Traffic Speed Deflectometer

The Application of TSD Data in New Zealand for Asset Management and Design

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Report prepared by:

GeoSolve Limited

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GEOTECHNICAL WATER RESOURCES PAVEMENTS

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1 Introduction

Traffic Speed Deflectometer (TSD) testing has now been carried out on New Zealand highways in 2015 and 2016 with the raw data available on RAMM. Worldwide, there has been considerable effort collecting and filing TSD information, but most agencies use only the central deflection, or central deflection and curvature[1], despite the availability of six laser readings.

Pavement practitioners can adopt a variety of empirical or mechanistic approaches from the TSD such as:

- Central deflection (equivalent to Benkelman Beam)
- Central deflection and curvature
- Central deflection and CBR
- Mechanistic analysis (of the full deflection bowl) using a linear layered elastic model
- Mechanistic analysis that accommodates either linear or non-linear moduli

General discussion on these approaches is given in the Austroads Guide[2] and the RIMS publications.[3]

The purpose of this study is to establish a nationally consistent, readily updatable database, and to document procedures intended to make all TSD deflection data more useable (able to be applied to all forms of pavements for both rehabilitation design and asset management by practitioners electing to use any of the above approaches).

Owing to the differences in the load configurations and forms of sensors used to calculate deflection bowls resulting from the FWD and TSD machines, a conversion is required to generate a directly comparable output. The TSD device records the deflection slope measured from the device's Doppler lasers, and a deflection bowl is calculated using integration, whereas the FWD vertical deflections are determined by geophones.

The aim is to allow the TSD data to be converted to the more familiar FWD output which would allow any TSD data collected to be directly compared to any historically collected FWD dataset.

An excel workbook is available, which will execute the various calculations documented in this report.

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[1] While the Curvature Function in Austroads is defined as the standardised (40 kN) value of D0-D200, overseas literature tends to use the similar Surface Curvature Index D0-D300 or SCI 300.

[2] Austroads 2012 Guide to Pavement Technology

[3] RIMS Body of Knowledge
http://rimsnz.yolasite.com/resources/Documents/RIMS_BoK_Documents/3.4i.%20BoK%2011_001%20Collection%20Pavement%20Structural%20Parameters%20Part%20I%20.pdf
http://rimsnz.yolasite.com/resources/Documents/RIMS_BoK_Documents/3.4ii.%20BoK%2011_001%20Collection%20Pavement%20Structural%20Parameters%20Part%20II.pdf

2 Data Formats and Parameters

2.1 Basic bowl profiles

FWD bowls are typically stored with deflections for offsets at 0, 200, 300, 450, 600, 750, 900, 1200 and 1500 mm from the centre of the 300 mm diameter load plate.

The TSD deflections necessarily differ from the FWD because different forms of load are applied (as shown in the following diagrams).

Falling Weight Deflectometer

- Force applied through stationary plate
- Deflections measured with Geophones
- High Accuracy
- Zero speed for measurement (static)
- Directions of stress and strain vectors remain constant during test

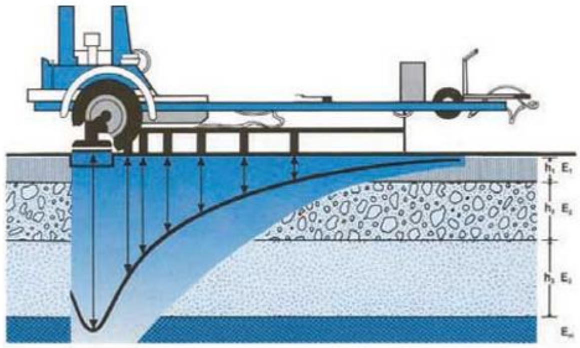


Figure 2.1-1: Falling Weight Deflectometer profile

Traffic Speed Deflectometer

- Force applied through wheels
- Deflections integrated from velocity measurements with Doppler lasers
- Accuracy loss compensated by averaging
- High measurement speed
- Short measurement intervals
- Dynamic load is highly representative of actual traffic loading
- Vectors for stresses and strains rotate during test

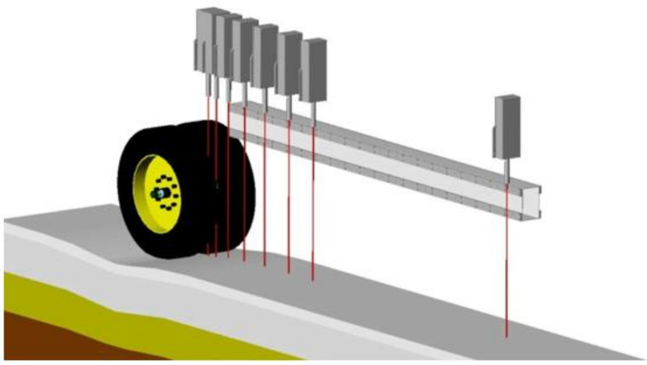


Figure 2.1-2: TSD Deflectometer profile

Because the loadings differ, any correlation between the two devices is dependent on the visco-elastic properties of the underlying pavement. Unless visco-elastic parameters can be adequately characterised for a proper dynamic analysis of the test, a rigorous correlation cannot be developed that encompasses all pavement/subgrade types.

Much international research is being directed towards this question, but until dynamic visco-elastic procedures are established, accurate transformations of TSD into FWD bowls can only be achieved with a specific algorithm developed empirically for each pavement/subgrade configuration, as shown in the following sections.

The dataset received from the supplier contains 2 different deflection bowls:

- the Greenwood bowl which considers any asymmetry of the bowl and extends from the bowl centre to 900 mm offset. However, no deflections are calculated for the customary FWD offsets at 1200 and 1500 mm.

- the ARRB bowl which assumes all bowls are symmetrical but does determine deflections at both 1200 and 1500 mm offsets.

Users of the data, therefore, have the option of using somewhat different bowls. Because the technology is new, there is not yet a consensus on which interpretation provides the more appropriate bowl for any specific circumstance, so it will be important for users to note which option they are adopting for any project.

Early trials with New Zealand data indicated that each of the two bowls could give more typical FWD bowl shapes in different circumstances, but on balance the ARRB bowl provided slightly more consistency. For that reason, only the ARRB bowl was used in subsequent transformations to "equivalent FWD" bowls. The equivalent bowl is intended to be used by practitioners with back-calculation software, layer modular ratios and fatigue criteria in exactly the same way as if the data were obtained from traditional Dynatest FWD equipment which has been used to populate the RAMM database over the last 20 years.

It should be noted that the deflection bowls and velocity slopes that are stored in the RAMM UDT tables have NOT been standardised to a standard load. [4] The readings apply to the wheel load used at the time, including any dynamic load from road roughness, eccentric loading from road camber, rotational momentum (acceleration/braking), cross-wind etc., represented by the strain gauge reading.

In order to make suitable comparisons between FWD and TSD (especially over multiple years), all deflections referred to in this report from this point on will be regarded as standardised to a 40 kN load.

To distinguish the TSD data from any future developments in technology, datasets containing the ARRB interpreted bowl are here referred to as ARRB-12[5], while the datasets for the transformed FWD equivalent bowl are referred to as NZ-16.1[6].

The basic deflection bowls may also be used to provide very approximate estimates of empirical parameters, i.e.

- Subgrade Modulus (MPa) = 25000 x $D_{600}^{-1.14}$ (where D_{600} is in microns)[7]
- CBR = 0.1 x Subgrade Modulus

2.2 Goodness of Fit Parameter

While R^2 is the most widely used and reported measure of error and goodness of fit, a model that provides a statistical evaluation of the 1:1 relationship between observed vs. predicted variables while maintaining the typical 0-1 range of goodness of fit was preferred.

The equation developed to express the relationship is:

$$1{:}1\ Correlation\ Statistic = \frac{\sum_{i=1}^{n} \min\left(\frac{obs_i}{pred_i}, \frac{pred_i}{obs_i}\right)}{n} \quad (1)$$

[4] Richard Wix (ARRB), pers. comm.
[5] Relates to the original paper, Muller & Roberts ARRB 2012
[6] NZ 16.1 indicates 2016 derivation.
[7] RIMS BoK details conversion of this isotropic modulus to anisotropic values used in CIRCLY
http://rimsnz.yolasite.com/resources/Documents/RIMS_BoK_Documents/3.4i.%20BoK%2011_001%20Collection%20Pavement%20Structural%20Parameters%20Part%20I%20.pdf
http://rimsnz.yolasite.com/resources/Documents/RIMS_BoK_Documents/3.4ii.%20BoK%2011_001%20Collection%20Pavement%20Structural%20Parameters%20Part%20II.pdf

This equation looks at the minimum of observed/predicted and predicted/observed (which will always be less than 1), sums all of those values up, and divides by the number of points.

2.3 Reliability ranking of bowl shapes

The reliability of any given bowl may be judged by inspection of the goodness of fit, which quantifies the relative compliance of any particular measured bowl with any other bowl generated from a methodical approach (e.g. integration of deflection slopes, forward analysis of moduli/layer thickness system etc.).

