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Time Series Analysis of Pavement Roughness Condition Data for Use in Asset Management

Hunt PD and Bunker JM

[a] *Queensland Department of Main Roads, PO Box 126, Roma, Q 4455, Australia*

[b] *School of Civil Engineering, Queensland University of Technology, GPO Box 2434, Brisbane, Q 4001, Australia*

Roughness is a direct measure of the unevenness of a longitudinal section of road pavement. Increased roughness corresponds to decreased ride comfort and increased road user costs. Roughness is relatively inexpensive to measure. Measuring roughness progression over time enables pavement deterioration, which is the result of a complex and chaotic system of environmental and road management influences, to be monitored. This in turn enables the long term functional behaviour of a pavement network to be understood and managed. A range of approaches has been used to model roughness progression for assistance in pavement asset management. The type of modelling able to be undertaken by road agencies depends upon the frequency and extent of data collection, which are consequences of funding available. The aims of this study are to increase the understanding of unbound granular pavement performance by investigating roughness progression, and to model roughness progression to improve roughness prediction methods. The pavement management system in place within the project partner road agency and the data available to this study lend themselves to a methodology allowing roughness progression to be investigated using financial maintenance and physical condition information available for each 1km pavement segment in a 16,000km road network.

1. Background

The goal of pavement management is to produce optimised pavement work programs at the network level, as well as optimised pavement rehabilitation designs at the project level. Within the pavement management process, performance predictions are important in developing optimal multi-year works programs and evaluating the life-cycle cost effectiveness of project designs [1].

Gordon [2] indicated that the monitoring of pavements is required in order to provide information on the manner in which they perform and behave. Such information can be applied to decision making processes in strategic planning, road asset management, current and future network performance, pavement design including checking of current processes, and identification of future rehabilitation works.

The use of a pavement management system provides reliable information on the condition of a network at any point in time, reliable evidence on the performance of materials and proprietary products over time, proof of the consequences of historical budget allocations, and reliable estimates of the need for future funding levels. A pavement management system allows fund managers to defend budget requests and to evaluate quickly and accurately the implications of alternative funding profiles on the resulting condition of the highway [3].

Pavements cannot be managed to the degree desired by decision makers, unless detailed and accurate information and analysis underpins the system. Road roughness data is considered to be one of the most important components of road condition information used in modern pavement management systems.

2. The Importance of Roughness in Pavement Management

World-wide, roughness is the most widely used pavement condition parameter because data is relatively inexpensive to capture, it is an objective measure, it correlates well with road user costs, and it is accepted as the most relevant measure of long term functional behaviour of a pavement network [4]. This measure assists in predicting future life, which in turn affects financial asset evaluation, prediction of remaining life and overall network condition, evaluation of affordable programs, estimation of future needs, and estimation of funding scenarios [5].

Roughness is considered to be a good condition measure as it relates well to road users' perception of acceptable ride comfort. A 1996 Coopers & Lybrand survey in the USA showed that pavement smoothness is the primary concern of the travelling public [6]. A recent survey by the Royal Automobile Club of Queensland, Australia [7] confirmed that road roughness is a primary concern of road users. Surprisingly, roughness received a higher number of complaints than those recorded for ‘narrow roads’, which were previously believed to be a more important issue.

Realistic and accurate life cycle costing analysis, and subsequent road funding scenarios, depend directly upon the accuracy of the roughness progression model used [8]. An indication of the importance of the model used was highlighted in a 1997 study that showed the rates of pavement deterioration, including roughness progression, had the greatest impact on annual maintenance and rehabilitation costs in analysis [9].

3. Measurement of Roughness

Roughness may be measured either by a response type device or by laser profilometer. The vehicle mounted NAASRA roughness meter has been used in Australia since 1972 to measure road roughness on a network wide basis. The essential component of this response type device is a transducer mounted in a car, or a single or two wheeled trailer, to sense and register the relative displacement between the sprung and unsprung masses [10]. NAASRA roughness (NRM), measured in counts/km, is the summation of the vertical movements between the vehicle’s differential and body, where 15.2mm of one way movement (measured either up or down, but not both) is equivalent to one count [11]. NAASRA roughness is usually reported at intervals of 100m.

