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Roughness Deterioration of Bitumen Sealed Pavements

Hunt PD[a] and Bunker JM[b]

[a]Principal Engineer (Network Performance), Queensland Department of Main Roads, PO Box 126, Roma, Q 4455, Australia; ph: +61 7 4622 9545; fax: +61 7 4622 9500; email: pdhunt@mainroads.qld.gov.au
[b]Lecturer in Traffic and Transport Engineering, School of Civil Engineering, Queensland University of Technology, GPO Box 2434, Brisbane, Q 4001, Australia; ph: +61 7 3864 5086; fax: +61 7 3864 1515; email: j.bunker@qut.edu.au

SYNPOSIS

Pavement engineers have used road roughness as an indicator of a road's functional performance for many years now. Generally, the roughness data has been viewed in terms of a pavement's current absolute condition in which excessively rough roads will be earmarked for further engineering investigation and possible remedial works. Engineers have also attempted to predict the future roughness of their road network so that appropriate funding can be proactively assigned to maintain an acceptable level of service for road users. To undertake these future predictions a roughness progression model, or deterioration model, is used to increase the roughness of the pavement in proportion to its age and other parameters. Many deterioration models are available, however anecdotal evidence from practitioners indicated that the theoretical roughness progression provided by many models is rarely mimicked in real life. As such, a research project partnership was established between the Queensland Department of Main Roads and the Queensland University of Technology to investigate road roughness progression.

This paper outlines the research effort undertaken in 2001 that reviewed the actual time-series roughness progression of approximately 16,000 individual pavement segments, each 1km in length. The research was undertaken using data from the Queensland Department of Main Roads' database and spans between 4 and 14 years of roughness information. The technical challenges and resulting methodology of analysis of the time-series roughness data is discussed. The research also investigated the effects of pavement maintenance and reviewed many of the common variables such as age, soil type etc that are used in roughness prediction models.

In 2003, the analysis was re-performed with three years of additional roughness data and revealed similar results to the 2001 research. Currently the Australian Road Research Board is investigating the use of roughness progression to assist in identifying under-performing pavements. Further improvements on the current methodology and future uses of actual pavement roughness progression are also discussed.

INTRODUCTION

The State and National Highway system within Queensland, Australia extends across approximately 26,500km of bitumen sealed pavements with an estimated pavement replacement value of US$18 billion. Pavement management systems are used to assist engineers in the management of this large asset, which incorporate the recording, rating, and prediction of a pavement's condition.

One of the fundamental components of a pavement management system is the method of determining a pavement's rate of deterioration over time. Throughout the world, pavement roughness is one of the most widely used methods of measuring the performance of a pavement (Martin 1996) and was the primary focus of this research.

Queensland is a large State consisting of many small communities separated by vast distances. The majority of bitumen sealed pavements exist in low traffic volume rural areas and consist of either a flexible unbound granular pavement or a semi-rigid modified granular pavement. This project has concentrated its investigation on the roughness progression of these pavement types. Accordingly the scope of this project was limited to rural highway pavements having a bitumen sealed surface or thin asphalt (< 80mm), flexible (unbound) or semi-rigid (modified granular) pavement, speed zone 80km/hr or greater, and traffic volumes less than or equal to 5000 vehicles per day.

This paper outlines the research objective, explains the definition of roughness, looks briefly at the causes of roughness, summarises world wide roughness modelling, investigates the effect of pavement maintenance on roughness progression, outlines the roughness progression methodology, and draws conclusions for the pavement management industry. The original work also converted the findings into measures of pavement performance, which although not addressed in this paper, can be reviewed by reading Hunt (2002), Hunt and Bunker (2002), or Hunt and Bunker (2003).

RESEARCH OBJECTIVE

Figure 1 (QDMR 2000) shows four roughness/age relationships being used widely in pavement asset management. Although each model assigns a roughness progression rate based on current age or current roughness value, it is apparent that these models vary substantially in their estimation of pavement behaviour.

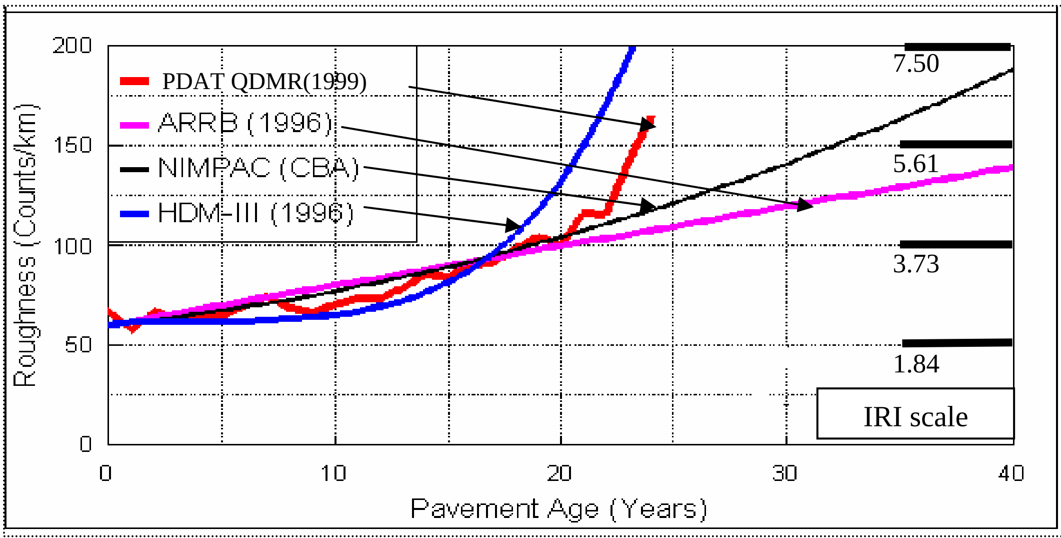

Figure 1 Comparison of the age/roughness relationship for four roughness progression models (QDMR 2000).

Within each model, a group or category of pavements with the same age or current roughness value would be assigned the same roughness progression rate in isolation to the pavement's historic performance. Many models also consider climate, structural, age, traffic loading, and surface maintenance variables. Similarly categorised pavements will also be allocated the same rate of roughness progression under these models.

However, road network engineers often observe variations in pavement performance for roads that exist in the same category. The most obvious example of this is the comparison of road projects constructed adjacent to each other at the same time. Roads constructed at the same time using the same or similar materials on the same subgrade soil type, in the same physical and traffic loading environments, often display varying rates of deterioration.

Figure 1 (QDMR 2000) indicates that many of the roughness progression models predict a rapid increase in roughness as the pavement approaches the end of its theoretical life. Road network engineers rarely observe such a rapid rate of pavement deterioration in practice. This is possibly due to maintenance that is applied to ensure that the pavement is maintained in the safe and functional condition expected by road users. This suggests that field observations do not always align well with the roughness progression models used. Therefore, the aim of this research is to better understand pavement roughness progression so that improved methods of roughness progression prediction may be achieved.

To assist in achieving this aim, pavement roughness data for 15,802 pavement segments, each 1km long, was studied. This data was supplied by the Queensland Department of Main Roads and includes physical pavement attributes and pavement maintenance cost information, supplemented with climate and soil type data.

This data was used to investigate:

- the effect of pavement maintenance on roughness progression;
- roughness progression trends and its effect on pavement performance;
- a macroscopic view of road network performance;
- the effect of independent variables on pavement performance; and
- use of this information to improve roughness progression modelling.

As mentioned above, not all of these topics are fully addressed in this paper.

ROUGHNESS

Roughness is literally the measure of the unevenness of a road surface. It is a useful term for the condition of a pavement, because it is a condition directly experienced by motorists. It is commonly reported in Australia by either the NAASRA Roughness Measurement (NRM) method (Austroads 2000), which is measured using the NAASRA Roughness Car, or by the International Roughness Index (IRI), which is calculated by applying an analytical ‘quarter car model’ to road profile data collected via laser profilometer. NRM can be reliably converted to IRI by a linear equation, and vica versa, where required.

Historically, the Queensland Department of Main Roads (QDMR) has collected NRM using the Roughness Car, a dynamic response type device, and reported both NRM and IRI. NRM is the most readily used. QDMR implemented laser profilometry in 2001 but still maintains the reporting of both NRM and IRI.

