Compliance testing using the Falling Weight Deflectometer for pavement construction, rehabilitation and area-wide treatments

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Abbreviations and acronyms

Benkelman deflection	Rebound deflection of a pavement under s standard wheel load and tyre pressure.
CAPTIF	Canterbury Accelerated Pavement Testing Facility
CBR	California bearing ratio
ELMOD	Evolution of layer moduli and overlay design
ESA	Equivalent standard axle
FWD	Falling Weight Deflectometer
GMP	General mechanistic procedure
IAL M-EP	Interim APT-LTPP mechanistic empirical procedure model for predicting life from FWD (APT = Accelerated pavement testing; LTPP = Long-term pavement performance)
k	Thousand (1000)
kN	Kilo Newton, unit of force
M-EP	Mechanistic empirical procedure
MESA	Millions of equivalent standard axles
MPa	Megapascal, unit of pressure
NZTA	New Zealand Transport Agency
PSMC	Performance-specified maintenance contract
VSD	Vertical surface deformation
Sc	Scaling factor
SH1	State Highway 1

Contents

Executive summary

The Falling Weight Deflectometer (FWD) measures the pavement surface deflection at various distances from the load. The result is a deflection bowl. This deflection bowl has been used by clients to predict the life of the recently constructed or rehabilitated pavement. In performance-based contracts the contractor's performance is judged on the life predicted. This project looks at the FWD's ability to predict pavement life on a range of pavements where the actual life is known or can be predicted by extrapolating roughness or rutting measurements. The pavements chosen were from the NZ Transport Agency's test track CAPTIF, state highways and low-volume roads that have failed, and from performance-specified maintenance contracts where there is an abundance of FWD measurements and high-speed pavement condition data.

Three methods to predict pavement life were trialled. The first was an Austroads simplified deflection approach where an equation is used to predict pavement life from the central FWD deflection only. The second and third methods were based on the Austroads mechanistic pavement design method where the pavement life is determined from a subgrade strain criterion that computes pavement life from the vertical compressive strain in the subgrade. The second and third methods differed only by a subgrade strain multiplier (ie a factor that is multiplied to the strains before input into the equation to predict life). A subgrade strain multiplier of 1.0 was used for the second method (ie no adjustment to the Austroads subgrade strain criterion), while the third method used a subgrade strain factor other than 1 which is found iteratively until the predicted life matches the actual life. To determine subgrade vertical compressive strain from the FWD deflection bowl a back-analysis software was used to calculate the stiffness/moduli of the pavement layers and subgrade so that the computed deflections were closely matched to those measured. A linear elastic pavement model was created from back calculated moduli to calculate strains within the pavement at critical locations (ie the vertical strain at the top of the subgrade for granular pavements).

The following table contains observations on the results of the FWD analyses.

Observations found from FWD project case studies

Topic	Observation	Relevant case studies
Simplified deflection method	Generally always over-predicts life by multiples of a 100 or 1000 times the actual life. (Note: the opposite occurs for low-volume roads No.2 and Kaituna Road where it underestimates life.) Conclusion: Simplified deflection methods are not recommended for future use.	All except the low-volume roads
10th percentile values	For any project the range in FWD predicted lives for each individual measuring point can range from 0.01 to 100 million ESA (or more). Further, prediction of actual life on an individual point does not correlate with the life assessed at the individual point. Averaging the FWD predictions is not appropriate as it is skewed by the sometimes very large predictions of life (>100 MESA). Therefore, assessing the FWD predictions by percentiles is best. The 10th percentile value was chosen as the preferred method as a pavement is assumed to be in need of rehabilitation when 10% of the area has failed. When more than 10% of the pavement area is in need of repair a pavement rehabilitation is justified due to the high cost of maintenance. The cost of maintenance is the main reason why pavements are rehabilitated in New Zealand (Gribble et al 2008).	All
50th percentile	For some sections in the PSMC001 projects and for the low volume roads it appears that the 50th percentile life is best. For others the 50th percentile value is	A few sections.

Topic	Observation	Relevant case studies
Values	generally too large by factors of 100 or more.	
Austroads M-EP – 10th percentile (not corrected)	Often underestimates life by a factor of 10 to 100 fold. Although there are exceptions with those sections that failed early because of weak granular layers (eg Alpurt Sector A and a couple of sections at CAPTIF).	All except roads with weak granular layers.
Austroads M-EP – 10th percentile (corrected)	The strain multipliers found in order to match the 10th percentile Austroads M-EP lives with the 10th percentile FWD lives ranged between 0.33 and 1.04 with a value of around 0.6 to 0.7 being the most common. It was found with CAPTIF data that it might not be possible to have a common strain multiplier, while when a value of 0.7 the FWD predicted lives were between 0.1 and 10 times the actual life.	All
Errors	If considering using a percentile value of the FWD Austroads M-EP predicted lives then it can be expected that a good prediction will be within a factor of 5 of the actual life. For example if the FWD prediction is one million ESAs then the actual life could be anywhere from 0.2 million ESAs to five million ESAs.	All
Austroads critical layer	When taking a percentile approach to this selected data set as a whole the consideration of the life found in a critical layer (where the subgrade strain criterion is also applied to strains in the granular pavement layers, the life is equal to the layer with the shortest life, referred to as the critical layer) within the pavement had negligible effect on the 10th percentile predicted life. However, a small proportion of cases exist where the critical layer is other than the subgrade.	All
Pavement depth	Often overlooked, but if the assumed pavement depth used in the analysis of FWD data to predict life is out by 31mm then this translates to two-fold difference in pavement life or an error of 200%. Given the pavement depth is often assumed and not measured then this error could occur often.	All

These observations were used to determine the recommendations below for a method to analyse FWD measurements for predicting life of newly constructed or rehabilitated pavements.

Recommended methods for analysing FWD measurements

Standard	Recommendation
Load	The impact load should be standardised and remain the same.
Analysis	The Austroads M-EP method should be used (without consideration of a critical layer for most cases) to predict life for individual FWD-measured points. A strain multiplier may be used (although only after careful consideration) if one can be determined from past projects.
Strain multiplier	For low-volume roads on volcanic soil subgrades in the Bay of Plenty (<1 million ESAs) a strain multiplier of 0.4 may be appropriate while a value of 0.7 is most common for other projects. These strain multipliers are only relevant if the 10th percentile value is used to determine the pavement life. However, past performance should be used to calibrate the subgrade strain criterion to local conditions.
Predicting life (ESAs until rehabilitation is required)	Within a project length all FWD-predicted lives (a minimum of 10 is required) should be combined and the 10th percentile determined and deemed the predicted life until pavement rehabilitation is required. The 50th percentile may be calculated and used for comparison.
Payment reduction	Because of errors in FWD predictions the estimated upper limit on life should be five times the 10th percentile FWD predicted life. If this upper limit is below the design life then a payment reduction or increased maintenance period could be considered.

Based on the above observations and recommendations, the use of the Falling Weight Deflectometer for compliance testing of pavement construction may be questionable. However, if the strain criteria used to calculate pavement life have been 'broadly' calibrated to the soil types then the FWD can predict the 10th percentile life of plus or minus 500%. This means if the FWD predicts the pavement life of two million ESAs then the actual life could range from 400,000 ESAs to 10 million ESAs. The range of life predicted makes it difficult to use in compliance and if penalties are imposed then the 'greater' life of 10 million is taken as the achieved life. It is recommended that the FWD is not the only tool used to determine compliance but the materials used, compaction, and pavement depth achieved are controlled. Pavement monitoring in terms of rutting and roughness could also be undertaken and models used to extrapolate the rutting and roughness to predict life.

Abstract

The Falling Weight Deflectometer (FWD) which measures pavement deflections was assessed for its ability to predict the life of a newly constructed or rehabilitated pavement. FWD measurements used in the study were from NZ Transport Agency's test track CAPTIF, roads that have failed and from two performance specified maintenance contracts where the actual life from rutting and roughness measurements could be determined. Three different methods to calculate life from FWD measurements were trialled. The first, a simple Austroads method that uses the central deflection only and was found to either grossly over predict life by a factor of 1000 times more than the actual life or grossly under predict the life. The second two methods trialled were based on Austroads mechanistic pavement design where the life is determined from the vertical compressive strain at the top of the subgrade. For the mechanistic approach the FWD measurements are analysed with specialised software that determines a linear elastic model of the pavement which computes the same surface deflections as those measured by the FWD. From the linear elastic model the subgrade strain is determined and life calculated using the Austroads equation. It was found when using this approach that predictions of life from individual FWD measured points within a project length can range from nearly 0 to over 100 million equivalent standard axles. To cater for this large scatter in results, the 10th percentile value was used as the predicted life of the pavement. In general the Austroads mechanistic approach under-predicted the life, sometimes by a factor of 10 or more. The third approach trialled was adjusting the Austroads mechanistic approach by applying a factor determined from past performance to calibrate the subgrade strain criterion to local conditions. This third approach greatly improved the predictions but it was found that the multiplying factor was not consistent for a geographical area and thus the factor found from one project might not be suitable for another similar project.

1 Introduction

The Falling Weight Deflectometer (FWD) measures the pavement surface deflection at various distances from a dynamic load. The result is a deflection bowl which is used in back-analysis software to calculate the stiffnesses/moduli of the pavement layers and subgrade so that the computed deflections are closely matched to those measured. A layered elastic pavement model is created from back-calculated moduli to calculate strains within the pavement at critical locations (ie the vertical strain at the top of the subgrade for granular pavements or the tensile strain at the base of cemented and asphalt bound materials). These strains are used in power law equations from the Austroads (2004a) *Pavement design: a guide to the structural design of road pavements* to compute the number of equivalent standard axle (ESA) passes until the end of life.

In some of the NZ Transport Agency's (NZTA) hybrid and performance-specified maintenance contracts (PSMCs), full payment is given for the area-wide treatment, pavement repair, construction or rehabilitation completed by the contractor if the computed ESAs from the FWD testing and analysis are greater than the design ESAs (ie the number of heavy commercial vehicle axle passes over the design life of say 20 years). A proportional payment is calculated if the FWD calculated ESAs are less than the design ESAs. Use of the FWD in this way as a means of contractual compliance and occasional reduced payment has raised significant concerns by the industry including:

1. The method of back analysis of FWD deflection bowls and software type for determining pavement layer stiffnesses and strains has not been well defined and agreed upon, since each FWD user has their own bias as to the best method to use. Unfortunately, each method of analysis can often result in significant differences in calculated strain and thus pavement life, which is unacceptable in a contractual environment. The more widely used method is the ELMOD software from Dynatest.

2. The calculated FWD life in terms of ESAs can indicate a short life of sometimes less than one year. However, the observed performance (rutting, surface integrity and roughness etc) of the construction along with quality records showing the pavement depth, materials, moisture content and density can indicate the opposite (ie where the design life is expected to be achieved) and thus the contractor is frustrated with a reduction in payment being applied.

3. Similar to point 2 above but vice versa where the observed performance is poor but the FWD computed life (ESAs) is greater than the design life.

4. The mass limits project, and other projects conducted at CAPTIF (NZTA's accelerated pavement testing facility), used FWD results to determine whether or not performance could be predicted. It was found that the traditional methods of analysing FWD results using the Austroads subgrade strain criterion could not predict pavement performance (in terms of the number of axle passes until a rut depth of 20mm).

5. International and local research (ie CAPTIF and Arnold's PhD) clearly indicate that a large contributor to rutting is the granular materials (compaction and shallow shear movements) but the Austroads method of predicting life only considers the vertical strain on top of the subgrade. This is considered to increase potential for the mismatch of FWD predicted to actual performance.

The research project analysed the FWD measurements on several CAPTIF and NZTA state highways and compared the different methods of predicting life with the observed life found by extrapolating rutting and roughness measurements or determining the number of axles until pavement rehabilitation was required. The aim was to assess the accuracy of FWD prediction of life and recommend a preferred approach which resulted in the closest answer to the actual life.

Other non-traditional approaches to FWD analysis are also discussed.

1.1 Repeatability of FWD measurements

Before comparing predicted life with actual life it was considered important to understand the repeatability of the FWD tests and associated life prediction. Therefore, a small study of FWD repeatability was undertaken in relation to life prediction of unbound granular pavements with a thin seal. Falling Weight Deflectometer tests were undertaken at a single point with no shift in plate position between drops, and all were completed within two minutes (constant temperature). The test site was located in Burgundy Crescent, Hamilton. The pavement consisted of a chip seal with 325mm of unbound granular layers.

A total of 12 repeat FWD tests and analysis was undertaken and subgrade strain and pavement life was calculated using various Austroads methods. Results are summarised below:

Table 1.1 Raw data

Test no.	Pressure	Displacements (from geophone at mm offset, mm)								
		D0	D200	D300	D450	D600	D750	D900	D1200	D1500
1	0.613	0.757	0.538	0.377	0.227	0.155	0.115	0.093	0.063	0.053
2	0.606	0.751	0.534	0.375	0.225	0.154	0.114	0.092	0.062	0.052
3	0.609	0.752	0.536	0.377	0.225	0.155	0.114	0.092	0.062	0.053
4	0.609	0.752	0.537	0.377	0.226	0.155	0.114	0.093	0.059	0.052
5	0.606	0.749	0.534	0.374	0.225	0.153	0.114	0.090	0.062	0.053
6	0.608	0.753	0.537	0.376	0.226	0.154	0.115	0.091	0.062	0.053
7	0.609	0.756	0.539	0.379	0.227	0.156	0.115	0.093	0.063	0.053
8	0.615	0.760	0.544	0.383	0.229	0.158	0.116	0.094	0.063	0.053
9	0.603	0.750	0.536	0.375	0.225	0.153	0.114	0.090	0.061	0.053
10	0.605	0.753	0.537	0.377	0.226	0.155	0.114	0.092	0.062	0.052
11	0.611	0.761	0.542	0.381	0.229	0.157	0.116	0.092	0.062	0.053
12	0.609	0.758	0.541	0.381	0.228	0.156	0.115	0.093	0.063	0.052

Table 1.2 Analysis results (ELMOD) back-analysed moduli (MPa) for the various layers

Test no.	E1	E2	E3	E4	E5	C0	n
1	736	380	210	125	88	108	-0.126
2	735	383	212	126	87	106	-0.131
3	740	390	216	128	85	105	-0.138
4	755	371	205	122	89	108	-0.123
5	714	415	229	136	81	102	-0.154
6	717	408	225	134	82	103	-0.148
7	740	383	212	126	86	105	-0.133

Test no.	E1	E2	E3	E4	E5	C0	n
8	752	385	213	127	85	105	-0.135
9	714	409	226	134	81	101	-0.154
10	731	388	214	128	84	104	-0.138
11	709	417	230	137	80	100	-0.157
12	747	376	208	124	86	105	-0.133

Table 1.3 Strains and lifetime MESA (millions of ESA) using alternative methods

Test no.	Vertical strain: in the subgrade under 1 ESA loading (mm)	Lifetime MESA: general mechanistic procedure using Austroads subgrade strain criterion (isotropic equivalent)	Lifetime MESA: Austroads 2004b deflection method	Lifetime MESA: Austroads 1992 deflection method
1	0.000808	3.600	3,148.423	1,566.742
2	0.000819	3.322	2,934.824	1,475.046
3	0.000825	3.162	3,148.423	1,566.742
4	0.000804	3.694	3,148.423	1,566.742
5	0.000848	2.693	3,148.423	1,566.742
6	0.000842	2.816	2,934.824	1,475.046
7	0.000823	3.214	2,833.521	1,431.231
8	0.000822	3.231	3,148.423	1,566.742
9	0.000854	2.584	2,641.286	1,347.467
10	0.000832	3.007	2,641.286	1,347.467
11	0.000858	2.499	2,550.116	1,307.441
12	0.000825	3.175	2,641.286	1,347.467

1.2 Summary

- Vertical strain at the top of the subgrade under 1 ESA changes by a factor of 1.07 (804 to 858 microstrain).
- GMP life, using the Austroads subgrade strain criterion (for isotropic moduli) for the 10 measurements, varies from 2.499 to 3.694 MESA or +/- 19%.
- Corresponding Austroads life predictions (2004b and 1992 procedures) are not credible (exceed 1000 MESA using extrapolation of charts).
- Using the Austroads Pavement Design Chart for a pavement of this thickness (325mm) requires only 31mm increase in pavement depth for a two-fold increase in design ESA, and 50mm for a three-fold factor. Given the pavement depth is often assumed and not measured then this error could occur often. In addition, the specification TNZ B/2 allows a pavement depth tolerance from -5mm to + 15mm which will change the actual pavement life from 0.9 to 1.4 times.

1.3 Discussion

A target for pavement life prediction (lifetime MESA) from recent research has been to aim for a factor of 3. The above sensitivity analysis suggests that equipment repeatability is a minor contributor to this factor. Point-to-point variation in material properties and pavement thickness variations within any treatment length dominate and are such that it is unlikely that a factor of better than multiply by 3 or divide by 3 is likely to be achieved in practice. However, this translates to a relatively small change in an as-built pavement depth of 50mm.

Another observation from this study is the sensitivity of pavement life to the pavement depth used. A 31mm error in pavement depth results in a two-fold error on pavement life (200%). Therefore a critical factor in estimating the pavement life is the pavement depth which could sometimes be unknown especially for area-wide treatments where an overlay is used.

2 Methods of FWD analysis and comparison with observed life

There are two principal approaches to analysing FWD data for predicting pavement life, the first is a mechanistic-empirical procedure (M-EP) and the second is a simplified approach using the FWD central deflection or Benkelman deflection. The M-EP method is further broken down into two methods either predicting life from the Austroads strain criterion or from a precedent/adjusted strain criterion. These two methods vary only in the final step with the equation used to predict life from calculated strains within the pavement (usually on top of the subgrade).

2.1 Austroads simplified deflection

The simplest alternative uses only Benkelman Beam or central deflection from FWD. The curve relating future traffic loading to deflection is given in the Austroads guide (Austroads 2004b) which is unchanged from the 1992 guide (Austroads 1992). The method has low reliability. It may well provide unconservative results if very stiff subgrades are present and results may be unduly conservative for very soft pavements or resilient soils which are resistant to permanent deformation (eg volcanic ashes). A principal disadvantage is that no fundamental criteria, namely subgrade strains, are assessed to give a mechanistic appreciation, and there is no check that shallow shear deformation will not occur.

2.2 Mechanistic-empirical procedure (M-EP)

2.2.1 Austroads M-EP and critical layer

This uses post-rehabilitation deflection bowls, back-analysed using as-built pavement layering and elastic theory, to determine vertical strains at the top of the subgrade and comparing these with Austroads allowable values (equation 2.1). (Note that M-EP is synonymous with GMP (general mechanistic procedure), but the former is now preferred as the more common terminology in both European and American usage.)

$$N = \left(\frac{10{,}000}{\mu\varepsilon_s} \right)^6 \qquad \text{(Equation 2.1)}$$

where:

N = the number of ESA load cycles

$\mu\varepsilon_s$ = the vertical strain at the top of the subgrade (microstrain) under a 1 ESA loading as determined by FWD assuming moduli are isotropic with any non-linearity determined for the subgrade

Note: Equation 2.1 is the isotropic equivalent of the Austroads subgrade strain criterion for anisotropic moduli (Stevens 2006; Austroads 2004b). The reason for using isotropy is that ELMOD evaluates only in terms of isotropic moduli (the most commonly adopted assumption worldwide), as there is currently no way for practical measurement of an isotropy for in-service pavements. ELMOD was selected primarily for its necessary accommodation of non-linear subgrade moduli (Ullidtz 1987), its speed of execution and its historic success in providing explanations of pavement distress mechanisms which have generally good credibility.

This method is also referred to in this research as the uncorrected Austroads method and is identified in the tables of results where the strain multiplier equals 1.0.

The Austroads M-EP method may also be applied to aggregate pavement layers assuming these could also experience rutting as a result of excessive vertical strains. This (Danish originated) approach is later identified as the 'critical layer' method because the life is governed by the layer in the pavement or subgrade that has the shortest life. However, it is expected that an aggregate will behave differently from a cohesive subgrade soil and thus the subgrade strain criterion (equation 2.1) may not be appropriate.

2.2.2 Precedent M-EP

This method is the same as Austroads M-EP except that a factor is applied to the Austroads strain criterion (K, equation 2.2) (eg for resilient volcanic soils) provided calibration from a precedent has proven the basic Austroads relationship can be modified. In this project the strain multiplier that gives the best fit to the observed life is determined. As there will have been only one set of FWD measurements on a particular piece of road it is not possible to determine if the strain multiplier is suitable for future use in the region. However, the test track data at CAPTIF from several projects can be used to test if a strain multiplier found from one project is suitable for using in the next project.

The strain multiplier should be related to the subgrade soil type (eg volcanic ash or silty clay soils). Therefore, it is possible to determine an appropriate calibration factor for each pavement section so that the 10th percentile FWD predicted life matches the 10th percentile life from roughness and/or rutting progression.

This method is also referred to in this research as the 'corrected Austroads method' and is identified in the tables of results where the strain multiplier is a value other than 1.0.

$$N = \left(\frac{10{,}000}{K\mu\varepsilon_s}\right)^6 \qquad \text{(Equation 2.2)}$$

where:

N = the number of ESA load cycles

$\mu\varepsilon_s$ = the vertical strain at the top of the subgrade (microstrain) under a 1 ESA loading as determined by FWD, assuming moduli are isotropic with any non-linearity determined for the subgrade (this is different from CIRCLY which uses anisotropic moduli but it is possible to convert between the two)

K = subgrade strain multiplier for the precedent M-EP method

Note: K as used here is the inverse of the 'subgrade strain rati'; a parameter that has been utilised in earlier analyses of New Zealand volcanic soils.

2.3 Comparison between FWD predicted life and observed life

2.3.1 Observed life

The observed life of a pavement is calculated as being the number of ESAs from the time of construction until rehabilitation is required. These ESAs are often assessed by extrapolating the trends found from annual measurements of rut depth or roughness data until a failure criterion is reached. For the CAPTIF test track data, the rut depth measurements were extrapolated to a failure criterion of 15mm as found to be suitable in the mass limits project (Arnold et al 2005).

2.3.2 Point by point method

The point by point method compares the FWD predicted life with the observed life for every FWD measurement point. This approach is not recommended as it produces a large scatter in results with no correlations between predicted and observed life. This is probably due to the observed life from high-speed rut depth data not being deduced from the exact location of the FWD measurement point. However, in the test track data, the rut depth data and observed life were from the exact point. Very poor correlation also resulted. Another possibility is that dynamic wheel loads can cause depressions in spots not identified as being weak from the FWD measurements. Further, the end of life of a pavement in terms of when rehabilitation is required is not defined by single points of high roughness or rutting but rather a collection in a project length. Hence, the project section method using percentile values is the preferred method.

2.3.3 Project section method – percentiles

The preferred and most suitable method for comparing FWD predicted and observed lives is on a per project section method. A common criterion for defining the end of life of a pavement is when 10% of the road section length has reached or exceeded a defined failure criterion, for example a 25mm rut. This approach allows for each project section to use the 10th percentile FWD predicted life to predict the 10th percentile observed life. This approach will be tested on CAPTIF data and actual road sections. In some cases, the 50th percentile values of FWD and observed lives are also compared, as these may be more appropriate for lower volume roads where 50% of the road needs to have failed before pavement rehabilitation is required. In the following analysis, the project section length is taken as the full project length to be rehabilitated, although project subsections could be determined based on common subgrade type. At least 10 FWD measurement points in each project section length are required for this method.

3 CAPTIF data

3.1 Introduction

The NZTA's test track CAPTIF results are analysed on a section by section basis in a manner that may be applied to an actual project when assessing remaining pavement life. The approach compares say the 10th and/or 50th percentile values of remaining life from FWD measurements with the 10th or 50th percentile pavement life found from extrapolating the rut depth measurements to a terminal value. CAPTIF should be the most reliable in terms of known construction depth, materials used and number of loads until end of life. Hence, CAPTIF data provides accurate information to check the different methods. However, the data from CAPTIF will have less scatter than a pavement in the field with varied terrain, moisture and substrate.

3.2 CAPTIF data

FWD and rutting data were used from three CAPTIF research projects in the 40kN (current legal standard load) wheel path. The FWD data used was that measured after approximately 100k load cycles to be similar to measurements taken 12 months after pavement construction. Pavement configurations of the three CAPTIF tests are detailed in figures 3.1, 3.2, 3.3 and 3.4. Table 3.1 and figures 3.6 to 3.8 summarise the observed pavement life found in each of the projects in the mass limits study concluding report (Arnold et al 2005).

