SERVICE LIFE ECONOMIC ANALYSIS FOR PAVEMENT DESIGN AND MAINTENANCE PLANNING

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ABSTRACT

This paper describes a methodology to perform service life economic analysis for cost-effective management of roads and highways. The methodology predicts service life pavement condition and quantifies agency costs, user costs, and benefits. Condition-responsive maintenance intervention policies include asphalt resurfacing, concrete overlays and reconstruction. Reasonably good agreement is shown with the vehicle operating cost stream predicted by the World Bank’s HDM-III program for typical asphalt pavement sections. Case studies are presented to illustrate the use of service life benefit and cost analysis to develop maintenance work programs and to prioritize competing alternatives for a new urban road. The paper also presents an example of the user cost methodology implemented for network-level pavement management applications in Mexico.

BACKGROUND

Service life analysis of costs and benefits is a recognized approach for cost-effective maintenance management of highways and roads [1,2]. The scope of pavement management systems (PMS) depends primarily on the size of the network, and the short-term and long-term goals of road investment planning. System complexity is generally related to pavement condition data collection and processing, maintenance treatment analysis, economic evaluation, and priority ranking of competing alternatives. A suitable database management software, and application programs for condition data analysis, maintenance programming and budget analysis, are important components of PMS. Decisions related to these items should be made at the outset of system design. The development of a maintenance, rehabilitation and reconstruction (M,R&R) programming and budget analysis methodology must address the following issues:

- A M,R&R policy to select suitable major, minor and routine M,R&R treatments based on the current serviceability, distress and other condition data analysis.
- Prediction of pavement condition deterioration using appropriate performance models over the analysis period considering the timing and effect of M,R&R intervention. Agency cost calculation for construction, current maintenance need, and future M,R&R treatments.
- User cost and benefit calculations. Single-year and multi-year M,R&R work program with priority ranking for road investment planning and network-level PMS applications.
- Economic evaluation of competing alternatives at the project-level design applications.

Service life analysis of costs and benefits for competing alternatives is fundamental to capital improvement programming and maintenance planning at both network- and project-level PMS applications. This paper identifies cost and benefit streams associated with agency and users, describes the service life cost and benefit analysis methodology, and presents selected applications.

SERVICE LIFE COST AND BENEFIT ANALYSIS METHODOLOGY

The importance of life-cycle analysis of both new pavements as well as overlay designs has been recognized since the 1960's [2,3,4,5]. Detailed rational procedures of vehicle operating cost (VOC) and the effect of pavement condition on VOC were established in an international UNDP/World Bank study of long-term pavement performance in Brazil which later followed by studies in India and Kenya [6]. A comprehensive VOC study was also conducted by FHWA [7] in the United States which produced detailed rate tables for individual VOC components, as well as total VOC tables, as a function of pavement condition. The World Bank Highway Design and Maintenance Standards Model (HDM) is a comprehensive program for pavement condition prediction, VOC calculation and life-cycle economic analysis [6]. However, the present version of the HDM III program, does not consider portland cement concrete (PCC) pavements.
The service life benefit and cost methodology, described in this paper, was developed to analyze all types of pavement surfaces considering the VOC rate tables developed by FHWA. It is incorporated in a microcomputer program, USER. The USER methodology is developed on a relational database platform for system integration with network-level PMS databases, and for applications in stand alone project-level analysis. The software also analyzes other related user benefits such as travel time savings and accident cost savings. It is a useful economic evaluation tool for applications in infrastructure capital programming, maintenance management, and transportation system management (TSM) studies. The USER methodology involves the following key steps for service life benefit and cost analysis:

- Enter section-specific data for pavement type, dimensions and geometrical characteristics, PSI0 or IRI0, and subgrade and environmental data.
- Enter section traffic data including average annual daily traffic (ADT), typical distribution of vehicle types, 18-kip (80 kN) equivalency factor for each vehicle type.
- Assign common unit cost data for agency and user costs and user benefits. The VOC unit costs for each vehicle type include; routine vehicle maintenance in $/1000 miles, oil consumption in $/quart, fuel consumption in $/gallon, and depreciation in $/new vehicle.
- Enter data for traffic delay cost including detour model, detour distance, time of traffic control, number of open lanes, percentage of vehicles affected, average vehicle delays, and hourly traffic distribution.
- Assign M,R&R intervention criteria and treatment policies for each pavement type, analysis period, discount rate, and inflation rate.
- Calculate directional ADT, corresponding ESALs and number of vehicles of each vehicle type for each year of analysis considering variable annual traffic growth rate; calculate yearly cumulative equivalent single axle load applications.
- Predict pavement deterioration every year over the analysis period for each pavement type based on the current condition (cumulative traffic being the primary causal factor). Identify M,R&R year and adjust for M,R&R intervention.
- Calculate agency cost for construction and/or M,R&R treatment during the analysis period.
- Calculate hourly traffic volume during the predicted period of M,R&R activity in the intervention years; calculate total traffic delay cost (TDC) in the intervention years.
- Calculate vehicle operating cost stream for each year of the analysis period as a function of pavement condition, vehicle type, associated VOC parameters and geometrical characteristics considering (a) with improvement and maintenance intervention and (b) without M,R&R for "do-nothing" policy.
- Calculate VOC benefits as the difference of VOC values for the cases of maintenance and "do-nothing" policies; calculate other benefits due to travel cost and accident cost savings.
- Perform present worth analysis of agency cost, user costs and benefits, and prioritize the analyzed sections/alternatives; generate reports.

PAVEMENT PERFORMANCE MODELS

Pavement condition deteriorates due to loading, material degradation, and environmental effects. Pavement performance is measured by pavement condition history. Performance prediction is essential for long-term maintenance analysis and life-cycle cost and benefit analysis. The condition prediction equations incorporated in the proposed methodology are selected from the state-of-the-art models developed in national and international pavement performance studies. Pavement condition is specified in terms of either PSR (present serviceability rating) on a scale of 5 (excellent) to 0 (worst) or IRI (International roughness Index). A pavement in excellent condition usually shows 0 to 2 m/km and a pavement in the worst condition may show as high as 12 m/km on the IRI scale.

Performance Models for Asphalt Surfaced Roads A comprehensive pavement performance model should include the effects of traffic, pavement strength, age, environment and initial pavement surface condition. A simplified time-series model, for example [8] to predict pavement condition as a function of age, is applicable for specific pavement types, and cannot adequately account for the above causal effects outside the inference space. The World Bank’s road roughness progression...
model used in the HDM III program [6] is a comprehensive model for asphalt road performance that includes independent variables of road surface distresses, environment, subgrade strength, traffic loads and time. The model has been used in numerous field applications for asphalt pavement life cycle analysis [6,9,10]. This incremental roughness prediction model also requires current and future surface distress data, which are not always readily available.

Paterson and Attoh-Okine [10] proposed a new simplified roughness progression model which does not require distress terms. The model was developed by analyzing a database generated from the HDM III computations based on a factorial design. It is applicable for maintained roads with the area of cracking not exceeding 30 percent. Pavement roughness at any time t, (IRI_t), is predicted using the following equation, as a function of initial roughness (IRI_0), time (t), environment coefficient (m), structural number modified by subgrade strength (SNC), and cumulative standard axle load applications at time t (CESAL_t), in millions.

\[
IRI_t = 1.04e^{mt} [IRI_0 + 263 (1 + SNC)^{-5} (CESAL)_t]
\]

This simplified World Bank roughness progression model has been incorporated into the USER software for all types of asphalt surface pavements. Several road sections at different distress levels are investigated using both the HDM III and USER programs. The results show reasonable agreement between the USER and HDM III predictions, as shown in Figure 1, for a pavement in poor condition having 5000 ADT (annual average daily traffic volume) and modified structural number of 4.4.

**Performance Models for Jointed Concrete Roads** The COPES pavement condition prediction models for jointed portland cement concrete pavements developed in a nationwide NCHRP study [11] have been incorporated into the USER software. These models predict PSR (Present Serviceability Rating) in the range of 0 to 5 at time "t" (PSR_t) as a function of initial PSR (PSR_0), cumulative equivalent standard axle load applications at time "t" in millions (CESAL)_t, environment parameters and pavement strength. Separate COPES models are included for jointed reinforced concrete pavements (JRCP) and jointed plain concrete pavements (JPCP).