NRM is measured in ‘roughness counts’ with one count equalling 15.2mm of accumulated vertical movement between the vehicle’s differential (unsprung mass) and the body (sprung mass). NRM is effectively the roughness measured as the vehicle travels in one lane (the difference in longitudinal roughness of each wheelpath is intrinsic in this method). IRI is measured by laser in each wheelpath and is averaged to provide an IRI_{Lane} value and thus is similar in nature to the NRM measurement. Table 1 is useful in understanding the relativity of roughness values, and provides a descriptive condition of NRM and the corresponding IRI value.

Table 1 Description of roughness values NRM(IRI)

Descriptive Condition	Ride Quality	Roughness Value NRM counts/km (IRI)
Excellent	Very smooth ride.	<40 (1.46)
Good	Some minor bumps encountered.	40 to 80 (2.97)
Fair	Constant small up and down movement, but reasonably comfortable driving.	80 to 110 (4.10)
Poor	Constant up and down and/or sideways movement. Can feel very rough in Trucks. Modern cars suspension makes car driving bearable, but with low comfort.	110 to 140 (5.23)
Very Poor	Uncomfortable rideability experiencing severe up/down and/or sideways movement. Drivers must maintain good control of steering and reduce speed in some circumstances.	>140 (5.23)

A 1996 Coopers & Lybrand survey undertaken in the United States, showed that pavement smoothness, the opposite of roughness, is the primary concern of the travelling public (Civil-Engineering-USA 1998). A recent survey conducted in Queensland, Australia (RACQ 2001) confirmed that road roughness is a primary concern for road users there. Surprisingly, roughness received a higher number of complaints or concerns than that recorded for ‘narrow roads’ which was previously believed to be a more important issue.

Roughness is seen as an important road condition measure right across the world. Martin (1996) stated that roughness is the most widely used condition parameter because roughness data is relatively inexpensive to capture, is an objective measure, correlates well with road user costs, and is accepted as the most relevant measure of the long term functional behaviour of a pavement network.

CAUSES OF ROUGHNESS

The study of roughness progression with time is a complex phenomenon and is viewed by Paterson (1987) 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 2 (Hunt 2002), illustrates the complexity of influences on the roughness, and hence performance, of a pavement. Influences relating to construction quality, 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 behavior, stone size and shape, permeability, and capillary rise, that influence pavement performance. However, it is difficult and typically not cost effective to measure these characteristics for all pavements making up a network.

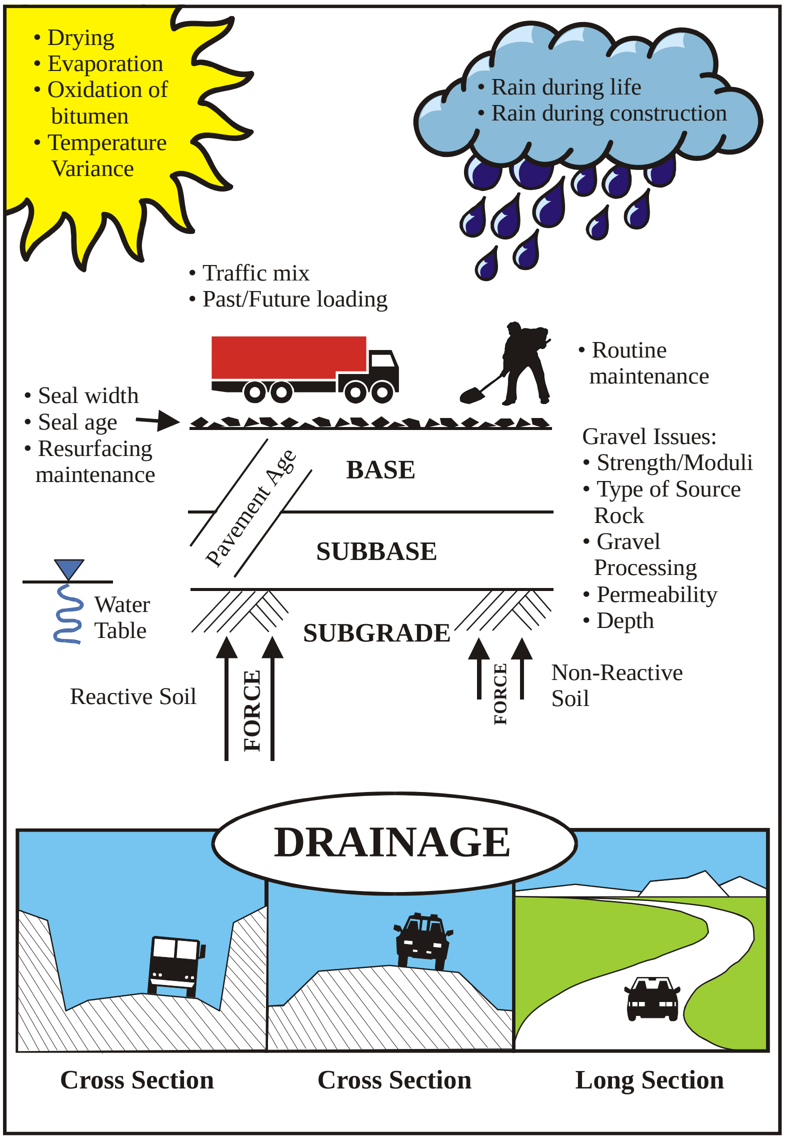

Figure 2 Influential factors on the roughness progression of an unbound granular pavement

It is hypothesized that the wide variation in pavement performance is attributable to the chaotic system in which pavements operate, as evidenced by Figure 2. This system promotes different proportions of influences that exist in seemingly similar environments, thus producing different behaviour. Because roughness is a measure of the effect of the manifestation of these influences, albeit empirical, consistent time series monitoring of roughness is useful in monitoring actual pavement deterioration. 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.

Interestingly, current Australian granular pavement design methods do not use roughness as a direct pavement design input parameter; however, the parameters used in pavement design are also often used in detailed roughness progression modelling. An indirect link exists between pavement design theory and roughness progression modelling.

ROUGHNESS PROGRESSION MODELS

The major model types currently used throughout the world have been categorised into the following four groups; Causal Models, Family Group Data-Fitting Models, Site Specific Data-Fitting Models and Pattern Recognition Models (Hunt 2002, Hunt and Bunker 2002).

1) **Causal Models** attempt to define the root cause or parameters of roughness progression. Equations are developed by subjecting the causal parameters to a variety of statistical techniques and mechanistically derived equation forms. Examples of this type of model include the HDM-3 Incremental Model, HDM-3 Aggregate Model, ARRB TR Project Model, and ARRB TR Network Model.

2) **Family Group Data-Fitting Models** predict future roughness progression based on the average deterioration curve for a series of similar type pavements.

3) **Site Specific Data-Fitting Models** base the future prediction for each individual pavement segment on the actual history of progression.

4) **Pattern Recognition Models** such as Artificial Neural Networks (ANNs) can store and recognise complex patterns described by many independent variables. When establishing a future prediction, the ANN relies on past similar patterns to predict the performance of the pavement.

A review of these model types (Hunt 2002) has shown that, because of the varying individual performance displayed by many pavements, the Site Specific Data-Fitting Models fit well into a pavement management environment and tend to provide a greater accuracy of roughness progression prediction when compared to multi-variable regression, family grouping techniques and causal models. Site Specific Data Fitting Models rely on the frequent, often annual, collection of road condition data, including roughness. This model type aligned well with the data available for the research project.

THE EFFECT OF PAVEMENT MAINTENANCE

Pavement maintenance works have the potential to ‘upset’ or ‘mask’ the true roughness progression rate of a pavement, so it was important to apply some effort into the investigation and understanding of this issue.

Ideally, the study of pavement maintenance costs and the interaction with pavement roughness would involve the measurement of the change in roughness with the associated pavement maintenance works. However, due to several data limitations the ideal situation was not practical to achieve.

Nonetheless, it was relatively easy to investigate the rate of pavement maintenance costs for any individual pavement segment. This analysis could only provide an indication of those pavements that perform poorly with respect to pavement maintenance costs over time and as such provide a ‘flag’ against those pavements where a roughness progression relationship may be either difficult to calculate or potentially unreliable.

A process was developed to identify pavements significantly affected by pavement maintenance intervention. 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 3. A representative value for roughness progression is not sought where excessive maintenance expenditure has occurred.