Figure 3.1 CAPTIF test PR3-0805

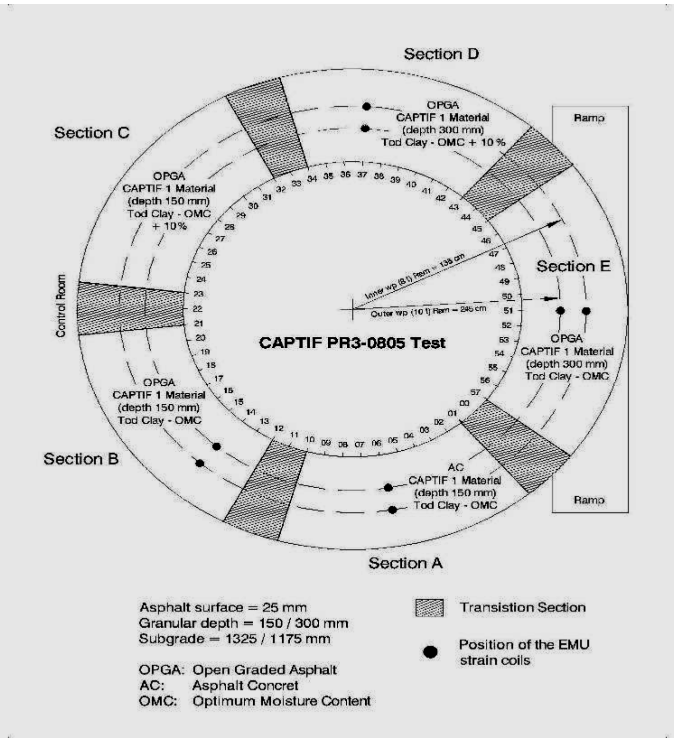


Figure 3.2 CAPTIF test PR3-0404

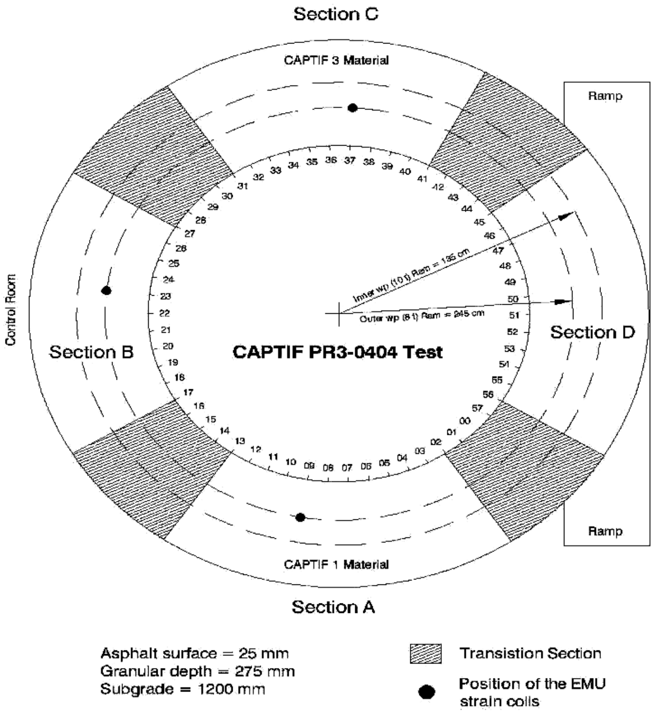


Figure 3.3 CAPTIF cross section example for test PR3-0404

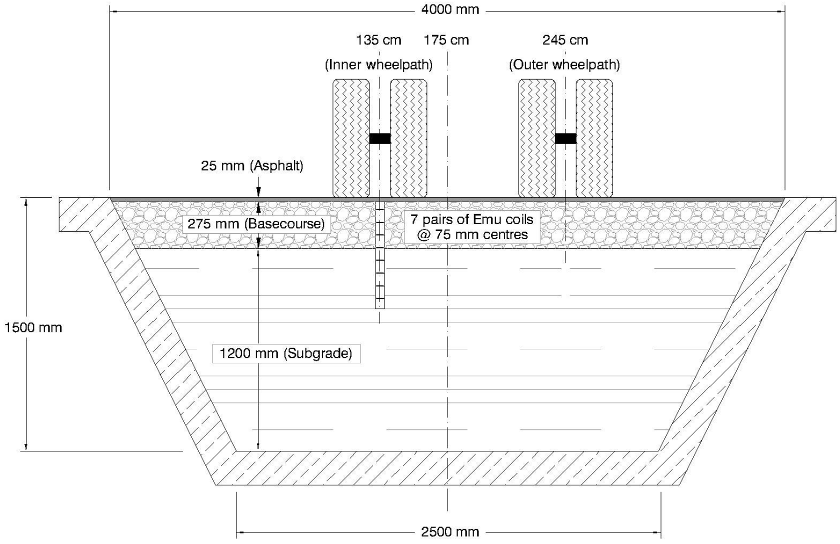


Figure 3.4 CAPTIF test PR3-0610

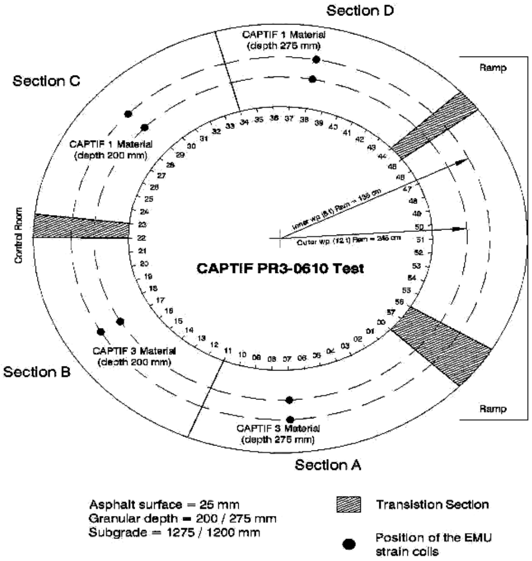


Table 3.1 Summary of CAPTIF test sections with 40 kN wheel loading

Section	Basecourse		Subgrade (in situ scala)	Life to *VSD = 15mm (linear extrapolation – see Arnold et al 2005)	
	Material	Depth	CBR	10th%ile	50th%ile
A_0404	TNZ M4 AP40 – (Christchurch)	275	10	2.7E+06	3.7E+06
B_0404	TNZ M4 AP40 (Christchurch) + 5% fines	275	10	2.3E+06	4.1E+06
C_0404	AP20 Crushed Rock from Melbourne	275	10	4.5E+06	5.0E+06
D_0404	TNZ M4 AP40 – (Christchurch)	275	10	4.3E+06	5.4E+06
A_0610	Melbourne AP20	275	10	3.1E+06	4.6E+06
B_0610	Melbourne AP20	200	10	4.2E+06	4.5E+06
C_0610	AP40 TNZ M4 (Christchurch)	200	10	3.3E+06	3.7E+06
D_0610	AP40 TNZ M4 (Christchurch)	275	10	4.2E+06	5.4E+06
E_0610	NZ AP40 M5 (rounded river gravel)	200	10	3.6E+05	5.3E+05
A_0805	AP40 TNZ M4 (Christchurch)	150	7	1.3E+06	1.4E+06
B_0805	AP40 TNZ M4 (Christchurch)	150	9	**1.5E+05	**1.5E+05
C_0805	AP40 TNZ M4 (Christchurch)	150	2	**5.0E+04	**5.0E+04
D_0805	AP40 TNZ M4 (Christchurch)	300	3	3.0E+06	3.8E+06
E_0805	AP40 TNZ M4 (Christchurch)	300	8	4.3E+06	6.7E+06

* VSD = Vertical surface deformation and is the vertical deformation from a datum reference level at the surface at the time of construction, while rut depth is defined as the depth of the rut from a straight edge laid across the pavement and takes account of shoving (figure 3.5).

** Pavement failed

Figure 3.5 Difference between rut depth and vertical surface deformation (VSD)

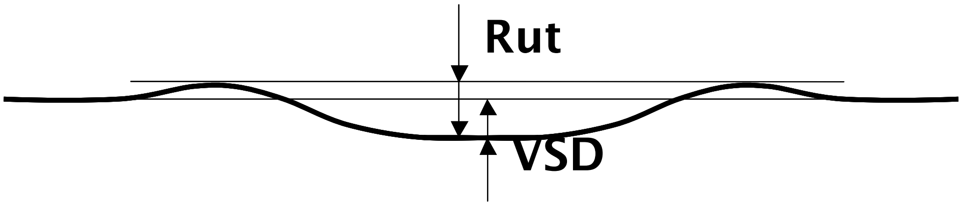


Figure 3.6 Lives of individual 1 metre stations at CAPTIF test track for the '404' project

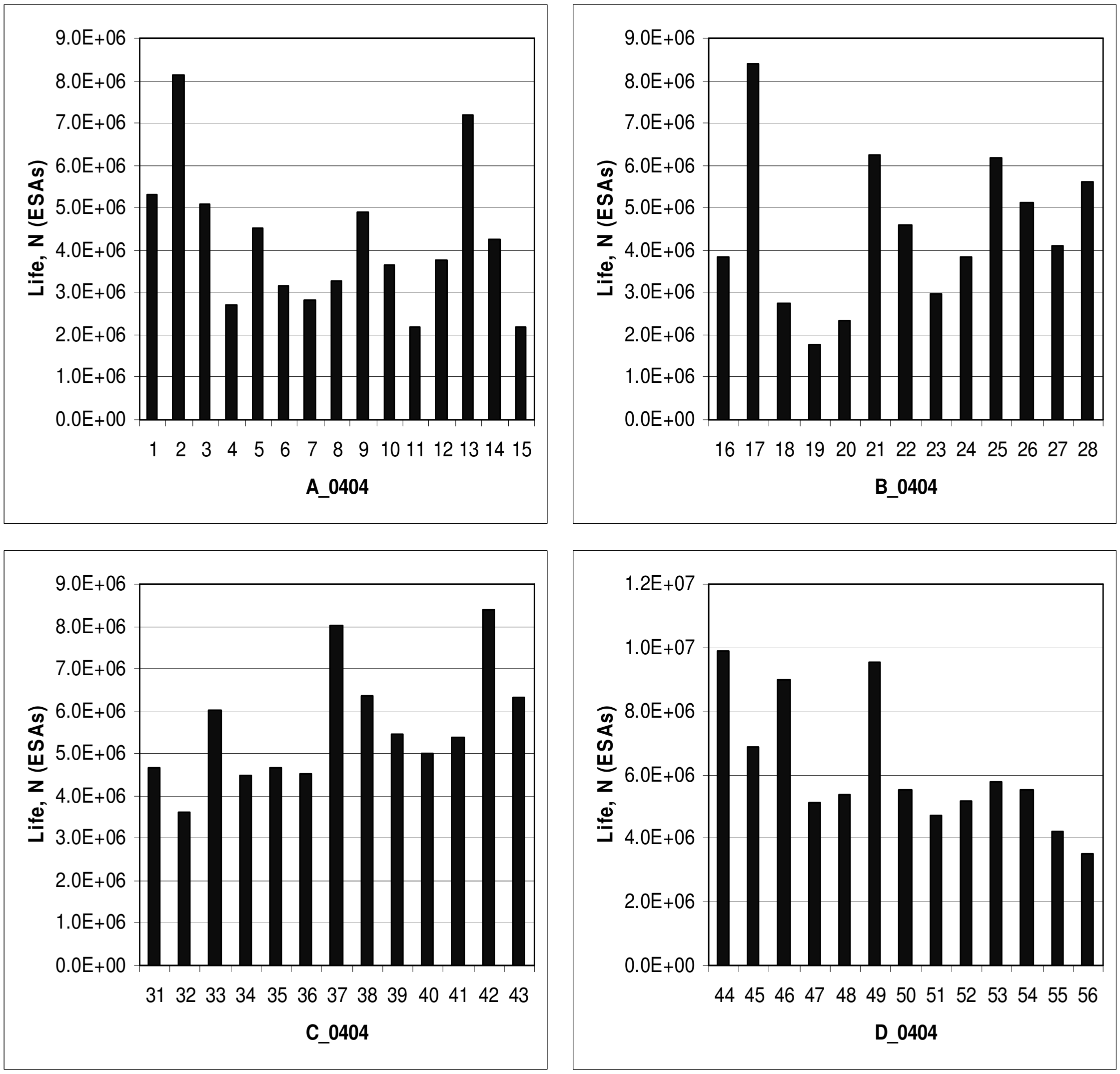


Figure 3.7 Lives of individual 1m stations at CAPTIF test track for the '610' project

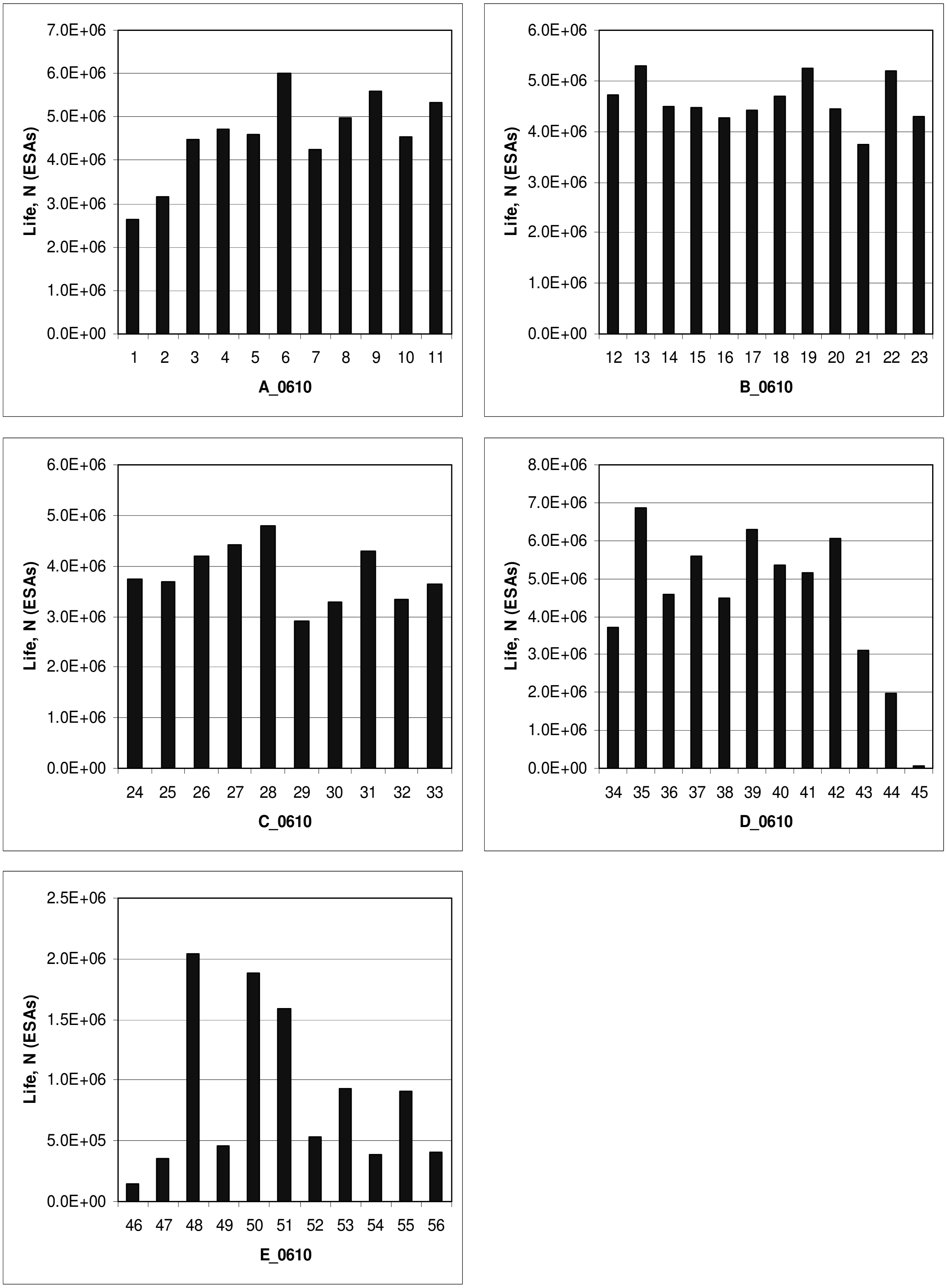
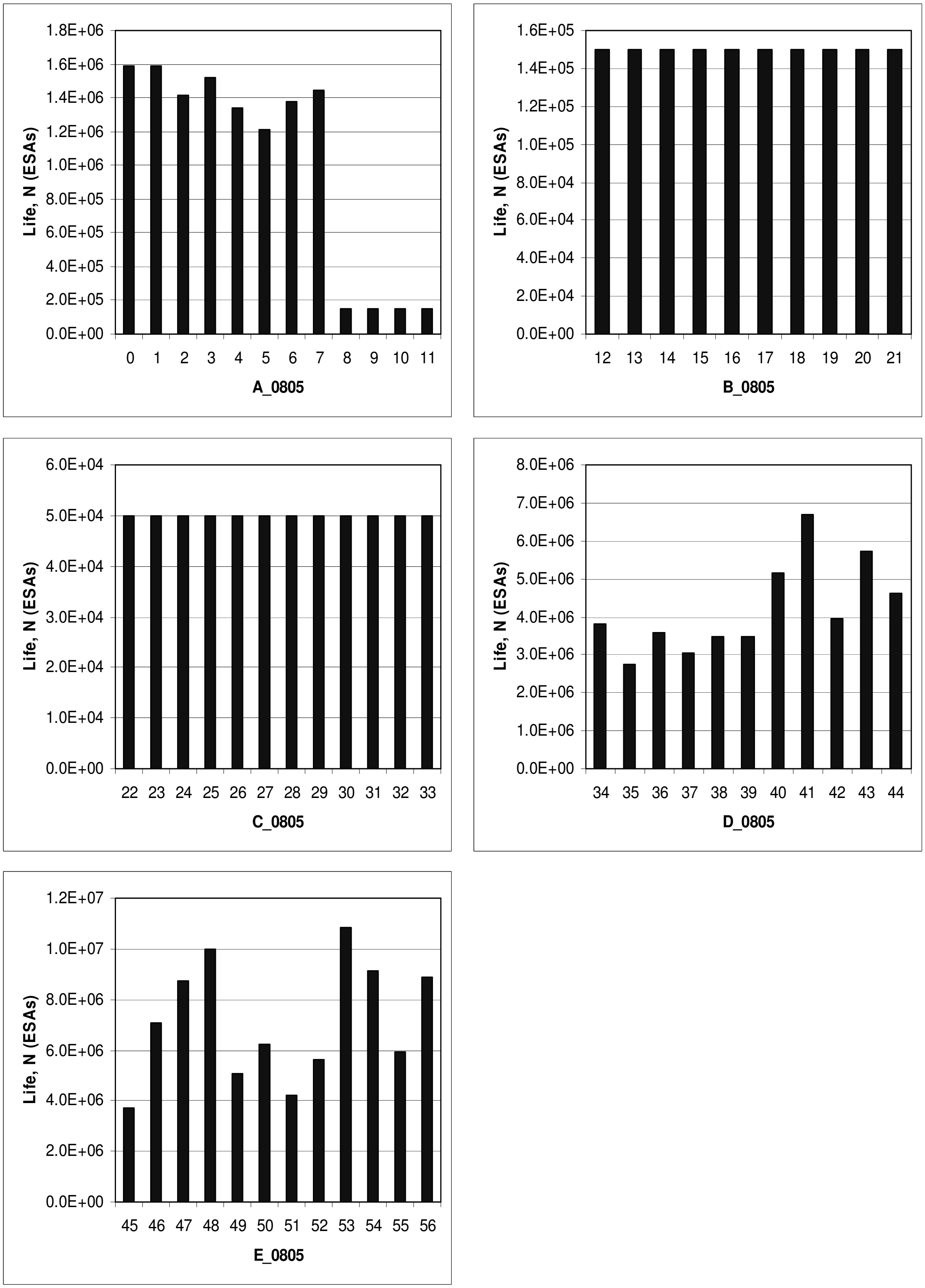


Figure 3.8 Lives of individual 1m stations at CAPTIF test track for the ‘805’ project



3.3 FWD CAPTIF results versus observed life

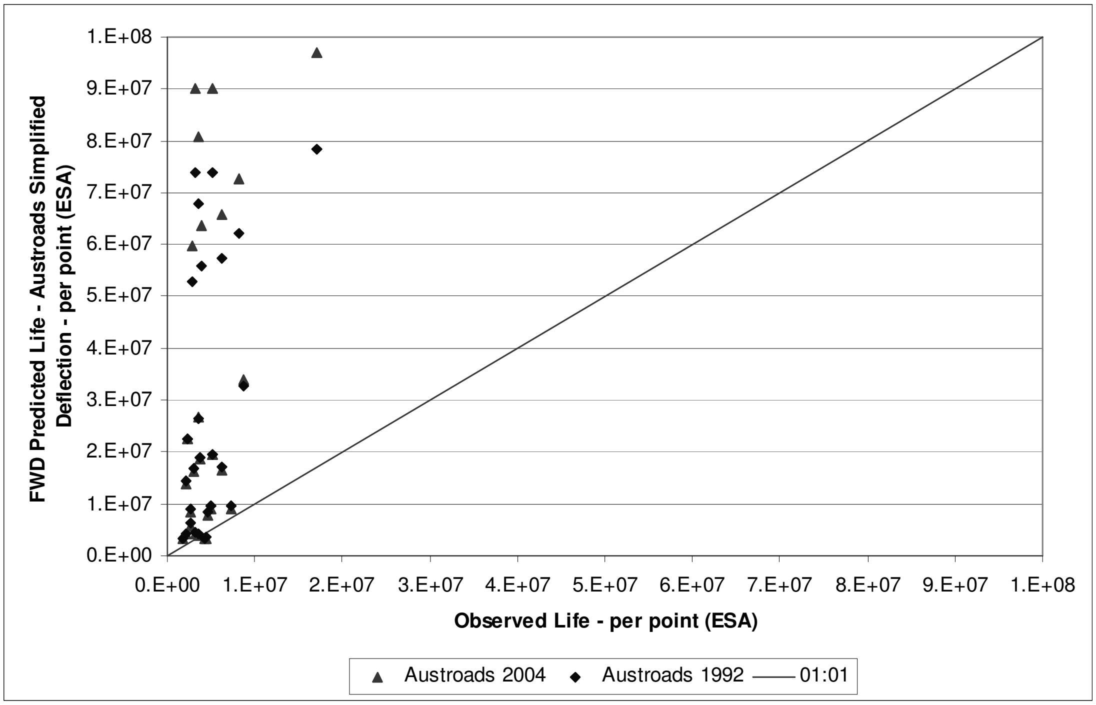
3.3.1 Observed life

Life at CAPTIF was determined when the rut depth reached 15mm when extrapolated linearly. Results are shown in table 3.1 and figures 3.6 to 3.8. This method of determining pavement life at CAPTIF was found to be the most suitable approach in the mass limits study (Arnold et al 2005) and is adopted here. It is considered that the life predicted would generally be lower than the actual life due to the linear extrapolation to a low rut depth of 15mm rather than a standard 25mm. However, it was found that soon after a rut depth of 15mm occurred the rutting rate increased exponentially producing a 25mm rut.

3.3.2 Austroads simplified deflection

The simplified deflection methods described in section 2.1 using the Austroads 2004b versions overestimates the life as shown for the 0404 CAPTIF project in figure 3.9. Similar results were obtained for the other CAPTIF projects. It appears that this method is not suitable for New Zealand type pavements, although it may be possible to establish a calibration factor.

Figure 3.9 FWD simplified deflection method versus observed life for CAPTIF test PR3-0404



3.3.3 Austroads M-EP

Full pavement analysis was undertaken to back-calculate the moduli of the pavement layers and using layered elastic analysis to calculate the number of allowable ESA passes using the Austroads procedures for mechanistic analysis. This method is described in section 2.2.1. Despite the considered conservative low number of ESAs found to reach failure in the CAPTIF test (section 4.3.1) the standard/uncorrected (ie strain multiplier = 1.00) Austroads method (section 2.2.1) in most cases was found to under-predict the actual life at CAPTIF (table 3.2). The exceptions to this were section E in PR3-0610 and sections C, D and E in PR3-0805 CAPTIF projects. Although in sections C and D in PR3-0805 the 10th percentile FWD lives under-predicted the observed lives indicating that this is a better measure than the average of 50th percentile values. The earlier than expected FWD predicted lives were due to deformation within the aggregate layers. Section E in PR3-0610 used a lower quality rounded aggregate; and section E in PR3-0805 was a thick granular material over a strong subgrade.

Table 3.2 Results of uncorrected Austroads mechanistic empirical method for CAPTIF projects

Section	FWD – Austroads MEP (un-corrected)			Observed life – (N to VSD = 15 mm)			Errors$^{(a)}$ – FWD life/observed life		
	10%ile	50%ile	Average	10%ile	50%ile	Average	10%ile	50%ile	Avg
PR3-0404									
A	5.8E+04	1.0E+05	1.5E+05	2.7E+06	3.7E+06	4.3E+06	0.02	0.03	0.03
B	7.8E+04	1.8E+05	1.9E+05	2.3E+06	4.1E+06	4.4E+06	0.03	0.04	0.04
C	3.4E+05	7.9E+05	1.1E+06	4.5E+06	5.0E+06	5.3E+06	0.08	0.16	0.21
D	4.9E+05	9.4E+05	1.1E+06	4.3E+06	5.4E+06	5.9E+06	0.11	0.17	0.19
PR3-0610									
A	6.7E+05	9.8E+05	1.1E+06	3.1E+06	4.6E+06	4.5E+06	0.22	0.21	0.24
B	3.0E+04	4.2E+04	4.5E+04	4.2E+06	4.5E+06	4.6E+06	0.01	0.01	0.01
C	2.4E+04	4.3E+04	4.1E+04	3.3E+06	3.7E+06	3.9E+06	0.01	0.01	0.01
D	3.9E+05	5.2E+05	6.2E+05	4.2E+06	5.4E+06	5.3E+06	0.09	0.10	0.12
E	4.5E+05	6.7E+05	1.4E+06	3.6E+05	5.3E+05	8.8E+05	1.25	1.26	1.59
PR3-0805									
A	5.7E+03	1.5E+04	6.9E+04	1.5E+05	1.4E+06	1.0E+06	0.04	0.01	0.07
B	1.7E+03	4.0E+04	3.9E+04	1.5E+05	1.5E+05	1.5E+05	0.01	0.27	0.26
C	1.4E+04	2.7E+05	9.6E+05	5.0E+04	5.0E+04	5.0E+04	0.28	5.4	19.2
D	2.4E+06	1.4E+07	2.2E+07	3.0E+06	3.7E+06	4.2E+06	0.80	3.8	5.2
E	1.7E+07	5.2E+07	8.5E+07	5.1E+06	7.1E+06	7.4E+06	3.3	7.3	11.5

(a) The error was calculated as the percentage difference between the FWD calculated and observed lives, a negative value indicates the FWD calculated life is less than the observed life.

