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# Pavement structural performance: Predicting remaining life using rapid non-destructive testing

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ABSTRACT: Non-destructive testing of pavements has progressed, from widely spaced pseudo-static methods, namely Falling Weight Deflectometer (with typically 300 tests per day), to Traffic Speed Deflectometer (40-70 km/hr), and now Multi-Speed Deflectometer (5-65 km/hr) testing both wheelpaths at 1m centres with 300,000 tests per day on urban roads. Analysis methods have also advanced so that interpretation can now be a matter of hours at most or close to real time in some instances. The technology has advanced, but has the interpretation and prediction of pavement performance? Deflection test studies of "Hit Rate" (defined as the success of predicting whether a given treatment length would reach a terminal structural condition within a prescribed time period) have been attempted previously, but well documented case histories are rare. This article presents the establishment of a study involving sites where different deflection methods have been applied, including some for which data were collected many years ago, with a long record of subsequent performance under known traffic loading. As well as documenting the necessary data for determination of Hit Rate, alternative methods of analysis and interpretation are used to compare the old and newer technologies as well as the outcomes using both traditional analysis methods and more recent developments, so that network managers, designers and contractors can evaluate the reliability of different techniques now available for predicting the remaining structural life of pavements.

*Keywords*: Pavement, life, prediction, traffic, speed

## 1 BACKGROUND

Prediction of pavement performance is a key issue where a medium- or long-term forward work programme for structural rehabilitation and its associated cost is a statutory obligation of roading authorities. Using surface condition data and visual observations, many experienced pavement practitioners can predict the lengths and extents of their roads which will reach a terminal structural condition in the next year, and maybe the next two years.

However, where the demand is for a Forward Work Programme for structural rehabilitation that predicts the timing of terminal structural condition out for more than 30 months (and out to 30 years), reliable methodology to produce a dependable annual budget over even a moderate time is a challenge.

This article addresses the success (or otherwise) of specific methods of pavement life prediction focusing on structural rehabilitation rather than resurfacing (as the former is usually the more uncertain cost per lane kilometre for any given network in any given future year).

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## 2 TERMINAL CONDITION & HIT RATE

Highway authorities with good subsurface (structural) information may define the terminal condition of a given treatment length as being when the net present value (NPV) of long term ongoing structural maintenance exceeds the value of structural rehabilitation. However, that necessitates what is often a highly subjective speculation on what type and extent of maintenance will be required to effectively calculate costs in every subsequent future year for the duration of the planned Forward Work Programme.

On the other hand, authorities for local roads tend to have less budget per kilometre, and for lesser trafficked roads they may have only surface condition (rather than any structural) information, hence there may be a tendency to place more weighting on visual inspections of the surfacing and surface condition indices (such as PCI, PSR or SCI). The visual Level of Service (LOS) approach usually adopts trend analysis and prescribes trigger criteria for individual distress modes (rutting, roughness, cracking etc) primarily to make decisions on timing of re-surfacing.

Whether structural rehabilitation is required at the same time or later is a separate issue necessitating structural information without which the approach is likely to be adequate only for the short term (1-2 years). The assignment of terminal condition may therefore be consistent within a network but could vary considerably between networks where different definitions (e.g., LOS vs NPV or other criteria) apply.

Historically, the industry's ability to predict pavement structural life in the range of say 30 months to 30 years has been at best questionable with some studies showing orders of magnitude error (Arnold et al, 2009). The terminal structural condition of a treatment length can be simply defined as its condition in the year in which the controlling authority (or others affected by the funding consequences) for that road finally confirms that rehabilitation is to commence (i.e., using reality of the situation rather than any calculations or assumptions made in NPV or LOS approaches).

To have a measure of the reliability of predicting pavement life, the Hit Rate could be defined as the success of predicting whether a given treatment length would reach a terminal structural condition within a prescribed period. Because that definition is qualitative, then for the purposes of this study, Hit/Miss outcomes will be assigned by assuming "useful prediction" to be when the number of years to terminal condition is within 1 year +/- 10% from the time of prediction. This allows for the necessary marginal cases whereby at least one treatment length may be either brought forward or deferred a year by the controlling authority for administrative or budget reasons regardless of the engineering evaluation.