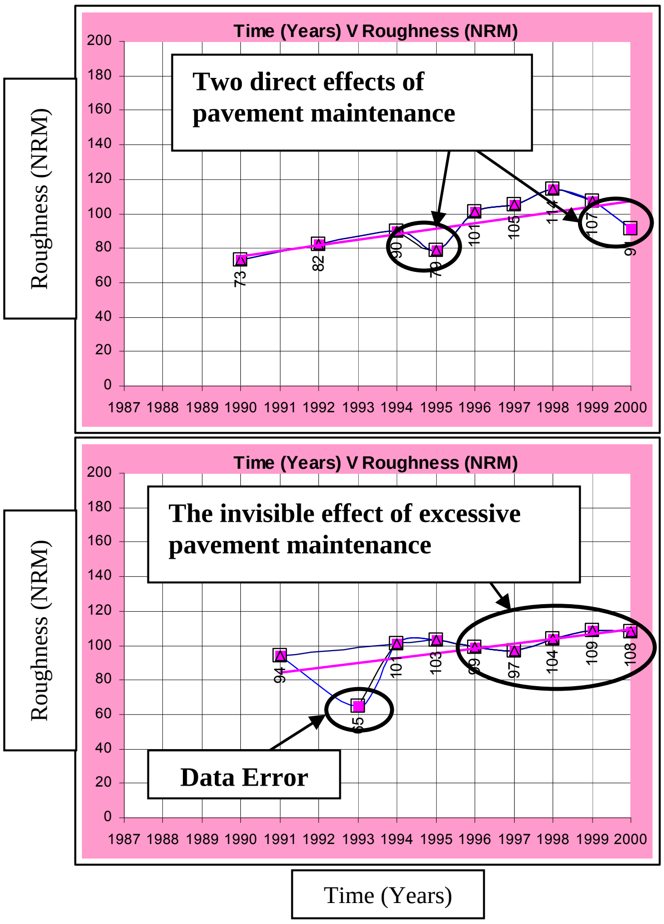

Figure 3 Masking effect of pavement maintenance on roughness progression (both examples have high pavement maintenance expenditure)

Five-year average pavement maintenance costs (5yr-APMC) were used following previous research (Hand et al 1999) that indicated that 'smoothing' the data over time provided a better indication of the pavement maintenance regime being demanded by the pavement's current performance. The 5Yr-APMCs were investigated with many independent variables including sealed width, traffic volume (AADT), annual traffic loading, treatment (pavement) age, and subgrade classification. A large scatter of results was recorded for all of these parameters. No distinct and reliable trends could be represented using a parametric relationship.

This indicated that pavements exist in all categories that required substantial maintenance funding to survive, while others require very little. This finding is an indication of the unique nature of pavement performance.

Further investigation using an existing classification of AADT enabled a better understanding of the 5Yr-APMC, as shown in Figure 4. Although large standard deviations were encountered, the analysis enabled high cost thresholds to be defined and be used in the development of a set of rules that defined excessive pavement maintenance. The following two rules were developed as an indicator of those pavements where roughness progression may not be reliable.

Rule 1. Any 3 years out 5 that have a pavement maintenance cost greater than or equal to the '1st Test Value' for its associated AADT range.

Rule 2. Any 2 years out of 5 that have a pavement maintenance cost greater than or equal to the '2nd Test Value' for its associated AADT range.

As shown in Figure 4, the '1st Test Value' is equal to the 90 percentile value for all AADT categories except for AADT 0-100 and AADT 100-500, which are slightly higher. This was done to ensure that the value used in testing each pavement's maintenance history, was realistic with respect to a practical maintenance quantum. That is, 90 percentile values could have been too easily achieved, and therefore not truly representing a poor pavement. The '2nd Test Value' is equal to the 98 percentile value.

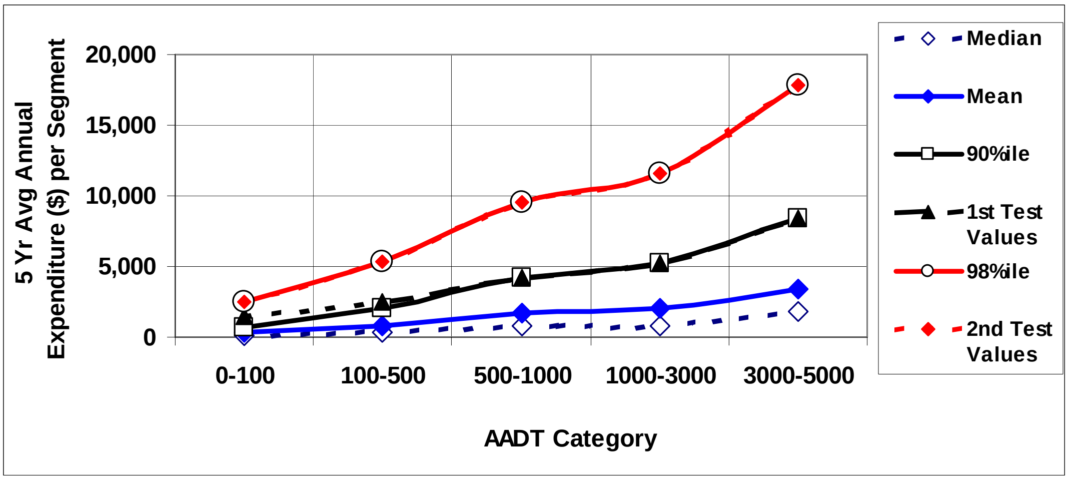

Figure 4 Network-wide maintenance cost analysis summary

These rules indicate that 3.1% of the road network has an excessive pavement maintenance cost regime, and should not be considered in any further roughness progression calculations.

It was concluded that this method, in principle, assists in excluding 'suspect' pavements from roughness progression calculations; however, the actual rule values should be the subject of ongoing research and consideration by engineering practitioners.

STUDY OF ROUGHNESS PROGRESSION

Initial Study of Roughness Data

For each of the 15,802 pavement segments a roughness progression trend was examined. Figure 5 displays the connected 'raw' roughness data points for 50 randomly selected pavement segments.

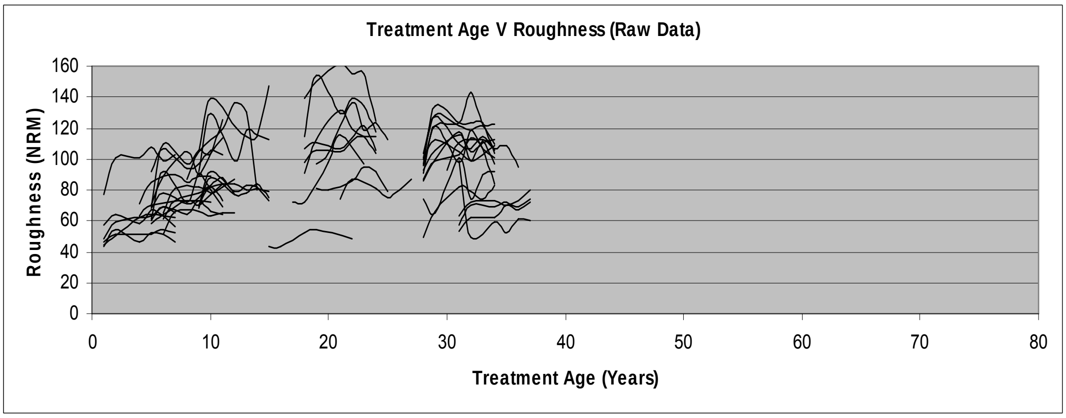

Figure 5 Roughness progression – raw data

It is evident from Figure 5 that the roughness progression of many pavement segments can initially appear quite erratic. Closer inspection of these records, as shown in Figure 6, often shows that one or two outlying data points upset what would be otherwise a straight forward relationship.

