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THE ANALYSIS OF ROAD CONDITION DATA

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Abstract

The paper describes the development of statistical models of road pavement deterioration based on rut progression data from 74 test sections in 8 locations over more than 20 years. Visualization led to deterioration model forms reflecting engineering experience. A full model was first proposed for each test site including all the significant variables. Reduced models were then systematically compared to isolate and remove variables with less than significant contribution to the predictive capability. A single model for all sections selected "traffic loading" as the sole factor.

INTRODUCTION

There are two perspectives associated with the maintenance of a nation's highway network. One is the network level approach, which is concerned with the overall budget for construction and maintenance, and is the perspective of senior government or funding agency officers involved in the support of development. Decisions concerning the budget for the next fiscal period are commonly based on adjustments to the previous budget, without a comprehensive view of the consequences of the increases or decreases being considered. The other perspective is called the project level approach, which is that of the engineer with responsibility for designing the individual projects which form part of the overall maintenance programme. When taken together, the costs of the engineer's annual plans invariably exceed the budget allocation and so work is left undone. In many cases the engineer believes that the delay in maintenance will lead to long term cost increases but is not in a position to demonstrate this.

This paper describes work which is part of a programme of research aimed at integrating network level highway maintenance management with the project level. The central requirement is the ability to predict the medium to long term consequences of decisions. Perhaps the first major step in the context of investment in roads was that of the World Bank in 1967 which took the decision to invest in research to develop a methodology and a model to allow a comparison of life cycle costs of roads described by Moavenzadeh et al, (1971). The three components of life cycle costs are the original construction costs of a road, the on-going maintenance costs throughout the life of the road and, finally, the costs incurred by users of a road over its lifetime. The methodology was to be aimed at the evaluation of competing demands for funds for new roads from different countries and the need for prediction of future costs with adequate precision was recognised and addressed.

The World Bank model HDM-III, described by Watanatada et al (1987a, 1987b) provided insights into the interactions between the components of life cycle costs for a single road. A less robust standard of initial construction will lead to more rapid deterioration unless there is more frequent maintenance. Lack of maintenance leads to poorer serviceability, which increases costs to those who use the road, and the number of users is a major factor in the rate of deterioration. The process of optimising the design and maintenance of even a single road is complicated. Optimising maintenance for a network involves trade-offs between different roads across the network, and further complexity is added. The overall budget may be divided into defined allocations for each class of road in the country, and it may be recognised that the strategic importance of roads varies within the classifications so all "A" roads may not be equally important. The problem of optimising maintenance over a network offers a high degree of intellectual challenge.

DETERIORATION

Roads deteriorate, resulting in poor riding quality and higher operating costs to road users. The increased vehicle operating costs (VOC) are due to higher rates of consumption of fuel, oil, tyres, vehicle depreciation, crew time, etc., and these user costs are generally the largest of the three components of life cycle costs. Timely maintenance will correct the deterioration and stop the escalation of road user costs, but the implementation of maintenance incurs costs. It may be seen that predictions of both maintenance costs and road user costs over the life of a road are critically dependent on predictions of deterioration. Such predictions were researched by, or on behalf of, the World Bank and the HDM-III software incorporates models to predict both the onset and subsequent progression of a range of defects. However the models were developed from studies on roads carrying relatively low volumes of traffic in non-freezing climates.

The need to extend the life cycle cost approach to roads carrying high volumes of traffic in countries with freezing climates was a major factor in the US Strategic Highway Research Program (SHRP) which incorporated the Long Term Pavement Performance (LTPP) data collection exercise. The aim was to begin a systematic collection of road condition data over an extended period of time for all types of road construction under various traffic loading regimes and various climates. Such a database is seen as an essential component of the research programme in order to develop or calibrate road deterioration models.

The Highways Group of the University of Birmingham is the repository of the LTPP data in the United Kingdom and also had access to data collected over a longer period by the Transport Research Laboratory (TRL) in the United Kingdom. These data sources provided the background for a successful application to the United Kingdom Engineering and Physical Science Research Council (EPSRC) for a fresh look at the statistical analysis of road pavement condition data. The aim of the three-year project was to investigate data analysis methods to be used in the development of pavement performance relationships. It was thought that multiple regression techniques, widely adopted in this and other areas, produce relationships which reflect the data upon which they are based but which lack the influence of any understanding of the underlying engineering mechanisms.