For example, if 10 years is the originally predicted life, a Hit would be assigned if the actual year in which rehabilitation is confirmed by the authority eventuates between 8 and 12 years while any other time estimate would constitute a Miss. Alternatively, rather than be constrained to a binary measure, a Hit Rate% could be defined as the minimum ratio of the two durations after allowing for the accepted margin, but expressed as a percentage. In the above case, if the actual rehabilitation is done after 6 years and the initial prediction of 10 years (considered acceptable at 10-(10*10%)-1=8 years), then the ratio becomes 6/8, i.e., the Hit Rate% is 75%, (relative to an ideal of 100%). For this study, the objective is to establish a quantitative (yet practical) performance measure for comparison of different methodologies for life prediction.

While the Hit Rate concept has been discussed for the last 20 years, since 2010 there have been no formally published local case histories, even though 6 years of Traffic Speed Deflectometer (TSD) data have been collected regularly throughout New Zealand's national state highways.

Some documentation exists for a case that arose after the Kaikoura Earthquake due to the rerouting of traffic from a heavily loaded primary highway onto 800 lane km of secondary highways. This presented an effective opportunity to observe accelerated trafficking of highways with inadequate structural capacity for the loads imposed, (Stevens et al, 2016). Over the following year, effectively 15 years of the customary heavy traffic was experienced. Predictions of the effects of such overloading were made from TSD structural data at 10m intervals: the model was prepared using generalised mechanistic procedures for the analysis but limiting the necessary site calibrations by adopting an "80/20" approach for expedience. The intention was to target 80% reliability for predictions while limiting site validation time to 20% of that desirable for a thoroughly calibrated model.

The calibration of the model used an approach termed Regional Precedent Performance (RPP, discussed below) which uses the historic performance of a wide selection of mature pavements from the local road network using field observations and monitoring under the actual traffic (rather than nominal fatigue criteria from laboratory or overseas studies). The findings were presented to the project engineer responsible for remediating the effects of overloading who remarked that the targeted 80% reliability for RPP life predictions from the 10m TSD data was achieved, and in his view was closer to 90%.

A second RPP case history was carried out at the same time for all highways in the Waikato region of New Zealand. This highway network also had full coverage with TSD Gen. II at 10m centres in each lane. Before visual site calibration was carried out, the GIS image showing the RPP remaining life throughout the network was presented to the roading authority's Regional Engineer, who considered the duration and spatial distribution entirely consistent with his substantial field experience and expectation.

These two specific cases indicated that TSD data and its interpretation can be highly effective for prediction. The findings were passed on at the following Deflection at Road Traffic Speed meeting (DaRTS, a forum of specialist TSD users and researchers led by TRL/Highways England) but met the response from one TSD user that 80% reliability was not considered achievable. Evidently, documentation of prediction versus reality for a more comprehensive range of cases histories is warranted.

## 3 ALTERNATIVE METHODS OF PAVEMENT LIFE PREDICTION

Many methods of pavement life prediction have been considered (most being empirical only), but with increasing ease of adopting highly efficient processing of large datasets from traffic speed structural data collection, mechanistic-empirical models can provide much greater insight. The bases of some of the models that have been (or are being) used locally, are given below.

