OPTIMAL LIFE-CYCLE MODELING IN PAVEMENT ANALYSIS

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ABSTRACT

Optimization within the field of asset management has often been described as the quest for the three Rs: Right treatment, Right place at the Right time.

When taking all possible influences into account, it is computationally intensive to evaluate the entire landscape of options and identify what is optimal. Whilst software exists which consider elements of user impact, these require extensive calibration. A common simplification to resolve this is the use of the Net Present Value (NPV) approach to Life Cycle Cost (LCC) when comparing treatment types based on cost, discounted to today’s value. The NPV calculation makes a key assumption that once a treatment is required, the same treatment type will be repeatedly applied to the pavement until the analysis periods for the treatments are equitable.

This paper describes a practical alternative for selecting treatment options based on a Benefit Cost Ratio (BCR). We show how it is feasible to measure a relative benefit using the integrated differential in condition parameters over the lifetime of the treatment. The BCR is computed by normalizing the total net change in condition parameters by the potential treatment cost. Benefits in future years are also discounted such that they may be directly comparable.

INTRODUCTION

The requirement for Highways managers to produce complete Asset Management Plans (AMPs) is growing worldwide. Governments have realised the value and importance of the road infrastructure asset in recent years and are now pushing forwards an Asset Management strategy both through best practice documents and guidance and through legislation such as the Moving Ahead for Progress in the 21st Century Act (MAP-21) (FHWA, 2012) in the USA. Studies have shown that a move from a reactive based maintenance regime to preventative can bring savings in the region of 20% across the life of infrastructure assets (HMEP, 2013).

A key part of asset management requires infrastructure owners to understand the current condition of assets, future condition over time and then plan maintenance proactively to select the right type of treatments at the right intervention points to achieve the lowest maintenance cost over the whole life of the asset (Crist P, 2013). This approach is normally referred to as optimization, as the analysis helps users select the optimal scenario to deliver best value over the whole life of an asset. Traditionally this has been a challenging question to answer as the comparison of treatment options requires asset owners not only to understand the relative cost of treatments, but also less tangible outcomes such as benefit to road users.

Whist software such as HDM-4 undertakes calculations to understand future benefit of specific projects, the software must be calibrated extensively across many factors to derive this. This calibration leads to some issues around sensitivity of the model in different geographies, whether all required information is available, and requires deep knowledge from the user, putting it in the hand of experts only. In addition to the challenges of complexity and calibration, this approach brings with it extensive computation, meaning calculations can take into days to complete, slowing the process and hampering an iterative approach to analysis (Remeyante-Prescott, 2011).

Up to now this exercise has been primarily undertaken in a simplified manner by calculating the Net Present Value to compare treatments by discounting to today’s value to give a direct comparison. This calculation relies on many assumptions, the key one being that once a
treatment is selected the same treatment type will be repeated over the life of the asset – which is highly unrealistic given the complexity of road infrastructure assets (Grimes, 2010).

This paper set out to define a new approach to calculating optimal treatments across the whole life of assets. As asset management becomes more prevalent, asset owners need more robust and transparent analysis tools and methods to justify their budgetary needs for asset maintenance. The benefit cost ratio method discussed here aims to provide a simple to understand approach to enable practitioners to easily analyse treatments and understand outcomes, whilst being more realistic and robust than an NPV style approach. Whilst our method considers user impact or benefit using a measure of level of service, it is not comprehensive in its ability to consider all non-hard factors which is discussed in our implementation findings.

MEASURING LIFE CYCLE COST

The Life Cycle Cost (LCC) is defined as the cost of an asset (or part) throughout its cycle life (BS/ISO 15686-5), while performing the expected level of service requirements. In the case of pavement assets, the life cycle cost captures both the routine and planned maintenance cost over the period to be analysed. The LCC may be affected by the choice of construction including material type for a given pavement intervention. Decisions can then be made to select the intervention method with the lowest overall LCC in order to deliver cost savings over the analysis period.

Routine and planned maintenance

Routine maintenance describes cyclic maintenance activities caused by a combination of traffic and environmental effects. Routine maintenance also describe the day-to-day programming of repairs that may be identified from regular or ad-hoc inspections or reported by the road users for example, crack sealing, patching, and edge repair.

The term Planned maintenance is used to refer to more major rehabilitation work in order to sustain defined levels of service.

Figure 1 illustrates the distribution of these costs over time. The costs associated with routine maintenance are therefore usually lower (than those for planned maintenance) but occur more frequently. The planned maintenance costs instead occur less frequently, specifically when the asset condition deteriorates to (or below) a defined intervention level. The intervention takes the form of a treatment that results in a positive change to the condition. There will then be a period of time before the pavement again reaches the intervention level (L_A) which we call the Treatment Life.
The condition and cost profile for a Rehabilitation Treatment (A).

