Application of Replacement Theory in Determination of Pavement Design Life

S. K. Bagui [1], A. K. Chakraborti [2] and S. M. Bhadra [2]

[1] Ph.D. Student, Dept. of Civil Eng., Bengal Eng. and Science University, Shibpur, India
[2] Associates with Emergency Flood Protection and Reconstruction Project, Mukalla

ABSTRACT

This paper presents a methodology to determine the economic life of pavement based replacement theory/decision. The replacement theory is generally used for the determination of the replacement period of machines, bulbs, vehicles, equipment, buildings, T.V. parts… etc. This theory has been used to determine the economic life pavement for a road project and a bridge project with a real case study. The economic life has been found out. The economic life of flexible pavement has been found to be 15 years for national highways. This theory can be also applied to determine the economic life of new developed items/useful materials for highway projects.

KEYWORDS: Replacement theory, Operation research, Bridge replacement, Pavement replacement, Discount rate.

INTRODUCTION

Machine replacement problem has been studied by many researchers and is also an important topic in operation research and management science (Nahmias, 1997).Renewal theory is a useful tool in modeling many systems. The quantity-based replacement policy and time-based replacement policy for a single machine problem are reported. These two kinds of policies have been applied to inventory management problems. In a quantity-based replacement policy, a machine is replaced when an accumulated product of size q is produced. In this model, one has to determine the optimal production size q. While in a time-based replacement policy, a machine is replaced in every period of T. For this model, one has to determine the optimal replacement period T in each production cycle. The time-based policy is more preferable than the quantity-based dispatch policy for satisfying timely customer service. Especially, time-based shipment consolidations have become apart of the transportation contract among the members of a supply chain. Two analytic models were compared according to their average long-run performance. Average long-run costs for both models have been developed by using renewal theory. The costs here include both the cost of a new machine and the machine maintenance cost.

Replacement theory is generally concerned with the problem of replacement of machines, bulbs and men due to deteriorating efficiency, failure or break down. Replacement is usually carried out under the following situations:

- When existing items have outlived their effective lives and it may not be economical to continue with them anymore.
- When the items might have been destroyed either by accidents or otherwise.

Accepted for Publication on 14/11/2011.

The above replacement situations may be categorized into the following four categories.

- Replacement of items that deteriorated with time.
- Replacement of items which did not deteriorate but failed completely after certain use.
- Replacement of an equipment that became out of date due to new development.
- Gradual diminishing of the existing working staff in an organization due to retirement, death… etc.

LITERATURE REVIEW

The Texas Department of Transportation (DOT) owns and maintains an active fleet inventory of approximately 17000 units and replaces about 10% of them annually. Any methodology that can improve Texas DOT's replacement procedures could potentially save millions of dollars. Private and public agencies do not routinely use life-cycle cost as a replacement criterion, because the only way to automate the inspection of thousands of life-cycle cost histories has been to define an acceptability threshold for annualized costs. Most fleet managers consider this practice too inaccurate. The most relevant information provided by a lifecycle cost graph is its trend. Units whose life-cycle costs have been increasing longer or at a faster rate should have higher replacement priority. The trend score concept allows a computer to mimic replacement decisions made by a person visually inspecting a series of life-cycle cost histories. A new economically sound methodology for assisting with equipment replacement at Texas DOT is presented. This new method takes full advantage of Texas DOT's comprehensive equipment operating system database, can prioritize the units on the basis of comparisons among all units within any desired class of equipment and uses life-cycle cost trends as a replacement criterion. This methodology was implemented through the Texas Equipment Replacement Model; a menu driven software that allows the fleet manager to efficiently apply the methodology (Weismann et al., 2006).

A comprehensive dynamic programming (DP) based optimization solution methodology is then proposed and implemented to solve the ERO problem. The developed ERO software consists of three main components: 1) A SAS Macro-based Data Cleaner and Analyzer, which undertakes the tasks of raw data reading, cleaning and analyzing, as well as cost estimation and forecasting; 2) A DP-based optimization engine that minimizes the total cost over a defined horizon; and 3) A Java based Graphical User Interface (GUI) that takes parameters selected by and inputs from users and coordinates the Optimization Engine and SAS Macro Data Cleaner and Analyzer. The first component (i.e., the SAS macro-based Data Cleaner and Analyzer) is presented in detail. Preliminary numerical results of the SAS data analysis, estimation and forecasting of several costs are also discussed. Then, in a following paper, the DP-based optimization engine and ERO software development (including the Java GUI) are presented in detail (Fan et al., 2011).

TxDOT uses the Texas Equipment Replacement Model (TERM, 2004) to identify equipment items as candidates for equipment replacement one year in advance of need (This one year allows sufficient time for the procurement and delivery of a new unit). TxDOT's Equipment Operations System (EOS), in operation since 1984, captures extensive information on all aspects of equipment operation. This system is used to provide historical data in a computerized approach. EOS historical cost data is processed against three preset standards/benchmarks for each identified equipment class. The criteria used for replacement in the approach are: 1) Equipment age, 2) Life usage expressed in miles (or hours), and 3) Life repair costs (adjusted for inflation) relative to original purchase cost (including net adjustment to capital value).

In other words, TERM uses threshold values for age, use of an equipment unit and repair cost as inputs for replacement. For example, current threshold values for dump trucks with tandem rear axles (referred to as class code 540020 within TxDOT) for age, use and repair cost are 12 years, (150000) miles and 100%, respectively. As a result, a dump truck with tandem rear axles, 43000+ lb. GVWR, State Series 990d, that is 12 years old, has accumulated 150000 miles of usage and whose life repair costs have exceeded one hundred percent of the original purchase cost, including net adjustments to capital value, meets all three criteria (TERM, 2004).