Table 1. Predictive Methods.

| METHOD | BASIS |
|---|---|
| Benkelman Beam | Central deflection |
| Shell - Asphalt Institute | Vertical strain at top of subgrade and horizontal strain at base of asphalt layer. General fatigue criteria. |
| NRB, Austroads | Subgrade CBR and pavement thickness |
| HDM III, IV, RIMS | Structural number (SN, SNC, SNP) |
| AASHTO '86 | Structural number |
| AASHTO '93 | Structural number |
| Austroads Simplified | Central deflection if unbound. Curvature function added for surface bound layer. |
| Austroads GMP | Vertical strain at top of subgrade and pavement layer thicknesses if unbound. Include horizontal strain for any bound layer. General fatigue criteria. |
| APT-LTPP (Accelerated Pavement Testing and Long-Term Pavement Performance Sites) | Vertical strains in all unbound layers and pavement layer thicknesses with horizontal strains in bound layers. General rutting fatigue criteria from FWD nationally. (Arnold et al, 2009; Salt et al 2010) |
| RPP (Regional Precedent Performance) | Vertical, horizontal and shear strains (and other parameters) determined in all layers (bound or unbound). Calibrated mechanistic fatigue criteria for all distress modes for each large network or region. Based on FWD (including full time histories) on terminal sites in the same region with extension to TSD and/or Multi-Speed Deflectometer (MSD). Extended to small network datasets using meta-analyses of nearby larger (external) datasets. |

Up until about 2010, pavement life prediction was relatively uncertain with moderate or long term predictions often being out by an order of magnitude in log time or more. Using the nominal definition of reliability in Section 2 above, predictions of either 1 year or 100 years compared to actual life of 14 years would translate to hit rate of 15%. Issues include the intrinsic natural variation of subgrade consistency and the variability (Ullidtz, 1987) of particulate materials whose properties vary both spatially and with time along any given treatment length. However, the primary issues until about 2010 were (1) usually only widely spaced FWD data were available and (2) preoccupation with empirical parameters such as deflection and Structural Number which effectively ignore much of the data recorded by each FWD test.

The near continuous, accurate measurement now available from TSD has transformed pavement engineering capability in this respect. The Kaikoura Earthquake study in 2016 provided the first occasion nationally for an ultimate reality check on TSD interpretation giving due recognition to Regional Precedent Performance (RPP).

Pavement engineering inherently provides an ideal environment to validate any new theory or innovative prediction as each treatment length provides for its own "experiment" - subject only to some delay as ongoing traffic loading progressively takes each to the terminal condition necessary to compare prediction with reality. However, the immediate limitation is that true independence is best ensured by enabling interested parties to unequivocally distinguish and compare predictions from the actual outcome. For this reason, raw data is being collated from multiple sites where either FWD and/or TSD has been carried out to establish a GIS database. Fields include the surveyed structural parameters at 10 or 20 m centres in each lane, and the predicted outcome(s) using one or more of the above methods in Table 1.

Using the widely accessible Google Street View (which now has historical imagery on roading networks in many locations, sometimes every few months), any reviewer can regularly inspect a suitable quality photograph and track whether the surface condition deterioration reflects the parameters and/or expectations of any of the predictive methods used.

A key objective is to validate and expand the database with all available alternative predictions using the same source data but interpreted with any other methodology, however simple or complex. At this stage, how the outcome is achieved is less important than to address the primary question "How reliable can predictions of remaining structural life be in practice?" Previous studies suggest that methods that do not include all elements of Table 2 (below) will have low reliability. However, the objective is to achieve the greatest reliability, regardless of the means, and establish a quantifiable measure to compare different techniques.

Establishing a baseline database enables any predictions to be subject to independent verification at any later date. On the weaker sections of the more heavily trafficked roads, either deterioration or repairs may well be visible within a year, and as more substantial distress becomes evident in the medium and longer term, the ongoing study will provide a sound basis for subsequent improvements of predictive models.

## 4 CONSTITUENTS OF A RELIABLE LIFE PREDICTION MODEL

Significant progress has been made from basic empirical models towards mechanistic-empirical procedures with much more facility for incorporating rational, evidence-based parameters for characterisation of pavement materials. In thick AC pavements, the number of visually recognisable distress modes can be relatively limited but with cement stabilised or unbound granular pavement with thin surfacings, a myriad of different modes of distress can be experienced in just one region.