Typical ranges for NZ TSD data are:

Table 2.3-1: Goodness of Fit – Typical Ranges

Goodness of Fit	Typical Reliability of Moduli	Typical Percentage of Values
1.000 - 0.975	Very Good	75%
0.975 - 0.950	Good	20%
0.950 - 0.850	Fair	5%
0.850 - 0.000	Poor	<1%

This parameter is useful for determining when decisions should give more weight to factors other than the TSD information, i.e. the visual survey and experience with historic performance, as well as indicating the need for as-built information or additional subsurface investigations.

2.4 Repeatability

Repeatability studies carried out without delay at the same vehicle speed have been undertaken by many agencies (see figure below), with most publications showing that, for all practical purposes, results carried out on the same day are essentially the same.

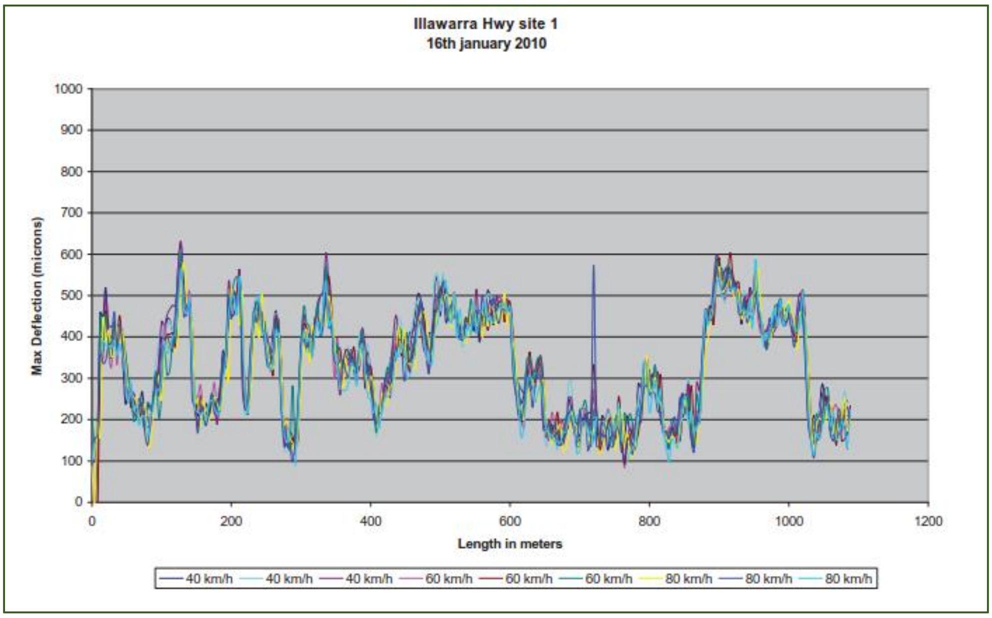
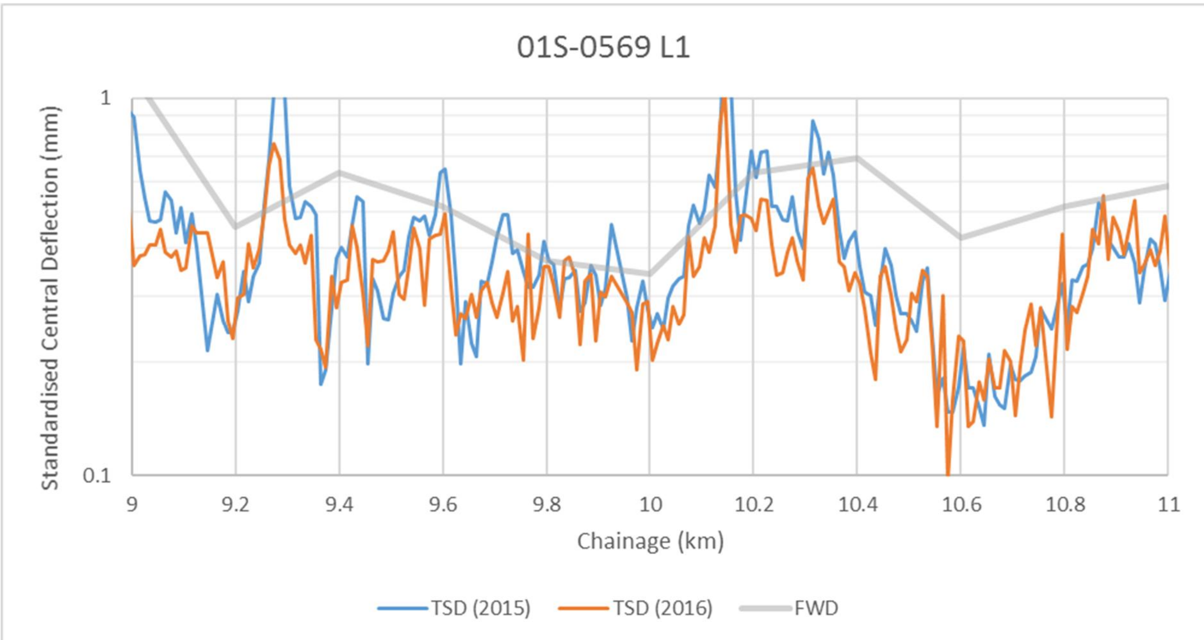


Figure 2.4-1: Vehicle Speed Comparison – from Queensland Trial of TSD (Weligamage et al)

Repeatability studies carried out without delay at different vehicle speeds show that deflection results can vary slightly at speeds over 30-40 kph, but for practical purposes may be considered similar.

However, at speeds under 30 kph, deflections tend to be higher, sometimes increasing by a factor of up to 2 or more, as speeds diminish towards 0 kph. This characteristic is well known and has been observed in Benkelman Beam studies. The greatest differences are on soft cohesive subgrades. As standard procedure is to collect all TSD data at not less than 30 kph, this characteristic (which should be considered carefully for intersection design) is not discussed further.

In order to determine what factor may apply between any two runs, the most convenient representation is to plot the deflection axis at a log scale, as shown below.



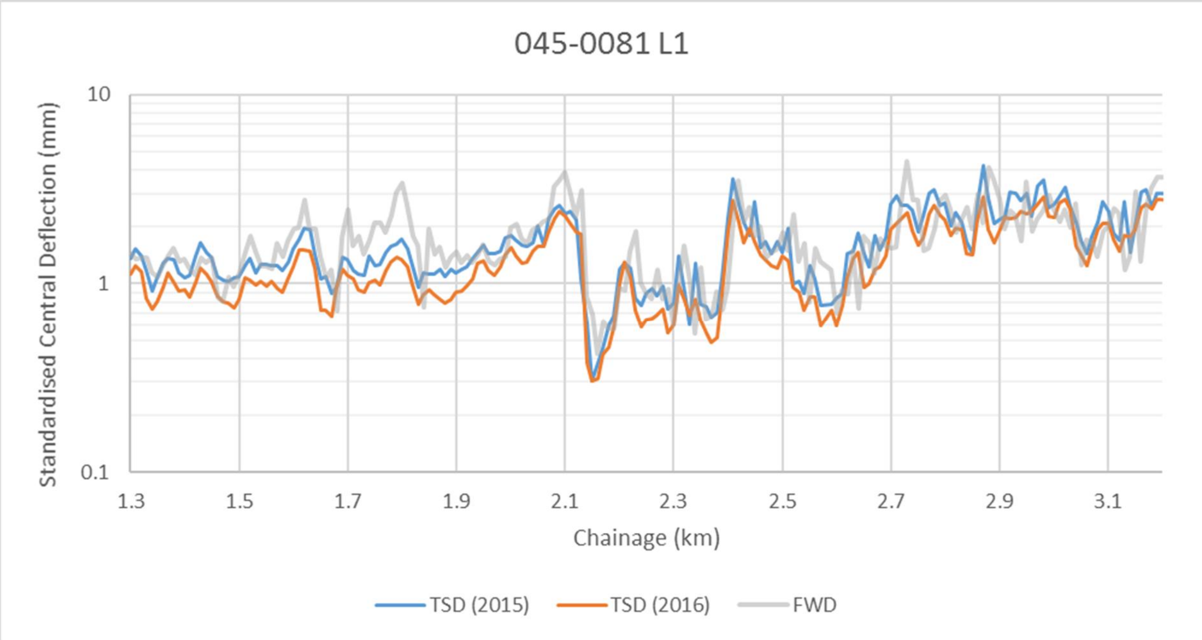


Figure 2.4-2: Two examples comparison of TSD runs (2015 - 2016) with FWD data

When comparing TSD data on NZ state highways in successive years (2015 and 2016), the *general trend* is reasonably strong.

However, as can be clearly seen in the following example, both TSD sets seem to be generally underestimating the FWD deflection (as expected, given differences between the contact area configurations of the two devices), but the TSD distributions also show differences between successive years.