Starting in 1997, UTSA created a SAS decision analysis tool to be used by the TxDOT in its equipment replacement process. The equipment replacement approach developed includes a multi-attribute priority ranking combined with a life-cycle cost trend analysis. It allows the manager to select the attributes used to compare the challenged unit with all other active units within a desired class or group, the life-cycle costs and multi-attribute ranking methodologies for equipment replacement. Weismann et al. (2003) summarized the computerized equipment replacement methodology in a paper as a condensed version of these three research reports.

While the UTSA-TERM analysis tool met project scope within the data limitations existing at the time of its delivery, an improved vehicle cost data base has been developed and will now allow a more normative decision support tool for fleet replacement optimization. It is known that there are several issues with the current UTSA-TERM model. First, it looks at individual pieces of equipment and does not track unit costs for use and replacement. Second, it is still very labor intensive, heavily depends on the fleet managers' experience and is not automated since it is based on units - 1 piece of equipment at a time, replaces equipment based on classes of equipment. TxDOT needs a new, more robust fleet optimization system that must use these class codes rather than individual pieces of equipment, can automate the process and optimize the equipment keep/replacement decision based on that class of equipment age, mileage, resale value and the cost of replacement equipment.

The future TxDOT TERM developed as a result of our work will be an advanced and fully automated equipment replacement optimization system that incorporates robust mathematical optimization models and reliable statistical cost estimation and forecasting models. With a click of the mouse button, the "one-stop shopping" seamless software system can/will automatically recommend robust optimization solutions based on the built-in cost statistical analysis. To accomplish this task, Java is carefully chosen as the programming language and DP as the designed optimization solution approach.

A significant number of software programs currently exist to assist in fleet management .One of the major fleet management software manufacturers is Asset Works. Their programs and services are offered to a number of state DOTs and other public organizations. DOT users of Asset Works' software include Arizona, Minnesota, California (Caltrans), Delaware, Georgia, Maine, Michigan, Nevada, New Hampshire, New Jersey, New York, Virginia and Washington (http://www.assetworks.com/ page/ state-government, 2009).

Many firms provide consultant services to fleet managers. For some firms, Mercury Associates in particular, consulting services are their primary operations. For other firms, consulting on fleet management is merely a part of an overall fleet management business model. These types of firms also work with a variety of clients on fuel management, vehicle leasing, driver management and other services.

Mercury Associates, a Washington D.C. fleet management firm, has experience with fleets of vastly different sizes, ranging from 25 to more than 650000 vehicles. Their clients include private companies such as Laidlaw and General Motors, the US federal government and a wide variety of state and local governmental agencies; clients have also owned a diverse set of fleets, from fire trucks, buses, trucks, bulldozers and many more. Mercury has worked with 28 of the 50 U.S. states (more than any other fleet management consulting firm), 33 of the 50 largest US cities and 30 colleges and universities. Mercury also provides an outsourcing feasibility study to any agency considering contracting with the company to handle some or all of the fleet management services. Mercury has worked with many state departments of transportation. Specific instances include the Delaware Department of Transportation contracting with Mercury in 2004 to perform a comprehensive fit-gap analysis of its existing information. The Delaware DOT then used this information to enhance its system of support for fleet operations .New México’s DOT, which manages about 6000 vehicles, has also contracted with Mercury for both consulting services and training in fleet management best practices. Other fleet management consultants also include Automotive Resources International (http://www2.arifleet.com/ strategicconsulting.htm, 2009) and Donlen Corporation (http://www. donlen.com/pdf/ Donlen_Product_SC_brochure. pdf, 2009).

The renewal theory can be applied in modeling the machine replacement problem. We begin with a deterministic model to illustrate the concept of a machine cycle, and then follow by a stochastic model with a general cost. We then compare two popular replacement policies: the quantity-based replacement policy and the time-based replacement policy for a single machine replacement problem. We also prove an interesting result that the optimal costs of both policies are the same under certain assumptions (Allen and Ching, 2005).

The Tancarville bridge across the Seine was the subject of numerous design efforts during the first part of the 20th century. In 1953, the final design of a suspension structure was selected by the French authorities. Construction began in 1954 and was completed in 1959. This marked the opening of the longest suspended span in Europe for that time. Indications of rapid corrosion in the suspension cables were observed as early as 1965, and by 1970 design work was under way for possible cable replacement. This development influenced the decision to build the Normandie Bridgeas a second river crossing. The matter became urgent in 1995 when as trand of one Tancarville cable broke because of advanced corrosion. Beginning with a historical review, this paper explains why the cables of the Tancarville bridge had to suffer from corrosion under tension. It shows how the owner organized the concurrent pursuit of many goals, guaranteeing structural safety, maintaining traffic and calling for bids while developing a design to replace the entire suspension system at the earliest possible time (Virlogeux, 2003).

Life-cycle assessment (LCA) is a tool that can be used to identify the environmental impact of a product or process. This paper compares three replacement options for an aging Portland cement concrete (PCC) pavement with the use of an LCA process-based protocol. The options are to remove and replace the aging pavement with PCC pavement; remove the aging pavement and replace it with hot-mix asphalt (HMA) pavement; and crack and seat the existing pavement and then place an HMA overlay. Each option investigated includes a detailed construction and rehabilitation schedule and is analyzed over 50 years. The results show that materials production (e.g., cement, asphalt, PCC and HMA) dominates the energy use, emissions and impacts for all three options. In general, HMA production tends to cause the HMAoption to have the highest energy use, whereas cement production tends to cause the PCC option to have the highest global warming potential(GWP). The crack, seat and overlay option was the lowest energy user, had the lowest GWP and produced the least emissions in morecategories measured than the other two options. This may become a strong argument for expansion of the crack, seat and overlay method of rehabilitation (Craig and Stephen, 2010).