**Performance Models for Asphalt Overlay on Concrete Pavement** The HPMS model developed in 1993 for asphalt overlaid concrete pavement has been incorporated in USER. This model predicts PSR at any time t as a function of initial PSR, age and cumulative ESALs.

**User Defined Pavement Performance Models** A user defined step-wise linear model (variable rate of deterioration with year) has been incorporated for continuously reinforced concrete (CRC) roads in the USER methodology. The default model is based on Texas data [12]. Similarly, a simplified user defined step-wise linear condition prediction model is included for unpaved and gravel roads.

**Effects of Maintenance Intervention** The pavement condition prediction routines of USER also account for the effects of current and future maintenance treatment intervention on pavement condition. This is accomplished by assigning appropriate values of either IRI_0, or PSR_0 after the planned overlay or other major maintenance treatment. The improved PSR after a major M, R&R treatment is 4.0. A major M, R & R alternative (excluding concrete pavement restoration that is performed on the affected areas) implies its application over 100 percent of the pavement area. If the PSR of any section falls below the maintenance intervention threshold (typically 2.0), then a global major M, R & R treatment is selected using the following major maintenance intervention policies:

- Asphalt concrete overlay option when PSR_t reaches 2.0 or IRI_t approaches 5.1 m/km. This default maintenance intervention criterion can be modified by the user.
- Concrete pavement restoration (CPR), reconstruction and other alternative major M,R&R treatment option for concrete pavements, using the intervention criterion shown for (1).
- Two alternatives for unpaved road maintenance: (a) grading maintenance triggered at IRI, of 6 m/km, and (b) upgrading to asphalt paved road when {IRI}_t approaches 12 m/km.

It is assumed that there is no significant effect of annual routine and emergency maintenance and localized minor maintenance treatment on pavement roughness condition. Figure 1 shows the effect
of maintenance intervention on pavement condition for an asphalt pavement in poor condition with 5000 ADT. Figure 2 illustrates pavement condition histories *with and without M,R&R intervention for a jointed concrete pavement section on highway SR 3N in northern Mississippi which is 0.78 km (0.48 mile) long in good condition at the time of distress survey (IRI = 2.5 m/km, PSR =3.31) having 229 mm (9 inch) thick concrete slab and high traffic level (ADT = 25,000).

VEHICLE OPERATING COST (VOC) ANALYSIS

The vehicle operating cost predictions for pavement life-cycle are based on the VOC rate tables and speed-change cycle parameters developed by FHWA [7,13]. The model includes the following VOC attributes: fuel consumption, oil consumption, tire wear, vehicle maintenance and repair, and depreciation. The VOC rate for each attribute is a function of vehicle type, speed, grade, curvature, and pavement condition in PSR. The VOC rate tables are incorporated in USER to calculate VOC values of each year of analysis at constant speed and for speed change cycles. The annual vehicle operating cost in year \( y \), \((\text{VOC})_y\), is calculated on annual basis using the VOC model which is expressed in the following functional form:

\[
(\text{VOC})_y = \sum_{i=1}^{5} \sum_{j=1}^{8} \left[ \left( \text{CONSTANT} \right) \left( \text{RATE} \right) \left( \text{DADTY} \right) \left( \text{UNITCOST} \right) \right]_i
\]

where

- \((\text{VOC})_y\) = total VOC for the year "y", at constant speed,
- \(i\) = \(i\)th VOC attribute (fuel consumption, oil consumption, tire wear, vehicle repair, and vehicle depreciation),
- \(j\) = \(j\)th vehicle type (from small car to semi-trailer and combination trucks),
- \text{CONSTANT} = a constant for constant speed VOC calculation, a function of section length and consumption rate unit for each VOC attribute,
- \text{RATE} = the consumption rate for each of the VOC attribute, a function of vehicle type, speed, grade, curvature and pavement condition,
- \text{DADTY} = directional traffic volume for the year "y" and vehicle type \(j\), and
- \text{UNITCOST} = unit cost associated with each VOC attribute.