There are many different road pavement defects which are indicators of deterioration and, arguably, the three most important are roughness, rutting and cracking. It is measurements of rut depth on the various test sections which are used in this paper to illustrate the methodology.

DATA FOR ANALYSIS

The data from the LTPP studies in North America will take a few more years to establish an adequate time series. Hence, a request was made to the TRL to provide a subset of data from their pavement performance research programme which has involved the monitoring of test sections for over thirty years. Construction records, traffic loading history, Benkelman Beam deflections and rut depth measurements (taken under a 2 metre straight edge) from 74 test sections in 8 locations distributed around England and Wales were supplied. The factors which varied in the data and which are thought to influence pavement performance were the independent variables for the analysis and are;

- surface thickness
- base course aggregate type
- road base thickness
- road base material/mix type
- road base aggregate characteristics (type and grading)
- road base binder content
- traffic loading.

Table 1 summarises the experimental design in a matrix format. The reason for the initial limitation to two variables per site will become clear as the analysis procedure is described.

Table 1 - Experimental Design Matrix

Site Number	Variable Number 1	Variable Number 2
1	Base thickness: 150, 200, 250 (mm)	Base material: DBM
2(a)	Surface thickness: 100, 150, 200 (mm)	Surface material: DBM, HRA
2(b)	Base thickness: 150, 200, 250	Surface thickness: 100,150
3	Base thickness: 100, 150, 200	Base material: HRA
4(a)	Base aggregate: CR, FG, QG, LG	Base material: DBM, HRA
4(b)	Base course: : CR, FG, QG, LG	Base course: HRA, DBM, DTM
5(a)	Base thickness: 140, 210, 290	Base material: DBM, HRA
5(b)	Base thickness: 75, 150, 225	Base material: DBM, WMX
6	Base thickness: 150, 225, 300	Base material: DBM, HRA
7	Binder content: 2, 2.5, 3, 3.5, 4, 5 (%)	Aggregate grading: 3 levels
8(a)	Base thickness: 140, 210, 290	Base material: DBM, HRA
8(b)	Base thickness: 75, 150, 225	Base material: DBM, WMX

Key
CR - Crushed Rock
FG - Flint Gravel
QG - Quartzitic Gravel
LG - Limestone Gravel
DBM - Dense Bitumen Macadam
HRA - Hot Rolled Asphalt
WMX - Wet Mixed Aggregate
DTM - Dense Tar Macadam

ANALYSIS

The work proceeded in four stages;

- data familiarisation
- data censorship
- model building and
- statistical analysis of the model.

Data familiarisation

An essential first step in data analysis is to plot appropriate graphs in order to gain some insight into the distribution of the data and any patterns which may lie therein. More specifically, visualization of the data helps to resolve issues such as

- the identification of any obvious outliers,
- gaining appreciation for the amount of variation,
- detecting repeated values in some of the variables,
- gaining appreciation of the functional form of any relationships, and
- any clustering of the data.

A formal process was adopted in which graphs were brought to meetings of the research team and discussed at some length. One outcome was growing appreciation of the quality of the data, and another outcome was to decide what should be plotted for the next meeting. Figure 1 shows a typical set of graphs, in this case for site number 6 at which there are sections with base material DBM (top row) and other sections with base material HRA (middle row). For each base material there are three sections with different base thickness of 150, 225 and 300 mm plotted in columns 1, 2 and 3 respectively. There are six individual graphs in two rows and three columns, and at the end of each row and at the bottom of each column there is a graph which contains all the plots for that row or column. The quantity which is being plotted is rut depth against cumulative traffic loading in each case and, as the same traffic passes over each section at site 6, there is no problem in combining the plots at a single scale.

It is immediately clear that the trend in rut depth progression is broadly similar, however there are surprises such as the more rapid development of ruts for the thicker base layer for HRA. If any one of the plots within the matrix exhibited a clearly different trend from the others then the results would be suspect and the data for that plot subject to the data censorship rules described below.

Data censorship

The rut depths plotted in Figure 1 are actually the averages of five readings taken at equally-spaced cross-sections within each test section. The variation between these readings raises important issues. Figure 2 is a plot of the maximum, minimum and the average value of the five readings against traffic loading up to 7 million standard axles (msa). The figures were obtained over a 20 year period. The standard deviation is displayed as a bar about the mean value. It may be seen that the maximum rut depth value within a year or so exceeds the average value after 7 msa.

