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Life cycle cost analysis of highways to assist design and construction decisions

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Abstract

Highway design and construction decisions have been traditionally made considering the initial construction cost with little or no attention paid to the various aspects of costs and performance during the life cycle of a road. This work aims to provide an assessment of these measures in order to assist strategic decisions for the construction of new roads or for the reconstruction of existing ones. The proposed approach incorporates three modules, one for performance prediction of critical highway elements in time, another for estimating the resulting costs associated with the condition of each type of element, and a third one for comparative evaluation of alternative design and construction strategies. Performance prediction is obtained through a fuzzy system approach with which qualitative information from engineering judgment is converted to numerical values to provide the prediction models under different design strategies. On the basis of these models, several cost components such as construction cost, operation and maintenance costs, road user costs, as well as environmental and sustainability impacts are estimated. The life cycle costs are further used for comparable evaluation of alternative design and construction decisions.

Keywords

life cycle cost, life cycle cost analysis (LCCA), highway, pavements, bridges, construction

1. Introduction

Highway design and construction decisions have been traditionally made considering the initial construction cost with little or no attention paid to the various aspects of costs and performance during the life cycle of a road. This work aims to provide an assessment of these measures in order to assist strategic decisions for the construction of new roads or for the reconstruction of existing ones. A life cycle cost analysis (LCCA) is recruited in the proposed approach, as it is suitable for calculating the overall costs of project alternatives throughout their life time. In this way, evaluation comparisons among highway design and construction alternatives can be performed based on these overall costs.

A number of research efforts can be found in the literature concerning highway life cycle cost analyses. The Federal Highway Administration (1998) launched a report that has recommended procedures for conducting life cycle cost analysis of pavements and for assessing work zone user costs. In addition, it introduced a probabilistic approach to account for the uncertainty associated with life cycle cost inputs. The Association mondiale de la Route (2000) described the status of techniques available for undertaking whole life cost analyses of road pavements while Goldbaum (2000) provided guidance, recommendations, and default values for costing based on several paving projects over a decade. Herbold (2000) proposed the use of Monte Carlo simulation for assessing the uncertainty hidden in the deterministic approach of the life cycle cost analysis. The Federal Highway Administration Primer (2000) provided background for transportation officials to investigate the use of life cycle cost analysis to evaluate alternative infrastructure investment options and demonstrated the value of such analysis in making economically sound decisions. The American Concrete Pavement Association (2002) presented the concept of life cycle cost analyses and provided guidance on the selection of values for life cycle cost sensitive factors. More recently, Lamptely et al. (2005) reviewed several aspects of the life cycle cost analysis and developed several sets of alternative pavement design and preservation strategies consistent with existing and foreseen Indiana practice.

While previous works mainly focus on certain highway elements (e.g., pavements) or cost components (e.g, work zone user costs), the present study aims at assessing life cycle costs based on several cost components, including construction and maintenance costs, user costs, and environmental costs, allowing, thus, comparative evaluation of alternative scenarios regarding design (e.g., horizontal/vertical alignment), construction (e.g., pavement design characteristics and materials used) or maintenance (e.g., type of maintenance and time of application). A mix of analytical models and the outcome of practical experience with regard to highway construction and maintenance (modeled through fuzzy systems) are used for this purpose. Figure 1 illustrates the proposed system architecture.