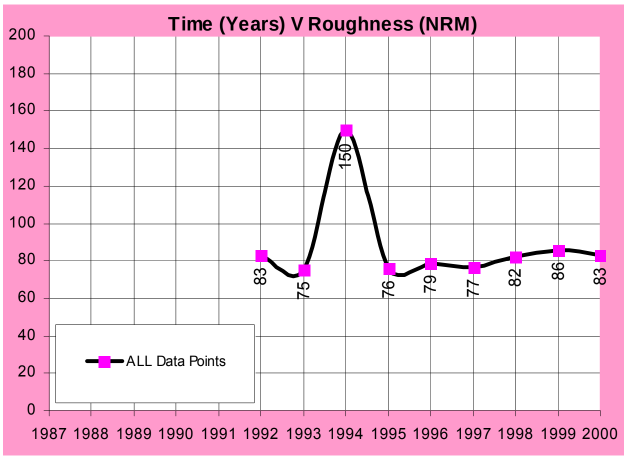

Figure 6 Closer view of a pavement segment showing erratic roughness progression

It was found that approximately 50% of pavement segments had isolated error points that show extreme variance from the surrounding data. Many of these error points are most probably due to faulty data collection, with some also due to unrecorded corrective treatments applied to pavements. It was also clear, that by ignoring the isolated error point(s), a reasonable roughness progression trend was usually disclosed. It was concluded that a filtering process applied to each pavement segment's roughness data could be useful in revealing the real roughness progression trend.

Although 50% of segments displayed an erratic roughness progression, the remaining 50% of segments did not show this extreme variance. An example is given in Figure 7.

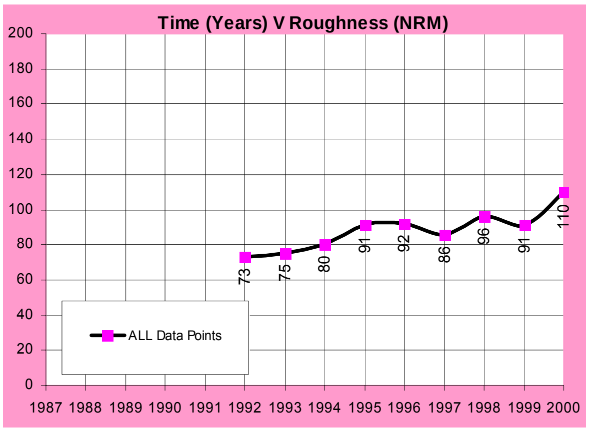

Figure 7 Closer view of a pavement segment showing steady roughness progression

It was also evident from the initial study of roughness progression that many of the roughness progression trends could be well represented by a straight line relationship. Figure 8 shows the effect linearisation can have on raw roughness data. It is evident that a robustly applied linear regression can provide greater clarity and understanding of the roughness progression relationship over time. This is considered very useful for the research of trends in roughness progression, and may provide some insight into why some pavements deteriorate faster than others.

The linearised trends of roughness against treatment (pavement) age were noted to be similar to that experienced by other international studies (Paterson 1987; Perera et al 1998). They were similar, in that, a wide variety of roughness progression rates were experienced for similar pavement types of similar ages. This highlights that pavement behaviour and the prediction of pavement roughness is complex.

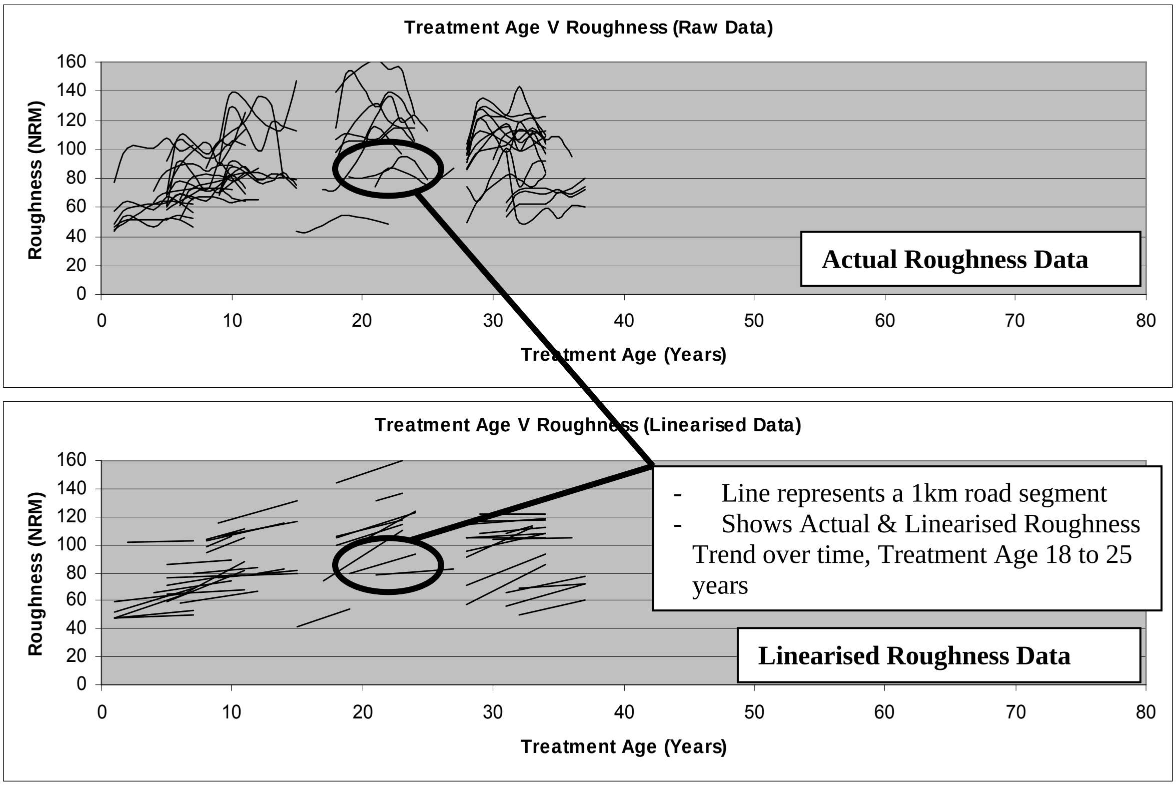

Figure 8 Linearisation effect of raw roughness progression data

It was concluded from an initial study of the roughness progression of many 1km pavement segments that:

- many pavements displayed a consistent increasing roughness trend over time;
- a large proportion of pavements (approx 80%) tended to exhibit a linear roughness progression over time;
- isolated points with extreme variance from the surrounding points were most likely from data collection error;
- some obviously unrecorded treatments existed - displaying a logical decrease (or step) in roughness data;
- some records had extreme data variance and required special consideration; and
- even the most consistent roughness data displayed a slight degree of fluctuation from year to year.

Linear Roughness Progression Rate (LRPR) Methodology

This initial work led to the development of a methodology of calculating a Linear Roughness Progression Rate (LRPR) for each pavement segment. In essence, the methodology consists of fitting two regression lines through time-series roughness data for each 1km segment, rating the accuracy of each line, and deciding which line should be adopted to represent the roughness progression of the pavement segment. This concept for handling time-series roughness data is summarized in the flowchart shown in Figure 9.

The first regression line is plotted through all points with a treatment age greater than zero (All Points LRPR). The second regression line is plotted through the data points that survive an “engineering filter”. The filter eliminates potential outliers and logical problems with the data (Filtered LRPR). It is an expert system approach, using a combination of statistics and engineering judgment, which is applied to the regression lines to select the most accurate and reliable representation. The engineering logic and approach used to perform the filtering and the selection of LRPR is extensive and more detail can be found in Hunt (2002). The LRPR chosen to represent the pavement segment is termed the Adopted LRPR.

In the event that neither LRPR is considered an accurate representation, a Default LRPR is assigned to the pavement. This is calculated by taking the most recent roughness value and subtracting a 'calculated start-of-life' roughness value and dividing the result by the treatment age. The purpose of the Default LRPR calculation is to ensure that a complete road network representation of a roughness progression rate is achieved. This is important for practicing engineers working in road asset management and is discussed further in Hunt (2002) or Hunt and Bunker (2003). However, for the purposes of research and study of relationships between LRPR and independent variables, the Default LRPR was disregarded.