The cost profile for the works is shown in the lower graph in Figure 1. Summing the costs over a specified analysis period can give an indication of the Life Cycle Cost although future costs are commonly factored into Present Value terms using a discount rate for comparison. This sum of discounts costs is known as the Net Present Value or NPV. Ignoring the costs for Routine Maintenance, the NPV for Rehabilitation Treatment A over $N$ years and a discount rate $d$ can be calculated as:

$$\text{NPV}_A = \sum_{t=1}^{N} \frac{\text{Cost}_{A,t}}{(1+d)^t} = \text{Cost}_{A} \frac{x^{nL_A} (x^{-(1+d)} - 1)}{x^L_A - 1}, \text{ where } x = (1+d)$$

Note that this method assumes the repeated application of the same treatment. The NPV for each treatment option will be different due to variations in Treatment Cost and treatment effect. The condition and cost profile for an alternative and less severe rehabilitation treatment (B) is shown in Figure 2.
Once the NPV has been calculated for each treatment option, they can be directly compared and the option with the lowest NPV selected.

The problem

Although the described approach is commonly used in determining the most economically viable option for treatment selection, it does present some challenges.

Firstly, the model assumes that a given treatment option, once selected, will be applied repeatedly over the analysis period. In practise however, the treatment selection will be a more complex process with potentially many condition parameters being utilised to determine the most appropriate treatment. Future treatments will therefore be dependent on the initial pavement condition and all prior treatments. This interdependency poses a difficult problem when trying to optimise treatments to deliver the lowest LCC.

An additional challenge relates to the selection of the analysis period. This period is selected to coincide with the end of a treatment cycle in order to capture the total benefit of the last treatment and is consequently an integer multiple of the Treatment Life. In order for a fair comparison to be made between treatment options, the period $T$ must also be identical for each treatment option. This results in the following constraint:

$$T = M L_A = N L_B$$

where $M$ and $N$ are integers.

Enforcing this constraint in practice can result in unnecessarily long analysis periods and wasted computational effort for the optimisation. One solution is to instead calculate the LCC over an infinite analysis period. This results in the following simplification to the NPV calculation:
Although this approach enables the direct computation of the NPV, it still assumes repeated application of the same treatment and additionally assumes that the discount rate will be applicable indefinitely. In reality, the discount rate includes the inflationary rates as well as the opportunity cost for investment which will vary more greatly over long time periods.

**BENEFIT COST RATIO APPROACH**

We propose an alternative to using the LCC method described above for treatment selection based on the Benefit Cost Ratio or BCR. Understanding and consequently calculating the precise benefit of a specific treatment is notoriously difficult. Systems such as HDM-4 aim to measure the benefit in terms of the reduction in user costs although this calculation involves many variables whose values may be difficult to determine precisely for a given road network. As a consequence, many simplifications and assumptions will be required in order to deliver an estimate of the overall benefit diminishing the confidence in the final result.

The cost element in our calculation is simplified down to the cost of each treatment type as a variable item (typically $m^3$) with an allowance for a level of fixed cost to cover mobilisation. Since our aim is to use the measure of benefit to compare treatment options as opposed to influence a Return On Investment decision, we choose not to calculate the final benefit to the user in monetary terms and instead focus on properties that are directly monitored as part of the survey process and also have an indirect effect on the user cost. In general, improvements in the pavement condition will lead to lower user costs through higher levels of service. We therefore propose that the net change in the pavement condition over the life of a treatment be used as a proxy for the benefit it brings to users.

![Figure 3: Calculating the Benefit of a given treatment option.](image)

The benefit of a treatment is illustrated by the shaded in Figure 3 and is dependent on the treatment effects and deterioration model for each condition parameter. Although depicted as a continuous function, the deterioration model may be approximated as piecewise linear and the benefit therefore calculated using the trapezium rule. Additionally, the benefit in future years may be discounted using the same formulation as that used by NPV to give a notional Present Benefit Value.

The shaded area in Figure 3 shows the summed total improvement in a condition above the intervention level. Where more than one condition parameter is affected by a treatment, the benefit should be aggregated over all condition parameters in order to ascertain the overall benefit.
To accommodate the fact that each condition parameter may have a different level of importance to a benefit measure and will invariably be measured using different units and scale, each condition parameter is first passed through a rating function to convert the measured value to a normalised dimensionless property. An example rating function is shown in Figure 4 where the condition parameter for rutting is linearly converted to a score in the range \([0, S_{\text{min}}, S_{\text{max}}, 1.0]\). The precise definition of the rating curve may be selected depending on the condition parameter with no limit on complexity. The maximum score value \(S_{\text{max}}\) may also be set to a value lower than 1.0 in order to down weight the contribution of a given condition parameter in the overall benefit calculation.

![Figure 4: Example Rating function for Rutting.](image)

The (discounted) benefit for treatment option A is therefore given by:

\[
\text{Benefit}_A = \sum_{m=0}^{M} \sum_{t=0}^{L} \frac{B_m(t)}{(1+d)^t}
\]

\[
B_m(t) = R_m(C_m(t)) - R_m(I_m), \quad \text{when } R_m(C_m(t)) > R_m(I_m)
\]

\[= 0 \quad \text{otherwise}\]

Where \(M\) is the total number of condition parameters, \(t\) is time, \(d\) is the discount rate, and \(B_m(t)\) described the Benefit function over time. \(C_m\) is the measured condition value of the parameter \(m\). \(R_m\) is the corresponding rating function. Finally, \(I_m\) is the defined intervention level for condition parameter \(m\).