Bridge managers have a duty to monitor and update the costs of bridge preservation activities and to implement cost-effective actions that are in the best interest of taxpayers. This paper presents details of replacement cost modeling for each bridge component (superstructure, substructure, approach and other costs) for bridges with concrete slab, concrete beam or steel superstructures. This was done with recent bridge construction data on the Indiana state highway network. It was determined that costs other than substructure and superstructure costs accounted for more than one-half of total replacement cost. The present study supports earlier studies by asserting that basic bridge characteristics such as type, length and deck area may generally be used to derive reliable estimates of bridge replacement costs. The study also shows that economies of scale can play a significant role in reliable bridge cost estimation. It was determined that the average overall unit cost of replacement for steel superstructure bridges was generally lower than that for concrete superstructure bridges. It was seen that differences in replacement costs across bridge types are attributable not necessarily to cost differences in material and construction procedures only but also to economy-of-scale effects. Cost models can be used to predict total costs of future bridge replacements and are therefore useful for vital bridge management functions such as needs' assessment, budgeting and programming (Rodriguez et al., 2006).

SCOPE OF WORK

It has been found that previous research works were carried out about the replacement theory of machine equipment and few research works were conducted on bridge and pavement replacement methodology. In road construction, generally rehabilitation is carried out every 5 to 10 years after verifying the existing strength of road. It is sometimes found that repair cost is high. In this case, it will be better to replace/reconstruct, removing existing asphalt/base course depending on pavement condition.

Based on past studies, it is felt that the replacement theory can be applied for the reconstruction/replacement of pavement and bridge. Two real case studies are considered.

OPERATION RESEARCH (OR) METHODOLOGY OF SOLVING REPLACEMENT PROBLEMS

OR provides a methodology for solving replacement problems. The steps adopted for solving such replacement problems in OR have been discussed as shown below (Kapoor, 1999).

Identify the items to be replaced and also their failure mechanism. There are two types of failure; i.e., gradual failure and sudden failure. Items such as machines, equipment… etc. follow the gradual failure mechanism and they deteriorate with time. Such type of failure accounts for increased expenditure in the form of operating costs, decrease of productivity of the equipment and decrease in the values of the equipment; i.e., salvage value.

The items which follow the sudden failure mechanism may fail any time, thus precipitating the cost of failure. The cost of failure of an item may be quite high as compared to the value of the item itself. Sudden failure may cause loss of production and may also cause faulty product. This type of failure may cause safety risk to workers/road users. The item should be replaced before it actually fails.

Recently, several old bridges collapsed in 2011 in India. A minimum of 300 people died. The replacement theory may have reduced death accidents.

Collect the data relating to the depreciation cost and maintenance cost over a time period from the available source for the items which follow gradual failure mechanism. In the case of the items following sudden failure mechanism, collect the data for failure rates cost of replacement for failing items and cost of preventive replacement.

REPLACEMENT THEORY

Using the above data, a suitable OR model has been developed for the determination of exact time of replacing the item.

There are two methods to determine time of replacement. These are:

- Replacement of item without discount rate (without considering the value of money with time).
- Replacement of item with discount rate (considering the value of money with time).

Replacement without Discount Rate

The optimum replacement of the equipment will be calculated according to the following methods.

1. If the scrap value of the equipment is zero; i.e., the depreciation cost is not given, then replace the equipment when maintenance cost becomes greater than the current average cost.
2. If we are given the resale value or depreciation cost, the maintenance cost and the cost of equipment,then optimum replacement period is determined by the minimum value of average cost to date.

Let us consider a simple case which consists of minimizing the average annual cost of equipment whose maintenance cost is a function increasing with time and whose scrap value is constant. As the time value of the money is not to be considered, the interest rate is zero and the calculation can be based on average annual cost.

Let

C = capital cost of a certain item.

S(t)=scrap value of the item after t years of operation.

F(t)=maintenance cost at time t.

N=replacement year.

Total maintenance cost incurred on the machine during N year is:

$$\int_0^N F(t)dt = \sum_0^N F(t)$$

Average annual cost, TA is given by:

$$TA = \frac{1}{N}[C - S(t) + \int_0^N F(t)dt]$$

To determine the optimum replacement time period, the above function is differentiated with respect to N and equated to zero.

Finally, it is found that:

$$F(N) = \frac{C - S(t)}{N} + \frac{1}{N}\int_0^N F(t)dt = TA\,.$$

It can be easily shown that this solution, TA=F(N) is minimum for T, provided that F(t) is not decreasing and F(t)=0. Hence,an item should be replaced when the average cost to date is equal to the current maintenance cost.

Replacement with Discount Rate

For finding the replacement period of any item, we first of all tabulate the net cash flow of the item and convert these costs to their present value by discounting at the relevant rate. Discounted cost has been used to establish the present value. Weighted average cost of each successive time interval is calculated by dividing the total cost by the cumulative value of the discount factor.

Suppose that the item is available for use over a series of time periods of equal intervals.

Let

C = Initial cost.

R_i = maintenance cost in the i th year.

r = discount rate.

V = 1/(1+r).

Let the item be replaced at the end of every n th year.

The year-wise present worth of the expenditure on the item in the successive cycles of N years can be calculated as follows:

Year	1	2---------N		N+1	N+2-------2N		2N+1
Present Worth	$C+R_1$	R_2V	R_NV^{N-1}	$(C+R1)V^N$	R_2V^{N+1}	R_NV^{2N-11}	$(C+R1)V^{2N}$

Assuming that the item has no resale value at the end of the replacement period, the present worth of all future discounted cost associated with the policy of replacing the item at the end of every N years will be given by: P(N)=

$(C+R1+R2V+---RNV^{N-1})(1+V^N+V^{2N}+V^{3N}+V^{4N}\dots)$

$=(C+R1+R2V+----RNV^{N-1})[1/(1-V^N)]$

P(N) is the amount of money required now to pay for all future costs of acquiring and operating the equipment when it is renewed every N years.