Table 1 provides an example of the descriptive condition and associated roughness values adopted by the Queensland Department of Main Roads (QDMR) [12]. AADT refers to the annual average daily traffic on the road.

Table 1
QDMR Descriptive condition by roughness values (NRM counts/km) for varying traffic ranges

Descriptive Condition	Annual Average Daily Traffic (AADT) Range (veh/day)			
	<500	501 – 1,000	1,001 – 10,000	>10,000
Excellent	<80	<60	<60	<60
Very good	81 – 95	61 – 95	61 – 80	61 – 70
Good	96 – 130	96 – 110	81 – 95	71 – 80
Poor	131 – 180	111 – 130	96 – 110	81 – 95
Very Poor	>180	>130	>110	>95

Laser profilometers were introduced to Australia in the late 1980s to continuously measure a road’s longitudinal profile. The electronic model of the shape of the road surface, which is created during this process, can be analysed to yield output that may be correlated with NRM or the International Roughness Index (IRI). The IRI is based on computation of the dynamic response to longitudinal road profile of a much simplified vehicle model, so called the ‘quarter car model’ [13].

By definition, the IRI is computed independently for each wheel track, which presents a problem for road roughness measuring devices such as the NAASRA roughness meter, which senses the average of left and right wheeltrack profiles. Vehicle roll motion is a result of input due to the difference between left and right wheeltrack profiles, and, to a large degree, is not sensed by the profilometer, whereas vehicle bounce motion, primarily sensed by the profilometer, is a result of input due to the average of the left and right wheeltrack profiles.

In general, a better correlation between the IRI and measures from two track devices when IRI computation is based on the average profile of the two wheeltracks (half car model) rather than the average of the IRI computed independently for each wheeltrack [10].

An empirical relationship between IRI and NRM is provided in Equation (1) [11]. IRI was computed by averaging the profile of the two wheeltracks for the test road, with NRM also measured. This type of IRI calculation is often referred to as ‘Profile Averaging Lane IRI’ or ‘Half car Lane IRI’. The coefficient of correlation, R^2, of this relationship was 0.994.

$$NRM = 33.67 * \text{Lane } IRI_{hc} - 1.95 \quad (1)$$

3.1 Error in Roughness Measurement

As with any testing apparatus, a system of error of measurement exists with roughness data collection. Errors have been sourced from the literature [11] and from interviewing QDMR Pavement Testing Services staff in November 2001.

Errors applicable to both response type and laser profilometer equipment include equipment malfunction, calibration error, longitudinal distance measurement error, error in alignment with permanent road reference point, changing lanes during test to avoid object, travelling on construction side tracks during test, travelling on unsealed shoulders on narrow test road while passing oncoming traffic, and driver tracking.

Errors specific to the response type equipment include calibration creep due to vehicle shock absorber wear or general spring stiffening over time, and non standard excess mass in vehicle at time of test. Errors specific to the laser profilometer include those caused by excessive dust, excessive surface reflection of sunlight, and excessive water on the test road.

Roughness repeatability testing undertaken by QDMR's Pavement Testing Services staff, indicates that the maximum difference between a series of four to five roughness tests was 4 counts/km. For example, if the calculated average NRM is 85 counts/km, then roughness values between 83 counts/km and 87 counts/km may have been experienced during the testing. The error of +/- 2 counts/km experienced during a run of successive tests is mainly due to differences in driver tracking. This inherent inaccuracy may explain why some pavement roughness values appear to decrease over time.

Dramatic errors in annual roughness data would not likely be caused by this inherent inaccuracy; rather, are more likely due to one or a combination of the errors listed above. A robust quality assurance and control system for data collection is necessary to minimise systemic errors, which could significantly affect analysis on a network wide basis.