It seemed appropriate to apply engineering judgement rather than routine statistics to the problem of identifying data likely to be spurious. The process is labelled data censorship to make it clear that it may be regarded as subjective. A set of rules was developed and they are summarised here.

i. The range of the measurements should not overwhelm the measured value. For example, if the observed variation in rut depth measurements is ±5 mm, then the value of including rut depth measurements where rutting is less than 5 mm is immediately questionable.

ii. The range of the measurements within a test section should not mask the parameter main effects. For example, consider two test sections one with 150 mm and the other with 225 mm thick road bases and the parameter in question is road base thickness, then if the variation in rut depth measurements within each section is such that the two sections are indistinguishable then the variation is masking the effect of the parameter in question: base thickness.

iii. Trends should generally agree with the engineering expectation of pavement performance. For example, if rutting in a pavement section with 300 mm of road base is observed to be greater than that for a section with 150 mm of road base, then that test section should be subject to scrutiny and possible censorship.

iv. The effect of measurement error must not influence the overall deterioration trend. For example, the rut depth at some test sections was recorded to be greater than zero immediately after construction, which would not be possible in a predictive model. Consequently the measurements on that section should be normalised to zero initially so that the progression of rutting is what influences the model building.

Additional studies were undertaken of outliers and clustering in the data and it may be reported that no data were eliminated as a result of these studies.

The effect of data censorship was to remove some pavement sections from the initial data set used to investigate performance relationships. It was argued that the highway engineer has good understanding of the mechanisms which operate within a pavement structure. The pattern of deterioration as a function of design (explanatory) variables should follow expected norms. If it does not then other mechanisms, such as faulty workmanship during construction, may have had an effect. These other mechanisms are also understood in broad terms but their effects are less predictable. Whilst it is clearly useful to eliminate extraneous effects from the model building, it must be remembered that the predictions of the models will be subject to these extraneous effects which must be incorporated in an analysis of performance variability.

Having censored the data, an assessment was made of the efficiency and effectiveness of the resulting experimental design matrix. It was inferred that the excluded sections had no significant effect on the design of the experiment, but this process revealed the importance of the design. This may be illustrated by considering sections built to a strong initial standard such that the influence of many of the variables on rut progression was designed out. The value of the parameter rut depth remained within the noise level for its measurement and therefore the effect of the designed out explanatory variable appeared not to be significant.

Model building

It was thought to be important to identify the forms of the model, based on engineering judgement, before using statistical techniques to estimate the parameters of the model from the data. Plots, such as those in Figure 1, showing rut depth progression on many test sections after censorship revealed two broad patterns. Figure 3 shows the quadratic and the cubic curves which seemed to underlie the two broad patterns. These forms correspond with engineering understanding as described by Snaith (1985). Both show the consolidation in the wheel track soon after a road opens to traffic which is not sustained. Eventually a road will fail and, being unable to bear the load, ruts will progress more rapidly as modelled by the cubic curve. It was decided to investigate both curve forms to develop models for rut depth progression.

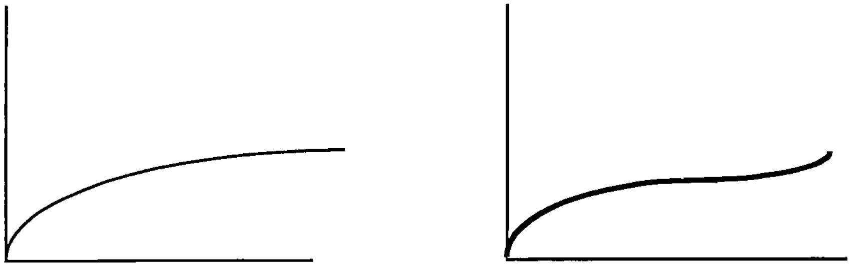

Figure 3 - Quadratic and Cubic Model Curve Forms

Statistical analyses of rut depth progression

Three explanatory variables were included in the experimental design, namely traffic loading (TR) as a continuous variable and road base thickness (BT) and base material (BM) as category variables. The models were generally of the form

Rut depth = Function of [TR, BT, BM, BT.BM]

Where BT.BM represents the interaction between base thickness and base material. Rut depth is taken to be a quadratic or cubic function of traffic whose parameters depend upon base thickness and base material. An additive model which is polynomial in TR has the advantage that it permits a study of the interactions between parameters.