Figure 3.10 Results of uncorrected Austroads mechanistic empirical method for CAPTIF project PR3-0404 (see also table 3.2)

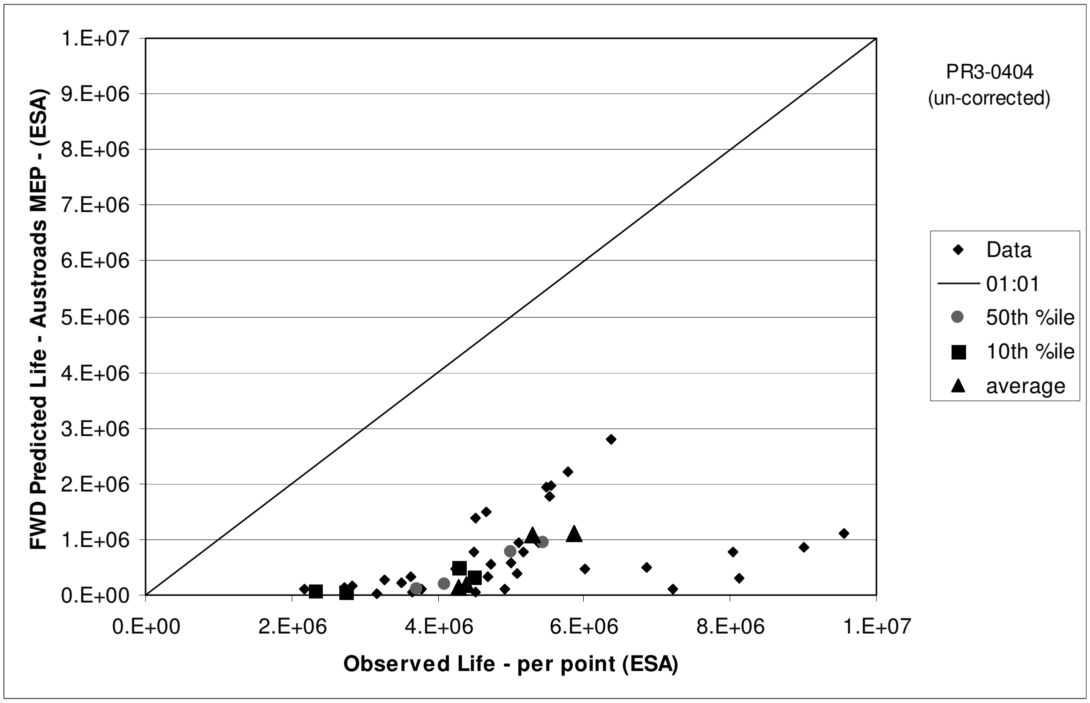


Figure 3.11 Results of uncorrected Austroads mechanistic empirical method for CAPTIF project PR3-0610 (see also table 3.2)

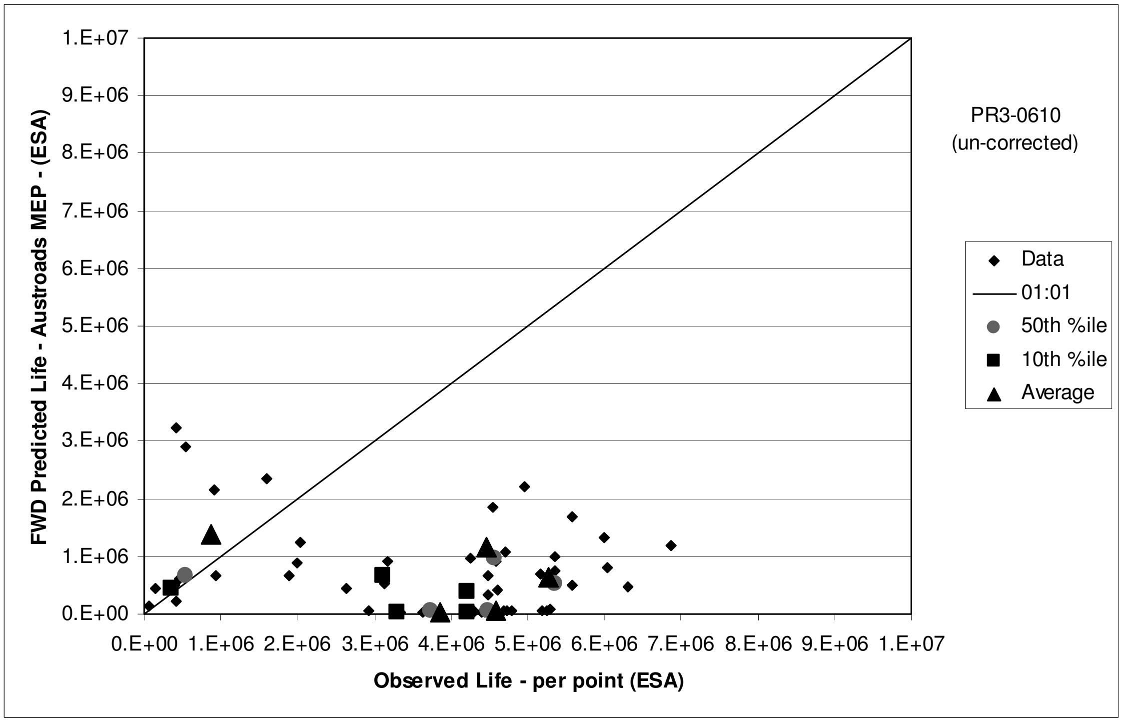
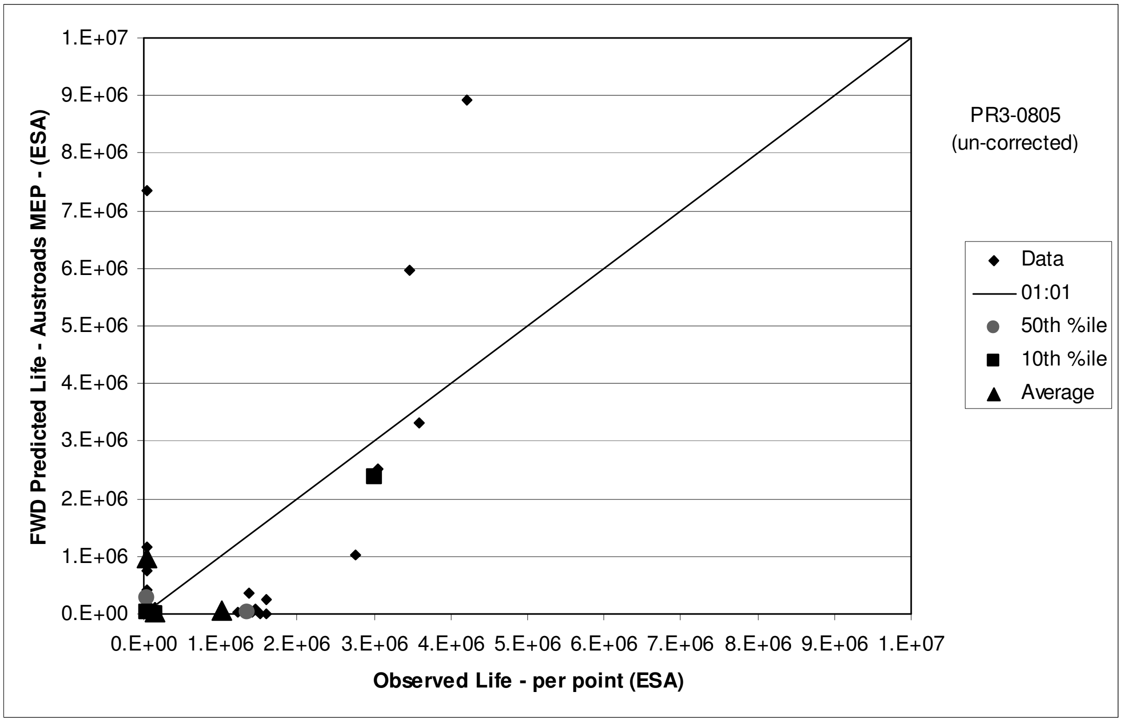


Figure 3.12 Results of uncorrected Austroads mechanistic empirical method for CAPTIF project PR3-0805 (see also table 3.2)



3.3.4 Precedent M-EP

A subgrade strain correction factor as per the precedent M-EP method is needed to improve the predictions of life for the CAPTIF tests (ie a strain multiplier other than 1.0). The correction factor could be determined in a number of ways, for example finding the correction factor where:

- the average FWD life and average observed life are equal
- there are equal number of over and under FWD predictions of life
- 50% of the FWD predictions are below the 10th percentile observed life
- the 10th percentile FWD predictions are matched with the 10th percentile observed life.

Two methods of determining the correction factors were investigated: the first was matching the 10th percentile FWD and observed lives and the second was ensuring 50% of the FWD predictions were below the 10th percentile observed life. Results when a subgrade strain multiplier is used to match the 10th percentile predicted and observed lives are shown in table 3.3 and figures 3.13, 3.14 and 3.15. Table 3.4 and figures 3.16, 3.17 and 3.18 detail the results of ensuring 50% of the FWD predictions are below the 10th percentile value. This latter approach protects the client by taking a conservative approach which ensures that 50% of the FWD measurements under-predict the life.

Table 3.3 Results of corrected (see section 3.2.2) Austroads mechanistic empirical method for CAPTIF projects (10th percentile matched)

Section[(b)]	Strain multiplier [(c)]	FWD – Austroads M-EP (un-corrected)			Observed life – (N to VSD=15mm)			Errors[(a)] – FWD/observed life		
		10%ile	50%ile	Average	10%ile	50%ile	Average	10%	50%	Ave.
PR3-0404										
A	0.53	2.6E+06	4.6E+06	6.8E+06	2.7E+06	3.7E+06	4.3E+06	0.96	1.24	1.58
B	0.57	2.3E+06	5.3E+06	5.5E+06	2.3E+06	4.1E+06	4.4E+06	1.00	1.29	1.25
C	0.65	4.5E+06	1.0E+07	1.4E+07	4.5E+06	5.0E+06	5.3E+06	1.00	2.00	2.64
D	0.70	4.2E+06	8.0E+06	9.3E+06	4.3E+06	5.4E+06	5.9E+06	0.98	1.48	1.58
PR3-0610										
A	0.77	3.2E+06	4.7E+06	5.5E+06	3.1E+06	4.6E+06	4.5E+06	1.03	1.02	1.22
B	0.44	4.1E+06	5.8E+06	6.2E+06	4.2E+06	4.5E+06	4.6E+06	0.98	1.29	1.35
C	0.44	3.3E+06	6.0E+06	5.6E+06	3.3E+06	3.7E+06	3.9E+06	1.00	1.62	1.44
D	0.67	4.3E+06	5.8E+06	6.9E+06	4.2E+06	5.4E+06	5.3E+06	1.02	1.07	1.30
E	1.04	3.6E+05	5.3E+05	1.1E+06	3.6E+05	5.3E+05	8.8E+05	1.00	1.00	1.25
PR3-0805										
A	0.58	1.5E+05	3.9E+05	1.8E+06	1.5E+05	1.4E+06	1.0E+06	1.00	0.28	1.80
B	0.48	1.4E+05	3.3E+06	3.2E+06	1.5E+05	1.5E+05	1.5E+05	0.93	22.00	21.33
C	0.81	5.1E+04	9.4E+05	3.4E+06	5.0E+04	5.0E+04	5.0E+04	1.02	18.80	68.00
D	0.96	3.0E+06	1.7E+07	2.8E+07	3.0E+06	3.7E+06	4.2E+06	1.00	4.59	6.67
E	1.22	5.1E+06	1.6E+07	2.6E+07	5.1E+06	7.1E+06	7.4E+06	1.00	2.25	3.51

(a) The error was calculated as the percentage difference between the FWD calculated and observed lives, a negative value indicates the FWD calculated life is less than the observed life.

(b) See table 3.2 and figures 3.10, 3.11 and 3.12 for spread of data on pavement lives (percentiles of lives were calculated from at least 10 points per section where rut depth was measured).

(c) These 'K' values/strain multipliers are determined by matching the 10th percentile FWD predicted life with the 10th percentile observed life and are only valid for the particular pavement section at the test track at CAPTIF from one particular trial.

Figure 3.13 Results of corrected (matching the 10th % values) (see section 3.2.2) Austroads mechanistic empirical method for CAPTIF project PR3-0404

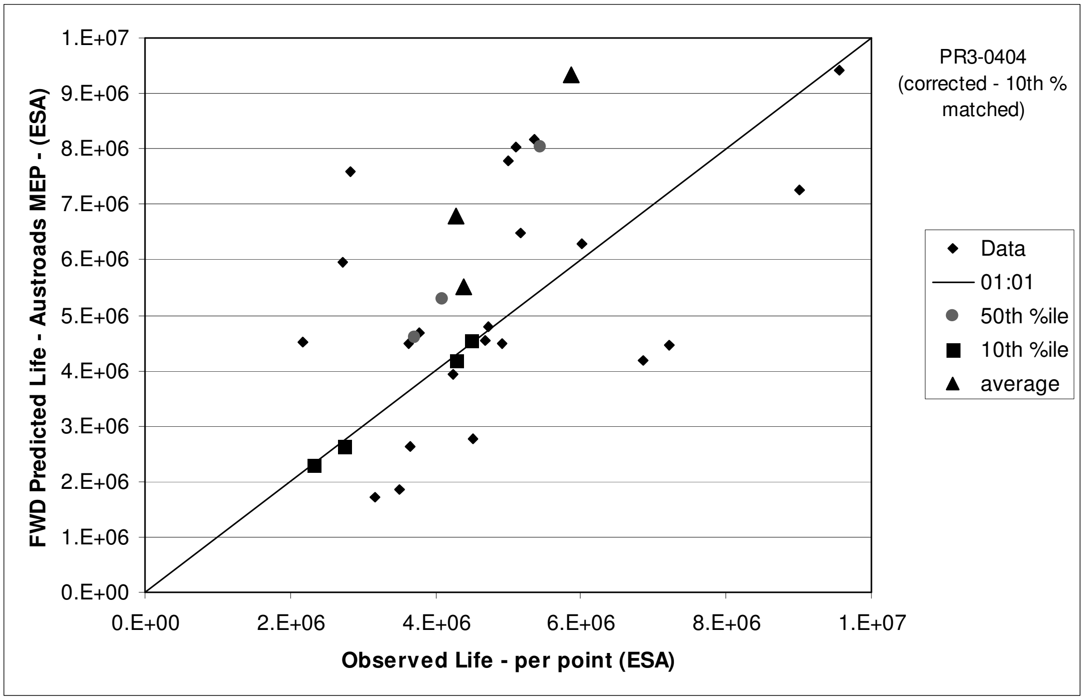


Figure 3.14 Results of corrected (matching the 10th % values) (see section 3.2.2) Austroads mechanistic empirical method for CAPTIF project PR3-0610

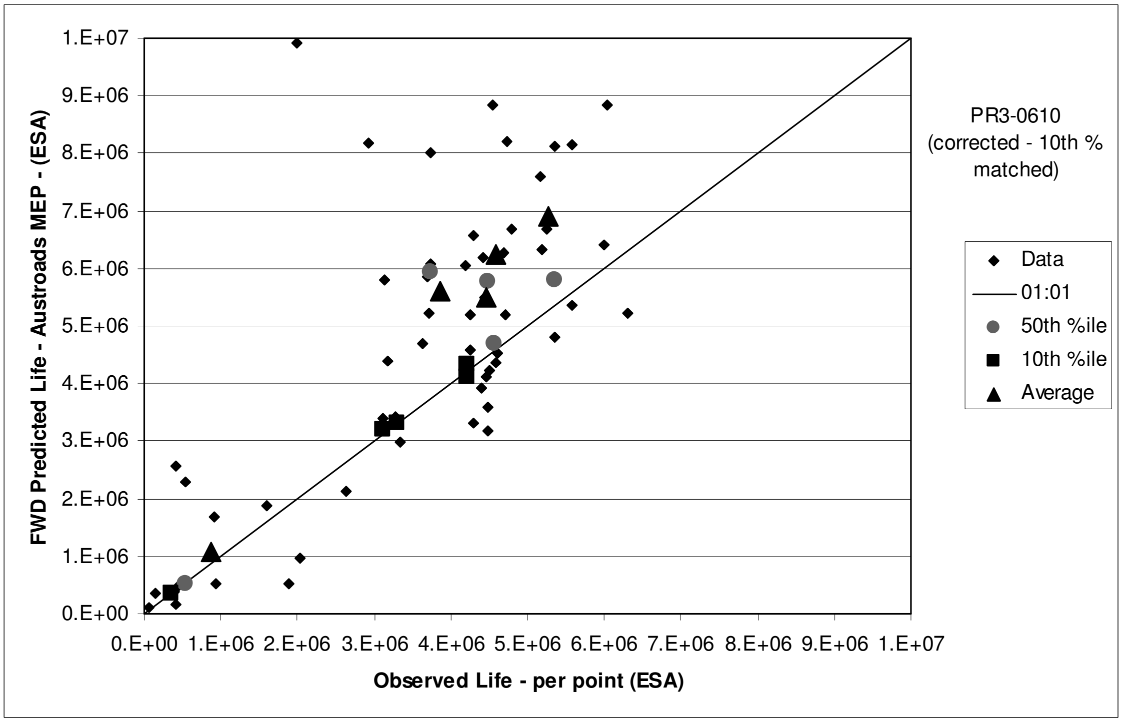


Figure 3.15 Results of corrected (matching the 10th % values) (see section 3.2.2) Austroads mechanistic empirical method for CAPTIF project PR3-0805

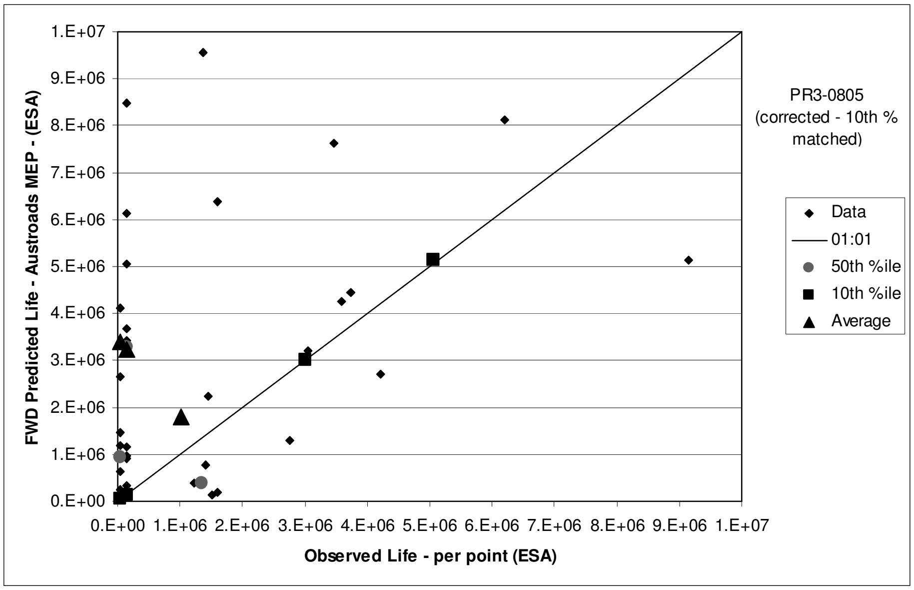


Table 3.4 Results of corrected (see section 3.2.2) Austroads mechanistic empirical method for CAPTIF projects (50% of predictions below 10th percentile observed life)

Section[b]	Strain multiplier	FWD – Austroads M-EP (un-corrected)			Observed life – (N to VSD = 15 mm)			Errors[a] – FWD/observed life		
		10%ile	50%ile	Average	10%ile	50%ile	Average	10%	50%	Ave.
PR3-0404										
A	0.58	1.5E+06	2.7E+06	3.9E+06	2.7E+06	3.7E+06	4.3E+06	0.56	0.73	0.91
B	0.65	1.0E+06	2.4E+06	2.5E+06	2.3E+06	4.1E+06	4.4E+06	0.43	0.59	0.57
C	0.75	1.9E+06	4.4E+06	6.1E+06	4.5E+06	5.0E+06	5.3E+06	0.42	0.88	1.15
D	0.77	2.4E+06	4.5E+06	5.3E+06	4.3E+06	5.4E+06	5.9E+06	0.56	0.83	0.90
PR3-0610										
A	0.82	2.2E+06	3.2E+06	3.8E+06	3.1E+06	4.6E+06	4.5E+06	0.71	0.70	0.84
B	0.47	2.8E+06	3.9E+06	4.2E+06	4.2E+06	4.5E+06	4.6E+06	0.67	0.87	0.91
C	0.49	1.7E+06	3.1E+06	2.9E+06	3.3E+06	3.7E+06	3.9E+06	0.52	0.84	0.74
D	0.71	3.1E+06	4.1E+06	4.9E+06	4.2E+06	5.4E+06	5.3E+06	0.74	0.76	0.92
E	1.11	2.4E+05	3.6E+05	7.4E+05	3.6E+05	5.3E+05	8.8E+05	0.67	0.68	0.84
PR3-0805										
A	0.68	5.8E+04	1.5E+05	6.9E+05	1.5E+05	1.4E+06	1.0E+06	0.39	0.11	0.69
B	0.80	6.6E+03	1.5E+05	1.5E+05	1.5E+05	1.5E+05	1.5E+05	0.04	1.00	1.00
C	1.25	3.8E+03	7.0E+04	2.5E+05	5.0E+04	5.0E+04	5.0E+04	0.08	1.40	5.00
D	1.28	5.4E+05	3.1E+06	5.1E+06	3.0E+06	3.7E+06	4.2E+06	0.18	0.84	1.21
E	1.47	1.7E+06	5.2E+06	8.4E+06	5.1E+06	7.1E+06	7.4E+06	0.33	0.73	1.14

(a) The error was calculated as the percentage difference between the FWD calculated and observed lives, a negative value indicates the FWD calculated life is less than the observed life.

(b) See table 3.2 and figures 3.10, 3.11 and 3.12 for spread of data on pavement lives (percentiles of lives were calculated from at least 10 points per section where rut depth was measured).

Figure 3.16 Results of corrected (see section 3.2.2) Austroads mechanistic empirical method for CAPTIF project PR3-0404 (50% of predictions below 10th percentile observed life)

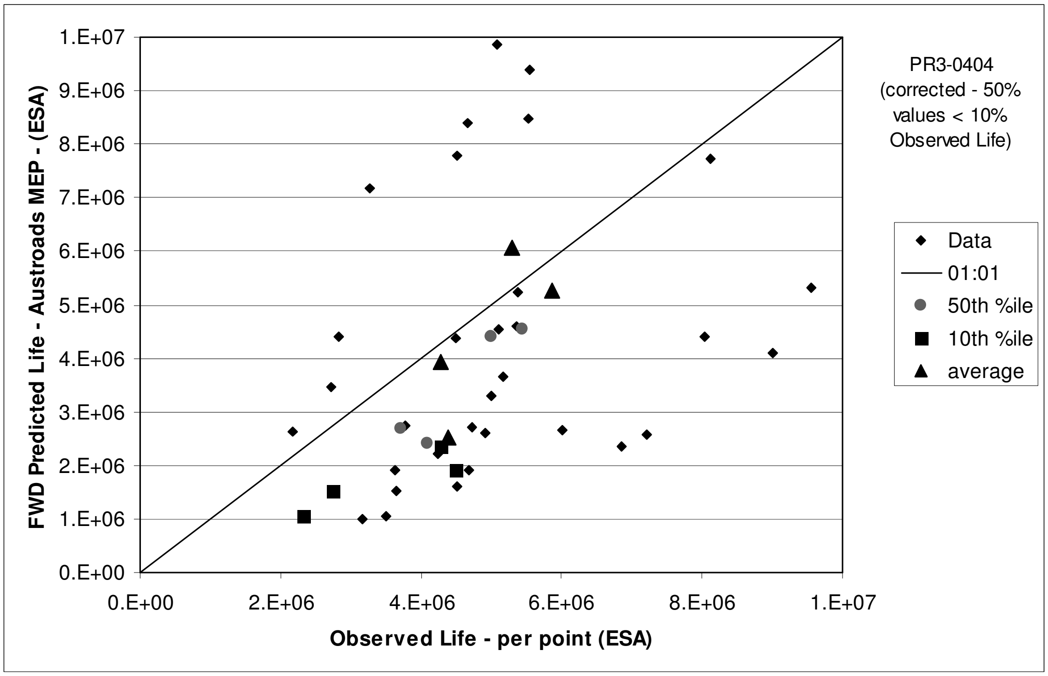


Figure 3.17 Results of corrected (see section 3.2.2) Austroads mechanistic empirical method for CAPTIF project PR3-0610 (50% of predictions below 10th percentile observed life)

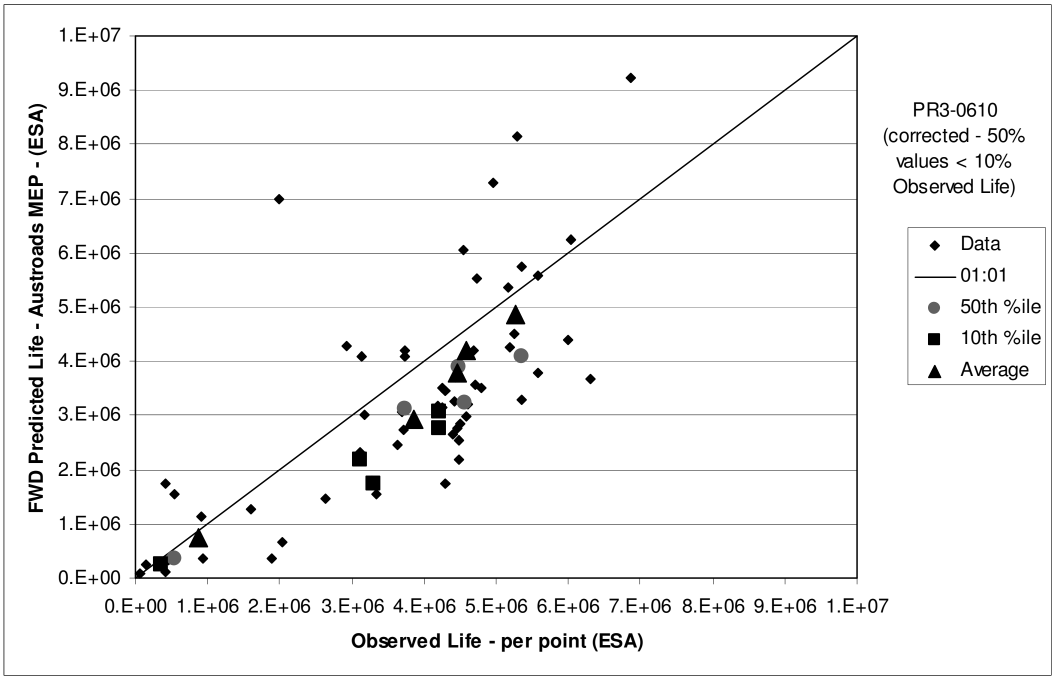
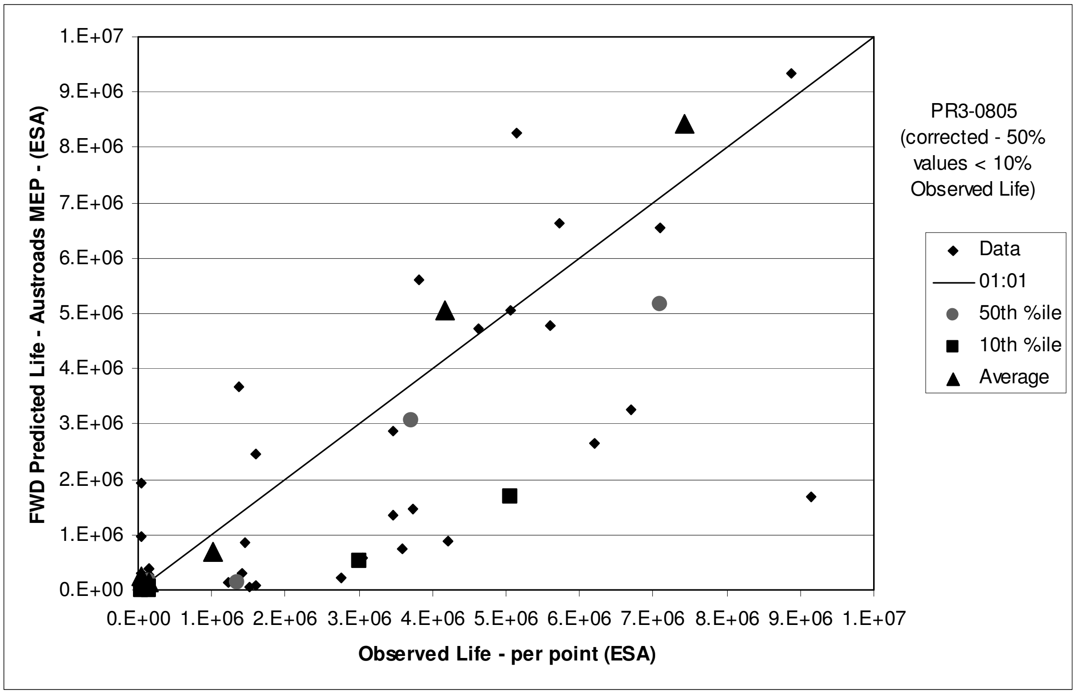


Figure 3.18 Results of corrected (see section 3.2.2) Austroads mechanistic empirical method for CAPTIF project PR3-0610 (50% of predictions below 10th percentile observed life)



3.4 Discussion

Results of FWD predictions at CAPTIF show that the simplified Austroads deflection methods grossly over-predict, by 100s of millions, the pavement life. Apart from pavement sections that failed early at CAPTIF (ie < 200k load cycles), predictions of life using the Austroads M-EP are underestimated by approximately a factor of 10. An overestimate of a factor of 10 can be corrected/calibrated by multiplying the strains by 0.68, before the life is calculated using the Austroads subgrade strain criterion. Applying correction factors does significantly improve the predictions but, based on individual points, the median error ranges from 0.5 to around 1.5 times the life. If the aim was to use the collection of FWD measurements per section to predict the life of the whole section, then it is possible to develop correction factors that will provide an exact match of say 10th percentile FWD and observed lives. However, despite the same subgrade type and strength for all sections in both the PR3-0404 and the PR3-0610 project, the appropriate strain multipliers are different. In theory, there would be only one strain multiplier applied to one particular subgrade soil type and strength.