The essential features of a suitable mechanistic model were the subject of study by Dawson (2002 Mechanistic Design Workshop) where he proposed over 20 distress modes. His briefing notes, along with those notes produced as a set of outcomes, have provided the basis for the effective advances made with unbound (and some bound) pavement performance predictions for local networks. Five critical elements for a reliable predictive model were nominated at the workshop to bring together a truly mechanistic procedure. Establishing and adhering to such

Table 2. Reliable Mechanistic Prediction of Pavement Structural Life.

| | |
|---|---|
| 1: Distress Modes | It is necessary to identify the myriad ways (up to 23 or more) in which individual treatment lengths deteriorate to a terminal condition for the specific network. Multiple terminal conditions may be defined based on NPV and/or LOS but ideally both. Allocate any necessary adjustments according to each road classification or situation.<br>Then identify a key mechanical measure for each, usually a vertical, horizontal or shear strain (or stress) at a specific depth and plan location relative to the contact patch of the design load, which will act as an indicator of the performance. |
| 2: Loading | Reliable measurement and systematic classification of heavy traffic vertical loading spectra for each road. Speed of loading, longitudinal shear (braking and acceleration), geometrics and transverse shear (roundabouts) can be critical in specific cases. |
| 3: Load Equivalency | Evaluation and assignment of load equivalency for the traffic spectrum for each individual distress mode/layer. Load damage exponents (LDEs) used to be considered to be constants. This came from short term studies of very dry pavements where strains were low (about half their critical fatigue limits). However, in recent years it has been widely acknowledged that is not the case: longer term in situ testing of in-service pavements demonstrates each distress mode has its own characteristic LDE and that each LDE increases exponentially over the life of the pavement (manifested by accelerated deterioration towards the terminal state). An alternative to LDE is to follow procedures for systematically calculating cumulative damage for each applicable axle group separately for each distress mode. |
| 4: Roading Database | A comprehensive roading database is required for modelling reliability. Surface condition and distress severity may in some cases be adequate for short term trends, but relevant structural data subjected to detailed quality assurance (including correction for seasonal bias) are necessary for moderate term and long-term analysis. |
| 5: Computational Analysis | A technique which reproduces all relevant deformation that develops in the in situ loaded state is needed and it should accommodate the properties of the range of materials encountered in each region. |
| 6: Material Characterisation | The validity of the computational technique rests, to a large extent, on the veracity of the constituent materials' stress-strain relationships. Modulus non-linearity with applied stress (or with ambient stress) needs to be addressed. The measurement techniques need to be accurate, and the correct parameters need to be evaluated. |
| 7: Sampling | Given the inherent variation of both subgrades and imported materials, test spacing needs to be commensurate with spatial variability and the application: network level, project level and maintenance level evaluations benefit from successively smaller averaging intervals, and local experience is that test sampling at 20m or closer in each lane is essential for adequate reliability (80% target).<br>Intervals of 20, 10 & 2m are feasible with TSD now that there is little difference in cost. Simultaneous testing of both wheelpaths is advantageous in mature networks where maintenance has been carried out. |
| 8: Treatment Length Designation | Systematic sub-sectioning procedures for identification and delineation of homogeneous structural treatment lengths (STL's) are fundamental to an optimised, cost-efficient Forward Work Programme. Incremental recursive techniques are required, with re-assignment of STL's each year. This is essential where material properties such as layer moduli undergo loading or environmental changes and where spatial changes are induced by patching, dig-outs or other inevitable maintenance requirements, particularly for thin-surfaced or mature pavements. |
| 9: Design Criteria | Each key mechanistic measure must be computable, and relevant terminal values (fatigue criteria) characterised. These need to be defined for each |

(*Continued*)

Table 2. (*Cont.*)

| | |
|---|---|
| | region or sub-region to accommodate what are now recognised as highly significant local effects, namely subgrade types, aggregate sources, construction practices, level of quality assurance, customary specifications, maintenance style/frequency and most importantly, climate (temperature, rainfall ingress, groundwater fluctuation and the impact of humidity on the equilibrium water content of unbound aggregates). |
| 10: Reality Checks and Calibration | Site inspection is essential, to ensure adequate characterisation of the wide variety of distress modes exhibited by treatment lengths which have reached or are close to terminal condition (programmed for the rehabilitation in the current year). These provide the ideal candidates for calibration. The transitions from consistently distressed to consistently non-distressed treatment lengths provide ideal points for fine tuning of distress modes and their limiting fatigue criteria. |

a basis has been found to be imperative in local practice since that time, hence those elements with some additional points are summarised below.