ANOVA techniques were considered to be inappropriate because of a lack of balance in the experimental design due to the exclusion of some test sections. The analysis was based upon the General Linear Models (GLM) procedure in the Statistical Analysis System (SAS) package which is described by the SAS Institute (1990a, 1990b). Dobson (1990) describes how the primary effects of the explanatory variables and their interactions may be explored. A nested modelling procedure was used, with an initial "full" model which included all the explanatory variables, together with their interactions. In general, the fitting efficiency of any model improves with the number of independent variables used, but the improvement offered by some of the variables may be negligibly small. The full model was therefore a starting point for a systematic elimination of variables with too small a contribution

The full cubic model may be represented as follows

$$\begin{aligned} RD = a_1.TR &+ a_2.BT.TR + a_3.BM.TR + a_4.BT.BM.TR \\ &+ b_2.BT.TR^2 + b_3.BM.TR^2 + b_4.BT.BM.TR^2 \\ &+ c_2.BT.TR^3 + c_3.BM.TR^3 + c_4.BT.BM.TR^3 \end{aligned}$$

where

RD = predicted rut depth (mm)
TR = traffic load (million standard axles)
BT = Base thickness (mm)
BM = Base material (DBM, HRA etc)
a,b,c = coefficients to be estimated within GLM.

The above symbolic representation shows, for instance, that a_4 represents the interaction of BT and BM on the linear term in TR. A more mathematical expression would be

$$RD = (a_1 + a_2 + a_3 + a_4).TR + (b_2 + b_3 + b_4).TR^2 + (c_2 + c_3 + c_4).TR^3$$

The full model was then systematically reduced by eliminating one variable or interaction at a time. The following is the cubic form reduced by the removal of the interaction BT.BM

$$\begin{aligned} RD = a_1.TR &+ a_2.BT.TR + a_3.BM.TR \\ &+ b_2.BT.TR^2 + b_3.BM.TR^2 \\ &+ c_2.BT.TR^3 + c_3.BM.TR^3 \end{aligned}$$

Elimination of the cubic terms reduces the cubic model to the "full" quadratic model, thus

$$\begin{aligned} RD = a_1.TR &+ a_2.BT.TR + a_3.BM.TR + a_4.BT.BM.TR \\ &+ b_2.BT.TR^2 + b_3.BM.TR^2 + b_4.BT.BM.TR^2 \end{aligned}$$

The nested analysis started with the estimation of the coefficients of the full model. A measure of goodness of fit is provided by the Error Sum of Squares (SSE) which is the sum of the squares of the residuals. The elimination of a variable or interaction will produce a model with a different SSE. It can be shown that

$$\frac{\left(SSE(reduced) - SSE(full)\right)\Big/(k-g)}{SSE(full)\Big/(n-k-1)}$$

is F distributed where

SSE = The Error Sum of Squares for the (reduced) or (full) model
k = Degrees of freedom for the (full) model
g = Degrees of freedom for the (reduced) model
n = number of observation times.

Hence the F test may be used to infer whether the reduced form of the model provides a significantly different goodness of fit from that of the full model.

Table 2 - Final reduced model forms

Site	Final reduced model form	SSE	r^2
1	$a_1.TR + a_2.BT.TR + a_3.BT.TR^2 + a_4.BT.TR^3$	3.0447	0.975
3	$a_1.TR + a_2.BT.TR$	13.452	0.962
4a	$a_1.TR + a_2.BM.TR + a_3.BA.TR + a_4.BM.BA.TR + a_5.BM.TR^2$	71.608	0.907
4b	$a_1.TR + a_2.BM.TR + a_3.BA.TR + a_4.BM.BA.TR + a_5.TR^2 + a_6.TR^3$	160.724	0.916
5a	$a_1.TR + a_2.BT.TR + a_3.BM.TR + a_4.BT.TR^2 + a_5.BT.TR^3$	14.769	0.885
5b	$a_1.TR + a_2.BT.TR + a_3.BT.TR^2 + a_4.BT.TR^3$	14.212	0.966
6	$a_1.TR + a_2.BT.TR + a_3.BM.TR + a_4.BT.TR^2$	8.9175	0.853
7	$a_1\ TR + a_2.BC.TR + a_3.GR.TR^2 + a_4.TR^3$	25.189	0.916
8a	$a_1.TR + a_2.BT.TR + a_3.BM.TR + a_4.BT.TR^2$	23.270	0.674
8b	$a_1.TR + a_2.BT.TR + a_3.BM.TR + a_4.BM.BT.TR + a_5.BT.TR^2 + a_6.TR^3$	58.176	0.896