Table 3.3 summarises the strain multipliers required to ensure an accurate prediction of the 10th percentile observed life from the 10th percentile FWD life. The strain multiplier for the Waikari clay appears to be a function of the California bearing ratio (CBR) and aggregate depth provided the basecourse aggregate is of good quality. Despite the same subgrade type and strength in both the PR3-0404 and PR3-0610 projects the appropriate strain multipliers are different. This finding in a controlled indoor test track means that it would also be difficult to obtain appropriate strain multipliers in the field. The Todd clay results are a little more scattered. An appropriate factor for the 10 CBR Waikari clay at a depth of 275mm for a good aggregate is calculated as 0.7, being the average value ignoring the outliers. The outliers are those with lower quality aggregate and section A in PR3-0404 due to the large, significant difference in results. These outliers would also be highlighted in the field as aggregates not complying with specifications for materials and construction. Results of applying the 0.7 strain multiplier value to the four similar pavement sections are shown in table 3.4. If the outliers are ignored (ie those sections that are not 275mm deep with good quality aggregate and thus the 0.7 strain multiplier is not relevant) then the error of the 10th percentile FWD life ranges from 0.3 to 1.8 times the observed life (sections highlighted in bold in table 3.6).

Table 3.5 Strain multipliers to predict the 10th percentile observed life from the 10th percentile FWD observed life

Section	Strain multiplier	Subgrade soil		Aggregate depth	Aggregate quality
PR3-0404					
A	0.53	Waiari clay	10	275	Good
B	0.57	Waikari clay	10	275	Average
C	0.65	Waikari clay	10	275	Good
D	0.70	Waikari clay	10	275	Good
PR3-0610					
A	0.77	Waikari clay	10	275	Good
B	0.44	Waikari clay	10	200	Good
C	0.44	Waikari clay	10	200	Good
D	0.67	Waikari clay	10	275	Good
E	1.04	Waikari clay	10	200	Poor
PR3-0805					
A	0.58	Todd clay	7	150	Good
B	0.48	Todd clay	9	150	Good
C	0.81	Todd clay	2	150	Good
D	0.96	Todd clay	3	300	Good
E	1.22	Todd clay	8	300	Good

Table 3.6 Results of corrected (section 3.2.2) Austroads mechanistic empirical method for CAPTIF projects (using common strain multiplier of 0.7)

Section(b)	Strain multiplier	FWD – Austroads M-EP (uncorrected)			Observed life – (N to VSD = 15 mm)			Errors(a) – FWD/observed life		
		10%ile	50%ile	Average	10%ile	50%ile	Average	10%	50%	Ave.
PR3-0404										
A	0.70	5.0E+05	8.7E+05	1.3E+06	2.7E+06	3.7E+06	4.3E+06	0.19	0.24	0.30
B	**0.70**	**6.7E+05**	**1.5E+06**	**1.6E+06**	**2.3E+06**	**4.1E+06**	**4.4E+06**	**0.29**	0.37	0.36
C	**0.70**	**2.9E+06**	**6.7E+06**	**9.2E+06**	**4.5E+06**	**5.0E+06**	**5.3E+06**	**0.64**	1.34	1.74
D	**0.70**	**4.2E+06**	**8.0E+06**	**9.3E+06**	**4.3E+06**	**5.4E+06**	**5.9E+06**	**0.98**	1.48	1.58
PR3-0610										
A	**0.70**	**5.7E+06**	**8.3E+06**	**9.8E+06**	**3.1E+06**	**4.6E+06**	**4.5E+06**	**1.84**	1.80	2.18
B	0.70	2.5E+05	3.6E+05	3.8E+05	4.2E+06	4.5E+06	4.6E+06	0.06	0.08	0.08
C	0.70	2.0E+05	3.7E+05	3.5E+05	3.3E+06	3.7E+06	3.9E+06	0.06	0.10	0.09
D	**0.70**	**3.3E+06**	**4.5E+06**	**5.3E+06**	**4.2E+06**	**5.4E+06**	**5.3E+06**	**0.79**	0.83	1.00
E	0.70	3.9E+06	5.7E+06	1.2E+07	3.6E+05	5.3E+05	8.8E+05	10.8	10.7	13.6
PR3-0805										
A	0.70	4.9E+04	1.3E+05	5.8E+05	1.5E+05	1.4E+06	1.0E+06	0.33	0.09	0.58
B	0.70	1.5E+04	3.4E+05	3.4E+05	1.5E+05	1.5E+05	1.5E+05	0.10	2.27	2.27
C	0.70	1.2E+05	2.3E+06	8.2E+06	5.0E+04	5.0E+04	5.0E+04	2.4	46	164
D	0.70	2.0E+07	1.1E+08	1.9E+08	3.0E+06	3.7E+06	4.2E+06	6,7	30	45
E	0.70	1.4E+08	4.4E+08	7.2E+08	5.1E+06	7.1E+06	7.4E+06	27	62	97

(a) The error was calculated as the percentage difference between the FWD calculated and observed lives, a negative value indicates the FWD calculated life is less than the observed life.

(b) See table 3.2 and figures 3.10, 3.11 and 3.12 for spread of data on pavement lives (percentiles of lives were calculated from at least 10 points per section where rut depth was measured).

4 FWD field data – low-volume roads – Kaituna and No.2 roads

4.1 Introduction

Kaituna and No.2 roads are sections recently rehabilitated in the Bay of Plenty. They were chosen to show the differences that can occur between low-volume roads and state highways. As these roads have been recently rehabilitated, the traffic loading until the end of life can be easily determined. Although the actual life is the amount of traffic until the section is rehabilitated, the observed life per individual FWD measured point was determined from extrapolating the roughness and rutting data. However, some points were not extrapolated as the end-of-life criteria was already reached.

4.2 Austroads simplified deflection

The Austroads (2004b) simplified deflection method was applied to the FWD central deflection data. Results (table 4.1 and figures 4.1 and 4.2) show the simplified deflection method to underestimate the life by a factor of 100 or more (a common finding in North Island volcanic ash subgrades). However, the 50th percentile predicted and observed lives are a close match for the No.2 road and from the plot the predictions are 'not bad'. This is in contrast to the CAPTIF results which show this method tends to overestimate the life.

Table 4.1 FWD Austroads (2004b) simplified deflection predicted life compared with observed life for low volume roads

Road	FWD – Austroads (2004b) simplified deflection			Observed life – (N to VSD = 15mm)			Errors – FWD/observed life		
	10%ile	50%ile	Average	10%ile	50%ile	Average	10%	50%	Average
No.2 Road	7.00E+01	2.84E+04	1.11E+06	2.45E+04	3.75E+04	9.74E+07	0.0029	0.76	0.011
Kaituna Road	3.00E+00	1.21E+02	9.19E+03	1.36E+04	9.63E+04	9.26E+07	0.0002	0.0013	0.0001

Figure 4.1 No.2 road – Austroads (2004b) simplified deflection compared with observed life

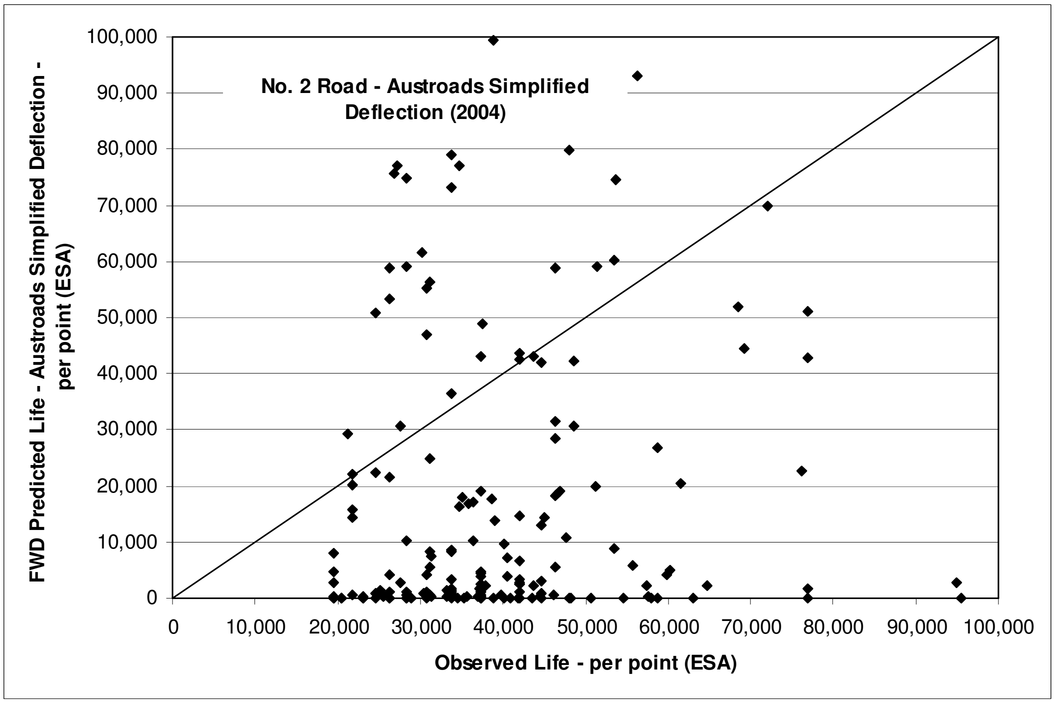
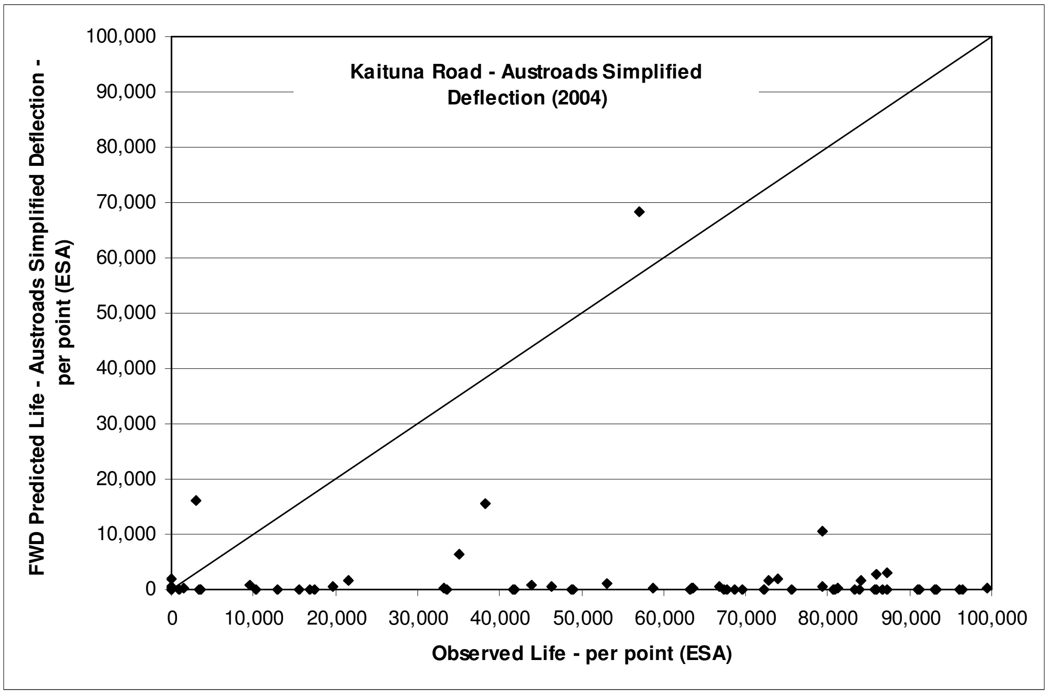


Figure 4.2 Kaituna Road – Austroads (2004b) simplified deflection compared with observed life



4.3 Austroads M-EP

Applying the Austroads M-EP (without any correction factor) to the FWD measurements on the low-volume roads resulted in a predominantly under-prediction of life. Figures 4.3 and 4.4 illustrate the result while percentile values and errors are detailed in table 4.2. Percentile values were calculated assuming a normal distribution and based on the standard deviation. The resulting percentiles were checked by sorting the data based on life and ensuring that 10% of the lives calculated were less than the 10th percentile value. A similar check was undertaken for the 50th percentile.

Table 4.2 FWD Austroads M-EP predicted life compared with observed life for low-volume roads

Road	FWD – Austroads M-EP – life (ESAs)			Observed life – (N to VSD = 15 mm)			Errors – FWD/observed life		
	10%ile	50%ile	Average	10%ile	50%ile	Average	10%	50%	Average
No.2 Road	34	903	4728	24,500	37,500	97,400,000	0.0014	0.02	0.00005
Kaituna Road	42	138	7707	13,600	96,300	92,600,000	0.0031	0.0014	0.00008

Figure 4.3 No.2 road – Austroads MEP (not corrected) compared with observed life

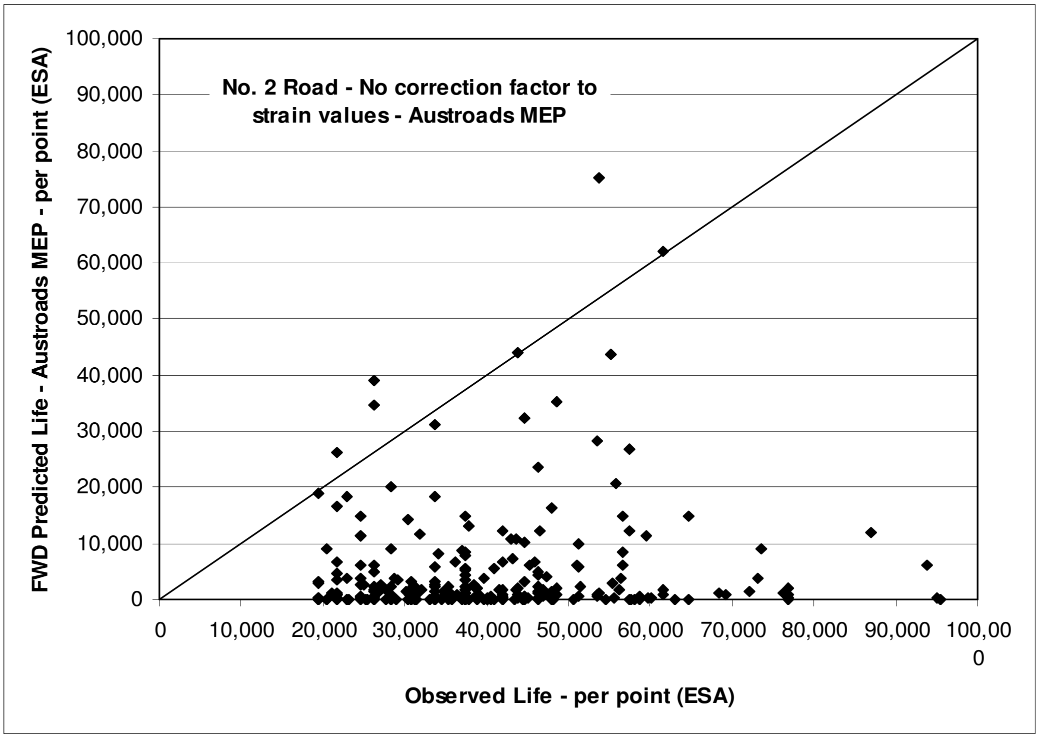
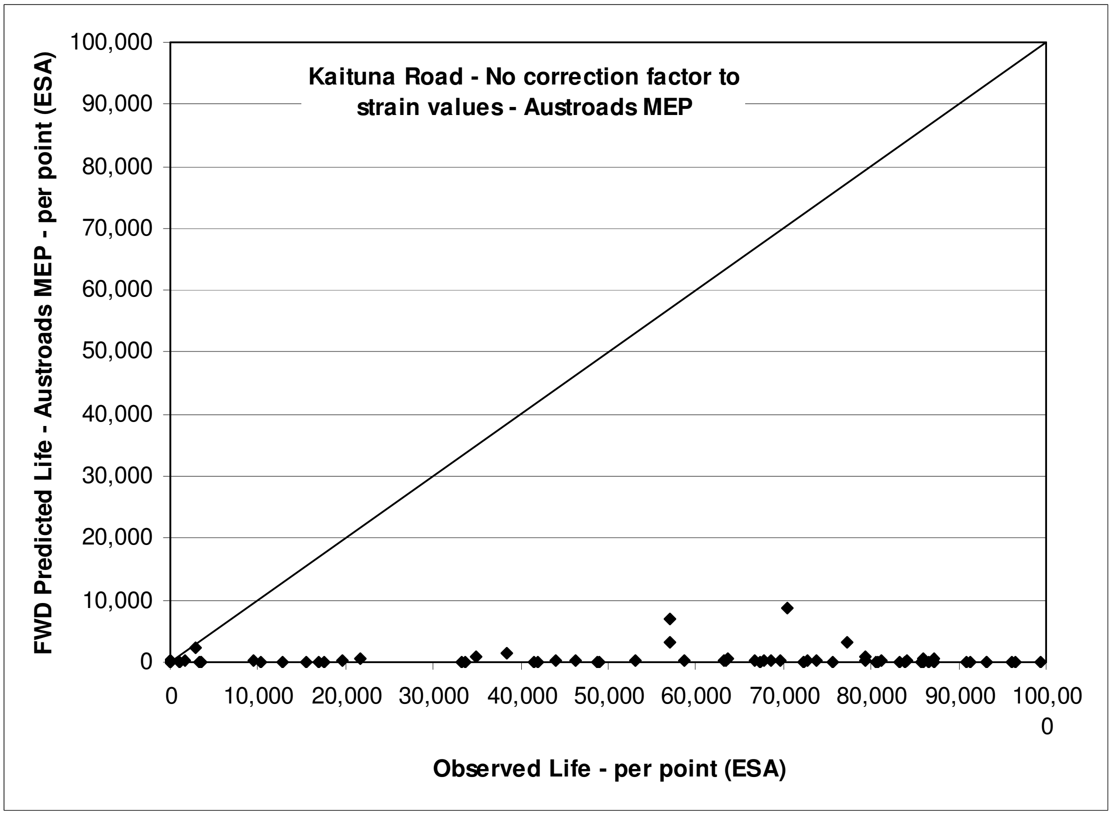


Figure 4.4 Kaituna Road – Austroads M-EP (not corrected) compared with observed life



4.4 Precedent M-EP

Following the precedent M-EP principles a strain multiplier was determined for the low-volume roads where the 10th percentile FWD and observed lives are equal. It was found that values of 0.33 and 0.38 were needed to multiply the subgrade strains before they were input into the Austroads subgrade strain criterion to predict life. This means that the subgrade strains are three times higher than Austroads design criteria would expect them to be. The accuracy of the strain multipliers cannot be determined as there are no other projects on these roads where they can be trialled. Table 4.3 and figures 4.5 and 4.6 show the result of applying the subgrade correction factors. It can be seen that a strain multiplier can be chosen so that the 10th percentile values match exactly but there is still a large spread in calculated lives. The strain multiplier of 0.33 implies that for these roads the strains can be three times higher than allowed by the Austroads subgrade strain criterion.

Table 4.3 FWD Austroads M-EP predicted life with a subgrade strain multiplier compared with observed life for low-volume roads

Road	Strain multiplier	FWD – Austroads M-EP corrected life (ESAs)			Observed life – (N to VSD=15mm)			Errors – FWD/observed life		
		10%ile	50%ile	Average	10%ile	50%ile	Average	10%	50%	Average
No.2 Road	0.33	24,503	651,612	3,412,418	24,500	37,500	97,400,000	1.0	17	0.035
Kaituna Road	0.38	13,647	44,718	205,155	13,600	96,300	92,600,000	1.0	0.5	0.002

Figure 4.5 No.2 road – Austroads MEP (corrected) compared with observed life

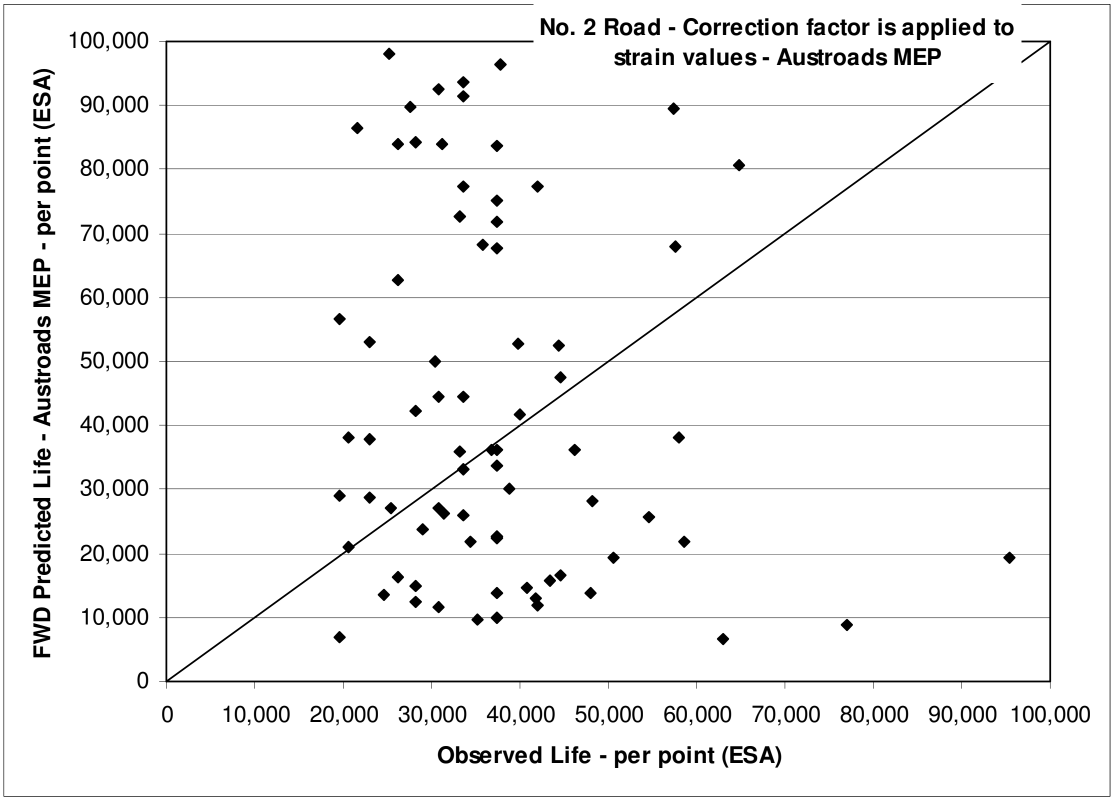
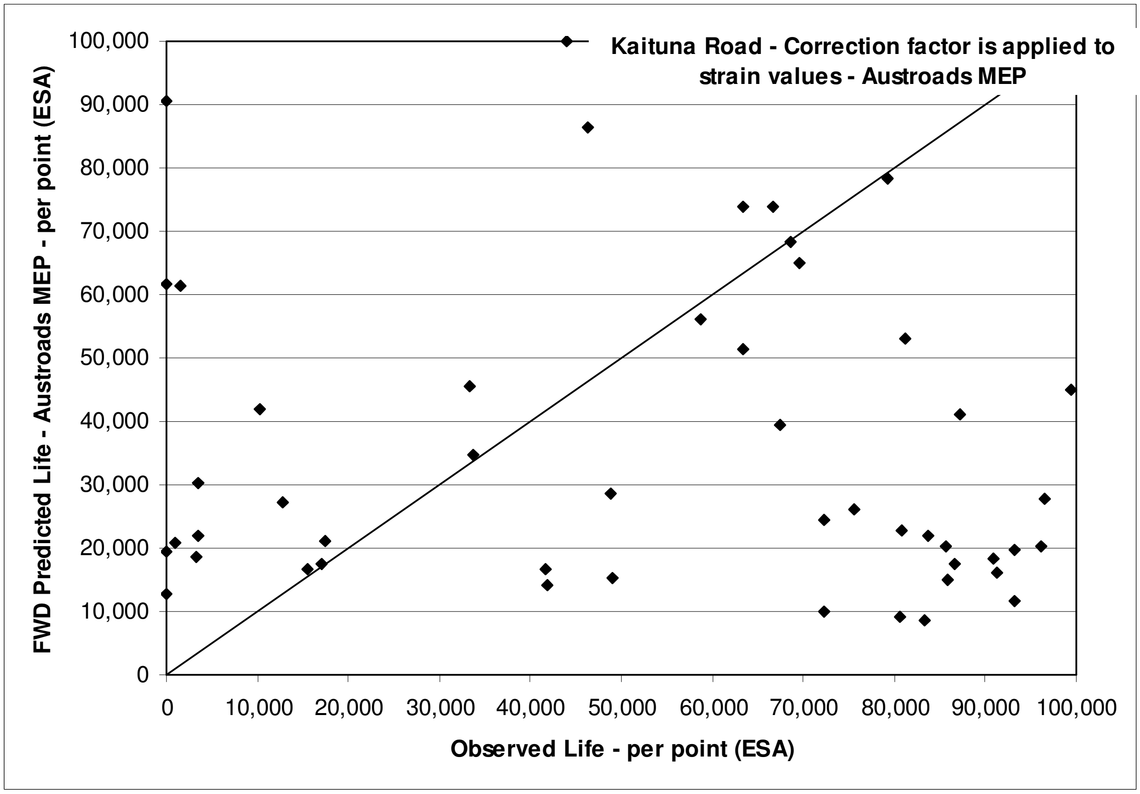


Figure 4.6 No.2 road Austroads M-EP (corrected) compared with observed life



4.5 Discussion

For low-volume roads in the Bay of Plenty the deflections are high and as such the lives predicted using the FWD measurements and Austroads criteria are significantly lower than was achieved. Combining the data to determine percentiles shows that the Austroads methods will always under-predict life and a calibration factor of around 0.35 strain multiplier may be appropriate in the Bay of Plenty for low-volume roads to predict the 10th percentile life from the 10th percentile FWD life. Although this case study was for low-volume roads there is other evidence in the central North Island with pumice subgrade soils that result in similar strain multipliers for high-traffic roads.