4. Causes of Roughness

Paterson [14] described roughness as a composite distress comprising components of deformation due to traffic loading and rut depth variation, surface defects from spalled cracking, potholes and patching, and a combination of ageing and environmental effects.

A great deal of effort has been invested in the study of roughness progression of pavements over time. Three major efforts include the development of the World Bank's HDM-3 model between 1974 and 1987, the current Long Term Pavement Performance (LTTP; ex SHRP) program in the USA, which commenced in the early 1990s, and the Australian Road Research Board's (ARRB) LTPP sites monitoring since the early 1990s. Each of these studies indicates that roughness progression is complex and that considerable variability in the rate of roughness progression between similar pavement types is experienced. Consequently it is difficult to define parameters that can reliably predict the roughness of a pavement.

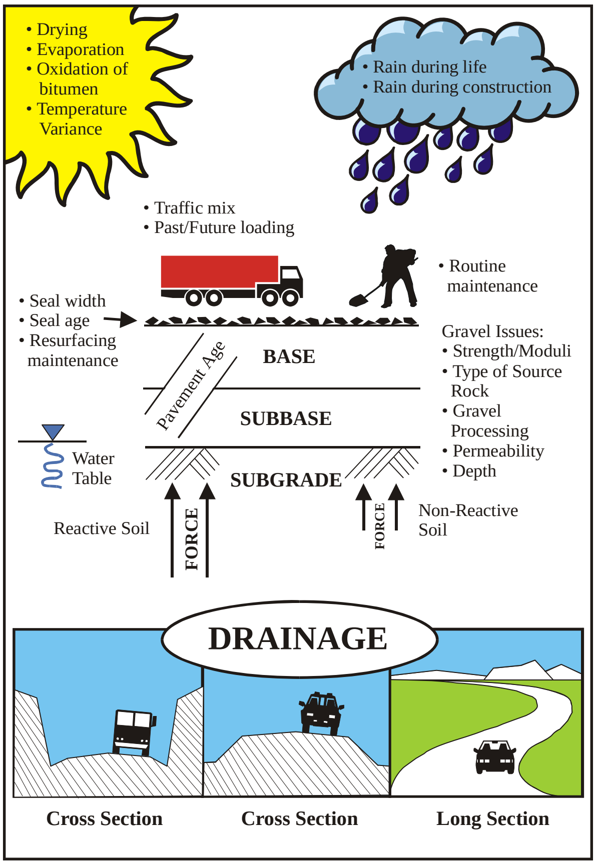


Figure 1 was developed in this study from a review of the literature and experience in pavement asset management to illustrate the complexity of influences on the roughness, and hence performance, of a pavement. Influences relating to quality – construction, material and maintenance – are not contained in the figure, however these will also influence pavement performance. There are also many material characteristics such as microscopic particle behaviour, stone size and shape, permeability, capillary rise, etc, that influence pavement performance. However, it is difficult and typically not cost effective to measure these characteristics for all pavements making up a network.

It is hypothesized that the wide variation in pavement performance is attributable to the chaotic system in which pavements operate, as evidenced by Figure 1. This system promotes different proportions of influences that exist in seemingly similar environments, thus producing different behaviours. Because roughness is a measure of the effect of the manifestation of these influences, it is considered that consistent time series monitoring of roughness is useful. However, the prediction of future roughness is still considered a somewhat imprecise science and one that is difficult to predict across a population of pavements.

Figure 1. Influential Factors on the Roughness Progression of an Unbound Granular Pavement

5. Roughness Progression Prediction Models

It is apparent from the literature the prediction of roughness progression is complex and that many variables have been used to explain it. The 'roughness progression rate', a measure of change in roughness with time, is a notion that many models use to estimate a pavement's roughness progression and hence future condition. Martin [4] provided two broad classifications of approaches used to predict pavement performance; probabilistic and deterministic.