The Benefit Cost Ratio (BCR) for a rehabilitation treatment (A) is then simply calculated as:

\[
\text{BCR}_A = \frac{\text{Benefit}_A}{\text{Cost}_A}
\]

The cost for the given treatment option may also be discounted to a present value prior to taking the ratio. The BCR for various treatment options can then be directly compared without the need for long analysis periods or the assumption of repeated application. Choosing the treatment option with the highest BCR yields the treatment which is the best value for money for the life of the treatment.
Implementation

The BCR approach described above has been fully implemented and is utilised within an Asset Management optimisation framework of Horizons. Horizons has been implemented in over 30 road infrastructure owners, being used to help manage in excess of 60,000km of roads. Figure 5 shows an excerpt from a report generated by Horizons comparing the BCR for two treatment options. The BCR for an Inlay of 50mm is shown to be a factor 4 time higher than a 150mm Inlay for a given scheme location.

![Figure 5: Excerpt from a report generated by Horizons comparing the BCR for two treatment options.](image)

At this point in time, no empirical comparison of the outcomes using the new BCR approach have been tested directly against a traditional NPV calculation of Life Cycle Cost to give a comparator. However, use cases have been applied to test the outcomes from the BCR analysis with local engineering knowledge and expectation.

Lancashire County Council in the UK utilise Horizons to manage and strategically plan maintenance on approximately 7950km of local roads. Since the implementation of the BCR approach, testing has been undertaken to assess the suggested treatment locations and dates against local engineering knowledge. Initial tests showed an 85% correlation with expectation and agreement in the selection of treatment types in over 95% of locations. Further correlation of the model on the basis of the triggering parameters has seen the correlation move to over 95% providing evidence that the approach provides a realistic and improved approach.

Whilst the BCR approach considers impact on road users by the use of treatment effect, this is done by drawing assumptions that improved road condition equate to better journey times, reliability and reduced congestion. Whilst this is largely the case in most instances, as discussed in the introduction, this road user impact does not cover the full breadth of elements required to fully optimize treatments across a road network. Soft, non-engineering factors such as politics, population, and accident rates should also be considered to achieve optimization.

To achieve this in implementation, the BCR approach discussed in this paper is in place in a wider analytical framework of Horizons. This approach allows for a wide range of other datasets to be considered as an additional analytical step to weight or factor the results produced by the BCR and add these soft factors.
Any spatial dataset can be applied to the results of the BCR analysis, allowing users to consider a complete range of non-engineering data. Each dataset can be weighted manually, or automatically using an Analytic Hierarchy Process to create weightings (Figure 6). These weightings can then be applied to the BCR outputs as an additional step to further optimize the results not simply considering the improvement in condition, but also a wider set of non-engineering data.

![Figure 6: Excerpt from Horizons user interface adding soft weightings from non-engineering data.](image)

**CONCLUSIONS**

This paper has outlined a new approach to treatment selection for pavement asset management. Existing approaches to identifying the most cost effective treatment have relied on complex, difficult to compute calculations or in a simplified method by estimating the Life Cycle Cost (LCC) and then selecting the option with the lowest cost. The assumptions of repeated treatments over long analysis periods that are required in order to calculate the LCC can lead to an imprecise understanding of the true benefit.

We have proposed an alternative approach to treatment selection that is based on the data more readily available within most asset and pavement management systems. Our approach utilises pavement condition, projected deterioration and treatment effects to calculate a benefit defined as the net improvement to the pavement over the life of the treatment. We argue that measuring benefit in this way acts as a sufficient proxy to the actual user benefit for the purpose of comparing treatments. Our method does not suffer from the assumption of repeated application of the same treatment and is able to consider each single treatment application in isolation. This in turn results is much shorter, and therefore faster, analysis processes further enhancing the usability of the method.

Whilst the BCR approach gives allowance to an assumed level of improved user service, it does not allow full optimization in the wider context of using non-engineering data. The BCR model is implemented within a wider framework which allows the weighting of treatments on the basis of non-engineering factors to further optimize outputs. The method has been implemented into existing asset management software and has been shown to deliver a step towards optimal life-cycle modelling in pavement management.

Whilst the approach to user cost is simplistic in this approach, simply considering variable cost and a fixed cost for each treatment the model will allow for more development in this area. Additional user costs such as reduction of availability during maintenance, traffic levels and inputs from more complex models such as QUADRO (DfT, 2002) could be harnessed to further improve the BCR approach.
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AUTHOR BIOGRAPHIES

Manish is the Chief Technology Officer at Yotta and has a PhD from Massachusetts Institute of Technology. His thesis work investigated the 3D reconstruction of Urban Environments from Imagery. Manish also hold a Masters in Engineering Science from the University of Oxford specialising in Machine Vision. He has worked across the entertainment and film industries in the field of motion capture before turning his hand to Highways applying this knowledge to Asset Management.

Simon has worked within Asset Management for 7 years and is a Director at Yotta Ltd. He has worked with over 50 Roads Authorities in the UK helping them to improve their Asset Management strategies from policy through to implementation.

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