

Having this information about the pavement network condition, deterioration behaviors, repair options, and vehicle operation costs (VOC), an asset manager needs to decide on the best repair actions and allocate available funds cost-effectively. In the next section, the proposed heuristic approach is described and further implemented within a spreadsheet-based pavement management system to handle the case study.

TABLE 1 Annual rate of IRI increase.

Road Class	AADT	Rate of Increase in IRI (m/Km/Yr.)
Interurban	>8000	0.069
	<8000	0.077
Rural	>1500	0.091
	<1500	0.101

TABLE 2 Unit cost of treatment.

Intervention Type	Cost ($)
1. Preventive Maintenance	6.45
2. 40mm Overlay	6.75
3. Cold Mill & 40mm Overlay	10.50
4. 75mm Overlay	15.75
5. 100mm Overlay	16.50

TABLE 3 IRI trigger levels and Relative Importance.

AADT	IRI Trigger (mm/m)	Relative Importance Factor (RIF)
<400	3.0	1.0
400-1500	2.6	1.4
1500-6000	2.3	1.7
6000-8000	2.1	1.9
>8000	1.9	2.1

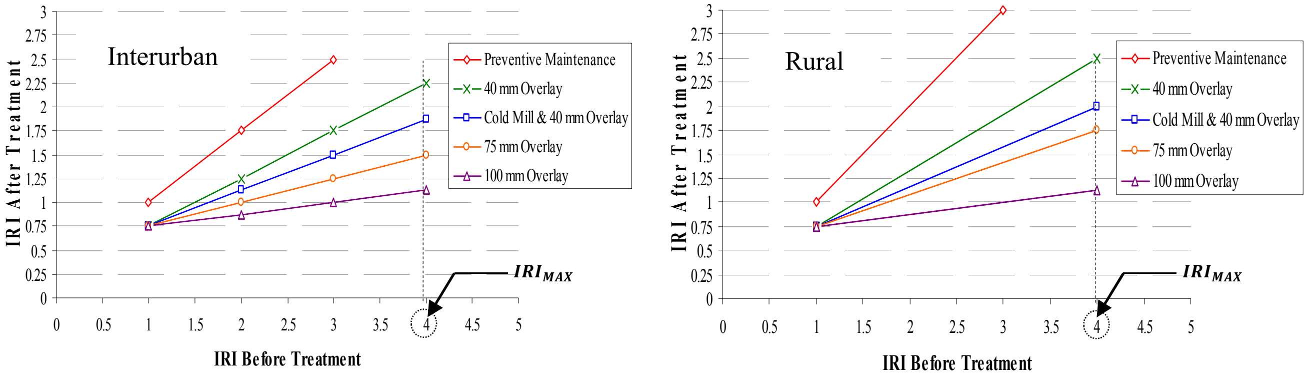


FIGURE 1 The improvement effects of various treatments.

3. HEURISTIC APPROACH FOR REPAIR FUND ALLOCATION

In order to select the best pavement treatments within the planning horizon, this study proposes a heuristic repair fund allocation approach. The method uses a ranking function based on a calculated priority index for pavements, which reflects the need for urgent repair actions. As shown in Table 3, the IRI trigger values (i.e., the minimum acceptable IRI values) are smaller as the traffic becomes heavy. This is logical because heavily used roads need to be maintained with good ride quality (smaller IRI). In the same sense, it is possible to consider that heavily used roads are relatively more important and their importance factor is a function of the IRI trigger value as well. As such, a relative importance factor (RIF_j) for each pavement j can be determined based on AADT as follows:

$$RIF_j = IRI_{MAX} - IRI\ Trigger\ Levels \qquad (1)$$

where, IRI_{MAX} is the maximum IRI value of 4, as shown in Figure 2. Using Eq. (1), therefore, the last column of Table 3 shows the calculated relative importance factors.