5.1 Probabilistic Approach

Probabilistic approaches inherently recognise the stochastic nature of pavement performance by predicting the probability distribution of the dependent variable. Survivor curves of pavement performance over time or cumulative traffic loading are usually based on historical records. A survivor curve, or reliability function, is literally a graph of probability of pavement condition versus time. The Markov approach is based on the existing pavement condition and assumes that the probability of changing from one condition state to another is independent of time. The Semi-Markov approach is a simple modification designed to overcome the assumption of independence with time [4].

Models using the probabilistic approach include Network Optimisation System (NOS), Treatment Scheduling Network Optimisation System (TNOS), and Financial Planning Network Optimisation System (FNOS). The approach used in these models is suited to road network level prediction of pavement performance as the model requires limited data. However, the approach is based on a number of significant assumptions about probability distributions and future pavement performance based on current performance and is consequently limited to a 'whole of network' analysis task [4].

5.2 Deterministic Approaches

Deterministic approaches predict a single value of the dependent variable based upon statistical relationships with the independent variables, and are usually classified as mechanistic, mechanistic-empirical, or empirical [4].

The mechanistic approach is based on a fundamental and primary response to predicting pavement performance, such as elastic theory. Very few mechanistic models predict long term performance. The mechanistic-empirical approach is based upon theoretical postulation of pavement performance, but models are calibrated using regression on observed data. The empirical approach is developed from regression analyses of experimental or observed data. Models using this approach are useful when the mechanism of pavement performance is not understood. These models should not be used outside the ranges of observed data [4].

The deterministic models reviewed have been classified into the following four categories:

Causal models, which are based on the mechanistic-empirical approach, attempt to define the root cause of, or parameters influencing, roughness progression. These include HDM-3 Incremental Model, HDM-3 Aggregate Model, ARRB TR Project Model, and ARRB TR Network Model. The data required of these models is extensive and not widely available for pavements in Queensland.

Family group data fitting models, which are based on the empirical approach, use groups of data for similar pavement types or conditions, such as climate, subgrade type, traffic loading, or structure type. The average performance of each group or family is considered by a representative deterioration curve of age versus roughness, or some other pavement condition. Cardoso & Marcon [15] concluded that roughness progression was predicted more accurately under curve fitting of grouped data than by models including HDM-3 Incremental Model.

The advantage of using the family group data fitting models is that additional data can be added in the future to update family curves. In modelling a pavement's roughness progression, the pavement is identified as belonging to one of the available families, and the average roughness progression curve for that family is applied. Hence, one inherent disadvantage of this model type is the averaging effect.

Site specific data fitting models, also empirical, consider each individual pavement segment. Regression is applied to historic roughness data, and future predictions are extrapolated from the trend. The advantage of this model type is that observed performance is more closely matched for each individual segment on the network than average models. Where historic data for an individual pavement segment is inconclusive, the average family curve may be used. The QDMR data available for this study suits this type of model.

Pattern recognition models using artificial neural networks (ANNs) can store and recognise complex patterns described by many variables. Few studies have used this approach to date. Because it is still empirical, when predicting future performance, the ANN models rely upon past similar patterns. This model type is subject to the size and range in the database when seeking to recognise patterns for estimation of progression.

5.4 Modelling in a Pavement Management Context

The pavement management system must be addressed when considering the applicability of pavement roughness prediction models.

The frequency of data collection affects the pavement management system and the methodology for analysing roughness data, and predicting roughness progression.

Some models require a large amount of data, which may be expensive and time consuming to acquire, for instance pavement distress data required by the HDM-3 Incremental Model.

The cost of pavement condition data collection, processing, and storage is a major consideration in the management of a pavement network. In general, road asset managers tend to collect roughness data because it provides an objective and cost effective method of determining pavement condition, and they do not necessarily possess the resources to collect detailed distress data at an acceptable level of accuracy.

Within the overall pavement management task, different types of information are required by field practitioners, life cycle modellers, mid term and long term works programmers. A good modelling system should be able to assist all of these functions.