Key	TR	-	Traffic Loading	BA	-	Base Aggregate
	BM	-	Base Material	BC	-	Base Course thickness
	BT	-	Base Thickness	GR	-	Aggregate Grading

A separate model of rut depth progression was developed for each of the sites with satisfactory data. Table 2 summarises the results which may be compared with engineering expectation. In the initial stages of rut formation a linear model could be expected to be sufficient and as the rut development progresses first a quadratic model and then a cubic model will probably be required. In Table 2 it may be seen that the majority of sites require a cubic model but that both quadratic and linear models are found to be the appropriate fit to some of the data sets.

The statistical model assumes that the residuals are independent random variables. The residuals were plotted and also tests were performed using the MIXED procedure in the SAS package. It was concluded that the residuals behave as independent random variables and that an auto-regressive model would not be significantly better than the model adopted.

A SINGLE MODEL

The analysis described above led to a separate model of rut progression for each of the test sites. Whilst it is believed that the methodology adopted provided greater insight into the characteristics of the problem than earlier deterioration modelling work, the requirement for a single model which can be applied to a variety of flexible pavements had yet to be met. Hence an attempt was made to derive an overall rutting model which would be applicable to all base materials, base thickness and aggregate types. The pavement structural number concept was adopted as a proxy for pavement strength for the different pavement structures on the test sites. A Pavement Strength Number (PSN) was defined as follows

$$\text{PSN} = E * H$$

where

E = base layer modulus (MN/m^2)

H = base layer thickness (mm)

The modulus values for the pavement layers on the test sites were not available. Values for the base layers were assigned from engineering judgement based on experience of the material types used on the test sites. The assigned values were

DBM = 3100 MN/m^2

HRA = 3500 MN/m^2

WMX = 600 Mn/m^2

Table 3 - Regression models using pavement strength numbers

Site	Final regression models	SSE	r^2
1	$a_1.TR + a_2.TR/PSN + a_3.TR^2/PSN + a_4.TR^3/PSN$	8.152	0.9775
3	$a_1.TR + a_2.TR/PSN$	34.046	0.9625
4a	$a_1.TR/PSN + a_2.TR^2$	140.026	0.9348
4b	$a_1.TR + a_2.TR/PSN + a_3.TR^2/PSN + a_4.TR^3$	244.435	0.9652
5a	$a_1.TR/PSN + a_2.TR^2/PSN + a_3.TR^3/PSN$	15.299	0.9591
5b	$a_1.TR/PSN + a_2.TR^2/PSN + a_3.TR^3/PSN$	62.542	0.9463
6	$a_1.TR/PSN + a_2.TR^2/PSN$	11.004	0.9394
8a	$a_1.TR + a_2.TR/PSN$	30.908	0.8454
8b	$a_1.TR + a_2.TR/PSN + a_3.TR^2 + a_4.TR^3$	98.882	0.9441

Engineering judgement would also expect the rate of rut progression to decrease as pavement strength increases, so an inverse relationship between rut depth and PSN is indicated. Table 3 summarises the models produced for each site by the REGR procedure in SAS.

It will be noted that the error sum of squares (SSE) for each of these models is larger than for the models in Table 2. Furthermore the models were found to be little different from a single curve fitted to all pavement sections within a test site. It may be concluded that the PSN as formulated does not contribute to predictive capability. This was confirmed intuitively by plotting the coefficients found by the individual fits to test sections against the PSN values. No relationships were evident.

CONCLUSIONS

The research achieved the objective of developing a statistical procedure to be followed in the development of pavement performance models.

The paper considered only the rut progression models and it was shown that it was not possible to produce a single model with predictive capability based upon factors other than traffic loading from the available data.

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