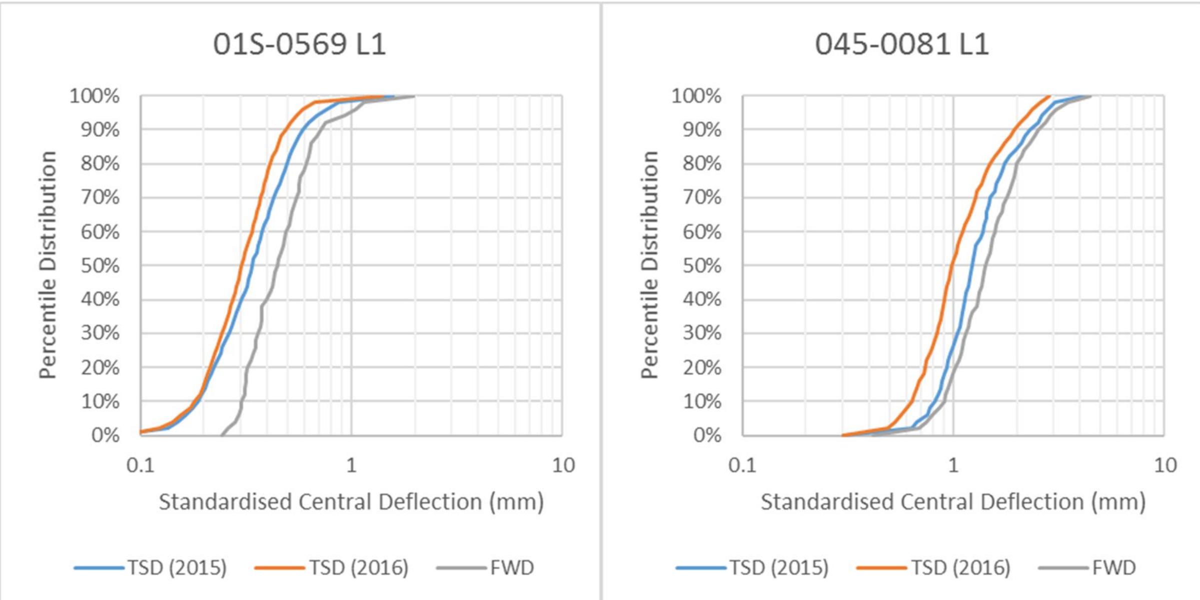


Figure 2.4-3: Cumulative distribution comparisons of TSD runs (2015 – 2016) with FWD data

The entire 2015 and 2016 RAMM TSD data sets were collated into one file and filtered down so that the road id, lane, start_m and end_m matched across the row for both sets allowing a direct comparison from 2015 to 2016 for each 10 m section.

Of the 684,978 matching records, 666,269 (97.2%) and 651,843 (95.2%) records had values for load and raw d0 (i.e. were not blank or zero) for the 2015 and 2016 sets respectively.

The 2016 raw TSD deflections are on average about 15% smaller than the previous year (that is without standardising the deflections using the applied load). Another anomalous observation is that the applied load (from the strain gauge readings) is recorded to have gone *up* approx. 8% from 2015 to 2016, which compounds the standardised deflection error to a 25% drop between the years.

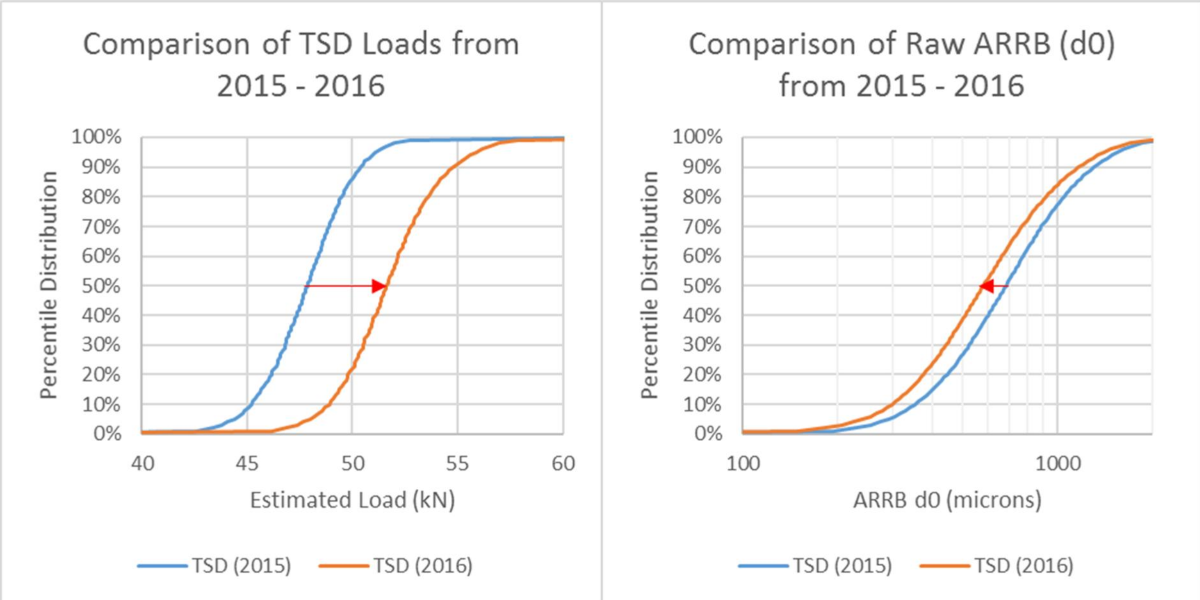


Figure 2.4-4: Cumulative distribution comparisons of the RAMM TSD data sets (2015 – 2016)

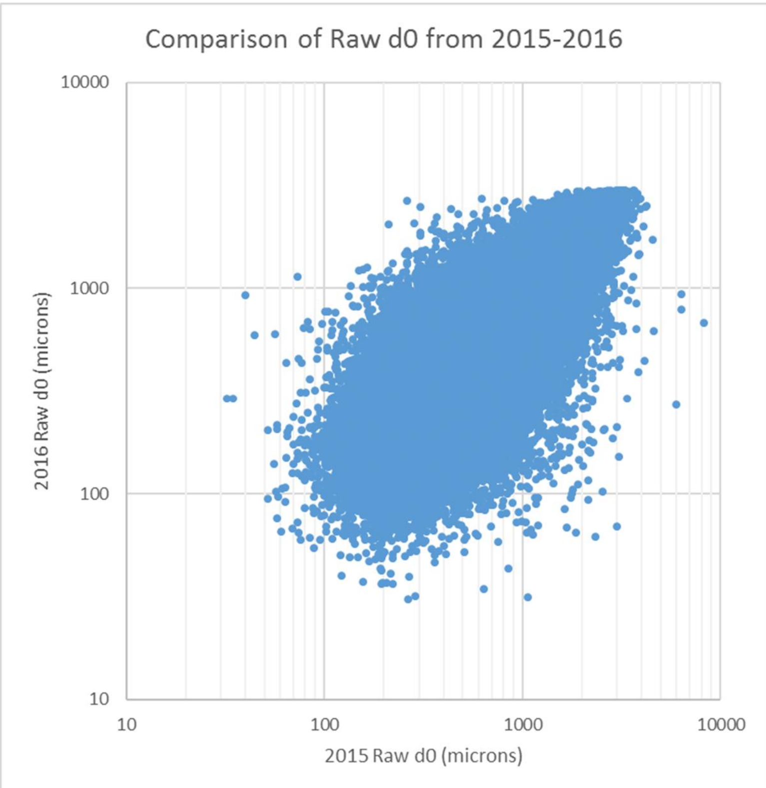


Figure 2.4-5: Comparison of Raw TSD central deflections (2015 – 2016)

Some of the difference may be due to preceding rainfall, humidity and temperature effects, and further studies can be carried out readily for any particular case of interest by comparing the changes in respective layer moduli in relation to climate data, materials and water table fluctuations. Vehicle wander is obviously another factor which may account for differences in successive years, which would be more likely where there are wide lanes and sharp bends.

Deflections on bridges are not reported in the dataset. Assuming that information would be collected automatically, deleting it has drawbacks in that it discounts the use of this data as regular checks for repeatability, bearing in mind that seasonal effects are likely to cause minimal change to deflection in concrete structures. Access to unfiltered data files would be advantageous.

Fluctuations of deflections or strains may often be in the range of 10%, and therefore when using the Austroads subgrade strain criterion (which relates pavement life inversely to the 7th power of subgrade strain), a 10% difference in strain translates to a factor of 2 in pavement life. This is significant, but not unduly so when it is noted that in practice, most "homogeneous" treatment lengths on rural highways tend to exhibit an order of magnitude range in pavement life e.g. 2 to 20 years or say 10^6 to 10^7 ESA.

3 Transformation of TSD to FWD-equivalent

3.1 Introduction

This section summarises alternative methods that may be used to transform Traffic Speed Deflectometer (TSD) deflections to Falling Weight Deflectometer (FWD) deflections. A spreadsheet can be provided that can be used to calculate the transformed bowls.

3.2 Methods

3.2.1 Application of Transfer Function generated from TSD vs FWD relationship – Route Station Specific

This method was originally developed in search of a national transformation, but case histories soon demonstrated that it is best used for more localised applications after calibration for a set of roads where both FWD data and TSD data exist.

A simple transfer function is generated comparing the distribution of FWD deflections (d_x) at any given offset position (ranging from 0 to 1500 mm) from the centre of the load (x) with the corresponding distribution of deflections under TSD. This result is a plot of FWD d_x against TSD d_x for the specific Route Station (RS), but the same concept could potentially be applied to an entire network.