Relative importance factors are not sufficient alone to prioritize a pavement for repairs because a less important road can be in a worse condition and thus deserves to be in higher priority. As such, to develop a simple priority index (PI_j) for repairing pavement j, the relative importance factor can be combined with a condition indicator (such as the current condition, IRI_{0j}), as follow:

$$PI_j = RIF_j \times IRI_{0j} \qquad (2)$$

After calculating all PIs, pavements are sorted from high to low priority. This helps in allocating the available funds to pavements with urgent repair needs prior to less critical ones to improve the overall network condition effectively. The overall condition of the whole network is therefore calculated by averaging the IRI values over the network in the entire planning horizon, as follow:

$$Overall\ Pavement\ Nework\ Condition = \frac{\sum_{j=1}^{N}\sum_{k=1}^{5} IRI_{jk}}{N} \quad (3)$$

$$\forall\ j\ \in network\ , \forall\ k\ \in planning\ horizon$$

After prioritization, the proposed heuristic approach involves two functions that are discussed in the following subsections: (a) Determining the minimum budget that maintains network condition above an acceptable level; and (b) Selecting the best repair types and timings under budget limit (near-optimum fund allocation).

Determining Minimum Funding Needs

This proposed heuristic procedure is used to determine the minimum required budget to bring the pavement network above an acceptable level. It combines project level decisions that are related to selecting the best treatment types, and network level decisions for addressing the repair timings during the planning horizon. Basically, each pavement is selected and its yearly IRI values are checked to see in which year the pavement will deteriorate to he unacceptable trigger level (i.e., year 2 in Figure 3). Once the year of repair is selected, a minimum-cost treatment can be selected as the one that maintains the pavement above the IRI trigger level during the planning horizon (e.g., repair action 4 in the figure). This approach spends minimum money only in the necessary year so that to preserve the condition of individual pavements above the IRI trigger level in all years. Repeating this process for all pavements accumulates the necessary budget level that is required for the whole network. This answers the important question of how much level of funding is needed to keep our assets at minimum acceptable level during the planning horizon.

Near-Optimum Allocation of Limited Repair Funds

Since most municipalities receive lower funding levels than they ask for, or what is necessary, two heuristic approaches are proposed to determine a near-optimum allocation of the limited pavement rehabilitation fund. There are as follow:

Method 1: This heuristic method is a project-wise approach that analyzes 'asset-by-asset'. Since pavements are prioritized based on their priority index, pavements with higher priority index that are in urgent need of repair are considered first. In this method, each pavement is evaluated over the planning horizon to find the violation time and the least-costly repair (Figure 4a). The process is similar to the one in Figure 3, except that when an asset is decided to be repaired in a certain year that has no remaining funds, then the asset will not be repaired and the process continues to the next one until all assets are evaluated.

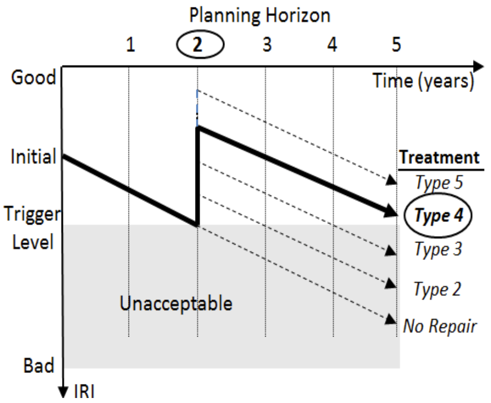
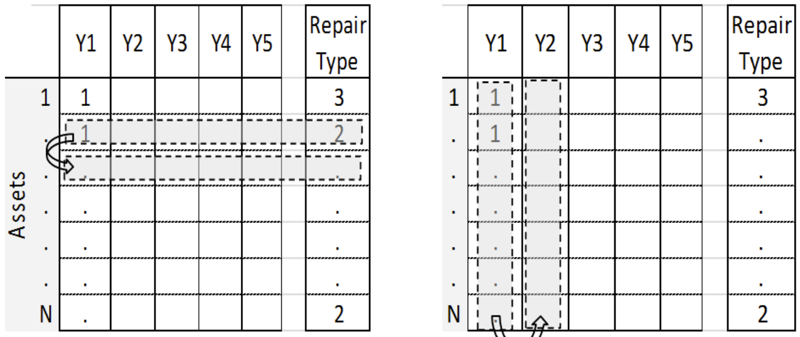


FIGURE 3 Repair type and timing under no budget constraint.



(a) Asset-by-asset (b) Year-by-year

FIGURE 4 Two fund-allocation heuristics under budget constraint.

Method 2: This heuristic method is a network-wise process that allocates available budgets 'year-by-year' (Figure 4b). In this method, each year is considered separately and the assets that violate the trigger level in that year are considered and then a least-costly treatment is decided for them one-by-one until the budget limit of that year is reached. The process starts from year 1 and moves to the next year, until the end of planning horizon.