If P(N) is less than P(N+1), then replacing the equipment each N years is preferable to replacing it each N+1 years.

Further, if the best policy is the replacement every N years, then two inequalities

P(N+1)-P(N)>0 and P(N-1)-P(N)<0 must hold, without giving proof.

As a result of these two inequalities, rules for minimizing costs may be stated as follows:

- Do not replace if the operating cost of the next periods is less than the weighted average cost of the previous years.
- Replace if the operating cost of the next periods is greater than the weighted average cost of the previous years.

Working Steps

- Write in a column the maintenance costs of the equipment.
- Write the discount factor in the next column.
- These two columns are multiplied to get the present value.
- Calculate the cumulative maintenance cost in the fourth column.
- Calculate the cumulative discounted factor in the fifth column.
- Total cost= C+ $\sum R_N V^{N-1}$.
- Divide the total cost by the cumulative discount factor.
- Compare the maintenance cost with the last column and find out the replacement year.

Depreciation

Straight Line Method

Depreciation is a noncash expense. It only reduces taxable income and provides an annual tax advantage equal to the product of depreciation and the (marginal) tax rate, but it does not lead to a cash outflow from the company. The most common method for depreciation is the straight-line depreciation. Under this method, the annual depreciation equals a constant proportion of the initial investment. In this model, it is assumed that TPC can be depreciable in its entirety. Thus,

$$DEPi = \frac{TPC}{m}; \qquad (1)$$

where m is the operation period and DEP_i is the depreciation for each year.

Written Down Value Method

Under this method, the depreciation is calculated in accordance with the following equations:

$$DEP_1 = BV_0 r_0$$

$$DEP_2 = BV_0 r_0 (1 - r_0)$$

$$DEP_i = BV_0 (1 - r_0)^{(i-1)} r_0 \qquad (2)$$

where

DEP = depreciation charge;

BV= TPC; and

r_0 = depreciation.

EFFECT OF CLIMATE ON PAVEMENT LIFE

The effects that climate will have on pavement must be considered as part of pavement engineering. Temperatures will cause pavements to expand and contract creating pressures that can cause pavements to buckle or crack. Binders in flexible pavements will also become softer at higher temperatures and more brittle at lower temperatures. Precipitation can increase the potential for water to infiltrate the base and sub-base layers, thereby resulting in increased susceptibility to erosion and weakening of the pavement structural strength. In freeze/thaw environments, the expansion and contraction of water as it goes through freeze and thaw cycles, plus the use of salts, sands, chains and snow plows, create additional stresses on pavements. Solar radiation can also cause some pavements to oxidize.

Climate also has a strong influence on the pavement performance and may be accounted for in the design to some extent. This is particularly true for the Middle East, Africa and North America, as well as other places where a wide range of climatic zones is encountered, from desert to cold climate.

The average annual air temperature is considered in design, and the bitumen grade is fixed based on the average annual air temperature, as well as minimum and maximum pavement temperatures. In cold climate, frost depth penetration is considered and additional sub-grade thickness is provided to reduce frost effect. Pavement life varies from hot climate to cold climate. Pavement life can be increased by providing functional and structural overlay in time before major distresses occur in pavement in the form of cracks, potholes, patches… etc. In general, initially flexible pavement is designed for 10 years and major rehabilitation is recommended at the end of 10^{th} year. It also varies among countries and places of the same country. An example is mentioned in Table 1.

Table 1. Pavement life

Country/Agency	Design of New Flexible Pavement (Year)	Rehabilitation of Flexible Pavement (Year)
British Columbia	20	-
Alberta	20	20
Ontario	20	20
Saskatchewan	15	15
India National Highway Major District Road/Other District Roads	 20 20	 10 10
Ethiopia	15	10
Yemen	15	10

CASE STUDY

Replacement of pavement is an important criterion. Pavement should be replaced after a certain number of years of use which can be termed as economic life. This section represents the use of replacement theory pavement design. Economic life of flexible pavement has been determined using this theory.The same methodology as discussed above is used, and the discounted method has been adopted, since this method takes care of time value money. Following steps are used to determine the replacement period of pavement:

- Determine the initial cost of pavement.
- Determine the annual maintenance cost.
- Determine the periodic maintenance cost and the year in which it is to be provided.
- Determine the structural maintenance cost and the year in which it is to be provided.

Two case studies have been conducted. Traffic study has been carried out in December 1999 on a selected section of existing two lanes of NH 2 and growth factors for vehicle-modewise have been established. The growth rate has been determined based on the following methods:

- Past Trend Analysis.
- Net State Domestic Product and *Per Capita* Income.
- Previous Study.

Considering all the above-mentioned methods, suitable growth factors are established for projected traffic. Opening year traffic (Tollable) is shown in Table 2.