The transfer function is generated in the form:

$$FWD(TSD\ d_x) = A * TSD\ {d_x}^2 + B * TSD\ d_x \qquad (2)$$

This function is applied to the raw TSD data at the corresponding geophone offset d_x. The function for the example case below is illustrated by the dashed trend line below:

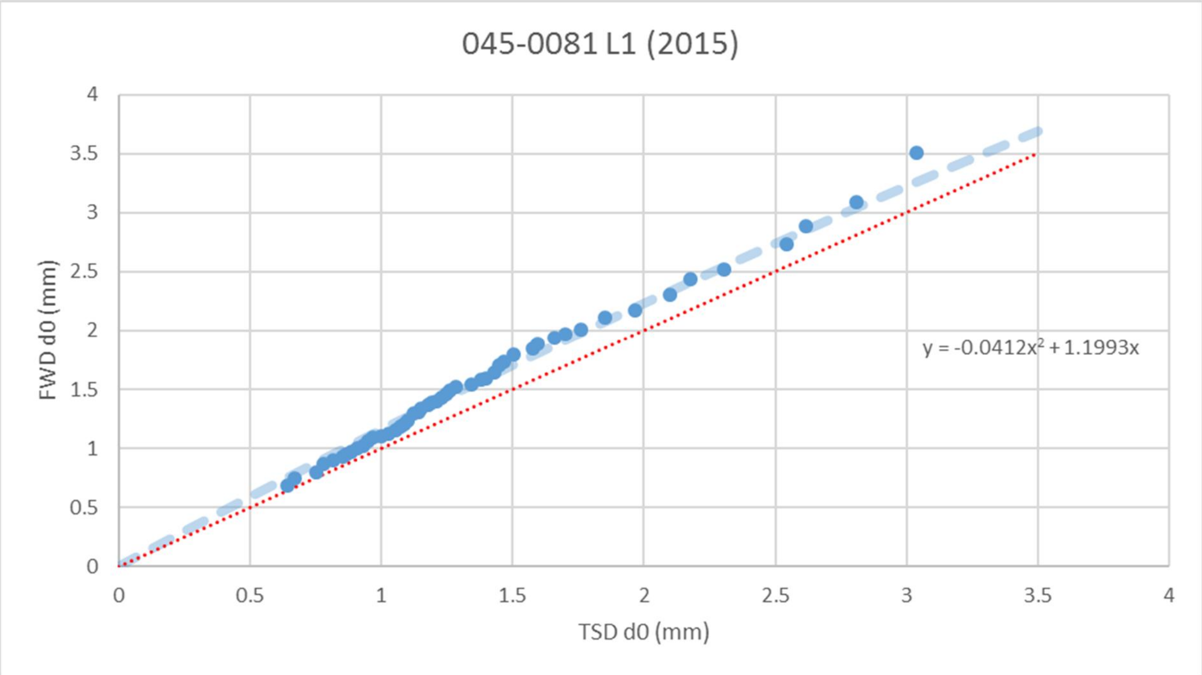


Figure 3.2-1: Example case plot of FWD d0 vs TSD d0 comparison

The FWD d_0 vs TSD d_0 example plot shows that TSD deflections appear to be underestimates when compared to the FWD deflections.

For the example case above that was analysed, a goodness of fit value of 0.886 was determined across the entire distribution of d_0 prior to transformation, which upgraded to a value of 0.981 following transformation. The FWD data were compared to the transformed TSD data as a cumulative distribution to quantify the effectiveness of the relationship, as illustrated below.

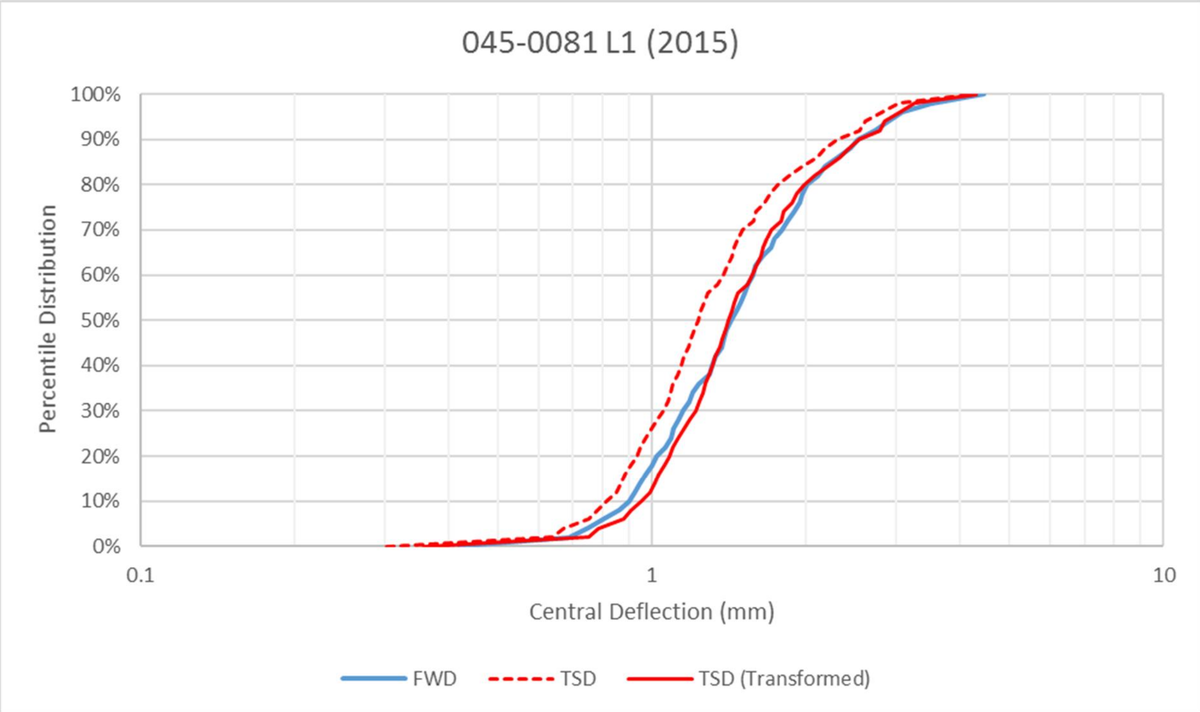


Figure 3.2-2: Example plot of cumulative distribution of FWD and 2015 TSD compared for the same route station before and after transformation

This plot illustrates a significantly improved TSD deflection distribution post-transformation when comparing to the FWD deflection distribution.

Plotting the same data against chainage shows that the transformation has largely modified the data in the right direction, and relative to the magnitude of the original deflection.

However, there are still a few sections where the FWD and TSD still do not correlate well (e.g. 1.7 - 1.8 and 2.9 - 3.0 km on the following plot).

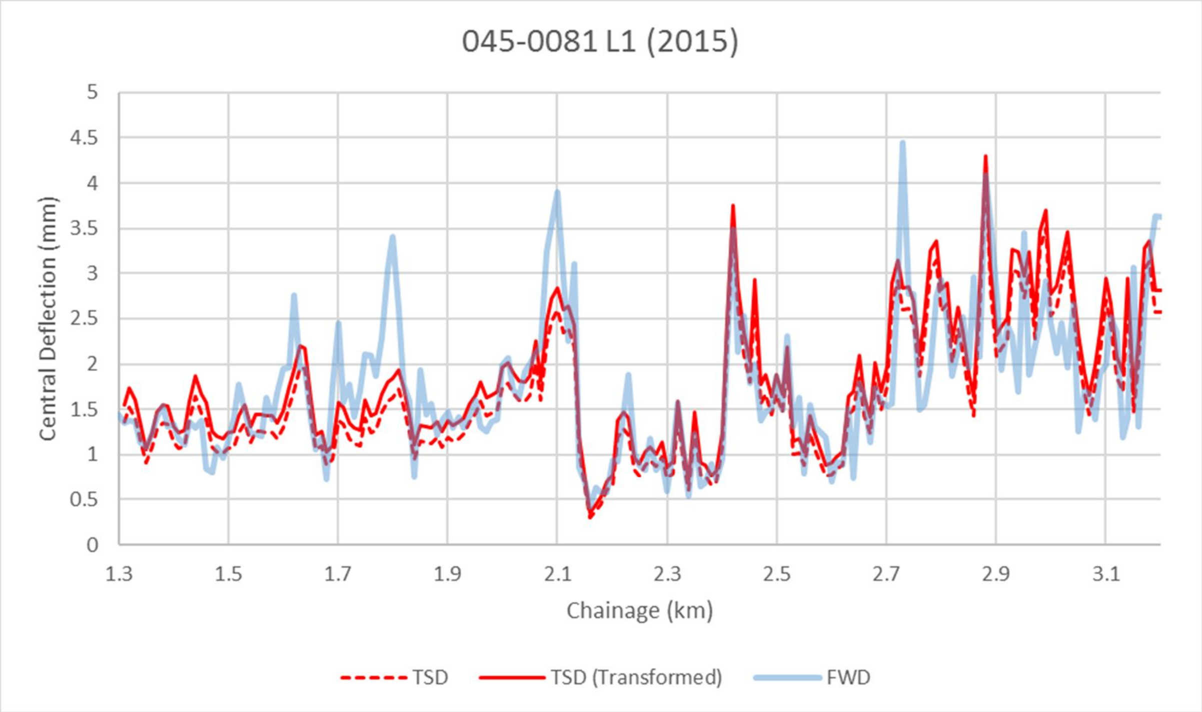


Figure 3.2-3: Chainage plot of FWD and 2015 TSD compared for the same route station before and after transformation

The same transfer function was then applied to the following year's TSD data to conclude if reliability exists between data sets for the 2015 versus 2016 TSD runs.