Spreadsheet-based Implementation

In order to evaluate and compare the proposed fund allocation heuristics, they have been implemented within a spreadsheet-based PMS. An overview of the developed spreadsheet model is shown in Fig. 5 showing all the sheet portions that relate to the various asset management functions. As shown in Figure 5, each road is represented as a separate row and all the data related to each road are represented in columns. The model in Figure 5 is formulated considering a tactical asset management plan of five years. The two main decisions in the model are:

- The index to one of five repair types in column "Repair Type" for each road (integer variables); and

- The index to one of the five repair years "Year 1 to Year 5" for each road (binary variables).

These two decisions for each road are linked by equations to all the related functions of current performance assessment, deterioration, repair costs, and improvements after repair, and all the LCCA details. These functions are explained in the following.

Priority Indices: The proposed spreadsheet combines the IRI with the AADT for each road, into Priority Index "PI", based on Eq. (2). This index varies from 0 to 5. When the road's PI is zero, performance is high and the road has low repair priority. Also, when the road is in worst performance, it gets the highest priority for repair (PI = 5), Thus the priority is higher for roads with higher deterioration.

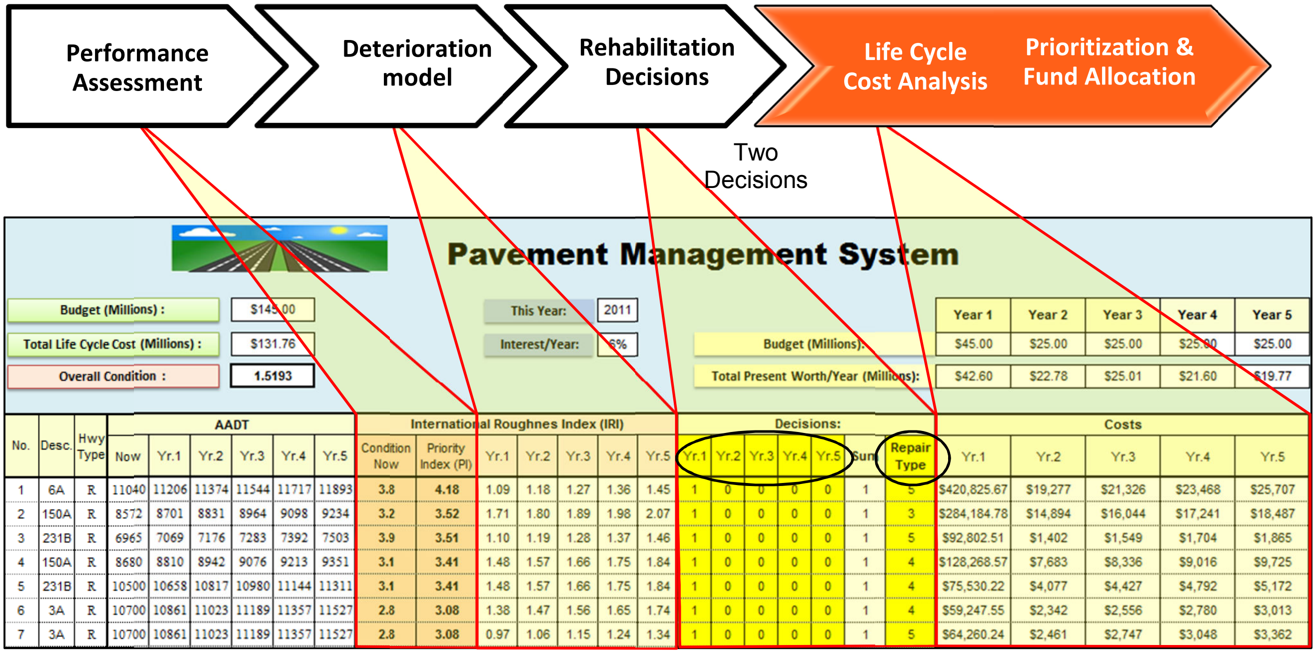
Deterioration Model: To enable life cycle analysis over a 5-year planning period, it is important to predict the future deterioration of the roads over the next five years. The future condition for each road has been evaluated based on the annual rate of IRI increased in Table 1 and the average annually daily traffic (AADT).