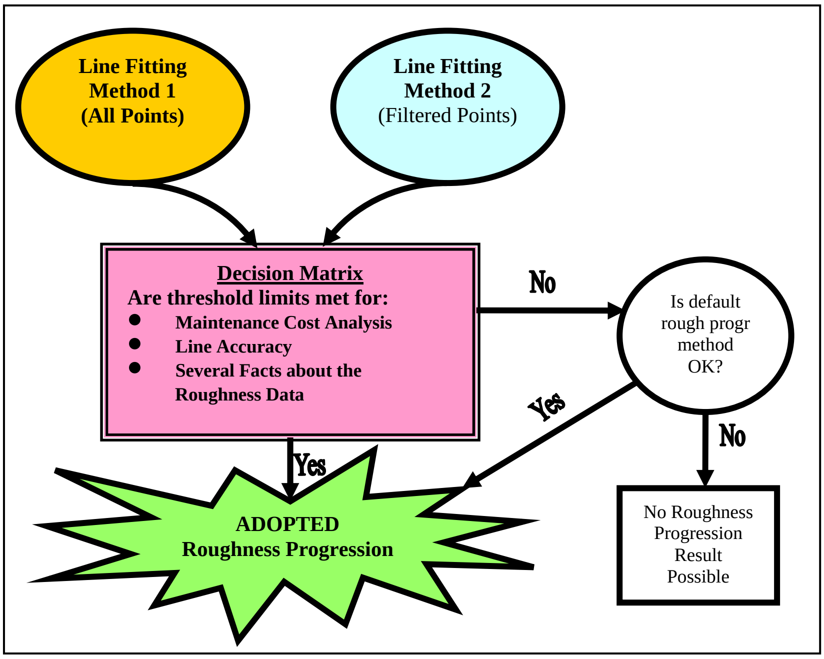

Figure 9 LRPR - Roughness progression calculation methodology

LRPR – Line Fitting Method 1 (All Points)

For a particular segment, the All Points Linear Roughness Progression Rate (LRPR) is the slope of the regression line plotted through all of the available roughness data points with a treatment age greater than zero, as shown for four examples in Figure 10.

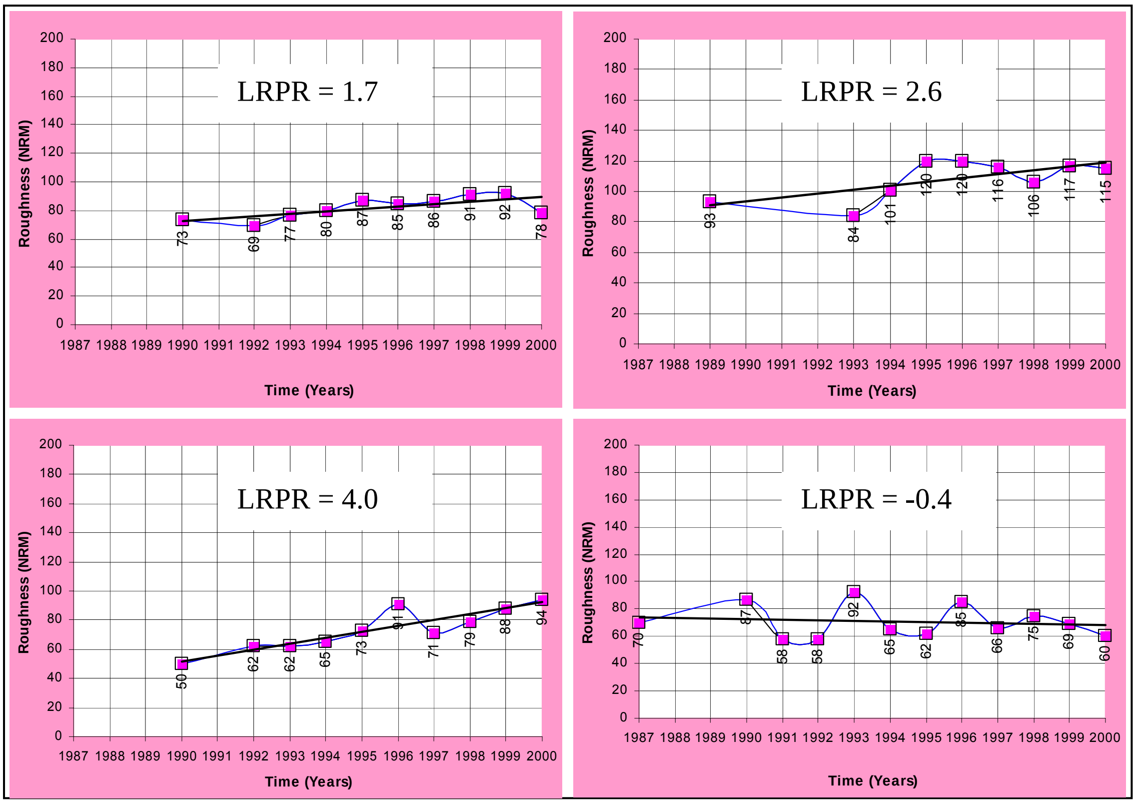

Figure 10 Examples of "All Points LRPR" for four pavement segments

The roughness progression diagrams on the left hand side of Figure 10 are examples of consistent reliable data, while the diagrams on the right hand side are examples of variable data.

The purpose of calculating the All Points LRPR is to define whether a reliable LRPR was present within the data. The measure of accuracy for the All Points LRPR is explained in Section "LRPR – Regression Line Accuracy", and is used to assist in deciding whether the LRPR is considered a reliable representation.

Based on the Pavement Maintenance Cost data and the Pavement Layer information available, it is apparent that both of the variable data examples shown in Figure 10 (RHS) have not received any physical intervention that might cause the variance shown. Therefore the variance shown has to be caused by either 'natural causes' or data collection errors. Regardless of the cause, it is considered that the lines shown, although not highly accurate, still provide a representation of the actual roughness progression experienced over time. Obviously there is a practical limit of acceptance of the All Points LRPR, based on the accuracy of the fitted line to the data. This is discussed later in Section "LRPR – Regression Line Accuracy".

As discussed earlier, many records suffered from one or two roughness data points in obvious error. One of the main reasons why a Filtered LRPR was required, was to filter out any obvious anomalies in the roughness data without compromising the integrity of the roughness data for each pavement segment. The Filtered LRPR would replace the All Points LRPR where a more accurate and more reliable relationship was found.

LRPR – Line Fitting Method 2 (Filtered Points)

Not unlike the human reasoning process an engineer performs when viewing time-series data, the purpose of the filter is to seek out a more logical and reliable roughness progression by filtering out potentially unreliable and obvious data errors, without compromising the integrity of the roughness data.

The process of developing a data filter was an evolutionary process and commenced by using simple logical rules about relationships between successive roughness data points and evolved into a complex set of rules comprising an array of data point tests to determine the acceptability of roughness data points.

The fundamental underlying assumption behind all of the current industry models is that roughness increases with time and therefore roughness progression must be a value greater than zero (or positive). This same underlying assumption was also used in the development of the filter, to primarily detect the increasing roughness progression trend over time. However, reliable decreasing roughness progression trends were also detected. Although not addressed in detail in this paper, it was considered that the majority of these 'negative LRPRs' were essentially slow deteriorating pavements, with the 'negative-ness' caused by the variation in measuring roughness from year to year (up to 4 counts/km different).

The fundamental workings of the filter are displayed in Figure 11 and consist of:

- a test that identifies the reasonableness of the most recent, or first roughness point. The most recent value is deemed the first because the backward filter commences from this value and progresses backward in time;
- a series of tests that check all the 'middle' points with the previous and the next roughness value. These tests identify 'spikey' points and roughness values that lead to excessive variability or large negative trends; and
- a series of stricter tests for the second last and last data points.

The threshold values, used to test the relationship between roughness data points, were derived from a combination of:

- the author's knowledge of pavement roughness deterioration;
- the base premise that pavement roughness increases with time; and
- the study of time-series roughness data for approximately two thousand pavement segments.

It was concluded that the Filter provides a process that mimics the engineer in the rationalisation of time-series roughness data, and was subsequently adopted. Some examples of a Filtered LRPR are displayed in Figure 12.