6. Study of Roughness Progression on an Unbound Granular Pavement Network

The aims of this study were to increase the understanding of unbound granular pavement performance by investigating roughness progression, and to model roughness progression to improve roughness prediction methods. The study used roughness data collected by QDMR across 16,000 segments of pavement each 1km in length.

If every pavement segment within the network were represented by its current roughness progression rate, and the frequency distribution of these rates were plotted for the entire network, a profile similar to that shown by the solid line in Figure 2 would be most likely evident.

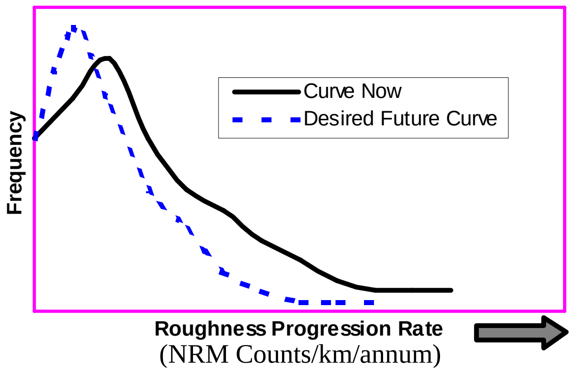
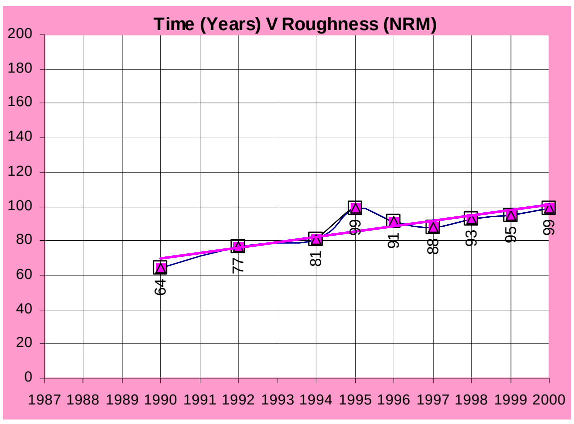


Figure 2. Idealised Road Network Roughness Progression Profile.

The proportions of poor performing pavements may be established from this distribution as those with high roughness progression rates. Once identified, research and investigation may be undertaken to understand the trends and causes of these high rates of pavement deterioration in order to derive new specifications and policies that will extend the lives of these pavements. In doing this, the network profile may be reshaped over time to a profile more similar to that shown by the dotted line. The consequences may be an increase in pavement life and decrease in annual road expenditure.

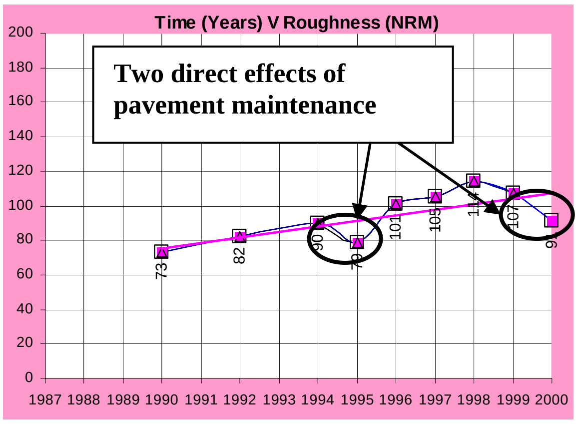
Following the review of the literature and examination of the pavement management system in place within QDMR, it was decided to adopt a methodology reflecting a combination of the *family group data fitting* and *site specific data modelling* approaches. This methodology allowed roughness progression to be investigated using information available for each 1km pavement segment in the network. The study was undertaken in the following manner:



1. Road segment (1km) data was extracted from the QDMR central database ARMIS and a data cleansing method developed to purify the data giving due consideration to data collection and handling error generation. QMDR staff assisted in this process.