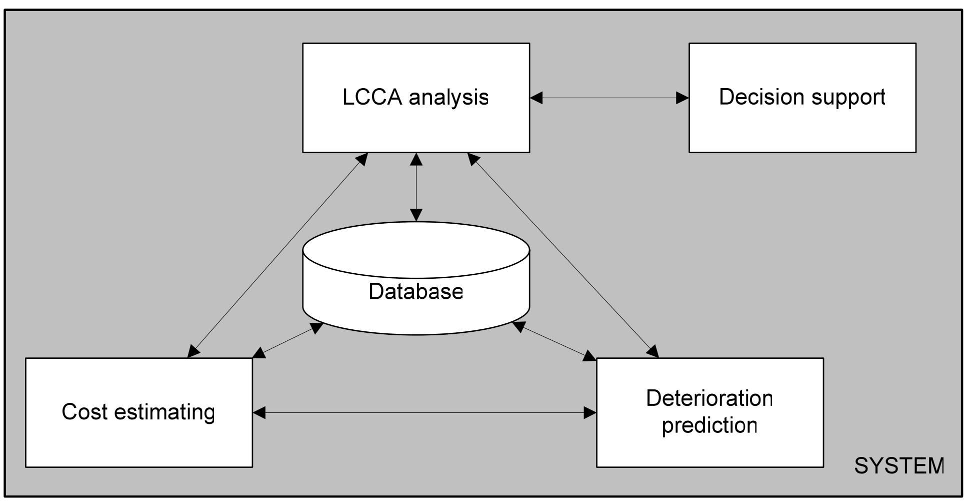

Figure 1: Overview of the system architecture

2. Life cycle cost analysis of highways

Life cycle cost analysis is suitable for assisting highway design and construction decisions through the assessment of overall costs of design and construction alternatives. The life cycle cost analysis consists of estimating all major costs involved in the lifetime of a highway. Apart from the initial capital invested in the construction of a highway (which represents a major percentage of the life cycle cost and can be estimated quite accurately), there are several other expenditures over the lifetime of the project with variable contribution to life cycle cost and high uncertainty in their estimation. The costs associated with a highway project can be grouped into four categories:

- agency costs,
- user costs,

- other costs, and
- negative costs.

The agency costs consist of the design, construction, maintenance and operational costs. Maintenance can be further classified according to the intensity and frequency of its application as preventive maintenance which includes activities planned to extend the life of the asset, day to day routine maintenance intended to address safety and operational concerns, and rehabilitation or restoration activities.

User costs refer to expenditures incurred by the traveling public. These costs involve vehicle operating costs (VOC), travel time costs and accident costs. Vehicle operating costs mainly include:

- fuel consumption,
- oil and other lubricants consumption,
- vehicle maintenance,
- depreciation, and
- crew costs where appropriate.

User delay costs are distinguished in stopping delay and queue delay costs while crash costs are further subdivided in property damage only (PDO), injury costs, and fatality costs.

Other costs involved in highway life cycle mainly refer to environmental impacts, in particular:

- vehicle emission rates,
- noise pollution levels,
- land loss,
- use of recycled materials for construction or maintenance,
- natural resource depletion, and
- habitat fragmentation.

Negative costs relate to the value of the asset at the end of the analysis period for which the life cycle cost analysis is performed. Two such values are identified, the salvage value and the remaining service life (RSL). Salvage value is the net value from the recycling of materials at the end of the analysis period while the remaining service life constitutes the residual value of the highway when its service life extends beyond the end of the analysis period.

Expenditure stream diagrams, such as the one presented in Figure 2, are recruited for visualizing the costs of each project alternative. In such diagrams, costs are depicted as arrows when they take place at a particular time point or as geometric schemas (triangles, trapeziums) when distributed over a period of time. The work presented in this paper includes only a part of the life cycle cost components with emphasis on construction and maintenance costs since the research project is underway and no full results are available yet. Figure 2 presents illustratively the initial construction cost, the maintenance costs, the user costs, and the remaining service life value.

Following the estimation of cost components and their distribution in time, costs occasioned at different times are converted to their values at a common point in time. This is necessary as a given amount of money has different values when received at different time points. The present value approach is suitable for such conversion, as it brings initial and future costs to a single point in time, usually the present or the first cost outlay. Finally, the overall costs for each project alternative are calculated, allowing the minimum cost ranking of the alternatives along the analysis period.