Analyses of the past performance of several pavements founded on unweathered volcanic ashes indicate that subgrade strains 1.5 to 1.75 times higher (or strain multipliers of 0.6 to 0.7) than that used for standard soils (Salt 2000) can be justified. It appears that unweathered volcanic ash provides unusually high resistance to permanent strain accumulation, probably attributable to the very high shear resistance provided by its sharply angular grains.

5 FWD field data – Alpurt

5.1 Introduction

The first NZTA state highway data analysed was Alpurt Sector A. Alpurt was chosen, as after six years the pavement failed in some places and hence the end of life was well defined. PSMC contracts were also an obvious choice as these contracts rely on performance measurements for payment and thus there is a significant amount of FWD and high-speed rutting and roughness data. Traffic loading for Alpurt is one million ESAs per year and, therefore, based on current performance the pavement did not last longer than 10 years or 10 million ESAs.

5.2 Alpurt Sector A

State Highway 1 Alpurt Sector A (SH1 RS 398) was constructed in 2000, and in 2006 significant rutting and cracks appeared on wheel paths in the slow lane between Silverdale intersection and Lonely Track road. The six years of trafficking, which denoted the end of life for this Alpurt section, were compared with predictions of life from FWD tests conducted soon after construction. High-speed data on roughness and rutting is used to determine life of individual pavement sections. It should be noted that some of the early pavement failure could be attributed to inadequate pavement depth although it was assumed at the time of FWD testing that the design pavement depth was achieved. Nevertheless, this study will show if the FWD is a useful tool for finding these construction and design inadequacies.

5.3 Austroads simplified deflection

Table 5.1 shows the results of the analysis for the simplified methods based on the raw FWD deflection values only. It was found that all central deflections were sufficiently low in value indicating that the life in ESAs was in excess of 10,000 million for all three deflection-based approaches. This is clearly a very poor prediction of actual performance and well in excess of the expected performance of a high-quality granular pavement.

Table 5.1 Results of deflection-based methods

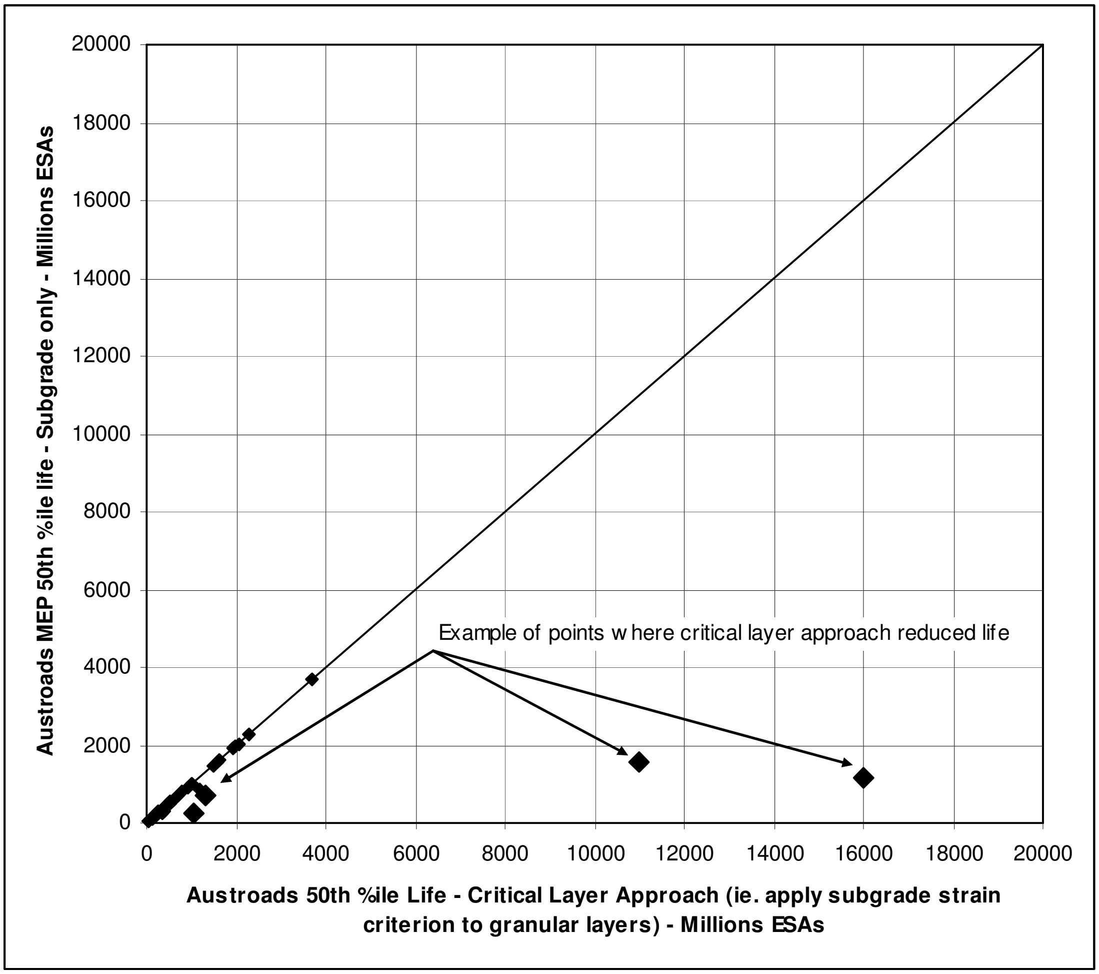
Filename	Section	Values	ESA – predicted MESA – Austroads 2004b – 50%	Actual life MESA	Error – FWD/observed life
All	All	All	10,000	10	1000

5.4 Austroads M-EP and critical layer

The Austroads M-EP and critical layer method described in section 2.2.1 were used on the FWD data collected on the Alpurt pavements one year after construction. Tables 5.2, 5.3 and 5.4 show predictions from FWD tests, using the Austroads M-EP procedures. It can be seen clearly that the Austroads M-EP over-predicts the life by orders of magnitude in most cases. However, reviewing the lower 10th percentile values from the predictions of life found that, in general, twice the actual life was predicted. This result is reasonable but still a 100% error. Plotting the predicted versus observed results on a log-log scale does show a trend but a poor correlation (figure 5.2).

On the data as a whole it was found that applying the critical layer approach (see section 2.2.1) affected the FWD predicted life for 12 points out of 50 when comparing the 50th percentile values (see table 5.2 and figure 5.1). This occurred even though the 50th percentile values for all the Alpurt sections combined were the same for both the standard Austroads method and critical strain approach as shown in table 5.5.

Figure 5.1 Effect of applying the critical layer approach



Combining all the Alpurt data and calculating the 10th percentile Austroads M-EP life yielded a life of 23 million ESA (table 5.5) compared with an actual life of 10 million ESA. Hence the 10th percentile data appears to be the better predictor of life for the Alpurt project.

Table 5.2 Alpurt part 1 results of FWD analysis using Austroads M-EP methods

Filename	Section	No. FWD pts	MESA – Austroads M-EP – 50%ile life		MESA – Austroads M-EP critical – 50%ile life		MESA – Austroads M-EP – 10%ile life		MESA observed MESA	Life (MESA)	*Prediction Ok?
				Error		Error		Error			
01N-0296 0.0 – 8.0 (1999) L1\	1	6	213	>100	213	21300	60	6000	0.01	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	2	15	128	0.5	128	0.5	25	0.1	254	<10	Yes
01N-0296 0.0 – 8.0 (1999) L1\	3	12	2050	23.0	2050	23.0	114	1.3	89	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	4	13	284	1.3	284	1.3	41	0.2	217	<10	Yes
01N-0296 0.0 – 8.0 (1999) L1\	5	11	1619	810	1619	810	17	9	2	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	6	3	1939	26.6	1939	26.6	1939	26.6	73	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	7	7	249	0.3	249	0.3	53	0.1	863	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	8	7	998	15.6	998	15.6	76	1.2	64	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	9	17	377	189	297	149	67	34	2	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	10	4	1049	1049	268	268	112	112	1	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	11	13	109	1.4	109	1.4	67	0.9	78	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	12	6	35	12	35	12	11	4	3	<10	Yes
01N-0296 0.0 – 8.0 (1999) L1\	13	7	1594	89	1594	89	1591	88	18	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	14	5	1922	641	1922	641	259	86	3	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	15	13	2283	176	2283	176	274	21	13	<10	No
01N-0296 0.0 – 8.0 (1999) L1\	16	11	187	21	187	21	31	3	9	<10	Yes
01N-0296 0.0 – 8.0 (1999) L1\	17	8	1477	18	1477	18	347	4	80	<10	Yes
01N-0296 0.0 – 8.0 (1999) L2\	1	7	89	8900	89	8900	48	4800	0.01	<10	Yes
01N-0296 0.0 – 8.0 (1999) L2\	2	33	512	0.5	512	0.5	72	0.1	1019	<10	No
01N-0296 0.0 – 8.0 (1999) L2\	3	26	399	0.5	399	0.5	50	0.1	768	<10	No
01N-0296 0.0 – 8.0 (1999) L2\	4	32	277	1.0	269	0.9	42	0.1	287	<10	Yes

Filename	Section	No. FWD pts	MESA – Austroads M-EP – 50%ile life		MESA – Austroads M-EP critical – 50%ile life		MESA – Austroads M-EP – 10%ile life		MESA observed MESA	Life (MESA)	*Prediction Ok?
				Error		Error		Error			
01N-0296 0.0 – 8.0 (1999) L2\	5	20	432	0.6	432	0.6	13	0.0	748	<10	No
01N-0296 0.0 – 8.0 (1999) L2\	6	9	3692	7.3	3692	7.3	412	0.8	509	<10	No
01N-0296 0.0 – 8.0 (1999) L2\	7	32	113	0.2	100	0.1	39	0.1	732	<10	Yes
01N-0296 0.0 – 8.0 (1999) R1\	1	6	511	>100	511	25550	54	2700	0.02	<10	No
01N-0296 0.0 – 8.0 (1999) R1\	2	11	176	1.0	154	0.9	14	0.1	175	<10	No
01N-0296 0.0 – 8.0 (1999) R1\	3	9	513	1.8	513	1.8	413	1.4	285	<10	No
01N-0296 0.0 – 8.0 (1999) R1\	4	11	1983	165.3	1983	165.3	76	6.3	12	<10	No
01N-0296 0.0 – 8.0 (1999) R1\	5	9	541	2.3	541	2.3	204	0.9	240	<10	Yes
01N-0296 0.0 – 8.0 (1999) R1\	6	15	235	47.0	235	47.0	88	17.6	5	<10	No
01N-0296 0.0 – 8.0 (1999) R1\	7	6	689	0.7	689	0.7	324	0.3	962	<10	No
01N-0296 0.0 – 8.0 (1999) R1\	8	9	513	6.3	513	6.3	79	1.0	82	<10	No
01N-0296 0.0 – 8.0 (1999) R1\	9	21	163	163.0	163	163.0	40	40.0	1	<10	Yes
01N-0296 0.0 – 8.0 (1999) R1\	10	6	202	11.2	202	11.2	124	6.9	18	<10	No
01N-0296 0.0 – 8.0 (1999) R1\	11	8	61	0.4	39	0.2	12	0.1	163	<10	No
01N-0296 0.0 – 8.0 (1999) R1\	12	18	499	249.5	499	249.5	59	29.5	2	<10	No
01N-0296 0.0 – 8.0 (1999) R1\	13	23	1187	148.4	878	109.8	36	4.5	8	<10	Yes
01N-0296 0.0 – 8.0 (1999) R1\	14	8	916	6.1	916	6.1	177	1.2	151	<10	No
01N-0296 0.0 – 8.0 (1999) R2\	1	6	15993	>100	1185	59250	189	9450	0.02	<10	No
01N-0296 0.0 - 8.0 (1999) R2\	2	20	408	0.4	301	0.3	16	0.0	1025	<10	No
01N-0296 0.0 - 8.0 (1999) R2\	3	21	308	0.4	308	0.4	72	0.1	799	<10	No
01N-0296 0.0 - 8.0 (1999) R2\	4	19	504	0.5	504	0.5	103	0.1	922	<10	No
01N-0296 0.0 - 8.0 (1999) R2\	5	11	277	1.3	277	1.3	24	0.1	206	<10	Yes

Filename	Section	No. FWD pts	MESA – Austroads M-EP – 50%ile life		MESA – Austroads M-EP critical – 50%ile life		MESA – Austroads M-EP – 10%ile life		MESA observed MESA	Life (MESA)	*Prediction Ok?
				Error		**Error**		**Error**			
01N-0296 0.0 - 8.0 (1999) R2\	6	16	1328	1.8	693	1.0	62	0.1	723	<10	No
01N-0296 0.0 - 8.0 (1999) R2\	7	6	800	2.9	800	2.9	38	0.1	278	<10	Yes
01N-0296 0.0 - 8.0 (1999) R2\	8	27	326	0.4	326	0.4	65	0.1	868	<10	No
01N-0296 0.0 - 8.0 (1999) R2\	9	3	11003	51.9	1574	7.4	1574	7.4	212	<10	No
01N-0296 0.0 - 8.0 (1999) R2\	10	13	457	0.4	457	0.4	102	0.1	1172	<10	No
01N-0296 0.0 - 8.0 (1999) R2\	11	7	664	0.7	664	0.7	126	0.1	890	<10	No
01N-0296 0.0 - 8.0 (1999) R2\	12	11	354	0.5	266	0.4	30	0.0	678	<10	Yes
10th percentile value		637	126	126	126	126	17	17	1	<10	No
50th percentile value			501	3.2	508	3.2	67	0.4	157	<10	Yes

* Is prediction within five times the observed life?

Table 5.3 Alpurt part 2 results of FWD analysis using Austroads M-EP methods

Filename	Section	No. FWD pts	MESA – Austroads M-EP – 50%ile life		MESA – Austroads M-EP critical – 50%ile life		MESA – Austroads M-EP – 10%ile life		MESA observed MESA	Life (MESA)	*Prediction Ok?
				Error		**Error**		**Error**			
01N-0296 11.6 - 15.8 (2003) L1\	1	1	223	0.24	223	0.24	223	0.24	938	<10	Yes
01N-0296 11.6 - 15.8 (2003) L1\	2	3	159	0.17	159	0.17	159	0.17	283	<10	No
01N-0296 11.6 - 15.8 (2003) L1\	3	1	23	0.02	23	0.02	23	0.02	28	<10	No
01N-0296 11.6 - 15.8 (2003) L1\	4	4	150	0.16	150	0.16	58	0.06	268	<10	No
01N-0296 11.6 - 15.8 (2003) L1\	5	7	883	0.94	883	0.94	599	0.64	19	<10	Yes
01N-0296 11.6 - 15.8 (2003) L2\	1	2	21	0.02	21	0.02	21	0.02	973	<10	No
01N-0296 11.6 - 15.8 (2003) L2\	2	4	29844	32	29844	32	9130	10	56	<10	No
01N-0296 11.6 - 15.8 (2003) R1\	1	13	1956	2.09	1956	2.09	107	0.11	43	<10	Yes
01N-0296 11.6 - 15.8 (2003) R2\	1	4	6	0.01	6	0.01	2	0.00	83	<10	No
01N-0296 11.6 - 15.8 (2003) R2\	2	4	1209	1.29	1209	1.29	852	0.91	977	<10	Yes
10th percentile value		43	19	0.02	19	0.02	19	0.02	27	<10	No
50th percentile value			191	0.20	191	0.20	133	0.14	175	<10	Yes
50th percentile value			501	3.2	508	3.2	67	0.4	157	<10	Yes

* Is prediction within five times the observed life?

Table 5.4 Alpurt part 3 results of FWD analysis using Austroads MEP methods

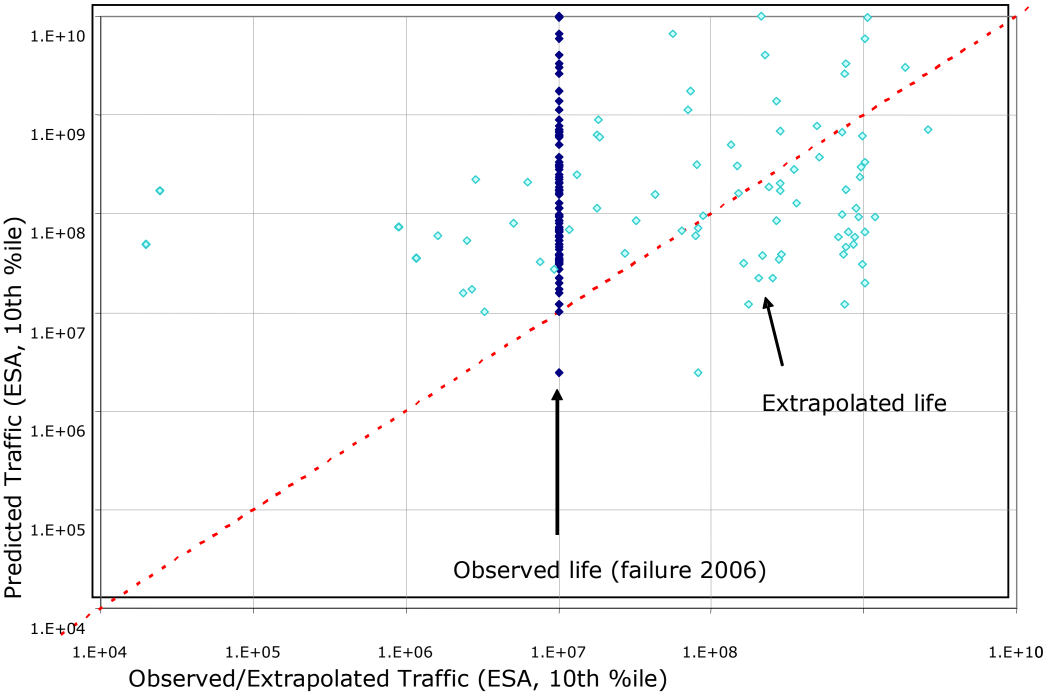
Filename	Section	No.	MESA – Austroads M-EP – 50%ile life	MESA – Austroads M-EP critical – 50%ile life	MESA – Austroads MEP – 10%ile life	MESA – observed/ extrapolated MESA – minimum of IRI and VSD – 10%ile life	Life (MESA) based on knowledge of rutting failures in 2006	Predictions within 5 times of the actual life?
01N-0296 7.8 - 10.2 (2000) R1\	1	17	132935	132935	3721	990	<10	Yes
01N-0296 7.8 - 10.2 (2000) R1\	2	15	8205	8205	633	2648	<10	Yes
01N-0296 7.8 - 10.2 (2000) R1\	3	16	462	462	157	763	<10	No
01N-0296 7.8 - 10.2 (2000) R2\	1	13	62381	62381	9215	121	<10	No
01N-0296 7.8 - 10.2 (2000) R2\	2	2	4874785	1436208	1436208	16	<10	No
01N-0296 7.8 - 10.2 (2000) R2\	3	2	19255	19255	204510	1097	<10	No
01N-0296 7.8 - 10.2 (2000) R2\	4	10	4573	4573	797	18	<10	No
01N-0296 7.8 - 10.2 (2000) R2\	5	4	8689	8689	77342	1019	<10	No
01N-0296 7.8 - 10.2 (2000) R2\	6	6	667	667	268	149	<10	Yes
01N-0296 7.8 - 10.2 (2000) R2\	7	12	390	390	186	6	<10	No
01N-0296 7.8 - 11.8 (2000) L1\	1	3	465613	32977	32977	2208	<10	No
01N-0296 7.8 - 11.8 (2000) L1\	2	18	109882	92168	205	1856	<10	No
01N-0296 7.8 - 11.8 (2000) L1\	3	13	246944	167210	228	763	<10	No
01N-0296 7.8 - 11.8 (2000) L1\	4	6	276420	276420	11327	224	<10	No
01N-0296 7.8 - 11.8 (2000) L1\	5	12	11435	11435	66	492	<10	No
01N-0296 7.8 - 11.8 (2000) L1\	6	8	1625	1625	632	134	<10	Yes
01N-0296 7.8 - 11.8 (2000) L1\	7	6	1208	1208	1208	285	<10	Yes
01N-0296 7.8 - 11.8 (2000) L1\	8	5	1444	1444	1444	71	<10	No
01N-0296 7.8 - 11.8 (2000) L1\	9	7	338	338	165	364	<10	No
01N-0296 7.8 - 11.8 (2000) L2\	1	9	177779	96576	1169	42	<10	No
01N-0296 7.8 - 11.8 (2000) L2\	2	8	13296	13296	17138	748	<10	No

Filename	Section	No.	MESA – Austroads M-EP – 50%ile life	MESA – Austroads M-EP critical – 50%ile life	MESA – Austroads MEP – 10%ile life	MESA – observed/ extrapolated MESA – minimum of IRI and VSD – 10%ile life	Life (MESA) based on knowledge of rutting failures in 2006	Predictions within 5 times of the actual life?
01N-0296 7.8 - 11.8 (2000) L2\	3	4	38750	38750	5702	97	<10	No
01N-0296 7.8 - 11.8 (2000) L2\	4	8	35973	25006	4102	1060	<10	Yes
01N-0296 7.8 - 11.8 (2000) L2\	5	4	1897807	1170449	677179	101	<10	No
01N-0296 7.8 - 11.8 (2000) L2\	6	20	24002	24002	7539	269	<10	No
01N-0296 7.8 - 11.8 (2000) L2\	7	8	1459	1459	107	32	<10	Yes
01N-0296 7.8 - 11.8 (2000) L2\	8	4	986	986	424	1019	<10	No
01N-0296 7.8 - 11.8 (2000) L2\	9	2	391	255	255	351	<10	No
01N-0296 7.8 - 11.8 (2000) L2\	10	11	115	115	22	3	<10	Yes
01N-0296 7.8 - 11.8 (2000) L2\	11	1	859	859	859	724	<10	No
10th percentile value		254	391	385	152	18	<10	No
50th percentile value			10062	10062	1014	318	<10	Yes

Table 5.5 Alpurt 10th percentile results of FWD analysis using Austroads ME-P methods.

Filename	Section	No.	MESA – Austroads M-EP – 50%ile life	MESA - Austroads M-EP critical – 50%ile life	MESA – Austroads M-EP – 10%ile life	MESA – observed/extrapolated MESA – minimum of IRI and VSD - 10%ile life	Life (MESA) based on knowledge of rutting failures in 2006	Predictions within 5 times of the actual life?
Alpurt Part 1 – 10th percentile value		637	126	126	17	1	<10	No
Alpurt Part 2 – 10th percentile value		43	19	19	19	27	<10	Yes
Alpurt Part 3 – 10th percentile value		254	391	385	152	18	<10	No
Alpurt all data combined					23		<10	Yes

Figure 5.2 Observed versus FWD predicted life for Alpurt Sector A



6 FWD field data – Northland PSMC002 – 2002

6.1 Introduction

The Northland PSMC database was chosen due to the readily available performance measurements of FWD and high-speed rutting and roughness data. Measurements in 2002 and 2005 were analysed. Sections were chosen within the Northland PSMC; FWD data assessed was on suitable sections that had been constructed at least four years earlier, thus having sufficient high-speed data to enable extrapolation and prediction of life based on a terminal rut depth and/or roughness.

6.2 Results – 2002 data

FWD results were initially grouped into sections ranging from a few hundred metres to two kilometre lengths defined by surfacing start and finish boundaries. Summary results are shown in tables 6.1 and 6.2. Figure 6.1 shows a plot of predominantly the 10th percentile predictions compared with observed life. Results show the 10th percentile observed life extrapolated from high-speed data is very low and less than one million ESA for a large number of sections. These short lives have not been verified.