Table 2. Base traffic

Vehicle Type	Number of Vehicles
Car	2480
Bus	1128
Light Commercial Vehicle	790
2-Axle Vehicle	1150
3-Axle Vehicle	576
Multi-Axle Vehicle	2160

Table 3. Determination of replacement year for flexible pavement

Year	Flexible Pavement	Maintenance Cost (Rs Million)	Cost after Depreciation/ Resale Value (Rs Million)	Discount Factor	Cum. Discount Factor	Discounted Maintenance Cost (Rs Million)	Discounted Total Cost (Rs Million)	Weighted Average Cost (Rs Million)	Remark
	Initial cost	50.000	50.000						
1	Maintenance cost	0.300	48.333	1.000	1.000	0.300	50.300	50.300	TRUE
2	Maintenance cost	0.318	46.667	0.893	1.893	0.284	50.584	26.724	TRUE
3	Maintenance cost	0.337	45.000	0.797	2.690	0.269	50.853	18.904	TRUE
4	Maintenance cost	0.357	43.333	0.712	3.402	0.254	51.107	15.023	TRUE
5	Maintenance cost	3.838	41.667	0.636	4.037	2.439	53.546	13.263	TRUE
6	Maintenance cost	0.401	40.000	0.567	4.605	0.228	53.774	11.678	TRUE
7	Maintenance cost	0.426	38.333	0.507	5.111	0.216	53.989	10.563	TRUE
8	Maintenance cost	0.451	36.667	0.452	5.564	0.204	54.193	9.740	TRUE
9	Maintenance cost	0.478	35.000	0.404	5.968	0.193	54.387	9.114	TRUE
10	Maintenance cost	5.987	33.333	0.361	6.328	2.159	56.546	8.935	TRUE
11	Maintenance cost	0.537	31.667	0.322	6.650	0.173	56.719	8.529	TRUE
12	Maintenance cost	0.569	30.000	0.287	6.938	0.164	56.882	8.199	TRUE
13	Maintenance cost	0.604	28.333	0.257	7.194	0.155	57.037	7.928	TRUE
14	Maintenance cost	0.640	26.667	0.229	7.424	0.147	57.184	7.703	TRUE
15	Maintenance cost	6.158	25.000	0.205	7.628	1.260	58.444	7.662	TRUE
16	Maintenance cost	0.719	23.333	0.183	7.811	0.131	58.575	7.499	TRUE
17	Maintenance cost	0.762	21.667	0.163	7.974	0.124	58.700	7.361	TRUE
18	Maintenance cost	0.808	20.000	0.146	8.120	0.118	58.817	7.244	TRUE
19	Maintenance cost	0.856	18.333	0.130	8.250	0.111	58.929	***7.143***	TRUE
20	Maintenance cost	6.388	16.667	0.116	8.366	0.742	59.670	7.133	TRUE
21	Maintenance cost	0.962	15.000	0.104	8.469	0.100	59.770	7.057	TRUE
22	Maintenance cost	1.020	13.333	0.093	8.562	0.094	59.864	6.992	TRUE
23	Maintenance cost	1.081	11.667	0.083	8.645	0.089	59.954	6.935	TRUE
24	Maintenance cost	1.146	10.000	0.074	8.718	0.085	60.038	6.886	TRUE
25	Maintenance cost	3.955	8.333	0.066	8.784	0.261	60.299	6.864	TRUE
26	Maintenance cost	1.288	6.667	0.059	8.843	0.076	60.375	6.827	TRUE
27	Maintenance cost	1.365	5.000	0.053	8.896	0.072	60.446	6.795	TRUE
28	Maintenance cost	1.447	3.333	0.047	8.943	0.068	60.514	6.767	TRUE
29	Maintenance cost	1.534	1.667	0.042	8.984	0.064	60.578	6.743	FALSE
30	Maintenance cost	12.586	0.000	0.037	9.022	0.470	61.049	6.767	TRUE

Table 4. Sensitivity analysis for replacement year for flexible pavement (Increasing cost by 15%)

Year	Flexible Pavement	Maintenance Cost (Rs Million)	Cost after Depreciation/ Resale Value (Rs Million)	Discount Factor	Cum. Discount Factor	Discounted Maintenance Cost (Rs Million)	Discounted Total Cost (Rs Million)	Weighted Average Cost (Rs Million)	Remark
0	Initial cost	57.500	57.500						
1	Maintenance cost	0.345	55.583	1.000	1.000	0.345	57.845	57.845	TRUE
2	Maintenance cost	0.366	53.667	0.893	1.893	0.327	58.172	30.732	TRUE
3	Maintenance cost	0.388	51.750	0.797	2.690	0.309	58.481	21.740	TRUE
4	Maintenance cost	0.411	49.833	0.712	3.402	0.292	58.773	17.277	TRUE
5	Maintenance cost	3.587	47.917	0.636	4.037	2.279	61.052	15.122	TRUE
6	Maintenance cost	0.462	46.000	0.567	4.605	0.262	61.314	13.315	TRUE
7	Maintenance cost	0.489	44.083	0.507	5.111	0.248	61.562	12.044	TRUE
8	Maintenance cost	0.519	42.167	0.452	5.564	0.235	61.797	11.107	TRUE
9	Maintenance cost	0.550	40.250	0.404	5.968	0.222	62.019	10.393	TRUE
10	Maintenance cost	6.885	38.333	0.361	6.328	2.483	64.502	10.193	TRUE
11	Maintenance cost	0.618	36.417	0.322	6.650	0.199	64.701	9.729	TRUE
12	Maintenance cost	0.655	34.500	0.287	6.938	0.188	64.889	9.353	TRUE
13	Maintenance cost	0.694	32.583	0.257	7.194	0.178	65.067	9.044	TRUE
14	Maintenance cost	0.736	30.667	0.229	7.424	0.169	65.236	8.788	TRUE
15	Maintenance cost	3.931	28.750	0.205	7.628	0.804	66.040	8.657	TRUE
16	Maintenance cost	0.827	26.833	0.183	7.811	0.151	66.191	8.474	TRUE
17	Maintenance cost	0.876	24.917	0.163	7.974	0.143	66.334	8.319	TRUE
18	Maintenance cost	0.929	23.000	0.146	8.120	0.135	66.469	8.186	TRUE
19	Maintenance cost	0.985	21.083	0.130	8.250	0.128	66.598	***8.073***	TRUE
20	Maintenance cost	7.346	19.167	0.116	8.366	0.853	67.450	8.063	TRUE
21	Maintenance cost	1.106	17.250	0.104	8.469	0.115	67.565	7.978	TRUE
22	Maintenance cost	1.173	15.333	0.093	8.562	0.109	67.674	7.904	TRUE
23	Maintenance cost	1.243	13.417	0.083	8.645	0.103	67.776	7.840	TRUE
24	Maintenance cost	1.318	11.500	0.074	8.718	0.097	67.874	7.785	TRUE
25	Maintenance cost	4.548	9.583	0.066	8.784	0.300	68.173	7.761	TRUE
26	Maintenance cost	1.481	7.667	0.059	8.843	0.087	68.260	7.719	TRUE
27	Maintenance cost	1.570	5.750	0.053	8.896	0.082	68.343	7.683	TRUE
28	Maintenance cost	1.664	3.833	0.047	8.943	0.078	68.421	7.651	TRUE
29	Maintenance cost	1.764	1.917	0.042	8.984	0.074	68.495	7.624	FALSE
30	Maintenance cost	8.171	0.000	0.037	9.022	0.305	68.800	7.626	TRUE