2. The roughness progression trend of each 1km pavement segment with time was established in a similar manner to efforts of Paterson [14] and Perera, Byrum & Kohn [16]. The observed trends were examined and summarised. Figure 3 illustrates a typical trend, having a LRPR of 3counts/km/annum.

Figure 3. Typical Roughness Progression Trend.



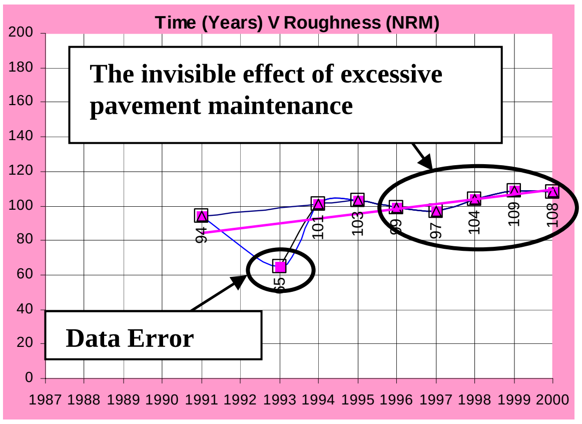


Figure 4. Masking Effect of Pavement Maintenance on Roughness Progression.

3. The literature highlighted the masking effect that pavement maintenance may have upon the true rate of pavement roughness progression. This was apparent in certain instances for the road segment data. A study of pavement maintenance data was undertaken and a process developed to identify pavements significantly affected by pavement maintenance. The masking effect of maintenance does not always directly show itself as a 'disturbance' in the roughness progression data. Two examples of pavement segments that have been identified with excessive maintenance expenditure are shown in Figure 4. A representative value for roughness progression is not sought where excessive maintenance expenditure has occurred.

4. Field practitioners commonly synthesise roughness progression information into a linear roughness progression rate (LRPR) for purposes of comparative analysis. Step 2 indicated that a linear rate could be established for majority of segments, as indicated in Figure 3. At the microscopic analysis level, a line of best fit over filtered roughness progression data was adopted for each pavement segment and the LRPR established.

5. At the macroscopic analysis level, a graphical representation was established of the distribution of LRPR across the entire network, termed the 'network profile'. This enabled a definition of pavement performance to be derived, using a 'good/fair/poor' scale. The network profile was further enhanced by the addition of poor performing pavement segments defined by high maintenance cost regimes.

6. The effects on LRPR of variables including pavement age, traffic loading, climate zone, rainfall zone, temperature zone, maintenance costs, subgrade type, seal width, and pavement structure were investigated. Whereas the study of LRPR with independent variables was unable to provide any clear trends on the prediction of pavement performance at the segment level, the study of the network profile with independent variables revealed much about pavement performance from the network perspective. This will allow the road agency to quantify the performance profile of a network of pavements with respect to meaningful variables, which can in turn inform the development of technical and funding distribution policies.

7. Preliminary analysis was undertaken, which indicates that the prediction of future roughness over a four to six year period may be based on a site specific approach, where at least six historic roughness data points are available. For other segments, use of a LRPR estimated based on AADT categories, would appear to be reliable.

The detailed outcomes of this study are to be the subject of future publication.

7. Conclusions

Roughness is the most widely used measure of pavement performance for use in managing the pavement network asset, as it is inexpensive to measure, and directly reflects road user ride comfort and costs.

Pavement deterioration occurs within a complex system influenced by the physical environment and management system. The analysis of roughness progression enables pavement deterioration to be quantified empirically over time. Numerous modelling approaches have been developed to study roughness progression, with varying levels of complexity. Selection of the appropriate model depends upon data availability and the pavement management system in place.

The methodology developed for the study of 16,000 1km segments of unbound granular pavement in Queensland, Australia will allow the effects of many variables on roughness progression to be examined empirically, which will in turn inform the development of technical and funding distribution policies.

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