Figure 6.1 Observed versus FWD predicted life for Northland 2002 data

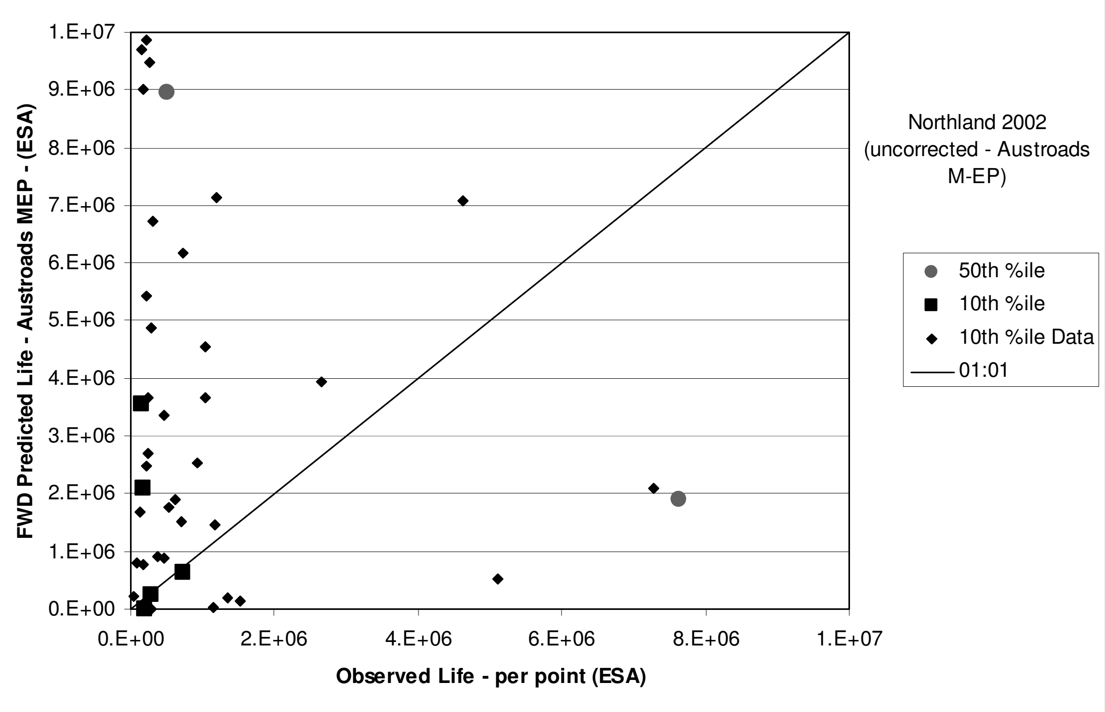


Table 6.1 Example of Northland 2002 FWD predictions of life compared with observed behaviour

Filename	Section	Values	MESA – Austroads 1992 (simplified ch 10) – 50%	MESA – Austroads 2004b – 50%	MESA – deflection curvature – 50%	MESA – Austroads M-EP – 50%	MESA – Austroads M-EP critical – 50%	MESA – Austroads M-EP – 10%	Observed life – MESA – minimum of IRI & VSD – 10%	Observed life – MESA – minimum of IRI & VSD – 50%	Austroads MEP diff. pred. & observed error – 10% values	Austroads MEP diff. pred. & observed error – 50% values
SH1 RP160 decreasing R1\	1	4	36	38	38	1	1	1	125.8	234.8	125	234
SH1 RP160 decreasing R1\	2	5	10,000	10,000	10,000	120	120	12	1.2	211.3	11	91
SH1 RP160 decreasing R1\	3	3	3	2	2	0	0	0	43.8	43.8	44	44
SH1 RP160 decreasing R1\	4	20	10,000	10,000	10,000	169	169	12	0.8	743.8	12	574
SH1 RP160 decreasing R1\	5	7	10,000	10,000	10,000	69,586	69,586	27,865	0.5	21.0	27,865	69,565
SH1 RP160 decreasing R1\	6	8	10,000	10,000	10,000	386	386	4	1.0	303.0	3	83
SH1 RP160 decreasing R1\	7	3	10,000	10,000	10,000	61,096	61,096	61,096	134.0	134.0	60,962	60,962
SH1 RP160 decreasing R1\	8	11	10,000	10,000	10,000	1360	1360	471	57.2	272.6	413	1088
SH1 RP160 decreasing R1\	9	36	10,000	10,000	10,000	82	82	5	0.2	3.4	5	78
SH1 RP160 increasing L1\	1	10	3	3	3	0.18	0.18	0.03	1.1	7.0	1	7
SH1 RP160 increasing L1\	2	30	10,000	10,000	10,000	195	195	3	0.5	54.2	3	141
SH1 RP160 increasing L1\	3	7	10,000	10,000	10,000	111,465	111,465	2421	2.1	83.2	2419	111,381
SH1 RP160 increasing L1\	4	5	10,000	10,000	10,000	187	187	15	4220.1	4220.1	4205	4033
SH1 RP160 increasing L1\	5	2	10,000	10,000	10,000	402,341	402,341	402,341	4220.1	4220.1	398,121	398,121
SH1 RP160 increasing L1\	6	4	10,000	10,000	10,000	5	5	4	4220.1	4220.1	4216	4215
SH1 RP160 increasing L1\	7	7	10,000	10,000	10,000	1,668,170	1,668,170	38,237	4220.1	4220.1	34,017	1,663,950
SH1 RP160 increasing L1\	8	4	10,000	10,000	10,000	9657	9657	586	0.7	45.1	586	9612
SH1 RP160 increasing L1\	9	1	577	2406	2406	0.22	0.22	0.22	0.1	0.1	0	0
SH1 RP160 increasing L1\	10	3	10,000	10,000	10,000	32,159	32,159	32,159	0.3	0.3	32,159	32,159

Filename	**Section**	**Values**	**MESA – Austroads 1992 (simplified ch 10) – 50%**	**MESA – Austroads 2004b – 50%**	**MESA – deflection curvature – 50%**	**MESA – Austroads M-EP – 50%**	**MESA – Austroads M-EP critical – 50%**	**MESA – Austroads M-EP – 10%**	**Observed life – MESA – minimum of IRI & VSD – 10%**	**Observed life – MESA – minimum of IRI & VSD – 50%**	**Austroads MEP diff. pred. & observed error – 10% values**	**Austroads MEP diff. pred. & observed error – 50% values**
SH1 RP160 increasing L1\	11	6	10,000	10,000	10,000	6	6	1	0.4	0.8	1	5
SH1 RP160 increasing L1\	12	2	10,000	10,000	10,000	400,148	400,148	400,148	8.9	8.9	400,139	400,139
SH1 RP160 increasing L1\	13	14	10,000	10,000	10,000	116	116	7	0.3	0.7	6	115
10th percentile value		192	90	275	275	0.3	0.3	0.3	0.3	0.7	1.3	10.5
50th percentile value			10,000	10,000	10,000	191	191	12	1.2	69	269.4	831.0
25th percentile value			10,000	10,000	10,000	25	25	3	0	7	5	85
75th percentile value			10,000	10,000	10,000	53,862	53,862	21,504	109	295	21,953	53,671

Table 6.2 Summary of percentile Northland 2002 FWD predictions of life compared with observed behaviour

Filename	**Values**	**MESA – Austroads 1992 (simplified ch 10) – 50%**	**MESA – Austroads 2004b – 50%**	**MESA -- deflection curvature – 50%**	**MESA – Austroads M-EP – 50%**	**MESA – Austroads M-EP critical – 50%**	**MESA – Austroads M-EP – 10%**	**Observed life – MESA – minimum of IRI & VSD – 10%**	**Observed life – MESA – minimum of IRI & VSD – 50%**	**Austroads M-EP diff. pred & observed error – 10% values**	**Austroads M-EP diff. pred & observed error – 50% values**
SH1 RP 0 increasing L1\											
10th percentile value	66	83	105	105	3.2	3.2	2.1	0.2	0.2	2	3
50th percentile value		10,000	10,000	10,000	90	90	21	0.2	0.5	21	89
25th percentile value		10,000	10,000	10,000	37	37	7	0	0	7	33
75th percentile value		10,000	10,000	10,000	1550	1550	1507	1	5	1507	1549

6 FWD field data – Northland PSMC002 – 2002

Filename	Values	MESA – Austroads 1992 (simplified ch 10) – 50%	MESA – Austroads 2004b – 50%	MESA –- deflection curvature – 50%	MESA – Austroads M-EP – 50%	MESA – Austroads M-EP critical – 50%	MESA – Austroads M-EP – 10%	Observed life – MESA – minimum of IRI & VSD – 10%	Observed life – MESA – minimum of IRI & VSD – 50%	Austroads M-EP diff. pred & observed error – 10% values	Austroads M-EP diff. pred & observed error – 50% values
SH1 RP160 increasing L1\											
10th percentile value	192	90	275	275	0.3	0.3	0.3	0.3	0.7	1.3	10.5
50th percentile value		10,000	10,000	10,000	191	191	12	1.2	69	269.4	831.0
25th percentile value		10,000	10,000	10,000	25	25	3	0	7	5	85
75th percentile value		10,000	10,000	10,000	53,862	53,862	21,504	109	295	21,953	53,761
SH1 RP165 increasing L1\	99										
10th percentile value		10,000	10,000	8133	26	26	0.6	0.7	2.4	1.2	28.8
50th percentile value		10,000	10,000	10,000	318	318	14.0	2.6	5.2	26.6	315.6
25th percentile value		10,000	10,000	10,000	53	53	3	1	4	3	48
75th percentile value		10,000	10,000	10,000	9951	9951	1895	7	18	1864	9920
SH12 RP 0 increasing L1\											
10th percentile value	133	1	0.7	0.7	0.1	0.1	0.01	0.2	0.3	0.2	0.3
50th percentile value		10,000	10,000	10,000	19	19	2.5	0.5	8	2.4	16.2
25th percentile value		5	5	5	1	1	1	0.3	3	0.4	0.6
75th percentile value		10,000	10,000	10,000	41	41	7	5	72	18	90
SH14 RP 0 increasing L1\											
10th percentile value	207	10,000	10,000	10,000	28	28	3.5	0.2	0.4	1.6	33.9
50th percentile value		10,000	10,000	10,000	669	669	314	16	91	330.5	2655.5
25th percentile value		10,000	10,000	10,000	113	113	13	0	5	10	187
75th percentile value		10,000	10,000	10,000	20,747	21,120	16,760	156	635	15,267	20,621

Observations from table 6.1 and figure 6.1 show that the Austroads M-EP along with 10th percentile values gives the best predictions. However, 50% of the predictions have an error of 269 million or less and 10% of the predictions are within 1.3 million ESA of the observed life. The simple deflection methods again show they grossly over-predict the life. It appears that combining the sections to calculate 10th percentile predictions and thus using 192 FWD test results significantly improves the predictions. In fact the 10th percentile predictions and the 10th percentile observed life are the same at 0.3 MESA for SH1 RP 160 increasing L1.

Results in table 6.2 show a good result for SH12 (RP 0 increasing L1) with the 50th percentile error of 2.4 MESA. This means that 50% of the results are within 2.4 MESA of the life predicted from roughness and rutting progression. Overall the 10th percentile values are best and the simplified deflection measurements always over-predicted the life. For the Northland results there was no advantage in using the critical layer approach and calculating the strains in the granular layers.

7 FWD field data – Northland PSMC002 – 2005

7.1 Introduction

A 2005 dataset of Northland state highways was analysed in a similar way to the 2002 FWD dataset. This dataset included many more project sections with a significantly higher number of FWD measurements per project section. Predicted lives using the different methodologies were determined at each FWD measured point. Predictions for each point were collated by project and the 10th, 30th and 50th percentile values were determined.

7.2 Results

The 10th and 50th percentile of the observed life from roughness and rutting measurements were calculated for each project length and compared with the predicted FWD percentile lives. Results of these analyses are summarised in tables 7.2 and 7.3 while table 7.1 explains the method used to calculate the errors.

Table 7.1 Explanation of method used to assess the error of using different percentile values as detailed in tables 7.2 and 7.3

Observed life percentile:	10%	50%	FWD predicted values compared with either the 10th percentile observed life or the 50th percentile observed life.
50th % error:	245%	-54%	This is the median error value as a percentage of observed life. A positive value indicates the FWD predictions are much higher than the observed life and vice versa for a negative value
% FWD predicted below:	23%	64%	This is the percentage of FWD predicted values that are below the observed life. A value of 50% indicates that half the values are below and half are above the observed life.

Table 7.2 shows that using the Austroads M-EP together with the critical layer approach (ie considering vertical strains on aggregate layers also) had a negligible effect on the results statistically. Mean and median errors were the same. Closer examination of the accuracy of predictions for individual projects found that using the critical layer approach changed the predicted life for 18 of the 64 projects. However, of the 18 changed lives only four had an improvement in the predicted life (ie closer to the observed life); even though the Austroads M-EP critical method will always compute the same or less life than the standard Austroads M-EP method. Thus, this suggests checking strains in the granular layers is unnecessary, as is the case using the current Austroads pavement design method. However, there are specific cases involving weak or degraded basecourse or subbase layers where this check (first promoted by Ullidtz 1987) has considerable significance. There is a current research project funded by NZTA titled *Development of a basecourse/subbase design criterion*, which will determine a more appropriate basecourse and subbase strain criterion for design purposes which could also be used to calculate life from FWD measurements.

Other observations of the Austroads M-EP show that 77% of the time the 10th percentile Austroads M-EP will predict lives less than the 10th percentile observed life and the median error is -77%. The 30th percentile Austroads M-EP will 51% of the time predict lives less than the 10th percentile observed life with a median error of -5%. Figures 7.1 and 7.2 show results of the 10th and 30th percentile Austroads M-EP lives versus the 10th percentile observed lives.

Table 7.2 Example of Northland 2005 FWD predictions of life compared with observed behaviour

	Observed life percentile		10%	50%	10%	50%	10%	50%	10%	50%	10%	50%	10%	50%
	50th % error		254%	–54%	–77%	–98%	–5%	–87%	–77%	–98%	–5%	–88%	246%	–54%
	% FWD predicted below		23%	64%	77%	95%	51%	79%	79%	95%	51%	79%	26%	64%
Northland 2005 – filename	**Observed life MESA 50%**	**Observed life MESA 10%**	**MESA Austroads M-EP 50%**		**MESA Austroads M-EP – 10%**		**MESA Austroads M-EP – 30%**		**MESA Austroads M-EP critical 10%**		**MESA Austroads M-EP critical 30%**		**MESA Austroads M-EP critical 50%**	
SH1N RS083 3.056 – 3.256 KAIMAUMAU L1_R1	1.4	0.4	8.0		0.4		3.1		0.4		3.1		8.0	
SH1N RS083 7.816 – 8.216 PAPARORE ROAD L1_R1	3.2	0.6	1.5		0.2		0.6		0.2		0.6		1.5	
SH1N RS083 9.445 – 14.460 WAIHARARA REHAB & WAIPAPAKAURI	42.3	3.5	182.4		0.7		23.4		0.6		23.4		182.4	
SH1N RS104 0.701 – 0.951 AWANUI STRAIGHT 1 L1_Detail	2519.7	163.4	72.9		34.3		50.2		34.3		50.2		72.9	
SH1N RS104 2.147 – 2.382 AWANUI STRAIGHT 2 L1_Detail	917.0	223.2	18.5		7.0		11.7		7.0		11.7		18.5	
SH1N RS104 9.100 – 9.600 KAITAIA SOUTH	25.7	2.1	2.2		0.1		0.6		0.1		0.6		2.2	
SH1N RS119 1.300 – 1.600 PAMAPURIA	26.2	3.2	4.8		1.8		3.6		0.9		3.5		4.8	
SH1N RS149 8.300 – 8.900 OGLES HILL	0.8	0.5	7.0		0.7		2.5		0.7		2.5		7.0	
SH1N RS149 12.900 – 14.800 HUATAU HILL & RANGIAHUA HILL	0.5	0.2	2.7		0.1		0.9		0.1		0.7		2.3	
SH1N RS167 7.567 – 8.079 PUKEPOTO REHAB	12.3	6.3	10.0		0.7		3.8		0.7		3.8		10.0	

	Observed life percentile		10%	50%	10%	50%	10%	50%	10%	50%	10%	50%	10%	50%
	50th % error		254%	-54%	-77%	-98%	-5%	-87%	-77%	-98%	-5%	-88%	246%	-54%
	% FWD predicted below		23%	64%	77%	95%	51%	79%	79%	95%	51%	79%	26%	64%
Northland 2005 – filename	**Observed life MESA 50%**	**Observed life MESA 10%**	**MESA Austroads M-EP 50%**		**MESA Austroads M-EP – 10%**		**MESA Austroads M-EP – 30%**		**MESA Austroads M-EP critical 10%**		**MESA Austroads M-EP critical 30%**		**MESA Austroads M-EP critical 50%**	
SH1N RS167 12.133 – 12.445 OKAIHAU STH REHAB	43.9	1.8	81.7		9.3		19.1		9.3		19.1		81.7	
SH1N RS167 12.899 – 17.192 OKAIHAU SOUTH	21.0	3.0	107.9		1.3		17.4		1.3		16.1		93.6	
SH1N RS198 3.770 – 4.210 MARSHALLS REHAB	4.0	1.7	145.8		3.0		40.0		2.3		8.3		118.9	
SH1N RS211 1.864 – 2.085 KAWAKAWA TRUCK RIDE	14.7	3.4	16.9		1.4		3.7		1.4		3.7		16.9	
SH1N RS215 9.589 – 9.992 TOWAI TRUCK RIDE	2.8	1.7	2.9		0.2		1.2		0.2		1.2		2.9	
SH1N RS215 17.055 – 17.324 HUKERENUI TRUCK RIDE	3.6	1.9	2.3		0.5		1.4		0.5		1.4		2.3	
SH1N RS233 3.285 – 4.775 HUKERENUI SAFETY IMPRV	34.4	3.8	15011.4		59.6		3235.1		59.6		3235.1		15011.4	
SH1N RS245 0.617 – 1.742 OTONGA	39.9	12.1	98.4		3.1		15.4		3.1		15.4		98.4	
SH1N RS245 11.620 – 12.700 SPRINGS FLAT	61.9	28.3	5.9		0.3		1.9		0.3		1.9		5.9	
SH1N RS273 7.299 – 8.418 MANGAPAI PASSING LANE	9.2	3.2	36.3		0.7		11.2		0.7		11.2		36.3	
SH1N RS273 9.777 – 10.963 HEWLETT PASSING LANE	5.5	3.4	0.9		0.1		0.3		0.1		0.3		0.9	
SH1N RS273 11.297 – 11.557 MATA REHAB	15.1	5.6	68.2		7.6		39.2		7.6		39.2		68.2	

	Observed life percentile		10%	50%	10%	50%	10%	50%	10%	50%	10%	50%	10%	50%
	50th % error		254%	-54%	-77%	-98%	-5%	-87%	-77%	-98%	-5%	-88%	246%	-54%
	% FWD predicted below		23%	64%	77%	95%	51%	79%	79%	95%	51%	79%	26%	64%
Northland 2005 – filename	**Observed life MESA 50%**	**Observed life MESA 10%**	**MESA Austroads M-EP 50%**		**MESA Austroads M-EP – 10%**		**MESA Austroads M-EP – 30%**		**MESA Austroads M-EP critical 10%**		**MESA Austroads M-EP critical 30%**		**MESA Austroads M-EP critical 50%**	
SH1N RS273 12.659 – 12.682 CAMBRIAN	62.7	33.5	7.0		2.0		3.9		2.0		3.9		7.0	
SH1N RS273 12.906 – 12.928 CAMBRIAN	16.0	15.7	26.4		3.7		11.4		3.7		11.4		26.4	
SH1N RS273 14.270 – 15.741 FLYGER PASSING LANE	8.8	4.7	1.7		0.1		0.7		0.1		0.7		1.7	
SH1N RS273 15.741 – 17.277 TAUROA PASSING LANE	13.1	2.8	1.4		0.1		0.4		0.1		0.4		1.4	
SH1N RS292 3.631 – 4.513 LAGOON BRIDGE PASSING LANE	17.6	5.8	52.5		5.4		23.8		5.4		23.8		52.5	
SH1N RS292 6.638 – 7.484 URETITI PASSING LANE	16.6	4.0	5.9		0.1		1.8		0.1		1.8		5.9	
SH1N RS303 6.640 – 7.170 WAIPU GORGE ROAD	187.8	70.2	39.5		4.1		11.4		4.1		11.4		39.5	
SH1N RS319 3.868 – 4.882 MOUNTAIN ROAD SLIP	45.8	9.5	54.8		7.7		29.9		7.7		26.5		54.8	
SH1N RS319 14.900 – 16.000 ROSS ROAD CRAWLERLANE	4.4	2.5	2.6		0.2		1.1		0.2		1.1		2.6	
SH1N RS319 16.327 – 17.295 ROSS ROAD	159.2	30.3	53.5		6.9		27.6		5.9		27.6		51.5	
SH10 RS007 9.149 – 9.204 CRAFT SHOP 1	313.0	31.7	51.6		6.4		25.0		3.5		25.0		51.6	
SH10 RS017 0.000 – 0.110 CRAFT SHOP 2 R1_Detail	2.2	0.6	0.2		0.0		0.1		0.0		0.1		0.2	

	Observed life percentile		10%	50%	10%	50%	10%	50%	10%	50%	10%	50%	10%	50%
	50th % error		254%	-54%	-77%	-98%	-5%	-87%	-77%	-98%	-5%	-88%	246%	-54%
	% FWD predicted below		23%	64%	77%	95%	51%	79%	79%	95%	51%	79%	26%	64%
Northland 2005 – filename	**Observed life MESA 50%**	**Observed life MESA 10%**	**MESA Austroads M-EP 50%**		**MESA Austroads M-EP – 10%**		**MESA Austroads M-EP – 30%**		**MESA Austroads M-EP critical 10%**		**MESA Austroads M-EP critical 30%**		**MESA Austroads M-EP critical 50%**	
SH10 RS017 0.400 – 2.100 PUKETOTARA	1.1	0.6	0.3		0.0		0.1		0.0		0.1		0.3	
SH10 RS017 2.788 – 3.302 WAIPAPA SOUTH	7.0	1.3	1.3		0.1		0.2		0.1		0.2		1.3	

Table 7.3 Example of Northland 2005 FWD predictions of life based on simplified deflection methods compared with observed behaviour

	Observed life percentile		10%	50%	10%	50%	10%	50%	10%	50%	10%	50%	10%	50%
	50th % error		104919%	7534%	223%	-73%	165,493%	7991%	213%	-78%	67,166%	6938%	175%	-80%
	% FWD predicted below		3%	7%	41%	56%	3%	7%	41%	56%	3%	10%	41%	61%
Northland 2005 – filename	**Observed life MESA – 50%**	**Observed life MESA – 10%**	**MESA Austroads 1992 – 50%**		**MESA Austroads 1992 – 10%**		**MESA Austroads 2004b – 50%**		**MESA Austroads 2004 – 10%**		**MESA Deflection curvature 50%**		**MESA Deflection curvature 10%-**	
SH1N RS083 3.056 – 3.256 KAIMAUMAU L1_R1	1.4	0.4	10,000		20.6		10,000		20.4		4004		18.5	
SH1N RS083 7.816 – 8.216 PAPARORE ROAD L1_R1	3.2	0.6	544		3.2		2112		3.0		316		3.0	
SH1N RS083 9.445 – 14.460 WAIHARARA REHAB & WAIPAPAKAURI	42.3	3.5	10,000		7.2		10,000		6.8		10,000		4.8	
SH1N RS104 0.701 – 0.951 AWANUI STRAIGHT 1 L1_Detail	2519.7	163.4	10,000		10,000		10,000		10,000		10,000		1630.8	

	Observed life percentile		10%	50%	10%	50%	10%	50%	10%	50%	10%	50%	10%	50%
	50th % error		104919%	7534%	223%	-73%	165,493%	7991%	213%	-78%	67,166%	6938%	175%	-80%
	% FWD predicted below		3%	7%	41%	56%	3%	7%	41%	56%	3%	10%	41%	61%
Northland 2005 – filename	**Observed life MESA – 50%**	**Observed life MESA – 10%**	**MESA Austroads 1992 – 50%**		**MESA Austroads 1992 – 10%**		**MESA Austroads 2004b – 50%**		**MESA Austroads 2004 – 10%**		**MESA Deflection curvature 50%**		**MESA Deflection curvature 10%-**	
SH1N RS104 2.147 – 2.382 AWANUI STRAIGHT 2 L1_Detail	917.0	223.2	136		5.4		209		5.1		70		5.1	
SH1N RS104 9.100 – 9.600 KAITAIA SOUTH	25.7	2.1	5728		0.6		10,000		0.8		1496		0.8	
SH1N RS119 1.300 – 1.600 PAMAPURIA	26.2	3.2	8		0.6		8		0.9		8		0.3	
SH1N RS149 8.300 – 8.900 OGLES HILL	0.8	0.5	10,000		4.2		10,000		3.9		10,000		3.9	
SH1N RS149 12.900 – 14.800 HUATAU HILL & RANGIAHUA HILL	0.5	0.2	67		0.5		79		0.7		56		0.7	
SH1N RS167 7.567 – 8.079 PUKEPOTO REHAB	12.3	6.3	10,000		370.9		10,000		982.8		10,000		982.8	
SH1N RS167 12.133 – 12.445 OKAIHAU STH REHAB	43.9	1.8	10,000		10,000		10,000		10,000		10,000		3534.0	
SH1N RS167 12.899 – 17.192 OKAIHAU SOUTH	21.0	3.0	10,000		82.3		10,000		103.0		10,000		72.6	
SH1N RS198 3.770 – 4.210 MARSHALLS REHAB	4.0	1.7	10,000		81.5		10,000		103.6		10,000		103.6	
SH1N RS211 1.864 – 2.085 KAWAKAWA TRUCK RIDE	14.7	3.4	10,000		45.6		10,000		50.1		10,000		35.8	
SH1N RS215 9.589 – 9.992 TOWAI TRUCK RIDE	2.8	1.7	10,000		6.3		10,000		6.0		7290		6.0	
SH1N RS215 17.055 – 17.324 HUKERENUI TRUCK RIDE	3.6	1.9	271		7.6		568		7.2		275		7.2	

7 FWD field data – Northland PSMC002 – 2005

	Observed life percentile		10%	50%	10%	50%	10%	50%	10%	50%	10%	50%	10%	50%
	50th % error		104919%	7534%	223%	-73%	165,493%	7991%	213%	-78%	67,166%	6938%	175%	-80%
	% FWD predicted below		3%	7%	41%	56%	3%	7%	41%	56%	3%	10%	41%	61%
Northland 2005 – filename	**Observed life MESA – 50%**	**Observed life MESA – 10%**	**MESA Austroads 1992 – 50%**		**MESA Austroads 1992 – 10%**		**MESA Austroads 2004b – 50%**		**MESA Austroads 2004 – 10%**		**MESA Deflection curvature 50%**		**MESA Deflection curvature 10%-**	
SH1N RS233 3.285 – 4.775 HEKERENUI SAFETY IMPRV	34.4	3.8	10,000		10,000		10,000		10,000		10,000		10,000	
SH1N RS245 0.617 – 1.742 OTONGA	39.9	12.1	10,000		4.8		10,000		4.5		10,000		4.5	
SH1N RS245 11.620 – 12.700 SPRINGS FLAT	61.9	28.3	10,000		7.4		10,000		7.1		10,000		7.1	
SH1N RS273 7.299 – 8.418 MANGAPAI PASSING LANE	9.2	3.2	10,000		2.2		10,000		2.1		10,000		2.1	
SH1N RS273 9.777 – 10.963 HEWLETT PASSING LANE	5.5	3.4	33		0.6		35		0.8		35		0.8	
SH1N RS273 11.297 – 11.557 MATA REHAB	15.1	5.6	10,000		10,000		10,000		10,000		10,000		10,000	
SH1N RS273 12.659 – 12.682 CAMBRIAN	62.7	33.5	10,000		4024.1		10,000		4025.9		10,000		790.8	
SH1N RS273 12.906 – 12.928 CAMBRIAN	16.0	15.7	10,000		4023.0		10,000		4024.5		10,000		4024.5	
SH1N RS273 14.270 – 15.741 FLYGER PASSING LANE	8.8	4.7	45		1.0		50		1.0		50		1.0	
SH1N RS273 15.741 – 17.277 TAUROA PASSING LANE	13.1	2.8	77		0.5		95		0.7		95		0.6	
SH1N RS292 3.631 – 4.513 LAGOON BRIDGE PASSING LANE	17.6	5.8	10,000		10,000.0		10,000		10,000		10,000		2725.1	
SH1N RS292 6.638 – 7.484 URETITI PASSING LANE	16.6	4.0	10,000		1.0		10,000		1.2		10,000		1.2	