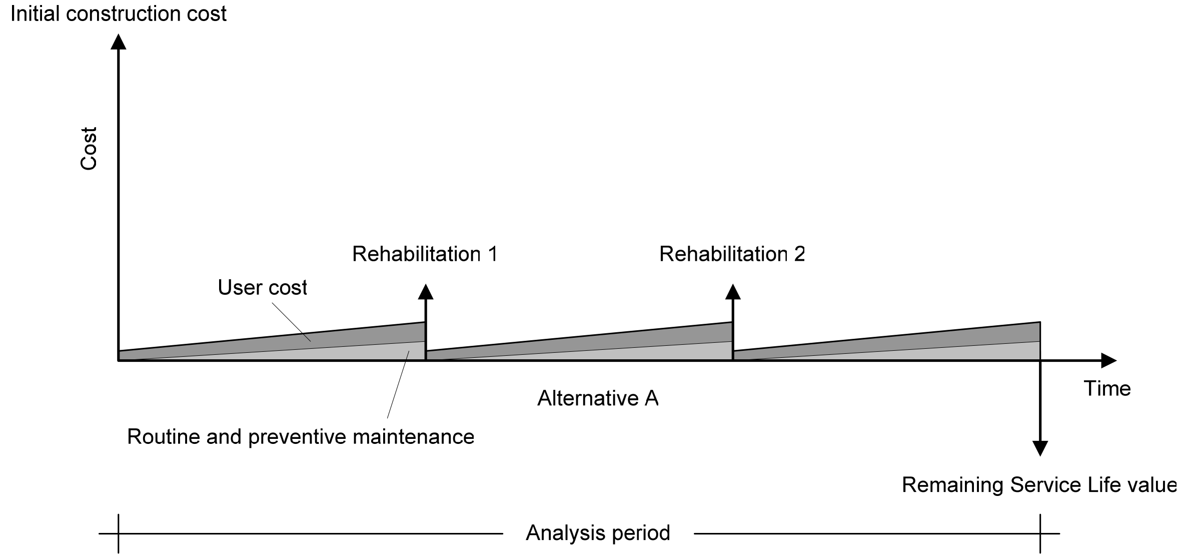

Figure 2: Life cycle cost analysis stream diagram

3. Highway deterioration and maintenance

Among highway elements, pavements, bridges, and structures are the most important with regard to work quantities, resource and cost requirements (both for construction and maintenance). The deterioration of these elements are taken into account in the life cycle cost analysis presented in this paper, as they strongly affect several costs included in the analysis, such as, maintenance or user costs. The most frequent pavement distresses in a typical road pavement (from surveys on the road network in Western Greece, Chassiakos et al., 2006) are the following:

- alligator cracks,
- slippage cracks,
- edge cracks,
- longitudinal – transverse cracks,
- rutting,
- local depressions,
- raveling,
- potholes,
- slipperiness.

The severity, extent, and location of these pavement distresses are influenced by several factors, such as the traffic load, the foundation ground, the environmental conditions and the pavement age.

Pavement deterioration can be predicted with models of the following general form:

$$\text{Distress Index} = \alpha_0 \, AGE^{\alpha 1} \, MSN^{\alpha 2} \, TRAF^{\alpha 3} \, QUA^{\alpha 4} \quad (1)$$

where α_0, α_1, α_2, α_3, and α_4 = coefficients to be estimated,
AGE = pavement age initiating from last construction,
MSN = structural strength parameter,
TRAF = traffic load parameter,
QUA = construction quality parameter.

Deterioration prediction models such as the one given in (1) have been derived employing fuzzy systems based on experts knowledge (Loukeri and Chassiakos, 2004). For example, the deterioration of transverse cracking over time can be modeled by:

$$transvcrack = 1.868941\ AGE^{1.1815}\ MSN^{-0.1394}\ TRAF^{0.1878}\ QUA^{-0.1630} \quad (2)$$

Frequent concrete bridge defects (observations from 300 bridges along the road network in Western Greece, Chassiakos et al., 2005) are the following:

- river bed / bridge foundation erosion,
- deck cracking and disintegration / rebar corrosion due to carbonation and chloride contamination,
- joint damage due to heavy traffic,
- bearing damage,
- deterioration of travelled surface (cracking, surface distortion, disintegration),
- railing damage due to vehicle collision,
- waterproof deterioration,
- deck drainage system failure.

The severity and extent of the above defects are influenced by several factors, such as the traffic load, the river bed characteristics, the environmental conditions, the bridge age, the foundation type and the superstructure type. An effort to develop models for bridge deterioration prediction based on existing literature and expert opinions is underway.

Maintenance costs are estimated on the basis of expected deterioration and the time of maintenance. Figure 3 depicts pavement condition deterioration along with time or traffic volumes. The pavement condition declines with time or traffic up to the point that rehabilitation is performed. The figure schematically illustrates the variation in pavement condition through time resulted from two alternative maintenance strategies.

4. Application of LCCA to assist highway development

A computerized system is being developed that can perform life cycle cost analysis to assist strategic decisions regarding the design, construction or maintenance of a road as well as to support resource allocation decisions within a network of roads. Alternatives that may be comparatively evaluated refer to:

- horizontal/vertical alignment
- design standards of specific elements (e.g., pavements)
- use of materials (for construction and/or maintenance)
- type of maintenance and time of application

The system contains a relational database designed to accommodate the data required for performing the life cycle cost analysis. The database has been created trough loops of entity modelling and normalization, and contains 22 entities. Among them, there are entities corresponding to road section geometry and pavement design measures, bridge characteristics, traffic characteristics, distress and maintenance characteristics, cost groups, elements, and units, and environmental characteristics.