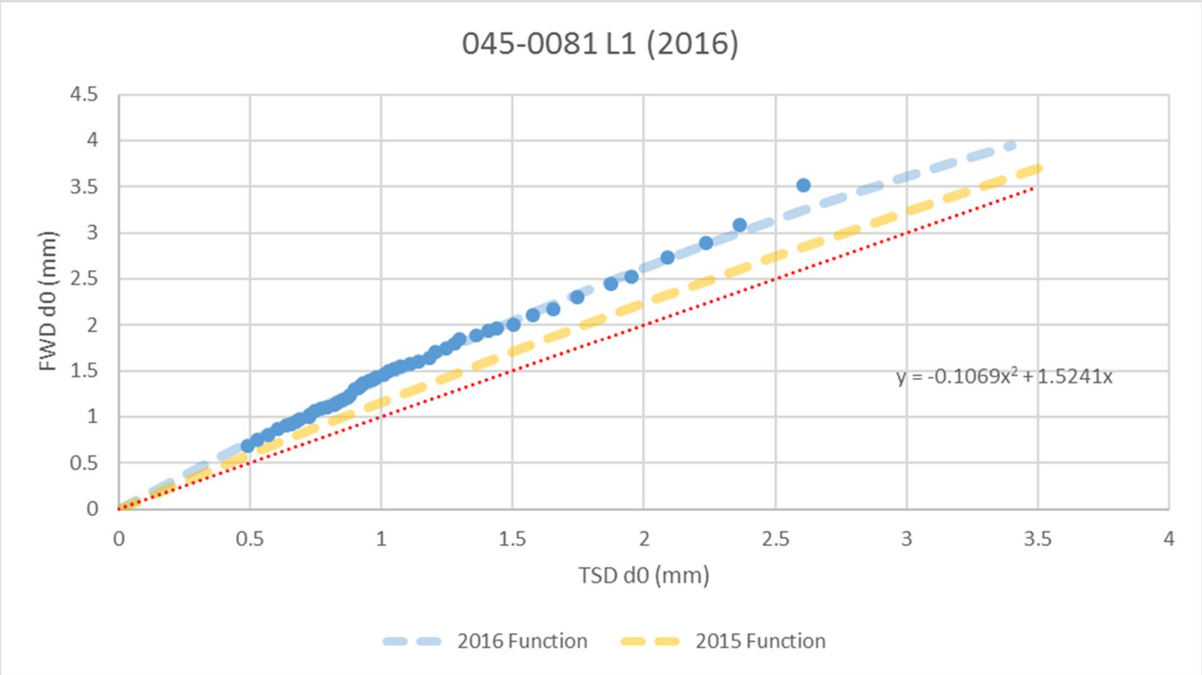


Figure 3.2-4: Example case plot of FWD d0 vs 2016 TSD d0 comparison, and showing 2015 transfer function

The comparison between TSD datasets from 2015 and 2016 shows a significant shift from year to year. This suggests that the transfer function generated from one year's data for a specific Route Station (RS) cannot be applied directly to historic or future data with a high degree of confidence, although relativity between chainages is still likely to be consistent.

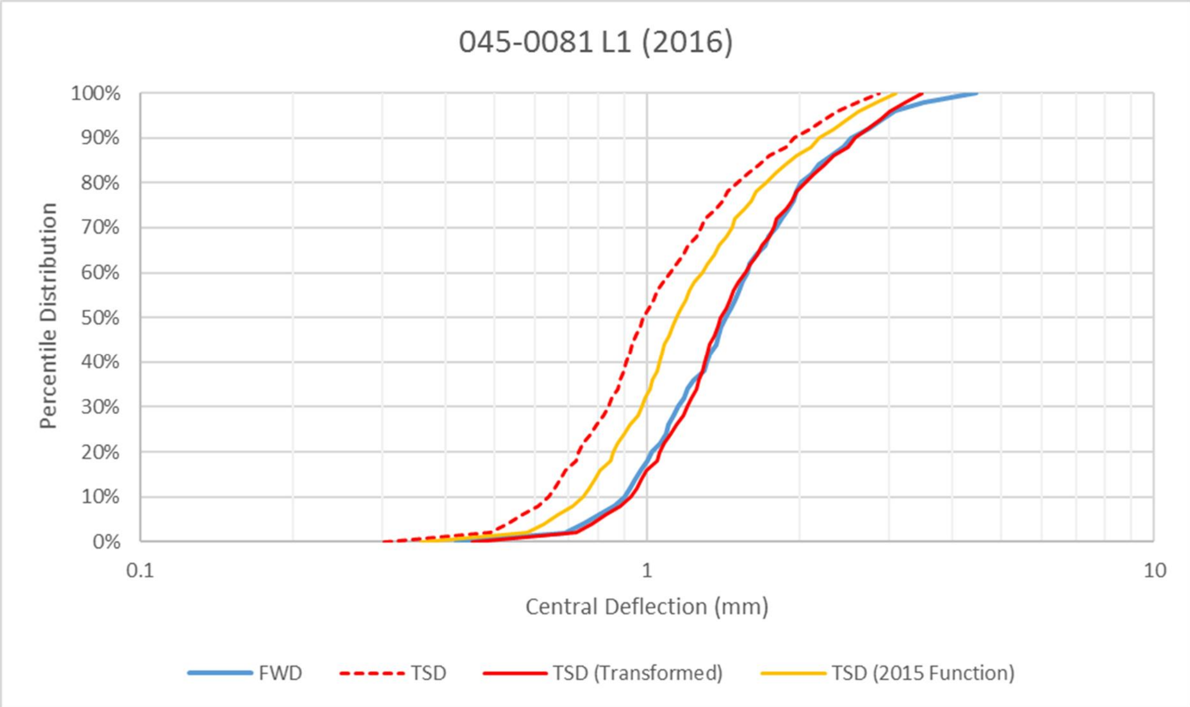


Figure 3.2-5: Example plot of cumulative distribution of FWD and 2016 TSD compared for the same route station before and after transformation, and showing equivalent 2015 function

The same level of confidence can be significantly less when applying the above generated transfer function to a different RS. This is illustrated below where the transfer function generated from the example case is applied to a different route station. This results in the transformed TSD distribution showing a less accurate representation of the FWD distribution across the length of the route station. The differences are relatively less at higher deflections - hence, critical points are less influenced in this case, but all the same, caution is required with any network-wide transformation.

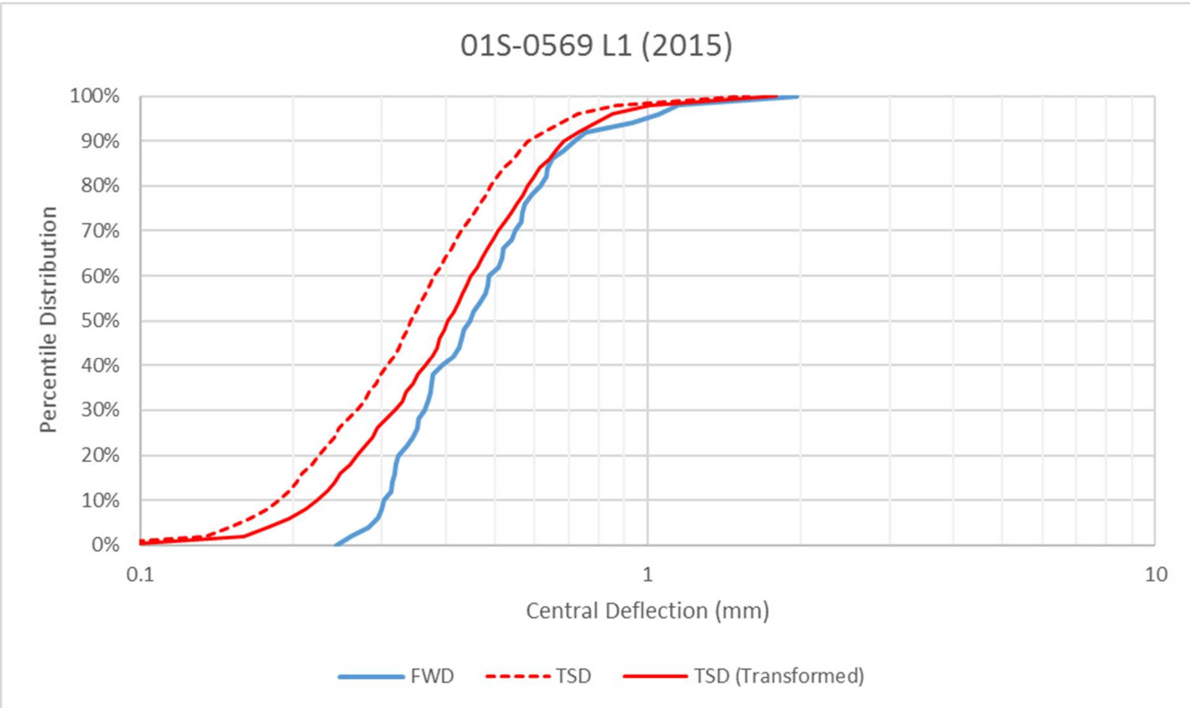


Figure 3.2-6: Example plot of cumulative distribution of FWD and TSD for 01S-0569 compared using the transformation from 045-0081

To use this method with any confidence, a transfer function should be generated from within each route station, and for each deflection offset.