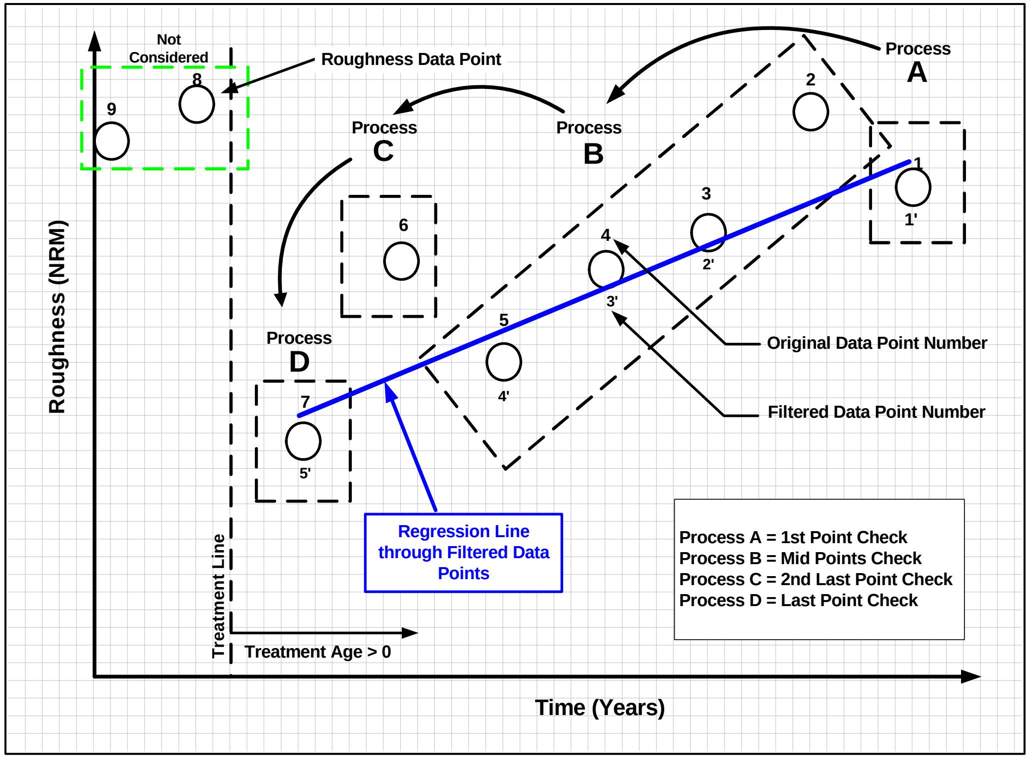

Figure 11 Summary of roughness data filter process

Process A : 1st Point Testing

1. Relationship between Points 1→ 2 are checked and compared with acceptance threshold limits. If OK, then Point 1 accepted. If not OK then goto 2.
2. Relationships between Points 2→1; 2→3; and 1→3 are checked. If OK, then Point 1 accepted. If not OK then goto 3.
3. If not accepted then next point subjected to tests. This is repeated until a reasonable first point is detected.

Process B : Mid Points Testing

1. Considers each point individually and compares the relationships between the previous accepted roughness data point and the following two data points, with itself.

(eg. Point 2 : Compares 2→1′; 2→3; and 2→4). If relationships are within threshold limits then accept point, otherwise moves to next point.

Process C : 2nd Last Point Testing

1. Compares the previous accepted point and the next point with itself. (eg. 6→4′; 6→7). If within acceptance limits then accept, otherwise reject.

Process D : Last Point Testing

1. Compares the previous accepted point with itself (eg. 7→4′).

If within acceptance limits then accept point, otherwise last accepted point is chosen as the last point.

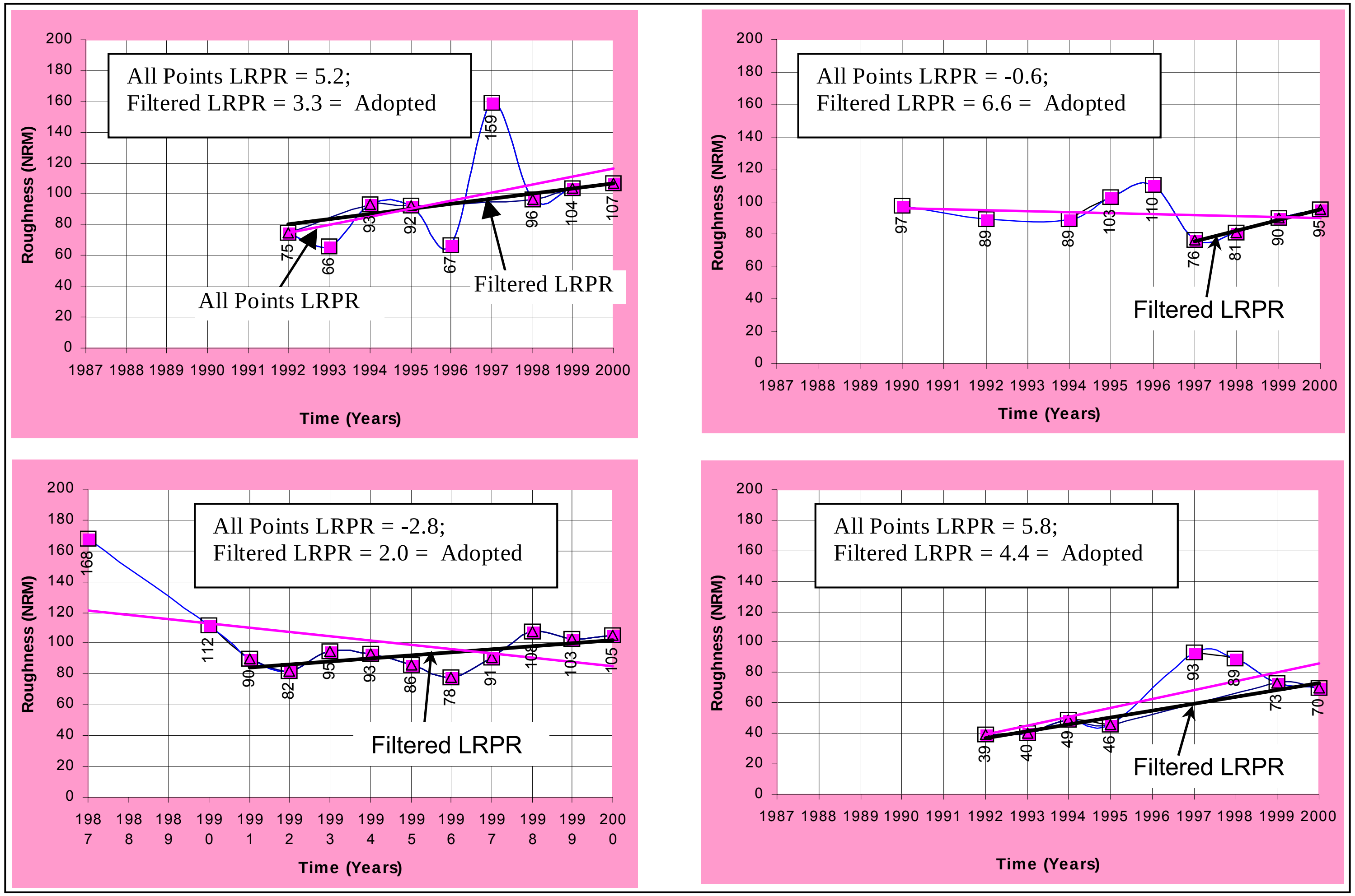

Figure 12 Examples of "Filtered LRPRs" for four pavement segments

LRPR – Regression Line Accuracy (Hunt 2002)
A linear regression can be performed through any set of data points. For this reason, it is important to also calculate an accuracy rating for the line, so that the proximity of the data points to the line can be expressed and understood.

The most common statistical method for determining how well a regression line fits the source data, is the sample correlation coefficient, r^2. The r^2 value ranges between 0 and 1, with the higher value indicating a stronger correlation.

The r^2 value is often mistakenly used purely as a means of proving how well a chosen representative line fits the source data (goodness of fit). The correlation coefficient cannot be used solely for this purpose, because the r^2 value exists to measure how strong the correlation between the independent and dependent variable is. For example, an r^2 value of 0.88 for a roughness progression over time relationship means that 88% of the variation in roughness is explained by the time (years) variable.

Therefore, a relationship with the general equation of $y = mx + c$ exhibiting a flat slope or an '*m*' value approaching zero, means that '*y*' approaches the value of constant '*c'*. In this case the r^2 value will also approach zero, as there is no correlation between *y* and *x*. This is detailed further in Hunt 2002.

Observation of roughness progression indicates many pavements deteriorate at a slow rate between 0 counts/km/year and 1 count/km/year. For these pavements, the calculated r^2 value approaches zero because '*m'* is also approaching zero, even though the regression line may fit the source data quite well.

Due to this problem, r^2 is not considered a good method of expressing the goodness of fit for a linear roughness progression line. Hence, a different way of expressing how well the regression line fits the source data, needed to be identified.