Table 5. Sensitivity analysis for replacement year for flexible pavement (Decreasing Cost by 15 %)

Year	Flexible Pavement	Maintenance Cost (Rs Million)	Cost after Depreciation/ Resale Value (Rs Million)	Discount Factor	Cum. Discount Factor	Discounted Maintenance Cost (Rs Million)	Discounted Total Cost(Rs Million)	Weighted Average Cost (Rs Million)	Remark
0	Initial cost	42.500	42.500						
1	Maintenance cost	0.255	41.083	1.000	1.000	0.255	42.755	42.755	TRUE
2	Maintenance cost	0.270	39.667	0.893	1.893	0.241	42.996	22.715	TRUE
3	Maintenance cost	0.287	38.250	0.797	2.690	0.228	43.225	16.068	TRUE
4	Maintenance cost	0.304	36.833	0.712	3.402	0.216	43.441	12.770	TRUE
5	Maintenance cost	2.651	35.417	0.636	4.037	1.685	45.126	11.177	TRUE
6	Maintenance cost	0.341	34.000	0.567	4.605	0.194	45.319	9.842	TRUE
7	Maintenance cost	0.362	32.583	0.507	5.111	0.183	45.503	8.902	TRUE
8	Maintenance cost	0.383	31.167	0.452	5.564	0.173	45.676	8.210	TRUE
9	Maintenance cost	0.406	29.750	0.404	5.968	0.164	45.840	7.681	TRUE
10	Maintenance cost	5.089	28.333	0.361	6.328	1.835	47.675	7.534	TRUE
11	Maintenance cost	0.457	26.917	0.322	6.650	0.147	47.822	7.191	TRUE
12	Maintenance cost	0.484	25.500	0.287	6.938	0.139	47.961	6.913	TRUE
13	Maintenance cost	0.513	24.083	0.257	7.194	0.132	48.093	6.685	TRUE
14	Maintenance cost	0.544	22.667	0.229	7.424	0.125	48.218	6.495	TRUE
15	Maintenance cost	2.906	21.250	0.205	7.628	0.595	48.812	6.399	TRUE
16	Maintenance cost	0.611	19.833	0.183	7.811	0.112	48.924	6.264	TRUE
17	Maintenance cost	0.648	18.417	0.163	7.974	0.106	49.030	6.149	TRUE
18	Maintenance cost	0.687	17.000	0.146	8.120	0.100	49.130	6.051	TRUE
19	Maintenance cost	0.728	15.583	0.130	8.250	0.095	49.224	***5.967***	TRUE
20	Maintenance cost	5.430	14.167	0.116	8.366	0.630	49.855	5.959	TRUE
21	Maintenance cost	0.818	12.750	0.104	8.469	0.085	49.939	5.896	TRUE
22	Maintenance cost	0.867	11.333	0.093	8.562	0.080	50.020	5.842	TRUE
23	Maintenance cost	0.919	9.917	0.083	8.645	0.076	50.096	5.795	TRUE
24	Maintenance cost	0.974	8.500	0.074	8.718	0.072	50.167	5.754	TRUE
25	Maintenance cost	3.361	7.083	0.066	8.784	0.221	50.389	5.736	TRUE
26	Maintenance cost	1.094	5.667	0.059	8.843	0.064	50.453	5.705	TRUE
27	Maintenance cost	1.160	4.250	0.053	8.896	0.061	50.514	5.679	TRUE
28	Maintenance cost	1.230	2.833	0.047	8.943	0.058	50.572	5.655	TRUE
29	Maintenance cost	1.303	1.417	0.042	8.984	0.055	50.626	5.635	FALSE
30	Maintenance cost	10.698	0.000	0.037	9.022	0.400	51.026	5.656	TRUE

Table 6. Bridge project (case study)