	Observed life percentile		10%	50%	10%	50%	10%	50%	10%	50%	10%	50%	10%	50%
	50th % error		104919%	7534%	223%	-73%	165,493%	7991%	213%	-78%	67,166%	6938%	175%	-80%
	% FWD predicted below		3%	7%	41%	56%	3%	7%	41%	56%	3%	10%	41%	61%
Northland 2005 – filename	**Observed life MESA – 50%**	**Observed life MESA – 10%**	**MESA Austroads 1992 – 50%**		**MESA Austroads 1992 – 10%**		**MESA Austroads 2004b – 50%**		**MESA Austroads 2004 – 10%**		**MESA Deflection curvature 50%**		**MESA Deflection curvature 10%-**	
SH1N RS303 6.640 – 7.170 WAIPU GORGE ROAD	187.8	70.2	10,000		4181.3		10,000		10,000		10,000		1809.6	
SH1N RS319 3.868 – 4.882 MOUNTAIN ROAD SLIP	45.8	9.5	10,000		10,000		10,000		10,000		10,000		699.8	
SH1N RS319 14.900 – 16.000 ROSS ROAD CRAWLERLANE	4.4	2.5	10,000		3.1		10,000		2.9		9232		2.9	
SH1N RS319 16.327 – 17.295 ROSS ROAD	159.2	30.3	10,000		5.0		10,000		4.7		2610		4.7	
SH10 RS007 9.149 – 9.204 CRAFT SHOP 1	313.0	31.7	10,000		5.2		10,000		4.8		1656		4.8	
SH10 RS017 0.000 – 0.110 CRAFT SHOP 2 R1_Detail	2.2	0.6	1		0.4		1		0.5		1		0.1	
SH10 RS017 0.400 – 2.100 PUKETOTARA	1.1	0.6	2		0.1		2		0.1		2		0.0	
SH10 RS017 2.788 – 3.302 WAIPAPA SOUTH	7.0	1.3	56		0.6		64		0.9		64		0.9	

Figure 7.1 10th percentile Austroads M-EP predicted life versus 10th percentile observed life

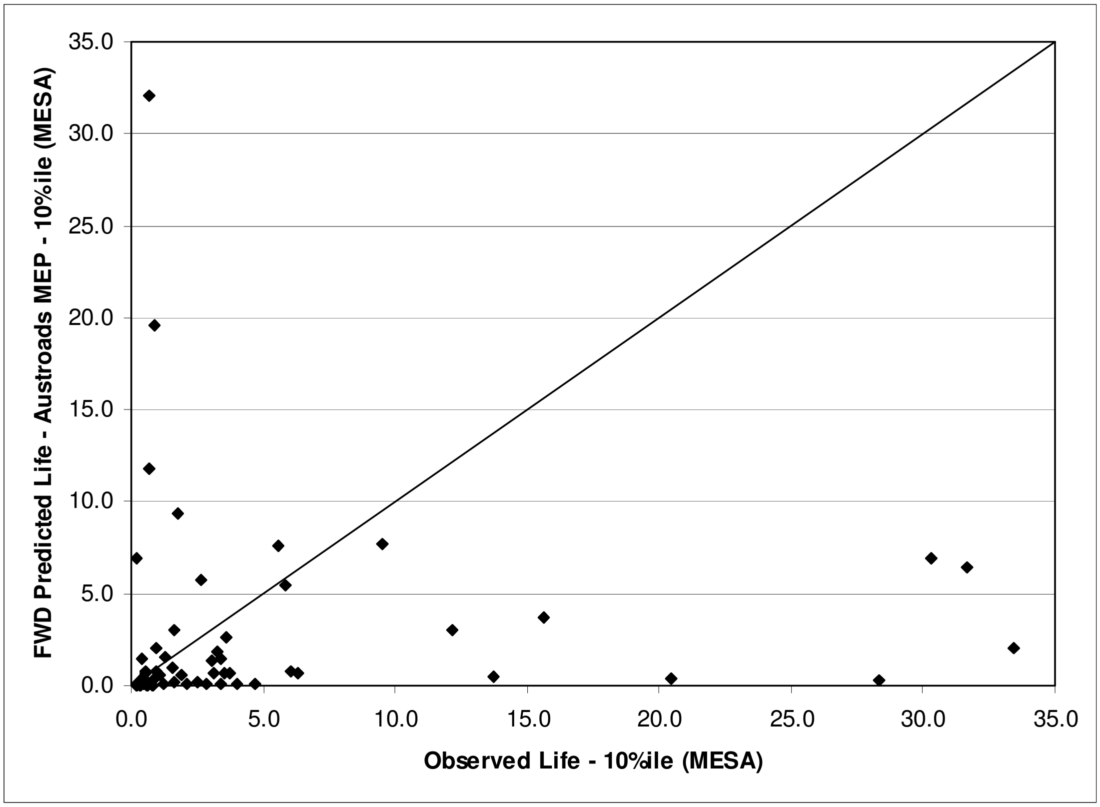
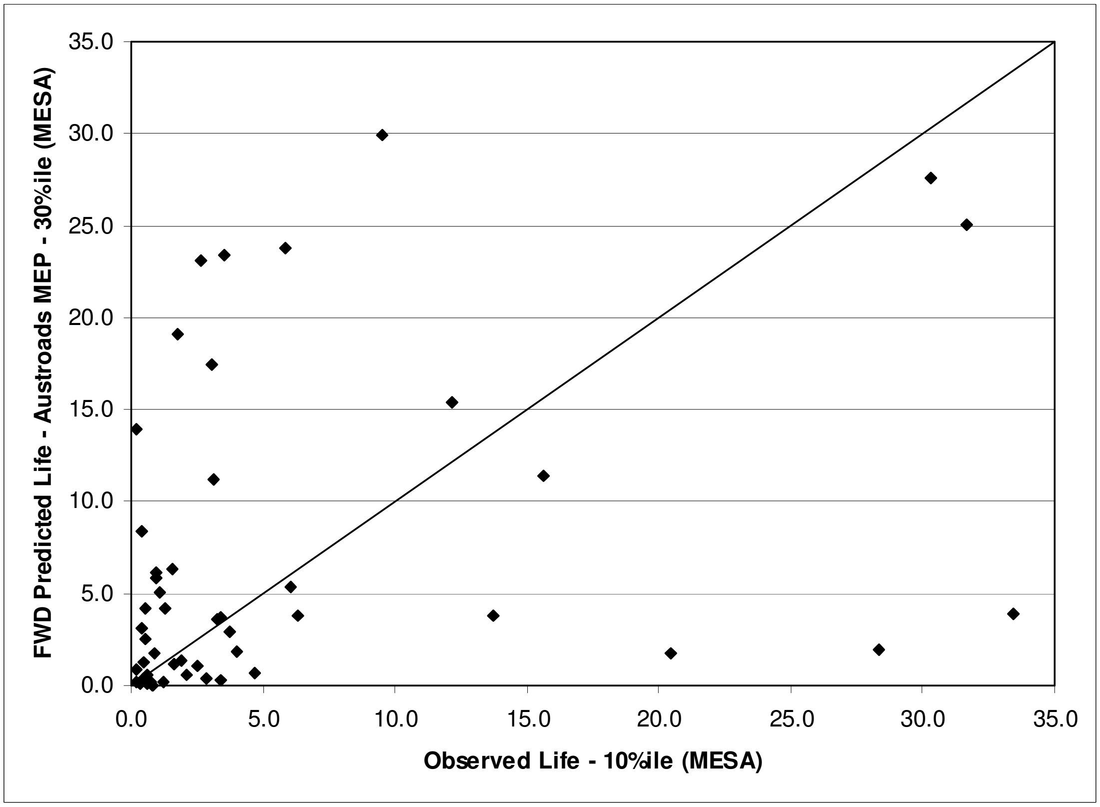


Figure 7.2 30th percentile Austroads M-EP predicted life versus 10th percentile observed life



8 FWD field data – Waikato PSMC001

8.1 Introduction

The Waikato PSMC001 contract is the first 10 years performance specified maintenance contract. Since the inception of this contract there has been a reliance on FWD measurements for confirming whether or not rehabilitations should meet the design life as determined by the Austroads M-EP procedure that relates subgrade strain to life. A total of nine rehabilitated road sections were selected for this study because their lives are readily predicted as they have since failed or have nearly failed and their lives can be predicted by extrapolating measured roughness and rutting data.

8.2 Simplified deflection and Austroads M-EP

FWD deflections were analysed and combined to produce 10th, 15th and 50th percentile values for life (both observed and predicted). Results are summarised in tables 8.1, 8.2 and 8.3. Figure 8.1 shows results for all data points comparing Austroads M-EP life with observed life.

Figure 8.1 FWD Austroads M-EP predicted life versus 10th percentile observed life

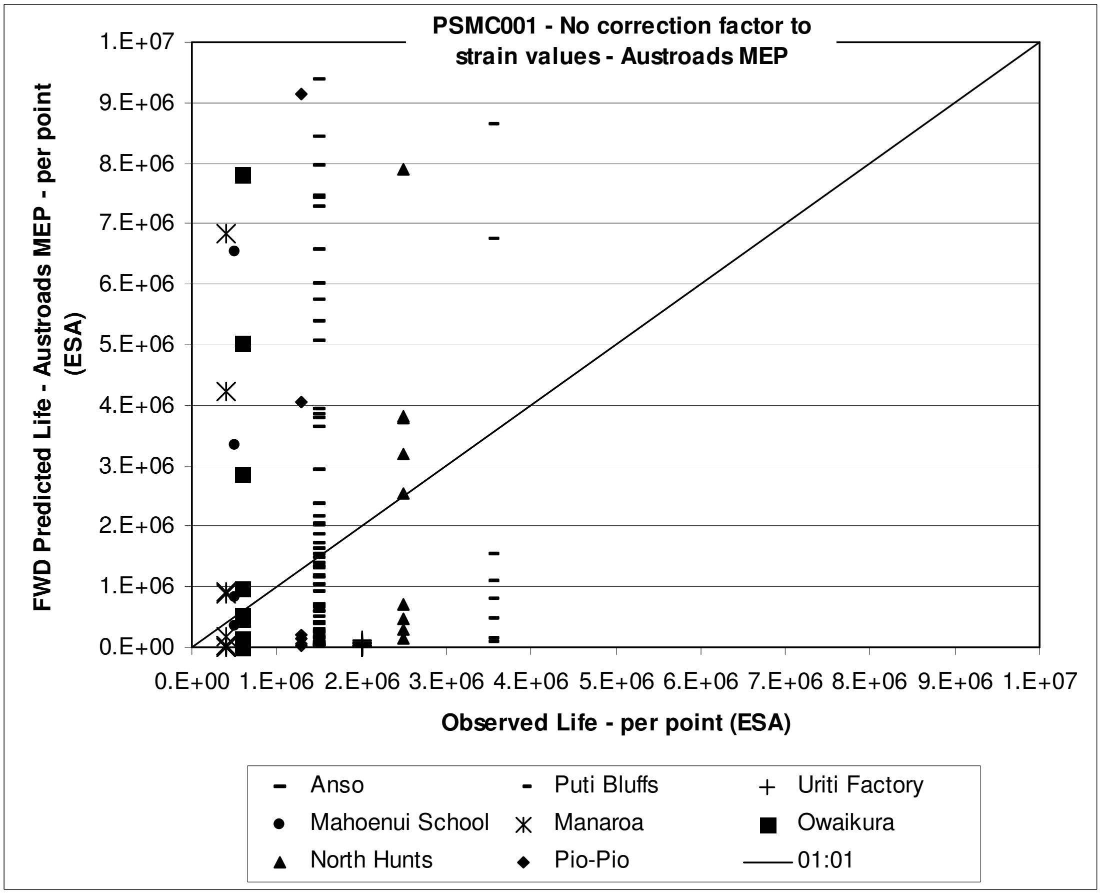


Table 8.1 50th percentile FWD deflections compared with 50th percentile observed life

Road	Observed life – 50%	Austroads 1992 (simplified) 50%	Error	Austroads 2004b (simplified) 50%	Error	Austroads M-EP- 50%	Error
	ESA	ESA		ESA		ESA	%
Pio-Pio	1.50E+06	1.00E+10	666,567	1.00E+10	666,567	177,265	-88
North Hunts	2.5E+06	1.00E+10	399,900	1.00E+10	399,900	1.7E+07	565
Owaikura Road West	5.0E+05	2.78E+05	-44	2.74E+05	-45	27,049	-95
Manaroa Stream	5.0E+05	7.35E+05	47	7.58E+05	52	102,702	-79
Mahoenui School	5.0E+05	1.00E+10	1,999,900	1.00E+10	1,999,900	6,536,932	1207
Uriti Factory	2.5E+06	1.90E+06	-24	1.83E+06	-27	13,780	-99
Puti Bluffs	2.5E+06	1.00E+10	399,900	1.00E+10	399,900	7,695,543	208
Anso Road	1.5E+06	5.16E+07	3,341	5.79E+07	3763	1,617,755	8

Note: ESA = equivalent standard axles as defined in Austroads pavement design guide (2004a).

Table 8.2 10th percentile FWD deflections compared with 10th percentile observed life

Road	Observed life 10%	Austroads 1992 (simplified) 10%	Error[(a)]	Austroads 2004b (simplified) 10%	Error[(a)]	Austroads M-EP 10%	Error[(a)]
	ESA	ESA	%	ESA	%	ESA	%
Pio-Pio	1.50E+06	5.30E+07	3,431	7.08E+07	4621	40,797	-97
North Hunts	2.5E+06	3.98E+06	59	3.75E+06	50	435,346	-83
Owaikura Road West	5.0E+05	1.41E+04	-97	2.75E+03	-99	749	-100
Manaroa Stream	5.0E+05	1.10E+05	-78	6.65E+04	-87	10,081	-98
Mahoenui School	5.0E+05	6.03E+09	1,205,817	6.04E+09	1,207,096	641,812	28
Uriti Factory	2.5E+06	2.97E+05	-88	3.03E+05	-88	2440	-100
Puti Bluffs	2.5E+06	3.19E+09	127,301	3.38E+09	135,193	237,199	-91
Anso Road	1.5E+06	1.83E+05	-88	1.43E+05	-90	51,763	-97

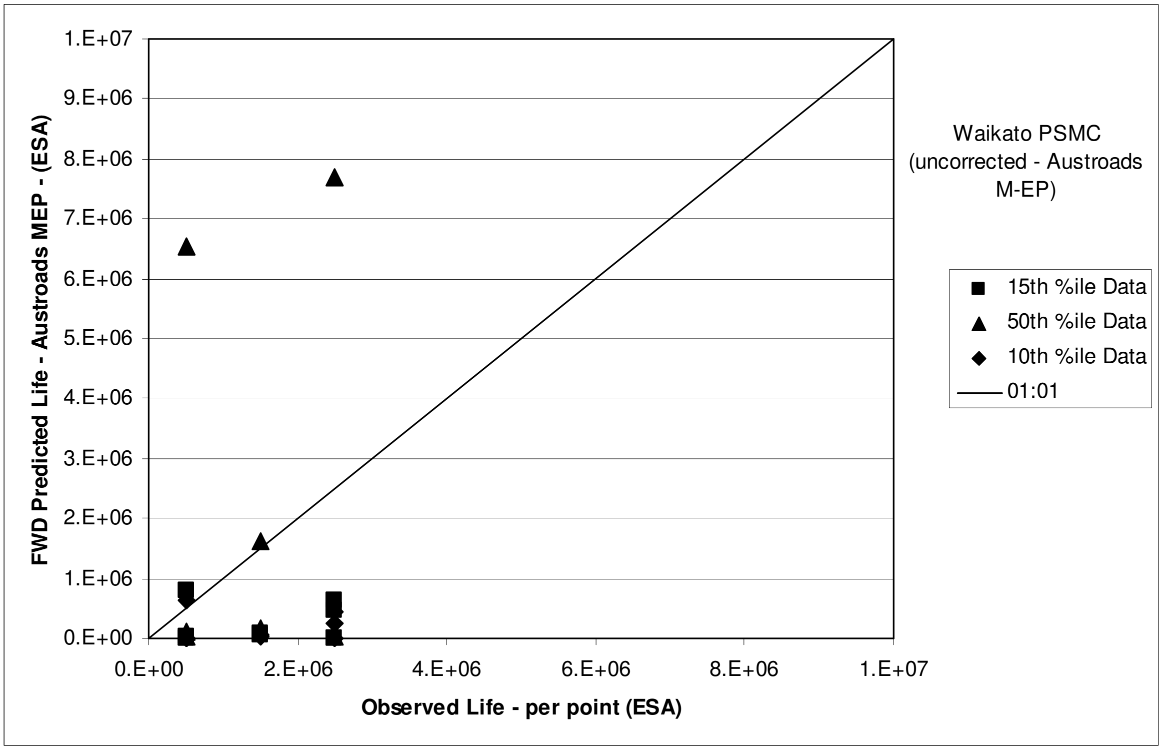
(a) Difference between observed life and calculated life (either 1992, 2004b or M-EP)

Table 8.3 15th percentile FWD deflections compared with 15th percentile observed life

Road	Observed life 15%	Austroads 1992 (simplified) 15%	Error[(a)]	Austroads 2004b (simplified) 15%	Error[(a)]	Austroads M-EP 15%	Error[(a)]
	ESA	ESA	%	ESA	%	ESA	%
Pio-Pio	1.50E+06	7.86E+07	5142	1.05E+08	6928	48,864	-97
North Hunts	2.5E+06	1.84E+07	638	1.85E+07	638	633,662	-75
Owaikura Road West	5.0E+05	6.09E+04	-88	2.64E+04	-95	4027	-99
Manaroa Stream	5.0E+05	1.53E+05	-69	1.12E+05	-78	15,098	-97
Mahoenui School	5.0E+05	9.01E+09	1,801,379	9.01E+09	1,801,699	788,581	58
Uriti Factory	2.5E+06	4.03E+05	-84	5.01E+05	-80	2697	-100
Puti Bluffs	2.5E+06	9.51E+09	380,429	9.53E+09	380,992	455,992	-82
Anso Road	1.5E+06	3.85E+05	-74	4.54E+05	-70	89,390	-94

(a) Percentage difference between observed life and calculated life (either 1992, 2004b or M-EP)

Figure 8.2 Summary of FWD predicted life versus observed life for various percentile values



The results in the above tables indicate that the 50th percentile values tend to overestimate the pavement life while the 10th percentile values underestimate the life. Errors are generally in the order of 100%.

8.3 Precedent M-EP

Strain multipliers were determined for Waikato PSMC projects so that the 10th percentile FWD predicted lives matched the actual life. Results are shown in table 8.4 and figure 8.3 where the strain multipliers range from 0.33 to 1.04. Matching the 50th percentile predicted life with the actual life yielded strain multipliers that ranged from 0.6 to 1.53 as shown in table 8.5 and figure 8.4.

Table 8.4 Strain multipliers required to match 10th percentile M-EP predictions with observed life

Road	Observed life 10%	Strain multiplier[(a)]	Austroads M-EP 10%	Error
Pio-Pio	1.30E+06	0.56	1.30E+06	0
North Hunts	2.5E+06	0.75	2.5E+06	0
Owaikura Road West	6.0E+05	0.33	6.0E+05	0
Manaroa Stream	4.0E+05	0.54	4.0E+05	0
Mahoenui School	5.0E+05	1.04	5.0E+05	0
Uriti Factory	2.0E+06	0.33	2.0E+06	0
Puti Bluffs	3.5E+06	0.64	3.5E+06	0
Anso Road	1.5E+06	0.57	1.5E+06	0

(a) The strain multiplier was determined so that the 10th percentile lives match exactly.

Figure 8.3 Austroads M-EP with strain multiplier applied to match 10th percentile values compared with observed life

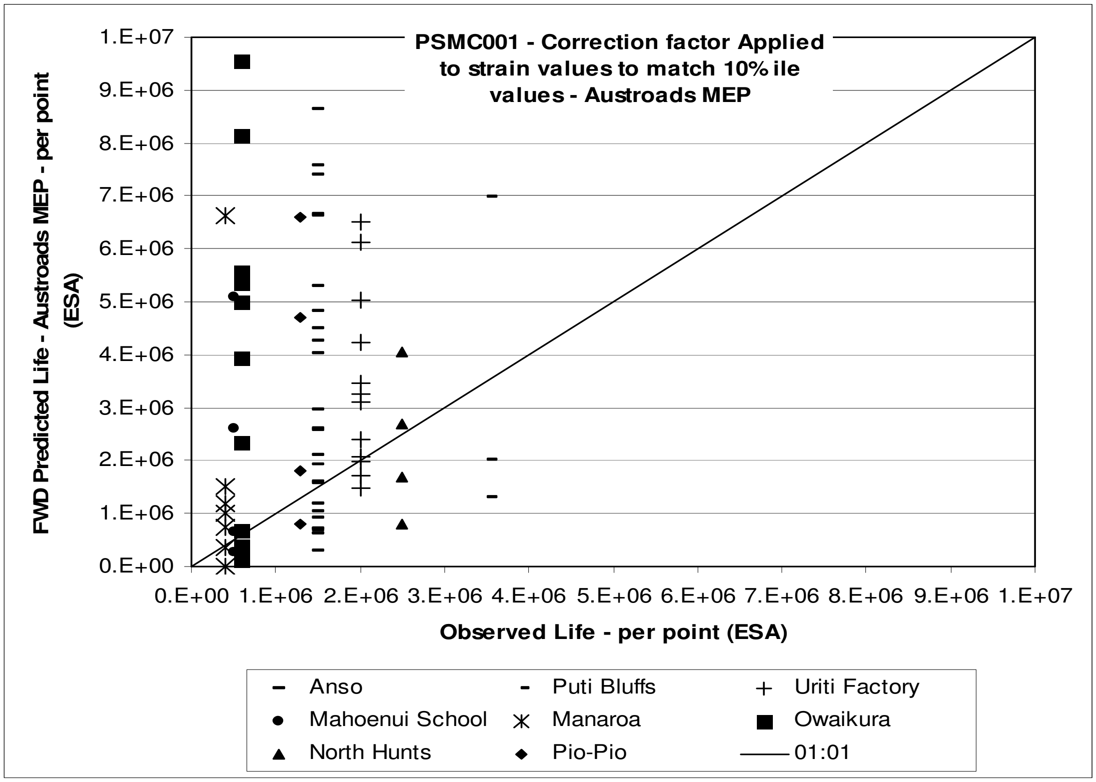
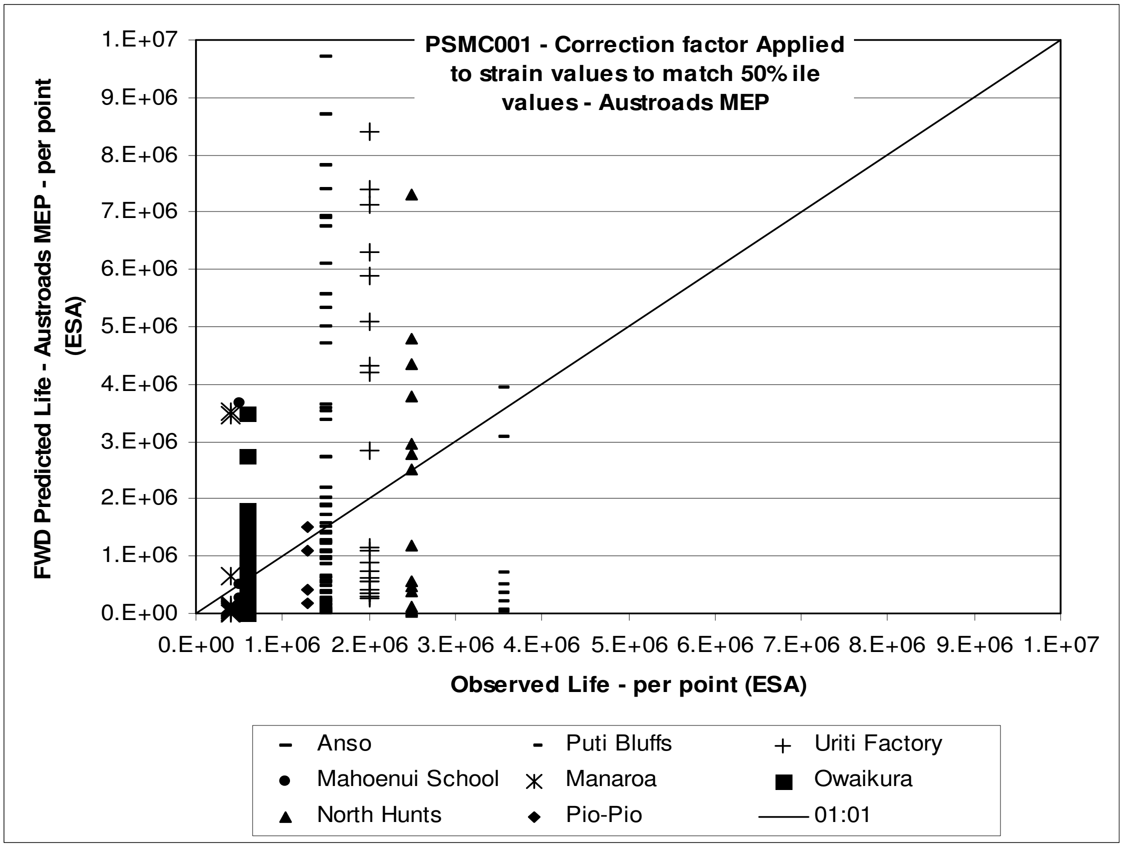


Table 8.5 Strain multipliers required to match 50th percentile FWD predictions with observed life

Road	Observed life – 10%	Strain multiplier[(a)]	Austroads M-EP – 50%	Error
Pio-Pio	1.30E+06	0.72	1.30E+06	0
North Hunts	2.5E+06	1.37	2.5E+06	0
Owaikura Road West	6.0E+05	0.60	6.0E+05	0
Manaroa Stream	4.0E+05	0.80	4.0E+05	0
Mahoenui School	5.0E+05	1.53	5.0E+05	0
Uriti Factory	2.0E+06	0.44	2.0E+06	0
Puti Bluffs	3.5E+06	1.14	3.5E+06	0
Anso Road	1.5E+06	1.01	1.5E+06	0

(a) The strain multiplier was determined so that the 10th percentile lives match exactly.

Figure 8.4 Austroads M-EP with strain multiplier applied to match 10th percentile values compared with observed life



9 Other FWD analysis methods considered

9.1 Development of a new subgrade strain criterion in Austroads M-EP

The CAPTIF data was analysed to explore whether a different constant and power law value was more appropriate to predict life as opposed to the values used by Austroads (equation 2.1). Plotting FWD back-calculated strains with actual life with best fit subgrade strain equations are shown in figures 9.1 to 9.4. Data is plotted on a log-log scale and therefore the scatter is larger than seen in the diagrams. Tables 9.1 and 9.2 summarise the power exponent values found. It appears that a separate strain criterion is needed depending on the pavement depth and thus not always practical to develop a new strain criterion for infield pavements where pavement depth is often variable across and along a road section.