Similarly, using the form of the above equation with the exception of CHANGE instead of CONSTANT, \((\text{VOC})_y\) is calculated for the year "y" at each speed change cycle. The method of estimating speed-change cycles is based on the FHWA's HPMS program [13]. Total VOC for each year is then calculated by the following equation:

\[
(\text{VOC})_y = (\text{VOC})_{cy} + (\text{VOC})_{sy}
\]

The average running speed and VOC rates are adjusted for the prevailing pavement condition. The USER vehicle operating cost (VOC) results compare closely with the World Bank's HDM III results for asphalt pavements [2]. The model can be used to evaluate the following scenarios:

- Alternate M,R&R methods and improved maintenance effectiveness.
- Maintenance deferment; change in M,R&R intervention criteria.
- Improved pavement condition and lane addition.
- Increased road capacity and reduced traffic congestion.
- Increase in vehicle average running speed by reducing traffic congestion.

ANALYSIS OF TRAFFIC DELAY COST (TDC) DUE TO CONSTRUCTION

The traffic delay cost (TDC) model calculates excess user costs associated with interruptions in traffic flow due to construction during M,R&R intervention. The model is based on the Texas studies [12,14]. The LCCI version [5] is adopted in the USER software. The model considers a number of user-specified traffic scenarios depending on the number of lanes, location and facility type.
USER BENEFITS AND ECONOMIC ANALYSIS

The pavement condition prediction considering M,R&R intervention is an important step in service life economic analysis, because this allows for the calculation of the difference in vehicle operating costs between a pavement with and the same pavement without M,R&R intervention (or “do-nothing”) scenarios. This reduction in VOC or saving is considered a surrogate for "user benefit". The following service life benefits are calculated by USER:

- Reduction in total VOC due to timely M,R&R intervention as compared to no maintenance (“do-nothing”) scenario. The "do-nothing" option is always analyzed by USER as a base alternative.
- Travel time saving as compared to the base “do-nothing” scenario.
- Traffic accident cost saving as compared to the base “do-nothing” scenario for fatal, non-fatal and property damage types of accident.
- Roadway salvage value.

The USER program performs comprehensive economic evaluation using a user defined discount rate, inflation rate and priority ranking options based on present worth of agency costs and benefit/cost ratio. Service life present worth analysis of costs and benefits can be performed on a section-by-section basis, up to 9 alternatives for a specified section, or for all the sections included in the database.

PROJECT-LEVEL APPLICATIONS

Selected example applications are presented for (1) two asphalt paved roads including a comparison with the HDM III results, (2) a concrete road section, and (3) one new asphalt road construction with three alternatives. These examples are based on an analysis period of 30 years, a discount rate of 10 percent and an inflation rate of 5 percent.

Asphalt Paved Roads in Poor and Good Conditions The asphalt paved roads described in this example, located in northern Mississippi, carry relatively low traffic volume (ADT=5000) at low strength (CBR = 10, Structural Number = 3.2). Road section SR 12 E (about 2 km or 1.22 miles) was in poor condition at the time of the distress survey, having IRI of 4.6 m/km (PSR = 2.17). Using the default intervention criterion, both USER and HDM III programs predicted the first major M,R&R or capital improvement in 3 years, as shown in Figure 1. On the other hand, Road section SR 14E (about 8.3 km or 5.2 miles) is in good condition with IRI of 2.5 m/km (PSR = 3.31) and requires maintenance intervention later in year 27 according to USER as compared to the HDM III prediction of maintenance intervention in year 11. Figure 3 compares the vehicle operating cost impacts in terms of US $ per vehicle-mile in base year unit costs, as predicted by the HDM III and USER programs for the two asphalt road sections. In both cases, USER predicts relatively lower unit costs than the HDM III model. Also, with timely M,R&R action, the USER-VOC benefit for the poor pavement is nine times greater than that for the good condition pavement. This analysis demonstrates the economic consequences of deferring maintenance treatment.

Concrete Roads in Good Condition Figure 4 shows VOC histories with and without M,R&R intervention for the concrete road section on SR 3N in northern Mississippi.

Investment Planning for New Urban Arterial Three competing alternatives, for the construction of a new 1.6 km (1 mile ) urban arterial road NEW ROAD, are analyzed by USER. The road will carry high traffic volume of 25,000 ADT. The alternatives represent different capacity and traffic flow characteristics. Initial pavement condition of the constructed road is assumed very good (IRI = 1.81 m/km; PSR = 4.0).