Year	Bridge Cost	Maintenance Cost (Rs Million)	Resale Value (Rs Million)	Discount Factor	Cum. Discount Factor	Discounted Maintenance Cost (Rs Million)	Discounted Total Cost (Rs Million)	Weighted Average Cost (Rs Million)	No Replacement
0	Initial cost	15.000	15.000						
1	Maintenance cost	0.075	14.700	1.000	1.000	0.075	15.075	15.075	TRUE
2	Maintenance cost	0.080	14.400	0.893	1.893	0.071	15.146	8.002	TRUE
3	Maintenance cost	0.084	14.100	0.797	2.690	0.067	15.213	5.655	TRUE
4	Maintenance cost	0.089	13.800	0.712	3.402	0.064	15.277	4.491	TRUE
5	Maintenance cost	0.395	13.500	0.636	4.037	0.251	15.528	3.846	TRUE
6	Maintenance cost	0.100	13.200	0.567	4.605	0.057	15.585	3.384	TRUE
7	Maintenance cost	0.106	12.900	0.507	5.111	0.054	15.638	3.060	TRUE
8	Maintenance cost	0.113	12.600	0.452	5.564	0.051	15.689	2.820	TRUE
9	Maintenance cost	0.120	12.300	0.404	5.968	0.048	15.738	2.637	TRUE
10	Maintenance cost	0.877	12.000	0.361	6.328	0.316	16.054	2.537	TRUE
11	Maintenance cost	0.134	11.700	0.322	6.650	0.043	16.097	2.421	TRUE
12	Maintenance cost	0.142	11.400	0.287	6.938	0.041	16.138	2.326	TRUE
13	Maintenance cost	0.151	11.100	0.257	7.194	0.039	16.177	2.249	TRUE
14	Maintenance cost	0.160	10.800	0.229	7.424	0.037	16.213	2.184	TRUE
15	Maintenance cost	0.470	10.500	0.205	7.628	0.096	16.310	2.138	TRUE
16	Maintenance cost	0.180	10.200	0.183	7.811	0.033	16.342	2.092	TRUE
17	Maintenance cost	0.191	9.900	0.163	7.974	0.031	16.373	2.053	TRUE
18	Maintenance cost	0.202	9.600	0.146	8.120	0.029	16.403	2.020	TRUE
19	Maintenance cost	0.214	9.300	0.130	8.250	0.028	16.431	1.992	FALSE
20	Maintenance cost	3.227	9.000	0.116	8.366	0.375	16.805	2.009	TRUE
21	Maintenance cost	0.241	8.700	0.104	8.469	0.025	16.830	1.987	TRUE
22	Maintenance cost	0.255	8.400	0.093	8.562	0.024	16.854	1.968	TRUE
23	Maintenance cost	0.270	8.100	0.083	8.645	0.022	16.876	1.952	TRUE
24	Maintenance cost	0.286	7.800	0.074	8.718	0.021	16.897	1.938	TRUE
25	Maintenance cost	0.604	7.500	0.066	8.784	0.040	16.937	1.928	TRUE
26	Maintenance cost	0.322	7.200	0.059	8.843	0.019	16.956	1.917	TRUE
27	Maintenance cost	0.341	6.900	0.053	8.896	0.018	16.974	1.908	TRUE
28	Maintenance cost	0.362	6.600	0.047	8.943	0.017	16.991	1.900	TRUE
29	Maintenance cost	0.383	6.300	0.042	8.984	0.016	17.007	1.893	TRUE
30	Maintenance cost	1.156	6.000	0.037	9.022	0.043	17.050	1.890	TRUE
31	Maintenance cost	0.431	5.700	0.033	9.055	0.014	17.065	1.885	TRUE
32	Maintenance cost	0.457	5.400	0.030	9.085	0.014	17.078	1.880	TRUE
33	Maintenance cost	0.484	5.100	0.027	9.112	0.013	17.091	1.876	TRUE
34	Maintenance cost	0.513	4.800	0.024	9.135	0.012	17.103	1.872	TRUE
35	Maintenance cost	0.844	4.500	0.021	9.157	0.018	17.121	1.870	TRUE
36	Maintenance cost	0.576	4.200	0.019	9.176	0.011	17.132	1.867	TRUE
37	Maintenance cost	0.611	3.900	0.017	9.192	0.010	17.142	1.865	TRUE
38	Maintenance cost	0.648	3.600	0.015	9.208	0.010	17.152	1.863	TRUE
39	Maintenance cost	0.687	3.300	0.013	9.221	0.009	17.161	1.861	TRUE
40	Maintenance cost	1.478	3.000	0.012	9.233	0.018	17.179	1.861	TRUE
41	Maintenance cost	0.771	2.700	0.011	9.244	0.008	17.188	1.859	TRUE
42	Maintenance cost	0.818	2.400	0.010	9.253	0.008	17.195	1.858	TRUE
43	Maintenance cost	0.867	2.100	0.009	9.262	0.007	17.203	1.857	TRUE
44	Maintenance cost	0.919	1.800	0.008	9.270	0.007	17.210	1.857	TRUE

Year	Bridge Cost	Maintenance Cost (Rs Million)	Resale Value (Rs Million)	Discount Factor	Cum. Discount Factor	Discounted Maintenance Cost (Rs Million)	Discounted Total Cost (Rs Million)	Weighted Average Cost (Rs Million)	No Replacement
45	Maintenance cost	1.274	1.500	0.007	9.276	0.009	17.219	1.856	TRUE
46	Maintenance cost	1.032	1.200	0.006	9.283	0.006	17.225	1.856	TRUE
47	Maintenance cost	1.094	0.900	0.005	9.288	0.006	17.231	1.855	TRUE
48	Maintenance cost	1.160	0.600	0.005	9.293	0.006	17.236	1.855	TRUE
49	Maintenance cost	1.230	0.300	0.004	9.297	0.005	17.242	1.855	FALSE
50	Maintenance cost	2.053	0.000	0.004	9.301	0.008	17.250	1.855	TRUE

Induced and Generated Traffic

After the improvement of the existing facility, traffic of other roads may be attracted to improved road for better road geometric, riding quality, lesser travel time, shorter distance… etc. Existing traffic may be capable to generate more trips due to lesser travel time/increasing travel speed for the up-gradation of the road. This traffic is assumed 10 % of the traffic at the time of opening. Year 2004 is the year of opening. Traffic at the opening year is obtained multiplying projected 2004 year traffic by 1.10.