3.2.2 QMR (Queensland Main Roads) Method

This method was developed to be used across the entire Queensland network, but when it was applied in practice to NZ situations, was found to be limited. The technique has been evolving, and the latest nominal relationship for Queensland just received[8] (yet unpublished) is shown in Equation 3.

Note: The unit for deflection used in this method is microns.

$$d_{0\,(FWD)} = \frac{40.129 + d_{0\,TSD}}{0.9845} \qquad (3)$$

$$d_{x\,(FWD)} = d_{0\,(FWD)} e^{\left(-\frac{x}{k_{2,x}}\right)}$$

Where the $k_{2,x}$ values are provided by the method to be:

$k_{2,200}$ = 590, $k_{2,300}$ = 460, $k_{2,450}$ = 444, $k_{2,600}$ = 463 and $k_{2,900}$ = 527

An example of this method is shown in Appendix D, Figure D2 showing the cumulative distribution of FWD d_0 against the raw and transformed TSD d_0 distribution for the same Route Station. The Queensland calibrated factors were applied to an example road in New Zealand to show the degree of applicability of this transformation to other regions.

A significant limitation of this method is that it transforms only d_0 (discarding the rest of the bowl) and then generates the remainder of the bowl using a characteristic bowl shape derived for the network. Discarding most of the collected data in this fashion is contrary to the goals of the NZ study. It is, however, reported here in case future versions do become more appropriate, as it is the only other attempt worldwide to address this issue from enquiries to date.

Owing to the above limitations, this method is only detailed further in Appendix D as the methodology presently used is not considered ideal. A suggested modification of this method to improve the reliability for New Zealand sites is also contained in Appendix D.

3.2.3 Application of Transfer Function generated from TSD vs FWD relationship – Network Specific Individual Offset Method

This method has been developed to be used across an entire network. The nominal relationships derived from FWD comparisons are shown below in Equation Set 4.

The transfer functions modify the composite moduli directly. Firstly, the TSD deflections (for the given offsets below) are converted into their corresponding composite moduli (CM_x). Next, the transfer functions below are applied producing transformed composite moduli (CM'_x) which are then converted back into an FWD-equivalent deflection bowl. The deflections for the remaining offsets (200, 450, 750 and 1200 mm) are interpolated.

[8] Gary Chai, pers. comm.

$$CM'_0 = (0.0225 * LN(CM_0) + 0.778) * CM_0$$
$$CM'_{300} = (-0.06 * LN(CM_{300}) + 1.071) * CM_{300}$$
$$CM'_{600} = (-0.11 * LN(CM_{600}) + 1.267) * CM_{600}$$
$$CM'_{900} = \left(1.119 * \frac{CM_{600}}{CM'_{600}}\right) * CM_{900}$$
$$CM'_{1500} = \left(-0.925 * LN\left(\frac{CM_{1500}}{CM_{900}}\right) + 1.239\right) * CM_{1500} \quad (4)$$

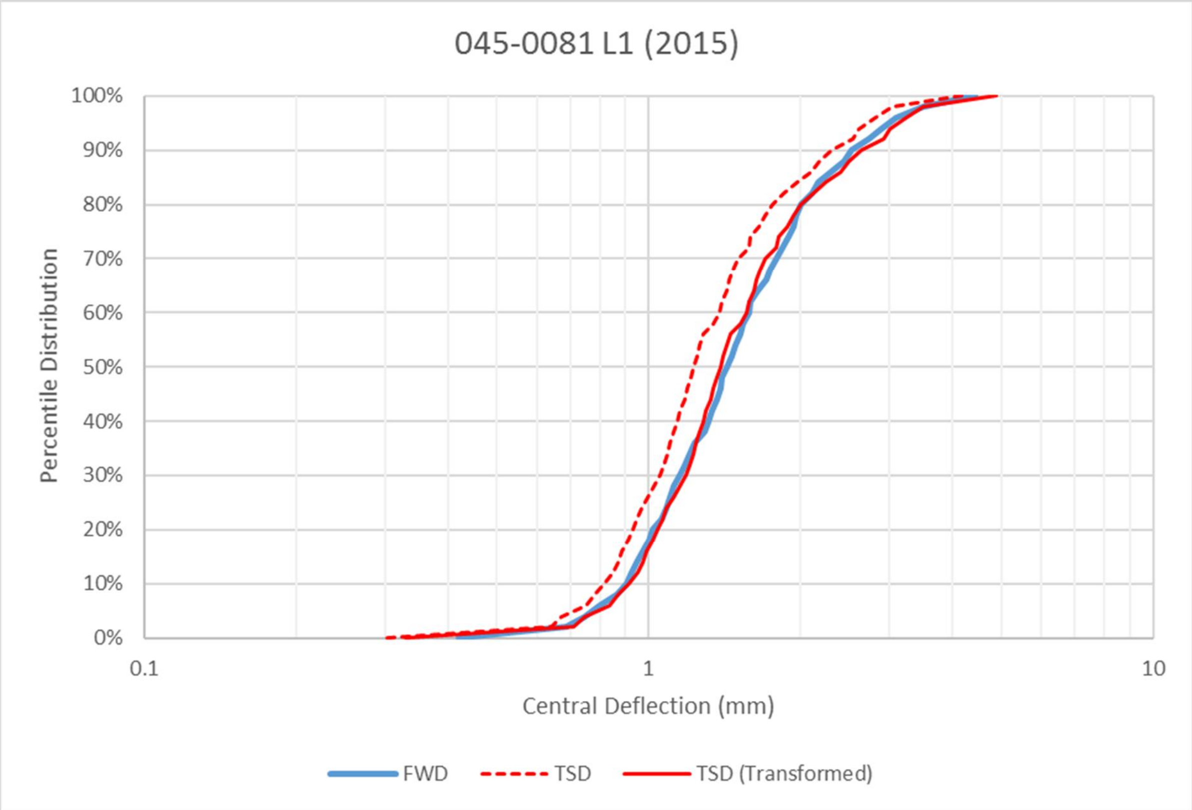


Figure 3.2-7: Transformation for d0 using Individual Offset Method showing a good correlation (0.98)

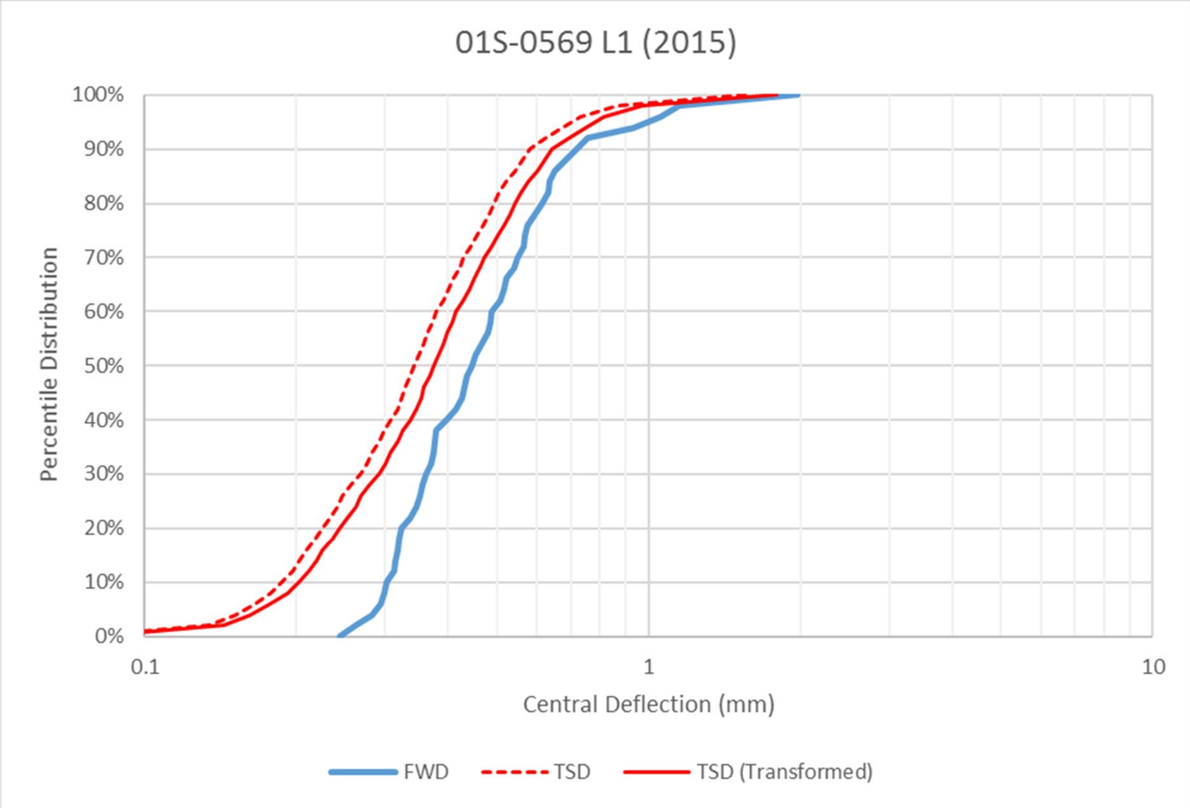


Figure 3.2-8: Transformation for d0 showing only a marginally improved correlation (0.83)

In this case, the critical points (with highest deflection) have relatively smaller differences, but it does need to be appreciated that any correlations applied across networks can have limited reliability in some situations.