Alternative 1: Two 3.6 m (12 ft) wide lanes; average running speed of 56 kmph (35 mph); predicted M,R&R intervention in year 20; VOC present worth benefit, $4,541,000; travel time and accident cost saving $none; agency present worth cost, $443,000.

Alternative 2: Three 3 m (10 ft) wide lanes; average running speed of 68 kmph (42.5 mph); predicted M,R&R intervention in year 22; VOC present worth benefit, $3,807,000; travel time and
accident cost saving, $none; agency present worth cost, $551,000.

Alternative 3: Three 3.6 m (12 ft) wide lanes; average running speed of 80 kmph (50 mph); predicted M,R&R intervention in year 22; VOC present worth benefit, $2,765,000.; travel time and accident cost saving, $23,928,000; agency present worth cost, $661,000.

Based on decreasing benefit/cost ratios, Alternative 3 is ranked the highest in priority order followed by Alternative 1, and Alternative 2 being the least cost-effective.

INTEGRATION WITH NETWORK-LEVEL PMS SOFTWARE

The network-level PMS software implemented in Mexico during 1995-96 for the municipal agencies in the City of Leon and City of Saltillo incorporates customized versions of the USER program to calculate vehicle operating cost, traffic delay cost during maintenance, and benefits in reduced user costs resulting from timely maintenance and improved pavement condition, travel time savings and accident cost savings. The USER program was integrated with the Program for Planning and Budget Analysis of Maintenance (PAM). The PAM methodology can be adapted for any combination of condition data attributes and data collection methods. The key concept is to associate each data category to four levels of maintenance requirement (from none to reconstruction), and then select a unique major maintenance strategy based on all the prevailing levels of the condition attributes.

The PAM methodology is applicable to all pavement types including asphalt, concrete, asphalt overlaid concrete pavements, and unpaved roads. The sum of short-term major and minor maintenance, lane widening/shoulder, annual routine/emergency costs, and long-term major M,R&R costs yields the total life-cycle agency cost for a section. The long-term M,R&R cost, vehicle operating cost, and user benefits are based on the USER program. Figures 5 and 6 show the and life-cycle VOC histories predicted for a concrete road section (at PSR of 2.6) in Leon, Mexico. A short-term M,R&R on distressed area applied initially in Figure 6 results in 18.4 percent reduction in VOC, as compared to the case in Figure 5. This analysis shows the benefit of timely maintenance for this poor condition section.

SUMMARY AND CONCLUSIONS

Service life benefit and cost analysis is essential to assist in cost-effective investment planning and maintenance management decisions. The USER software incorporates a comprehensive life-cycle analysis methodology based on state-of-the-art pavement performance and user cost models. The methodology is applicable to asphalt, concrete, overlaid pavement surfaces, and unpaved roads. Furthermore, the USER software can simulate and analyze a variety of short-term improvements in level-of-service, and also the consequences of roadway widening and high occupancy vehicle lane addition which are viable alternatives in transportation system management (TSM) activities.

The examples illustrate a few of the many applications of the service life economic analysis methodology described in this paper. Also, this methodology can be utilized for many other economic evaluation studies; for example, comparative evaluation of competing alternatives for new road/highway investment planning, selecting alternatives for existing roads, conducting user cost impact analysis, analyzing "what-if" scenarios, priority ranking of candidate roads/highways in a network, and long-term maintenance budget analysis. The integration of USER model with PAM in Mexico demonstrates that a rational road construction and M, R & R work program can be generated considering long-term maintenance costs and resulting VOC benefits over the pavement service life.

REFERENCES


Figure 1. Condition history for an asphalt pavement in poor condition

Figure 2. Concrete pavement condition history with and without maintenance intervention

Figure 3. Effect of initial pavement condition on life-cycle vehicle operating costs

Figure 4. VOC history predicted for the concrete pavement section in northern Mississippi

Figure 5. Life-cycle vehicle operating cost for a concrete pavement in Leon, Mexico

Figure 6. Life-cycle vehicle operating cost considering Short-term M,R&R for the section in Leon