5. Conclusion

The study presented in this paper aims at assisting highway design and construction decisions through the employment of life cycle cost analysis. Overall highway costs are assessed based on several cost components, including construction and maintenance costs, user costs, and environmental costs, allowing, thus, comparative evaluation of alternative scenarios regarding design (e.g., horizontal/vertical alignment), construction (e.g., pavement design characteristics and materials used) or maintenance (e.g., type of maintenance and time of application). The proposed approach employs three modules, one for performance prediction of critical highway elements in time, another for estimating the resulting costs associated with the condition of each type of element, and a third one for comparative evaluation of alternative design and construction strategies. The deterioration of the highway elements (e.g, pavement, bridges, and structures) are taken into account in the life cycle cost analysis as they strongly affect several costs included in the analysis, such as, maintenance or user costs. For this purpose, deterioration prediction models are recruited through a fuzzy system approach with which qualitative information from engineering judgment is converted to numerical values to provide the prediction models under different design strategies. All corresponding information needed for performing the life cycle cost analysis is accommodated by an appropriately designed database.

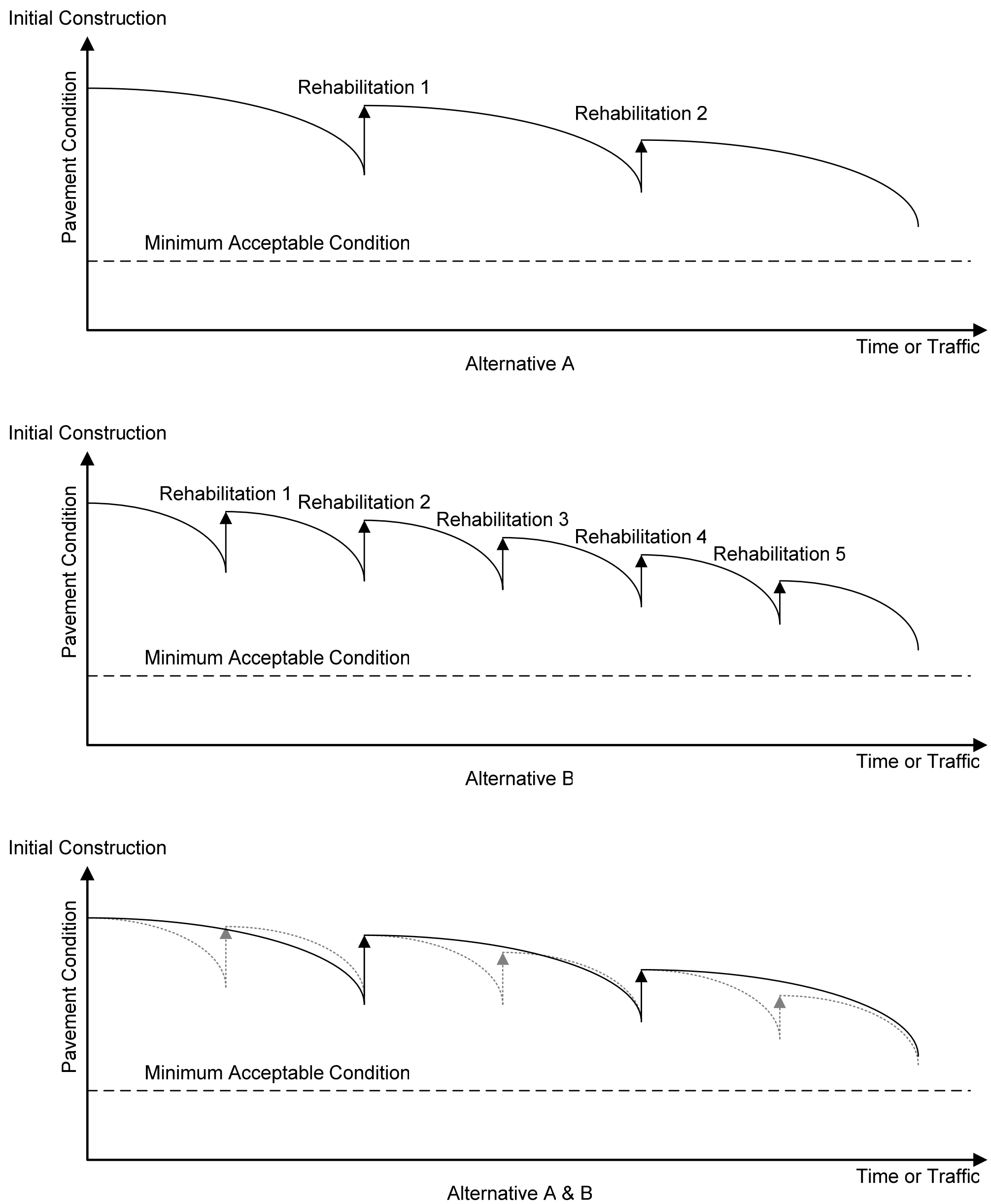

Figure 3: Life-cycle of two design alternatives

6. Acknowledgement

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