3.3 Conclusions

Several methods for transforming New Zealand TSD deflection bowls (d_x) into equivalent FWD deflection bowls have been examined and are (order of preference):

- (i) Network Specific Individual Offset Method
- (ii) Route Station Specific Method
- (iii) QMR Method

The most favourable method outlined is the Network Specific Individual Offset Method, which provides a strong transformation from TSD recorded deflection to an equivalent FWD deflection for the given offsets unlike the QMR method which only calculates an equivalent FWD deflection for d_0, d_{200}, d_{300}, d_{450}, d_{600} and d_{900}. The Route Station Specific Method does have the ability to be applied across the entire range of offsets but requires a direct calibration at each offset. Using this method produces good accuracy, but the calibration stage is case specific and therefore time consuming.

The current QMR methodology was determined to be unreliable when applied to the New Zealand road network. Using only the central deflection from the TSD dataset and then generating a deflection bowl from only this point gives significant uncertainty on the reliability of the method, particularly as the offset distance increases.

A workbook with all the evaluated methods, including the recommended Network Specific Individual Offset Method, is available.

4 Structural Treatment Length Sectioning

Sub-sectioning of any road where TSD data have been evaluated uses the same principles as FWD. However, because there are so many data points, in order to establish the start and end points of each structural treatment length, it is more convenient to use auto-sectioning techniques. Typically, this is done with a CUSUM-like method which examines the results of the analysis to delineate intervals where the remaining life is relatively uniform. Any sections which are in a terminal condition, are sub-sectioned further into intervals where similar thicknesses of treatments are required.

The outputs for each structural treatment length (remaining life, generic remedial treatment options and critical parameters) can then be provided in common formats, such as spreadsheets and Google Earth KMZ files, as well as RAMM fields and dTIMS output sheets. Case history examples from the New Zealand data are provided in an accompanying presentation.

5 Reality Check: Review of TSD Interpretation

As a reality check on how useful the TSD data could be in practice, 50 km pilot sections of state highways (one North Island and one South Island) were nominated so that both the basic empirical data and the more detailed mechanistic analyses could be subject to the scrutiny of NZTA RAPT[9] engineers that had close familiarity with the historic long term performance and current condition of the specific roads. This was carried out in two passes. The 50 km pilot sections are displayed in appendices E and F.

The first pass was an interpretation of the TSD data by an analyst with no familiarity with the networks and no incorporation of any RAMM information except the current traffic loading. The empirical design parameter was the Austroads Simplified remaining life method (which uses only the equivalent standard central deflection from the TSD, and the nominal granular overlay thickness).

The mechanistic analyses (without other RAMM information) were used to generate the corresponding parameters (remaining structural life and granular overlay). Presentation of this information revealed that the TSD outputs did correctly identify some of the treatment lengths planned for treatment in the next year or two, but there were also examples where interpretation of the TSD data identified treatment lengths in the medium term (3-7) years that were not on the current FWP. The issue then becomes which of the two predictions will eventuate, and while this will be established in due course, in the meantime it is clearly necessary to focus on the short to medium term, i.e. next 1-2 (or possibly 3) year plan for TSD reality checks[10].

From historic performance and visual inspections, NZTA's RAPT managers have identified the following rehabilitation treatment lengths:

South Island Sites (Appendix E)	Year for Rehabilitation
• SH 1 RP 583/ 310-900	16/17
• SH 1 RP 583/ 900-1700	17/18
• SH 1 RP 583/ 14970-15500	18/19
• SH 1 RP 651/156-800	16/17
• SH 1 RP 651/5700-6200	15/16
• SH 1 RP 683/ 7160-9200	15/16

North Island Sites (Appendix F)	Year for Rehabilitation
• SH 2 RP 544/ 5080-5190	16/17
• SH 2 RP 707/ 13040-13114	16/17

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[9] The Transport Agency's Review and Prioritisation Team

[10] The findings were sufficiently encouraging, for the RAP Team to recommend that the next step should be for the analyst to now incorporate the relevant RAMM data and establish a local link to the Roadrunner software to determine whether a closer calibration could then be achieved to the short term. This work is in progress.

6 Strain Gauge Modification

A review of TSD data has highlighted some areas of concern with regards to the strain gauges. Presented below is each successive year of TSD data for the left strain gauges on SH01N-0557. The two graphs below present the observed differences in the left strain gauge over the four years of TSD testing, uncorrected and corrected.

Using SH01N-0557 shift functions were developed for the TSD strain_gauge_left readings for each year (to map 2016, 2017 and 2018 onto 2015). The *modified* strain gauge_left reading to convert the mass into the average load applied by the dual wheels for each 10 m interval. Generally, the more concave upward the pavement is over any given 10 m, then the greater will be the average load applied by the moving wheels (and vice versa). The strain gauge corrections are critical when correlating FWD and TSD. However when calculating remaining life, because the static axle load of the TSD used to date in New Zealand has reportedly been constant, the most simple approach for determining remaining life is to make the assumption that all heavy axles will have similar dynamic components to their loads as exhibited by the TSD. Hence for analysis and design adopt the TSD load as its static value and the TSD deflections as their dynamic values (without any strain gauge correction. If shape correction is being adopted this will no longer apply.)

ARRB report that issues with the strain gauges have been referred to the manufacturer, and should be addressed in future.

Transfer functions:

2015 = *x*0.00981*

2016 = (*x* * 0.899+261)*0.00981

2017 = (*x**1.018+4)*0.00981

2018 = *(*x*1.035+1930)*0.00981

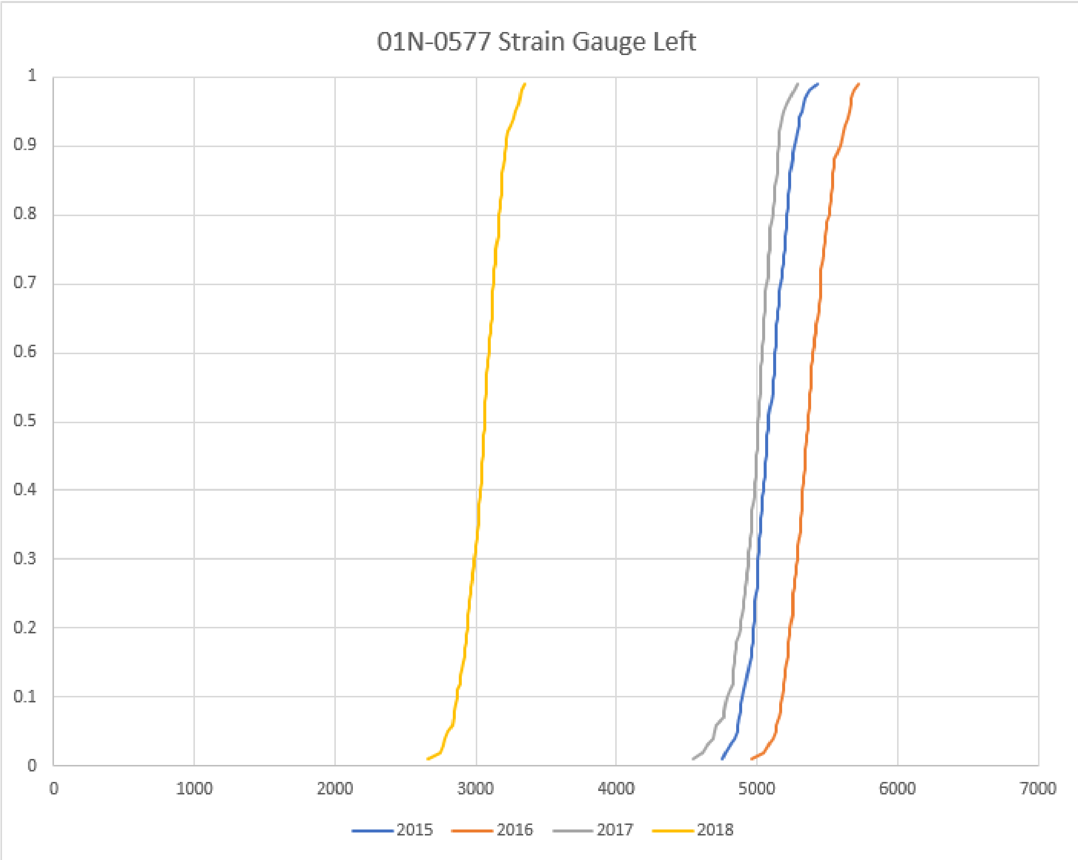
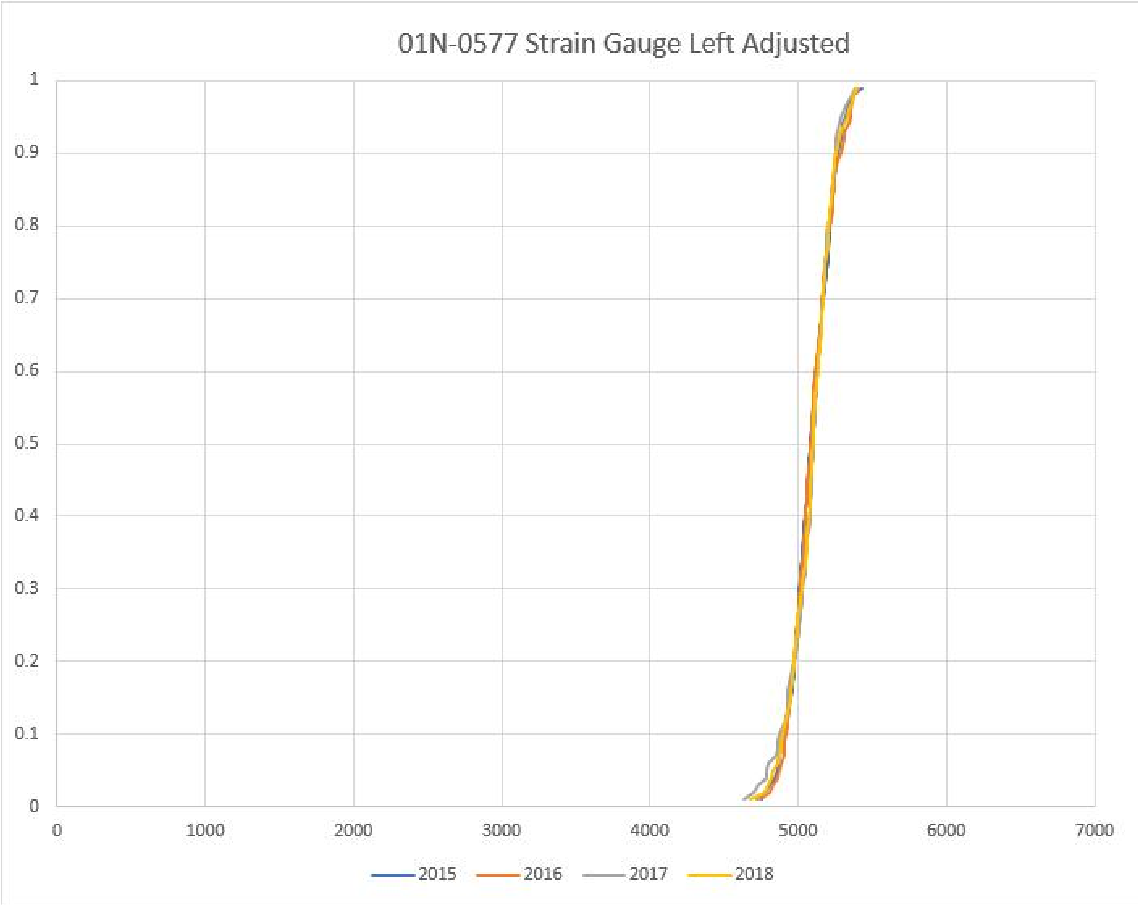