Decision Variables and Constraints: In the spreadsheet model, five treatments are available for each pavement (Table 2). These repair options are referenced using integer values from 1 to 5. Repair timing during the planning horizon is also referenced using binary variables (1 represents a repair action and 0 means no repair). Since the repair timing is only once within the planning horizon (i.e., a single visit), the sum of all the binary variables in all years must be either 0 (no repair), or 1.

Life Cycle Cost Calculation: In the spreadsheet, Life Cycle Cost over the five year plan is calculated yearly for each asset considering repair cost (according to the selected repair type) and the Vehicle Operating Costs (VOC). Accordingly, the present value of the total life cycle cost "TLCC" is calculated as follows:

$$\text{TLCC} = \text{Sum of } [(\text{Repair Costs} + \text{VOC})_n / (1+i)^n]$$

where, n is the year number and i is the applicable interest rate per year (user input).



Pavement Management System

Budget (Millions) : $145.00
Total Life Cycle Cost (Millions) : $131.76
Overall Condition : 1.5193

This Year: 2011
Interest/Year: 6%

	Year 1	Year 2	Year 3	Year 4	Year 5
Budget (Millions):	$45.00	$25.00	$25.00	$25.00	$25.00
Total Present Worth/Year (Millions):	$42.60	$22.78	$25.01	$21.60	$19.77

No.	Desc.	Hwy Type	AADT						International Roughnes Index (IRI)							Decisions:							Costs				
			Now	Yr.1	Yr.2	Yr.3	Yr.4	Yr.5	Condition Now	Priority Index (PI)	Yr.1	Yr.2	Yr.3	Yr.4	Yr.5	Yr.1	Yr.2	Yr.3	Yr.4	Yr.5	Sum	Repair Type	Yr.1	Yr.2	Yr.3	Yr.4	Yr.5
1	6A	R	11040	11206	11374	11544	11717	11893	3.8	4.18	1.09	1.18	1.27	1.36	1.45	1	0	0	0	0	1	5	$420,825.67	$19,277	$21,326	$23,468	$25,707
2	150A	R	8572	8701	8831	8964	9098	9234	3.2	3.52	1.71	1.80	1.89	1.98	2.07	1	0	0	0	0	1	3	$284,184.78	$14,894	$16,044	$17,241	$18,487
3	231B	R	6965	7069	7176	7283	7392	7503	3.9	3.51	1.10	1.19	1.28	1.37	1.46	1	0	0	0	0	1	5	$92,802.51	$1,402	$1,549	$1,704	$1,865
4	150A	R	8680	8810	8942	9076	9213	9351	3.1	3.41	1.48	1.57	1.66	1.75	1.84	1	0	0	0	0	1	4	$128,268.57	$7,683	$8,336	$9,016	$9,725
5	231B	R	10500	10658	10817	10980	11144	11311	3.1	3.41	1.48	1.57	1.66	1.75	1.84	1	0	0	0	0	1	4	$75,530.22	$4,077	$4,427	$4,792	$5,172
6	3A	R	10700	10861	11023	11189	11357	11527	2.8	3.08	1.38	1.47	1.56	1.65	1.74	1	0	0	0	0	1	4	$59,247.55	$2,342	$2,556	$2,780	$3,013
7	3A	R	10700	10861	11023	11189	11357	11527	2.8	3.08	0.97	1.06	1.15	1.24	1.34	1	0	0	0	0	1	5	$64,260.24	$2,461	$2,747	$3,048	$3,362

FIGURE 5 Pavement management spreadsheet.

4. EXPERIMENTATION

The proposed heuristic methods have been programmed using Excel's VBA programming language as macro programs. Before experimenting with fund allocation, the network had an overall condition of 2.473. Applying the first heuristic procedure to determine the necessary budget revealed that the total budget of $51.64 million is required for preserving the whole network above the acceptable level of service, which improves the overall condition from 2.473 to 1.82. More than 50% of this amount, however, is required to be spent in the first year since many assets have bad initial condition and require immediate intervention.