The local (RPP) methodology, based on Dawson's initiative as expanded above in Table 2, was established in view of the extensive national database containing 3 decades of systematically recorded full time histories of several million FWD points. FWD data were later used to transform the 6 years of repeated TSD dynamic tests into pseudo-static FWD equivalent deflection bowls providing millions more test points on the same highways (mostly at 10m intervals with some at 2m intervals).

Every database entry is scrutinised by a series of QA algorithms for any inconsistencies or anomalies within each bowl and along each road. Because this specific database includes many points on unbound pavements with thin surfacings, multi-layer non-linear elastic analysis reveals much greater insight into pavement performance than is obtained with thick structural AC roads where the subtle strains from lower layers are difficult to differentiate because they are effectively masked by the surface stiffness (deflections are an order less).

The highly fortuitous outcome from this database was that detailed models of stresses, strains and moduli of every layer were able to be more readily modelled and a wide spectrum of innovative fatigue criteria explored. A Forward Work Programme is generated after including the relevant non-structural data (traffic, surface condition progression, maintenance history etc). Reality checks ensued on the numerous instances of advanced terminal distress that characterise mature thin surfaced highway pavements.

RPP uses mechanistic analysis rather than solely pseudo-mechanistic or empirical parameters such as structural number or deflection for the reasons detailed and promoted by Ullitdz (1987). The "regional" aspect of RPP refers to the importance of developing individually tailored models of pavement performance to best reflect the various local characteristics such as systems for traffic spectra measurements, assigning load equivalency, back-analysis software, subgrade types, aggregate sources, construction and QA practices, customary specifications, maintenance style/frequency and, most importantly, climate. The "precedent performance" refers to the traditional use of this practice since its promotion by Major (1980), NRB (1989), for rehabilitation design, as well as the extension for network evaluation (GeoSolve, 2021).

The RPP methodology was reviewed and commended by Ullidtz (2015) who also proposed that it should be upgraded with recursive functionality to model the progressive change in layer moduli with both load repetitions and time (environmental ageing). This has been partially implemented with implicit recursive modelling of changes in Load Damage Exponents, but in relation to other bound and unbound layers remains a work in progress that is expected will further improve current capability for performance prediction of bituminous and unbound layers.

## 5 COLLECTION OF PAVEMENT STRUCTURAL DATA

Falling Weight Deflectometer (FWD) and Traffic Speed Deflectometer (TSD) testing have been carried out using customary methods on all national state highways in New Zealand. The FWD data have been supplemented with full time histories for each geophone providing additional characteristics for modelling.

TSD data have been collected consistently by using a specific Generation II device. The latter does not measure both wheel-paths or bowl asymmetry, nor precision in the manner now achievable with later generations, but locally calibrated methods have been developed to enable effective conversion to equivalent FWD bowls. This technique does not provide definition of subgrade modulus non-linearity as well as that obtained directly with FWD, but this is compensated to some degree by the closer sampling frequency.

Unfortunately, for unknown reasons, all local TSD data in New Zealand has been collected in peak summer. This may provide consistency, but requires considerable “rationalisation” of the data to reflect the more adverse conditions throughout the rest of the year, and it soon became evident that specific intervals of highways need to be entirely rejected (depending on the terrain).