Figure 9.1 **CAPTIF subgrade strain (all sections combined) for 15mm VSD for the green pavement**

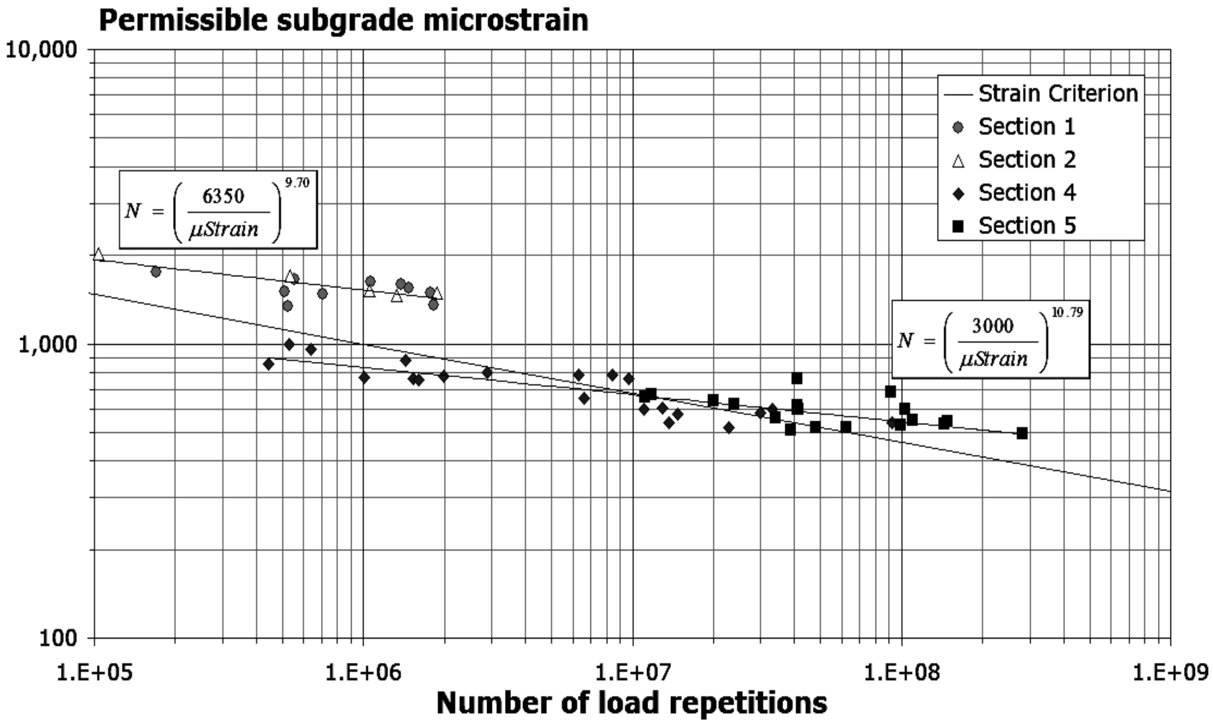


Figure 9.2 **CAPTIF subgrade strain (all sections combined) for 15mm VSD for the mature pavement**

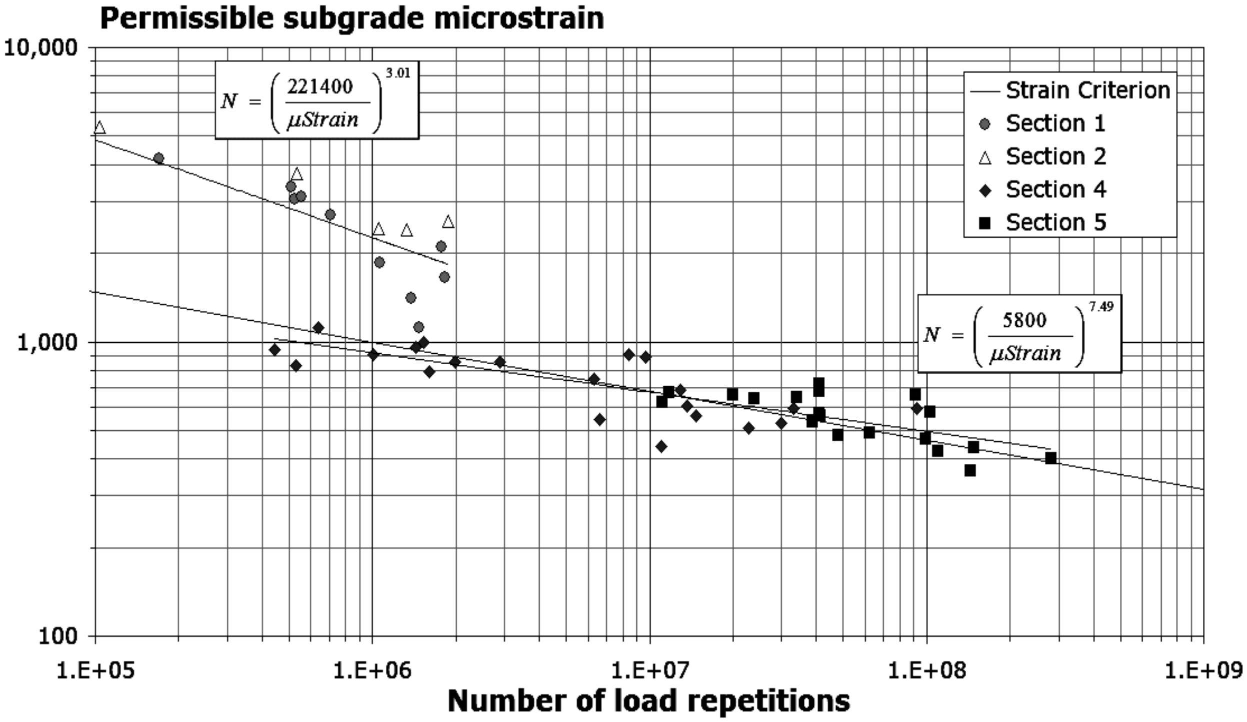


Figure 9.3 **CAPTIF subgrade strain (all sections combined) for 25mm VSD for the green pavement**

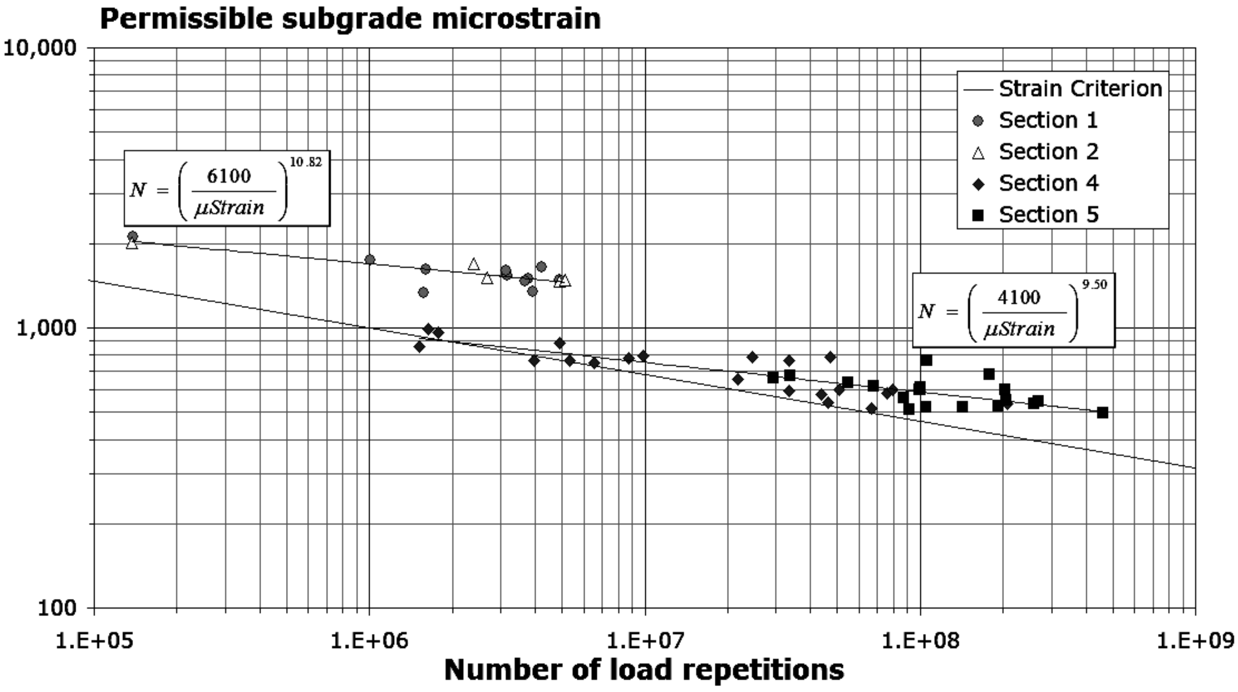


Figure 9.4 CAPTIF subgrade strain (all sections combined) for 25mm VSD for the mature pavement

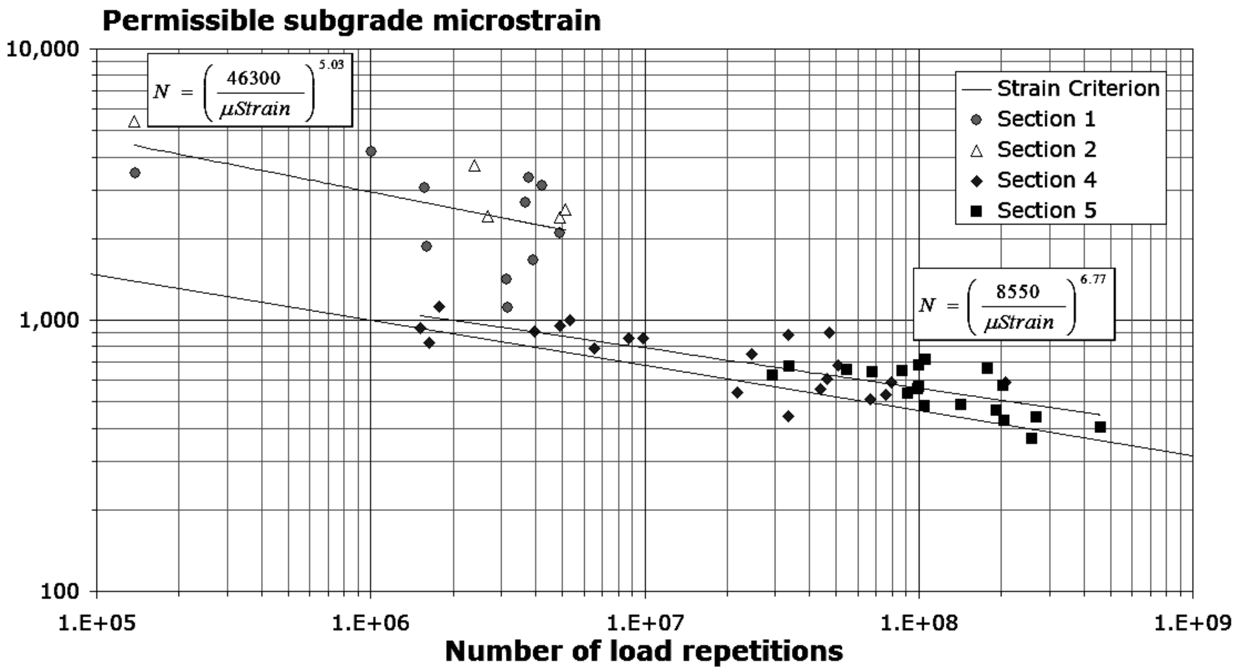


Table 9.1 Exponents of power fits of individual trend lines for the green pavement

Figure	Load (kN)	VSD (mm)	Exponent for 150mm pavement	Exponent for 300mm pavement
2	40	15	-	13.1
3	40	25	-	10.6
4	50	15	**8.2**	**12.5**
5	50	25	**11.0**	11.6
Those sections which require little or no extrapolation are shown in bold.				

Table 9.2 Exponents of power fits of individual trend lines for the mature pavement

Figure	Load (kN)	VSD (mm)	Exponent for 150mm pavement	Exponent for 300mm pavement
2	40	15	-	7.8
3	40	25	-	6.7
4	50	15	**5.6**	**9.1**
5	50	25	**7.3**	9.5
Those sections which require little or no extrapolation are shown in bold.				

9.2 Supplementary checks

At present, Austroads methods require that unbound granular pavements are checked only for vertical strain at the top of the subgrade. The Transit NZ supplement (2000) provides a significant advance in that a check for shallow shear in the basecourse layer is included. While this may be practical for rehabilitation, it is less suitable for post-construction verification, hence non-destructive FWD testing provides a more convenient alternative measure. It is also desirable to have a parameter that will confirm further densification of the basecourse and subbase layers is unlikely to be significant from the time of acceptance testing. This leads to four supplementary measures that may be applied in addition to the above five main approaches.

9.2.1 Curvature check on near-surface deformation

This uses the Austroads 2004b rehabilitation guide (Austroads 2004b) to check that residual life is not governed by curvature using the curves from appendix 6.2 (Austroads 2004b), or alternatively the Austroads 1992 guide (10.4, Austroads 1992). The curvature function was originally developed for bound asphaltic surfacing but more recent practice by some Australian authorities has been to use both curvature as well as central deflection for performance prediction of unbound granular layers. The curvature function is standardised to a 40kN load. This method can be over-conservative on very deep soft subgrades, or if the curvature function is applied in its original form. A scaling factor (Sc) may be applied to the curvature function for situations where a precedent has proven that the basic Austroads relationship requires modification. An interim factor of about 2 is suggested for trial in New Zealand unbound granular pavements.

9.2.2 CBR check on near-surface deformation

The Transit NZ supplement (figure 10.2, Transit NZ 2000) sets out a check for shear deformation in the pavement layers using CBR. Using a CBR-modulus correlation for aggregates, low-strength basecourse may be inferred from back-analysis of deflection tests. This procedure is a pass/fail criterion rather than progressive, ie failure downgrades life at a test point to zero. However, this approach should be used cautiously, as aggregates on ‘springy’ low modulus subgrades will result in a low modulus for the aggregate, which does not necessarily mean a low CBR. Thus option 9.2.4 below is the preferred check.

9.2.3 Strain check on near-surface deformation

A comparable check to the above method may be provided by limiting vertical strains in each layer (as with the M-EP critical layer method discussed above). In New Zealand, credible models for unbound pavements showing near surface distress have been obtained by factoring the Austroads subgrade strain criterion up by a factor between 1 and 2 and applying this at the mid-height of each unbound granular layer. The mid-height rather than the top of each layer is adopted for the normal case where moduli of successive overlying layers increase, but the top of the layer is taken if there is no increase. No in-depth study of a wide range of aggregate types has yet been documented, but the procedure does go some way to meet a call from practitioners requiring some constraint to safeguard against shallow shear. This strain check is already provided when using the critical layer M-EP or IAL M-EP, hence it need only be applied to the remaining methods.

9.2.4 Check on modular ratios

Austroads sets out the increase in modulus that can be expected in successive overlying granular layers in relation to the subgrade modulus. The concept has been widely verified in New Zealand unbound granular pavements, and provides a simple and robust technique for establishing that a pavement has been compacted as well as practicable (given the subgrade condition and thickness of overlying layers) and hence that ongoing settlement within the pavement layers will be minimal. Details are given in Salt and Stevens (2006).

9.3 Change in central deflection

Werkmeister and Steven (2005) found a relationship between pavement life (number of ESAs until the rut depth reaches the failure value) and change in initial deflection between 0 and around 100,000 load cycles (ie pre and post compaction FWD measurements) as shown in figure 9.5. The equation found from this relationship is shown below (equation 9.1):

$$\textit{Design Traffic Life (ESAs)} < 5{,}000{,}000\ e^{(-0.023 \times \Delta do)} \qquad \text{(Equation 9.1)}$$

Where

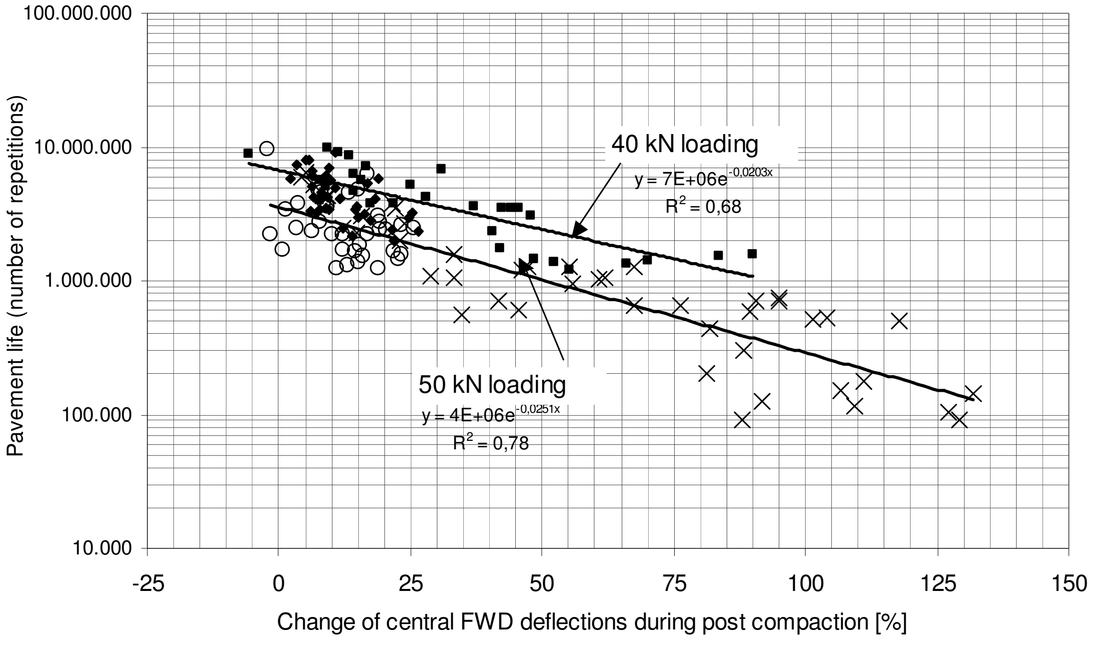
Δd_0 = mean (δd_0) + 1.65 x standard deviation (δd_0)

δd_0 = $(d_{0yr1} - d_{0yr0})/d_{0yr0} \times 100$

d_{0yr1} = Central Deflection at year 1

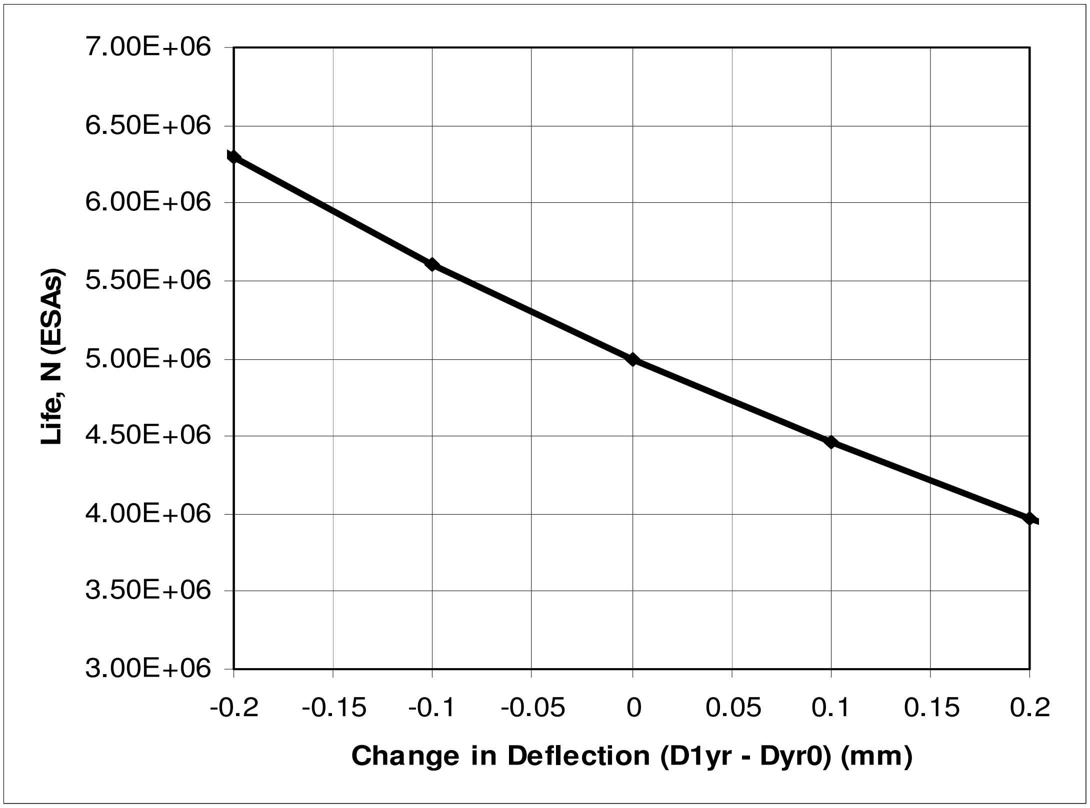
d_{0yr0} = Central Deflection at year 0

Figure 9.5 Relationship between initial change in central FWD deflection and pavement life at CAPTIF (Werkmeister and Steven 2005)



Applying equation 9.1 to a range of changes in deflections is shown in figure 9.6. The range of change of deflections shown is ± 0.2 mm as the use of this approach is not relevant for higher changes in deflections above those observed at CAPTIF. Considering the change in central deflection is a useful tool for the assessment of the quality of granular materials and whether or not they are bedding down.

Figure 9.6 Effect of change in deflection on pavement life (equation 9.1)



10 Observations

Table 10.1 contains observations on the results of the FWD analyses. These observations will help in determining the recommended method of analysing FWD measurements for predicting life of newly constructed or rehabilitated pavements. However, it appears that predictions of life are often poor and a conservative approach can be taken to protect the client. Further, over time local strain multipliers may be developed to improve future predictions.

Table 10.1 Observations found from FWD project case studies

Topic	Observation	Relevant case studies
Simplified deflection method	Generally always over-predicts life by multiples of a 100 or 1000 times the actual life. (Note: the opposite occurs for low-volume roads No.2 and Kaituna Road where it underestimates life.) Conclusion: simplified deflection methods not recommended for future use.	All except the low-volume roads
10th percentile values	For any project the range in FWD predicted lives for each individual measuring point can range from 0.01 to 100 million ESA (or more). Further, prediction of actual life on an individual point does not correlate with the life assessed at the individual point. Averaging the FWD predictions is not appropriate as it is skewed by the sometimes very large predictions of life (>100 MESA). Therefore, assessing the FWD predictions by percentiles is best. The 10th percentile value was chosen as the preferred method as a pavement is assumed to be in need of rehabilitation when 10% of the area has failed. When more than 10% of the pavement area is in need of repair a pavement rehabilitation is justified due to the high cost of maintenance. The cost of maintenance is the main reason why pavements are rehabilitated in New Zealand (Gribble et al 2008).	All
50th percentile values	For some sections in the PSMC001 projects and for the low-volume roads it appears that the 50th percentile life is best. For others the 50th percentile value is generally too large by factors of 100 or more.	A few sections
Austroads M-EP – 10th percentile (not corrected)	Often underestimates life by a factor of 10- to 100-fold. There are exceptions with those sections that failed early because of weak granular layers (eg Alpurt Sector A and a couple of sections at CAPTIF).	All except roads with weak granular layers.
Austroads M-EP – 10th percentile (corrected)	The strain multipliers found in order to match the 10th percentile Austroads M-EP lives with the 10th percentile FWD lives ranged between 0.33 and 1.04, with a value of around 0.6 to 0.7 being the most common. It was found with CAPTIF data that it might not be possible to have a common strain multiplier, while with a value of 0.7 the FWD predicted lives were between 0.1 and 10 times the actual life.	All
Errors	When considering using a percentile value of the FWD Austroads M-EP predicted lives, it can be expected that a good prediction will be within a factor of 5 of the actual life. For example if the FWD prediction is one million ESAs then the actual life could be anywhere from 0.2 million ESAs to five million ESAs.	All

Topic	Observation	Relevant case studies
Austroads critical layer	When taking a percentile approach to this selected data set as a whole the consideration of the life found in a critical layer (where the subgrade strain criterion is also applied to strains in the granular pavement layers, the life is equal to the layer with the shortest life referred to as the critical layer) within the pavement had negligible effect on the 10th percentile predicted life. However a small proportion of cases exist where the critical layer is other than the subgrade.	All
Pavement depth	Often overlooked, but if the assumed pavement depth used in the analysis of FWD data to predict life is out by 31mm then this translates to a two-fold difference in pavement life or an error of 200%. Given the pavement depth is often assumed and not measured then this error could occur often.	All

11 Recommended method to predict life of pavement construction from FWD measurements

Based on the observations and some basic principles, the following is recommended for the development of a standard method for predicting pavement life from FWD.

Table 11.1 Recommendations for FWD standard

Standard	Recommendation
Load	The impact load should be standardised and remain the same.
Analysis	The Austroads M-EP method should be used (without consideration of a critical layer for most cases) to predict life for individual FWD measured points. A strain multiplier may be used (although only after careful consideration) if one can be determined from past projects.
Strain multiplier	For low-volume roads on volcanic soil subgrades in the Bay of Plenty (<1 million ESAs) a strain multiplier of 0.4 may be appropriate while a value of 0.7 is most common for other projects. These strain multipliers are only relevant if the 10th percentile value is used to determine the pavement life. However, past performance should be used to calibrate the subgrade strain criterion to local conditions.
Predicting life (ESAs until rehabilitation is required)	Within a project length all FWD predicted lives (a minimum of 10 is required) should be combined and the 10th percentile determined and deemed the predicted life until pavement rehabilitation is required. The 50th percentile may be calculated and used for comparison.
Payment reduction	Because of errors in FWD predictions the estimated upper limit on life should be five times the 10th percentile of FWD predicted life. If this upper limit is below the design life then a payment reduction or increased maintenance period could be considered.

The above observations and recommendations indicate that the use of the FWD for compliance testing of pavement construction may be questionable. However, if the strain criteria used to calculate pavement life have been ‘broadly’ calibrated to the soil types then the FWD can predict the 10th percentile life of plus or minus 500%. This means if the FWD predicts the pavement life of two million ESAs then the actual life could range from 400,000 ESA to 10 million ESAs. The range of life predicted makes it difficult to use in compliance and if penalties are imposed then the ‘greater’ life of 10 million is taken as the achieved life. It is recommended that the FWD is not the only tool used to determine compliance but the materials used, compaction and pavement depth achieved are controlled. Pavement monitoring in terms of rutting and roughness could also be undertaken and models used to extrapolate the rutting and roughness to predict life.

12 Further work

This project focused primarily on predicting pavement life using vertical strains back-analysed from deflection measurements (primarily because that is the Austroads premise for unbound granular pavement design). However vertical strains alone could only be expected to govern one mode of pavement distress, ie rutting. Accordingly, as a result of this study, alternative mechanistic methods are now being trialled for the prediction of four modes of structural distress in unbound granular pavements with chip-seal surfacing (Stevens 2008). These modes are:

1 rutting

2 roughness progression

3 flexure (leading to cracking initiation in chip seal surfacing)

4 shear instability within the base layers.

The intention is to make effective progress in the evaluation of the 'myriad ways in which low volume pavements could conceivably fail' (Dawson 2002a). Many of these modes can be classed as non-structural (ie cannot be predicted with deflection measurements) but present similar challenges for effective prediction (Dawson 2002b).

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