In a more realistic fund allocation situation, an asset manager is assumed to have a budget limit of $10 million in each year (add up to the same total amount needed but are equally distributed among the years). Considering this budget limit, the two proposed heuristic methods (asset-by-asset, and year-by-year) were used for allocating the limited funds. Upon applying the proposed methods, the funds were allocated successfully and the heuristic approach improved the overall IRI as shown in Table 4. Both procedures are equally efficient (i.e., not much far from the case of no budget redistribution), but have the great advantage of avoiding the need for uneven fund distribution among the years of the plan. In order to validate the proposed approach further, its results were compared to the results of optimization using genetic algorithms (GA). Using GA-based optimization, which is a more time-consuming and complex process, the optimization could not improves the results of the heuristic approach by more than 0.6%.

TABLE 4 Comparison of results

	No Budget Limit	Budget Limit	
		Asset by Asset	Year by Year
Total Life Cycle Cost (Millions)	51.64	49.3	49.2
Overall Condition (IRI)	1.8237	1.9184	1.9262
No. of assets violated	0	221	232

5. CONCLUDING REMARKS

A practical heuristic approach has been proposed for efficient fund allocation of infrastructure repair funds, which is a large-scale and complex optimization problem. Using a case study of a pavement network of more than 1200 pavements, the proposed method proved to be efficient and can be easily used by asset managers to allocate limited funds cost-effectively while maintaining the serviceability criteria. Some key advantages of the proposed heuristic method are as follows: Efficient and easy-to-use; Determines the needed budget level and selects the best treatments under a budget limit; Considers both network level and project level decisions; Applicable to different size pavement networks; and Applicable to other assets such as bridges, culverts, etc.

There are several future extensions that can improve the performance of the prioritization and fund allocation mechanism further. It is also possible to combine the proposed heuristic method with GA-based optimization by using the good speedy results of the heuristic method as initial values for the optimization process to improve the results further. Also, the proposed heuristic can be improved by enhancing the condition assessment and deterioration model of the PMS, in addition to considering a combination of pavement quality measures such as surface distress index, and pavement quality index.

6. REFERENCES

[1] Vanier, D.J., "Why Industry Needs Asset Management Tools", **NRCC Seminar Series, Innovations in Urban Infrastructure**, APWA International Public Works Congress, Denver, USA, Vol. 15, 1999, 11-25.

[2] **Transportation Association of Canada TAC**, Primer on Highway Asset Management Systems. Ottawa, March,1999.

[3] Federal Highway Administration FHWA, **Asset Management Primer**. A Report prepared by the U.S. Department of Transportation, 1999.

[4] Hudson, W.R., Haas, R., and Uddin, W., **Infrastructure management**, New York, USA: McGraw-Hill, 1997.

[5] Haas, R., Hudson, W.R., and Zaniewski, J.P., **Modern Pavement Management**, Krieger Publishing Company, Malabar, Fla, 1994.

[6] Grussing, M. N., Uzarski, D. R., & Marrano, L. I., "Optimizing facility component maintenance, repair, and restoration investment strategies using financial ROI metrics and consequence analysis", Applications of Advanced Technology in Transportation - Proceedings of the **Ninth International Conference on Applications of Advanced Technology in Transportation**, Chicago, IL, 2006, 81-86.

[7] Karydas, D. M., & Gifun, J. F., "A method for the efficient prioritization of infrastructure renewal projects", **Reliability Engineering and System Safety**, Vol. 91, 2006, 84-99.

[8] Fukuhara, T., Terada, K., Nagao, M., Kasahara, A., and Ichihashi, S., "Automatic Pavement-Distress-Survey System", **Journal of Transportation Engineering**, ASCE, May/June, 1990. Vol. 116, 1990, 280-286.

[9] Yang, J., Lu, J. J., Gunaratne, M., and Xiang. Q., "Overall pavement condition forecasting using neural networks – An application to Florida highway network", Proceedings of the **82nd Transportation Research Board Annual Meeting** (CD-ROM), Washington, D.C. Issue 1853, 2003, 3-12.

[10] Butt, A.A., Shahin, M.Y., Feighan, K.J., and Carpenter, S.H., "Pavement Performance Prediction Model Using the Markov Process", Transportation Research Record: **Journal of the Transportation Research Board**, No. 1123, TRB, Washington, D.C., 1987, 12-19.

[11] Csiszár, S., "Optimization algorithms (survey and analysis)", LINDI 2007 - **International Symposium on Logistics and Industrial Informatics,** 2007, 185-188.