Project Cost

The project road is 15km long, and the project cost was worked out and found to be Rs 50 million per km (2000 costing) as base cost.

Economic life has been carried out taking the following major cost (per kilometer) components:

- Annual maintenance cost=Rs 0.3 million.
- Functional overlay cost=Rs 2.74 Million per km and to be provided after 5,15 and 25 years.
- Structural overlay cost=Rs 5.5 Million and to be provided after10,20 and 30 years.
- Using these data, the replacement year has been calculated and shown in Table 3. Inflation rate and discount rate are taken 6 and 12%. Linear depreciation method is considered.

A sample calculation for the 14^{th} year for better understanding is shown below.

Initial project costs: Rs 50 Million per Kilometer

Annual routine maintenance cost: Rs 0.3 Million per kilometer

Functional maintenance cost: Rs 2.74 Million per kilometer

Structural maintenance cost: Rs 5.5 Million per kilometer

Increase of maintenance cost: 6%

Discount rate: 12%

Inflated maintenance cost at 14^{th} Year:0.3*(1.06)^(14-1)

Discounted total cost: 57.184

Cumulative discount factor: 7.424

Weighted average cost for 14^{th} year= 57.184/7.424= 7.703

Maintenance cost for 15 th year: 6.158<7.703

13.11324 1.06^14(.3+5.5)

Since maintenance cost at 15^{th} year is less than weighted average cost of 7.703, replacement is not required.

Sensitivity Analysis

Sensitivity analysis is generally carried out varying one parameter at one time. Major maintenance cost, annual routine cost and periodic overlay cost are varied ± 15 % of the base cost and the economic replacement life is calculated for case 1 and shown in Tables 4 and 5.

Same year of replacement has been found out using sensitivity analysis.

Bridge Project

The Government of Uttarakhand, Engaged Consultants for Consultancy Services for Feasibility Study and Preparation of DPR for Construction of 45m span2 lane RCC Bridge over Bindal River in km. 157.950on NH-72 (7).

A bridge case study is considered.

Total cost = Rs 15Million.

Annual maintenance cost @0.5 % of initial cost= Rs 0.075 million.

Annual maintenance cost has been increased every year @6% of the previous year's maintenance cost.

Periodic maintenance cost=Rs 0.3 million to be provided every 5th year.

Periodic maintenance cost = Replacement of bearings 0.75 million to be provided every 20th year.

Using these data, the replacement year has been calculated and shown in Table 6.

CONCLUSIONS

Economic life of pavement can be determined using the replacement theory. The same principle can be used to determine economic life elevated segmental structure like elevated highway/elevated metro, underground metro, expressway, white trooping concrete pavement, runway… etc.

Reliable data of: initial cost, annual maintenance cost, periodic maintenance cost, strengthening cost and year of application are important parameters. These values should be determined by experts of these relevant fields for the determination of replacement period.

REFERENCES

Allen, H.T. and Ching, W.K. 2005. On the Use of Renewal Theory in Machine Replacement Models. *International Journal of Applied Mathematical Sciences*, 2 (2): 240-247.

Craig,W. and Stephen, T.M. 2010. Life-Cycle Assessment of Reconstruction Options for Interstate Highway Pavement in Seattle, Washington. *Journal of the Transportation Research Board*, No. 2170, Transportation Research Board of the National Academies, Washington, D.C., 18–27.

Destination: Strategic Consulting Services. 2009. Donlen Corporation product brochure. Available at http://www.donlen.com/pdf/Donlen_Product_SC_brochure.pdf.

Fan, W., Machemehl, R.B., Randy, B. and Kortum, K. 2011. Equipment Replacement Optimization: Part I. Solution Methodology, Statistical Data Analysis and Cost Forecasting. Published in: Transportation Research Record and Presentation at the 90th Annual Meeting of the Transportation Research Board, Washington, D.C., January 23-27.

Ghosh, J.K. 1994. Mahalanobis and the Art and Science of Statistics: The Early Days, *Indian Journal of History of Science,* 29 (1): 89-98.

(http://www.bath.ac.uk/cri/).

Kapoor, V.K. 1999. Operation Research. Sultan Chand and Sons, Educational Publisher, New Delhi, India.

Nahmias, S. 1997. Production and Operation Analysis, McGraw Hill International, Chicago.

Rodriguez, M.M., Labi, S. and Zongzhi, L. 2006. Enhanced Bridge Replacement Cost Models for Indiana's Bridge Management System. Transportation Research Record: *Journal of the Transportation Research Board,* No. 1958, Transportation, Transportation Research Board of the National Academies, Washington, D.C., 13-23.

State Government: State Customers. 2009. AssetWorks, Inc. Available at http://www.assetworks.com/page/state-government.

Strategic Consulting. 2009. Automotive Resources International. Available at http://www2.arifleet.com/strategicconsulting.htm.

TxDOT Equipment Replacement Model-TERM. 2004. Accessed on January 20, 2009, ftp://ftp.dot.state.tx.us/pub/txdot-info/gsd/pdf/txdoterm.pdf.

Virlogeux, M. 2003. Replacement of The Suspension System of the Tancarville Bridge. *Journal of Transportation Research Record*, 1654: 113-128.

Weissmann, J., Jannini, A., Weissmann, A.J. and Gona, S. 2006. Computerized Equipment Replacement Methodology. *Journal of Transportation Research Record,* (1824): 77-83.

Weissmann, J., Weissmann, A.J. and Gona, S. 2003. Computerized Equipment Replacement Methodology, *Journal of the Transportation Research Board,* (1824): 77-83, Washington, D.C.