Five alternative methods including Sum of Squared Differences, Variance, Root Mean Square Error, Standard Error and Mean Absolute Error were investigated, resulting in the Mean Absolute Error (MAE) being adopted. The MAE method is advantageous as it 'averages out' isolated outlying points and provides a stand alone meaningful value (eg. a value of five indicates that the average distance of the actual points from the regression line is five counts/km). The statistical representation of the MAE is:

Mean Absolute Error (MAE) = $\frac{1}{n}\sum_{t=1}^{n}\left|\left(y_t - \hat{m}t\right)\right|$ Equation 1.

Where y_t = Actual Data Point at time *t;* $\hat{m}t$ = Regression Line Value at time *t;*and n = number of samples.

A descriptive classification (Very Good, Good, etc) of the MAE values was developed to describe the goodness of fit. These are shown in Table 2.

Table 2 Descriptive classification of Mean Absolute Error (MAE) values (Hunt 2002)

Mean Absolute Error (MAE) (Roughness Counts/km)	Goodness of Fit Description
0 – 3	Very Good
3 – 6	Good
6 – 9	Average
9 – 12	Variable Data
> 12	Higher Variability

These MAE values were used in the development of rules which would assist in choosing the best fit regression line between the All Points regression line (method 1) and the Filtered Points regression line (method 2).

LRPR – Adopted LRPR

As already mentioned, the process that selects the better representation of roughness progression between the All Points LRPR and the Filtered LRPR is termed the 'Adoption Process', with the selected LRPR termed the 'Adopted LRPR'.

The Adoption Process assesses both the All Points LRPR and the Filtered LRPR giving due to consideration to the following attributes :

- Excessive Pavement Maintenance Costs;
- Sign (±) of the LRPR (negative or positive);
- Mean Absolute Error (MAE) value;
- Number of Points used in each of the LRPRs;
- Number of Points ratio (Filtered/AllPoints); and
- Consecutiveness of the roughness data points.

An expert system approach using a complex set of interacting rules based on the parameters above and engineering judgement was developed. This included the definition of suitable threshold limits and logical exclusion/inclusion limits for the above parameters to determine the most suited LRPR. Hunt (2002) provides a flowchart highlighting the summary algorithm and detailed process algorithms.

In the event that neither LRPR is considered an accurate representation, a Default LRPR is assigned to the pavement and is calculated by taking the most recent roughness value and subtracting an 'calculated start of life' roughness value and dividing the result by the treatment age. It is acknowledged that the current rules may be refined over time as exposure and discussions with other asset engineers occurs, however, the methodology proposed is considered sound.

The purpose of the Default LRPR calculation is to ensure that a complete road network representation of a roughness progression rate is achieved. This is important for practicing engineers working in road asset management. However, for the purposes of research and study of relationships between LRPR and independent variables, the Default LRPR was disregarded.

In summary, the Adoption Process performs the following tasks :

- All pavement segments classified as Poor Pavement Maintenance performers are segregated and are not subjected to the following Adopted LRPR processes.

- Each pavement segment is classified according to the 'sign' (±) of the All Points LRPR and the Filtered LRPR. (Groupings include (+,+), (+, -), (-,+), and (-,-)).

- For each sign (±) classification, a series of tests is applied to determine the better representative LRPR. These tests use a combination of the MAE, number of roughness data points, Points ratio (Filtered/All Points), and the consecutiveness of the data in its determination.

- Pavement segments that fail the above tests have a Default LRPR calculated.

- If the Default LRPR is not considered a reasonable value, the pavement segment is discarded and classified as 'no calculation'.

The results of the Adoption Process are shown in Figures 13 and 14, and indicate that the All Points LRPR is considered the most reliable representation of roughness progression 45% of the time. Together, the All Points LRPR and the Filtered LRPR were able to represent the roughness progression of 84% of pavement segments. Furthermore, it was noted that 61% (4289 km) of the All Points LRPRs were equal to the Filtered LRPR, which indicates a high degree of linearity in the data. LRPR values vary from –3 counts/km/yr to +10 counts/km/yr with values ≥ 4 counts/km/yr considered to be fast deteriorating pavements (Hunt 2002).