The Multi Speed Deflectometer (MSD) is an emerging technology initially developed as a rapid structural screening tool for low volume roads. The MSD simply comprises a tyre with embedded sensors that is mounted to a short wheel-based truck. The simplicity and portability of the system offers the advantage of being able to test roads all over the world at all times of the year. The utilisation of a shorter truck facilitates testing in locations that the longer TSD cannot access so that large urban networks can be collected at minimal cost.

Full network level testing of cities is best achieved with the MSD allowing the remaining budget to be allocated to closer spacing FWD testing confined to only the critical (weaker) sections of the road identified by the MSD. Additionally, being able to test on wet or unsurfaced materials, enables the MSD to be a highly effective tool for rapid screening of earthworks including surveys on each layer during construction to determine areas of weaker support or lesser compaction.

MSD surveys in New Zealand initially used single (outer) wheel-path data collection, but this has now been largely replaced with dual wheel-path surveys with readings at 1m centres, averaged to 10 or 20m intervals for presentation. Focus to date has been on conversion to equivalent FWD parameters so that all methods can be related to the widely recognised standard.

Future developments of the MSD include using the principles of RPP and big datasets to predict pavement life, develop structurally homogenous treatment lengths, and ultimately generate Forward Works Programmes for overall asset management.

## 6 CASE STUDIES

Summaries of the sites tested and monitored with the various types of deflection equipment are given by GeoSolve (2021).

### 6.1 *Falling Weight Deflectometer (FWD)*

All surveys used standard Dynatest FWD equipment with 9 geophones located out to 1500mm with full time histories recorded. The categories of sites do not include Portland Cement Concrete (PCC) but do include thick structural asphaltic concrete and foamed bitumen stabilisation as well as cement stabilised, cement modified and unbound granular with thin bituminous surfacing. Most sites are New Zealand (NZ) state highways, with reliable traffic counts.

### 6.2 *Traffic Speed Deflectometer (TSD)*

All surveys used the same TSD Gen II, but over the years, slightly faster speed was used which led to a steady decrease in deflection for many roads. All testing was done in midsummer requiring consideration of seasonal effects. All sites are NZ state highways with reliable traffic counts.

### 6.3 *Multi-Speed Deflectometer (MSD)*

The MSD has less accuracy than the TSD, providing relative parameters suitable for benchmarking, but has the advantage of manoeuvrability on winding roads and intersections, as well as the advantage of sampling at traffic speed at 1m centres in both wheel tracks. Most surveys are on NZ local roads, with some comparisons on NZ state highways where TSD and/or FWD were also available. An MSD study of thick structural asphalt pavement, with distress ranging from minimal (new) to severe (near terminal condition) is included, on the main arterials of Rome (300 lane km).

## 7 CONCLUSIONS

Since the development of the Benkelman Beam in 1953, pavement engineers have been making some form of prediction of pavement life, but only in the last few years has technology provided the potential for useful estimates of structural life in the moderate or long term. The combination of TSD with near continuous sampling supplemented with the accuracy of the FWD and subject to appropriate mechanistic procedures (Table 2) has proved effective on national and local roads, while MSD provides an additional tool for inclusion of urban streets and at more critical climactic conditions (i.e., wet season).

The reliability of predicting pavement life prior to 2010 has been questionable with studies indicating Hit Rates of seldom as high as 10%. Such a result is considered inevitable if any one of the 10 key criteria initiated by Dawson (Table 2) is ignored. To date, approaches based on empirical parameters alone or attempts to use sample intervals greater than 20m have been problematic. The database now established, provides for an ongoing study of Hit Rates for alternative approaches to predicting pavement life.

A Hit Rate of 80% for pavement life prediction is a reasonable expectation for large networks where currently available technology is used for systematic data collection of the relevant pavement characteristics, followed by state-of-the-art mechanistic evaluation, for generation of a reliable Forward Work Programme extending well beyond the current short-term models. Once the Forward Work Programme is generated, it provides the opportunity to quantitatively assess the “Hit Rate” from ongoing observation and monitoring. Reliability can hence be tracked over time, and the effectiveness of alternative prediction techniques can be evaluated independently by practitioners and potential users.

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