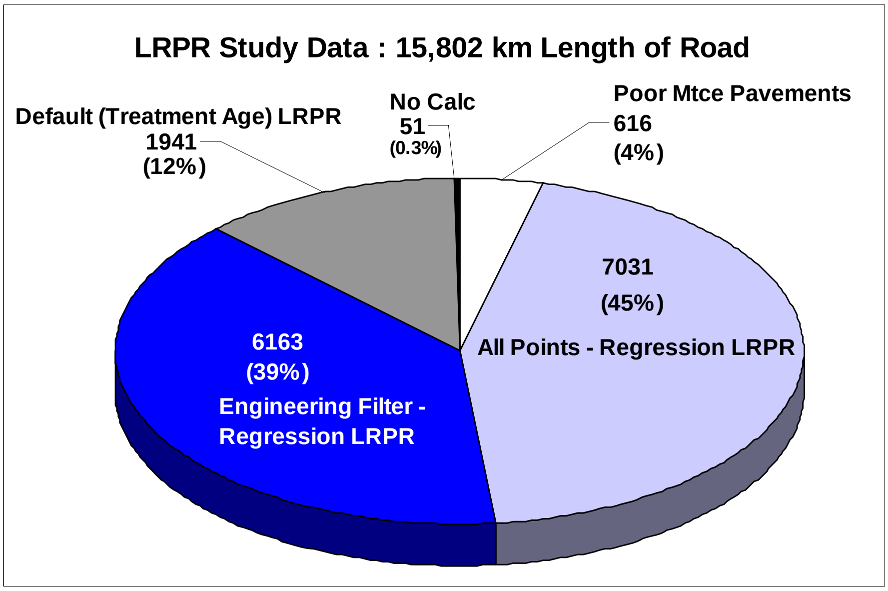

Figure 13 Summary of roughness progression (LRPR) calculations

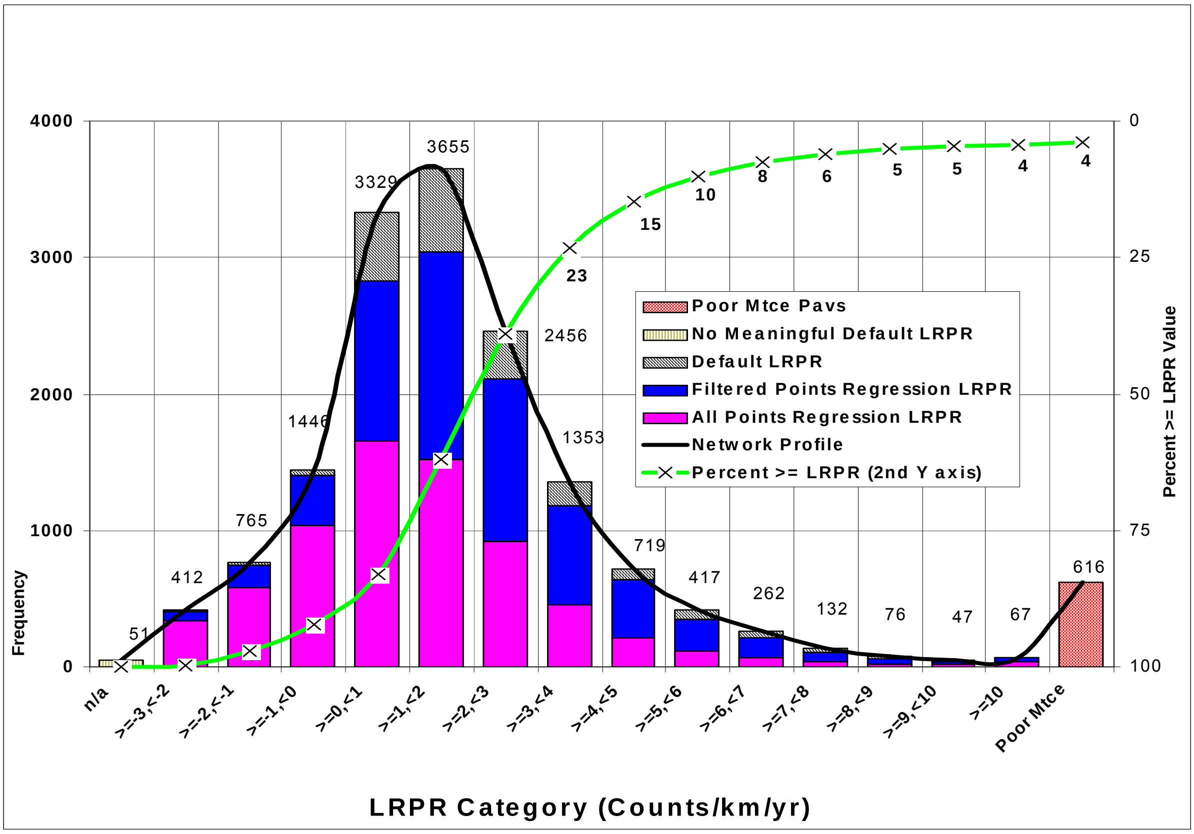

Figure 14 Summary of LRPR values per regression line origin

ROUGHNESS PROGRESSION (LRPR) WITH INDEPENDENT VARIABLES

Several key independent parameters have been used in previous roughness progression research, including pavement age, traffic loading, loading by heavy vehicle type, climate zones, rainfall zone, temperature zone, maintenance costs, subgrade type, seal width, pavement structure and structural number. With the exception of pavement structure and structural number, linear regression was applied between these parameters and LRPR to establish whether any trends were evident. Each regression returned a very low r^2 value. Given the considerable spread in the data between LRPR and each independent variable, it was concluded that LRPR, or roughness progression, could not be represented as a two-dimensional function.

Several data mining techniques including Neural Networks, Rule Induction (or Decision Tree Analysis), Memory Based Reasoning, and Logistic Regression, were used to determine whether any combination of the independent variables could be used to predict roughness progression. All methods failed to provide any useful predictive model.

The data indicates that each pavement segment is unique in its roughness progression (a bit like humans), and there is no one model that can accurately predict roughness progression across a population as a function of these independent variables. This questions the suitability and reliability of all 'formula based' roughness prediction models and is explained further in Hunt 2002.

PAVEMENT PERFORMANCE

The research effort spent considerable time investigating the use of LRPR and excessive pavement maintenance pavements as a definition of pavement performance. It was concluded (Hunt 2002) that these parameters were useful in assisting engineers identify poor performing pavements. The performance definitions were converted into Network Profiles (frequency distribution of performance for various independent variables). These Network Profiles proved very useful in understanding the overall performance of the road system. The Australian Road Research Board are currently investigating the use of such information in asset management practice.

PREDICTION OF ROUGHNESS PROGRESSION

The underlying aim of the research was to better understand roughness progression in order to improve the prediction capability of the roughness progression of a pavement segment.

The literature highlights that, where annual roughness data is collected, a Site Specific prediction approach (or individual pavement segment approach) is more successful than existing mechanistic-empirical formulae or average family deterioration curve fitting (Cheetham 1998, Hajek et al 1985, Garcia-Diaz and Riggins 1985, Ping and Yunxia 1998).

This research indicated that at least six data points were required to confidently project a fitted line through historical data and into a predicted future five-year timeframe (Hunt 2002).

CONCLUSIONS AND INDUSTRY APPLICATION

This research has focussed on a practical management approach to the investigation and understanding of the roughness progression of pavements.

As described by Gordon (1984) the goals of a pavement management system are to monitor pavements in order to provide performance information that can be applied to decision making processes in strategic planning, asset management, current and future network performance, pavement design (checking of current processes), and identification of future rehabilitation works.

In accordance with these goals, site specific methods were used to analyse individual pavement segment performance and is discussed in detail in this paper. This derived site specific performance was aggregated across a network of roads to produce network performance measures. These network measures have only been briefly discussed in this paper but are addressed in full detail in Hunt 2002.

The main conclusions and industry uses are that:

- The roughness progression of each individual pavement segment is unique. It is highly unlikely that there is a model that can easily and accurately represent the roughness progression of all pavements across a population, as a function of independent variables currently in use.
- Historic roughness progression of a pavement segment can be defined by linear regression (LRPR) for a majority of the road network.
- The monitoring of the excessive use of pavement maintenance funds to maintain pavement functionality, assists in 'unmasking' pavements that may provide a misrepresented LRPR.
- A combination of the LRPR and excessive pavement maintenance expenditure may be used to define a Pavement Performance, which aids in measuring the performance of a road network.
- Prediction of pavement roughness, based on an extrapolation of the pavement's LRPR, is a useful method of predicting roughness over a five year timeframe. A higher degree of accuracy is gained if at least six historic data points are used.
- A meaningful and useful roughness/age relationship, for use in the prediction of future roughness, could not be established.
- Currently, road network performance is commonly defined only by a measure of the road network's Absolute Condition. The Network Profile work outlined in this research will add measures of pavement performance to the current definition. By including a Current Network Profile, and a more robust method for predicting five year roughness values, engineers will now have a suite of information to enable historic, current, and estimated future road network condition, to assess the impact of previous and current management decisions.
- Study of network profiles for a variety of independent variables can assist the understanding of the in built risk of the current pavement design and delivery system. The knowledge gained from a global analysis of condition may form a catalyst for the assessment of material quality, design methods, construction technology, and contract delivery, to ensure that pavements have the best chance of performing well.

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REFERENCES

Austroads, *Guidelines for Road Condition Monitoring, Part 1 - Pavement Roughness*. (2000).

Cheetham, A. *Auto Adaptive Pavement Performance Prediction Methodology*. Fourth International Conference on Managing Pavements. (1998). Durban, South Africa.

Civil-Engineering-USA, *Study proves Smoothness Extends Pavement Life*, Civil Engineering (USA). (1998).p. 13-14.

Garcia-Diaz, A. and Riggins, M., *Serviceability and Distress Methodology for Predicting Pavement Performance.* Transportation Research Record, (1985). 997: p. 56-61.

Gordon, R. Monitoring of Pavement Performance. in South Western Division Queensland Department of Main Roads Symposium. (1984).

Hand, A.J., Sebaaly, P.E. and Epps, J.A., *Development of Performance Models based on Department of Transportation Pavement Management System Data.* Transportation Research Record, (1999). 1684(Pavement Design, Management and Performance): p. 215-222.

Hajek, J.J., Phang, W.A., Prakesh, A. and Wong, G.A. *Performance Prediction for Pavement Management*. in *North American Pavement Management Conference, March 18 to 21 1985,*. (1985). Toronto, Canada.

Hunt, P. *Analysis of Roughness Deterioration of Bitumen Sealed Unbound Granular Pavements for Use in Asset Management Modeling, (2002)*. Master of Engineering Thesis, Queensland University of Technology, Brisbane, Australia. p 232

Hunt, P. and Bunker, J. *Time Series Analysis of Pavement Roughness Condition Data for Use in Asset Management*. Third Asia-Pacific Conference on Systems Integrity and Maintenance (ACSIM), (2002). Cairns, Australia.

Hunt, P. and Bunker, J. *A study of Site Specific Roughness Progression for a Bitumen Sealed Unbound Granular Pavement Network*, Eighth International Conference on Low-Volume Roads, (2003), Reno, Nevada (USA). TRB Record No 1819 Volume 1

Martin, T.C., *A Review of existing pavement performance relationships*. (1996), ARRB Transport Research: Vermont South, Victoria, Australia. p. 60.

Paterson, W.D., *The Highway Design and Maintenance Standard Series - Road Deterioration and Maintenance Effects*. First ed. (1987): A World Bank Publication - The John Hopkins University Press - Baltimore.

Perera, R.W., Byrum, C. and Kohn, S.D., *Investigation of Development of Pavement Roughness : Long Term Pavement Performance project. (LTPP)*. (1998), FHWA - Federal Highway Administration : US Department of Transportation. p. 285.

Ping, W.V. and Yunxia, H.E., *Evaluation of Flexible Pavement Performance Life in Florida*. (1998), Department of Civil Engineering: Tallahassee Florida. p. 231.

QDMR, *A Brief Report on Pavement Deterioration Profiles (PDAT)*. (2000), Queensland Department of Main Roads. Asset Management Section : Road System Management Division: Brisbane, Australia. p. 15.

RACQ, *Unroadworthy Roads Survey 2001, (*2001), The Royal Automobile Club of Queensland Limited: Brisbane, Australia.

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