Figure 6.1 – Strain Gauge Left, uncorrected. Raw Percentile values.



6.2 – Strain Gauge Left, corrected.

7 Applicability

This report has been prepared for the benefit of NZTA with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Report prepared by:

Mike Plunket
Graduate Engineer

Gina Schmitz
Graduate Civil Engineer

Reviewed for GeoSolve Ltd by:

....

Dave Stevens
Pavements Team Leader

Authorised for GeoSolve Ltd by:

....

Graham Salt
Technical Director

Appendix A

SH8 RS169 L1 comparing 2015 and 2016 TSD datasets

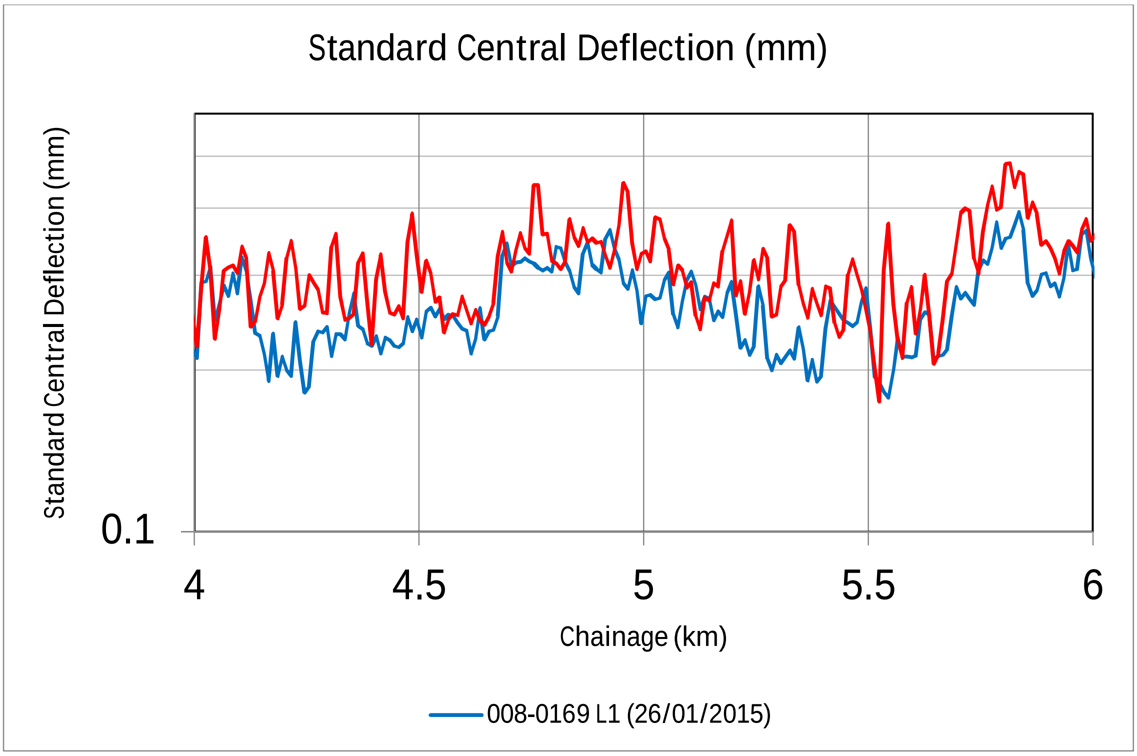


Figure A1: Standard Central Deflection plot comparing TSD data for 2015 and 2016 for SH8 RS169

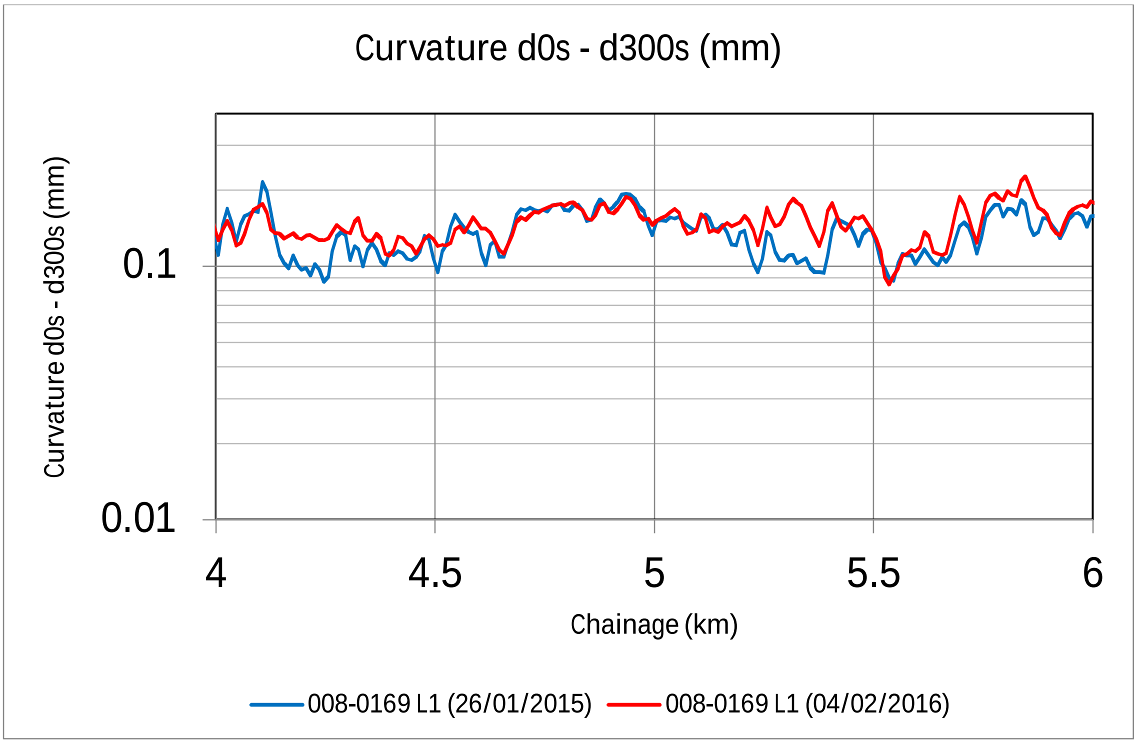


Figure A2: Curvature d0s – d300s plot comparing TSD data for 2015 and 2016 for SH8 RS169

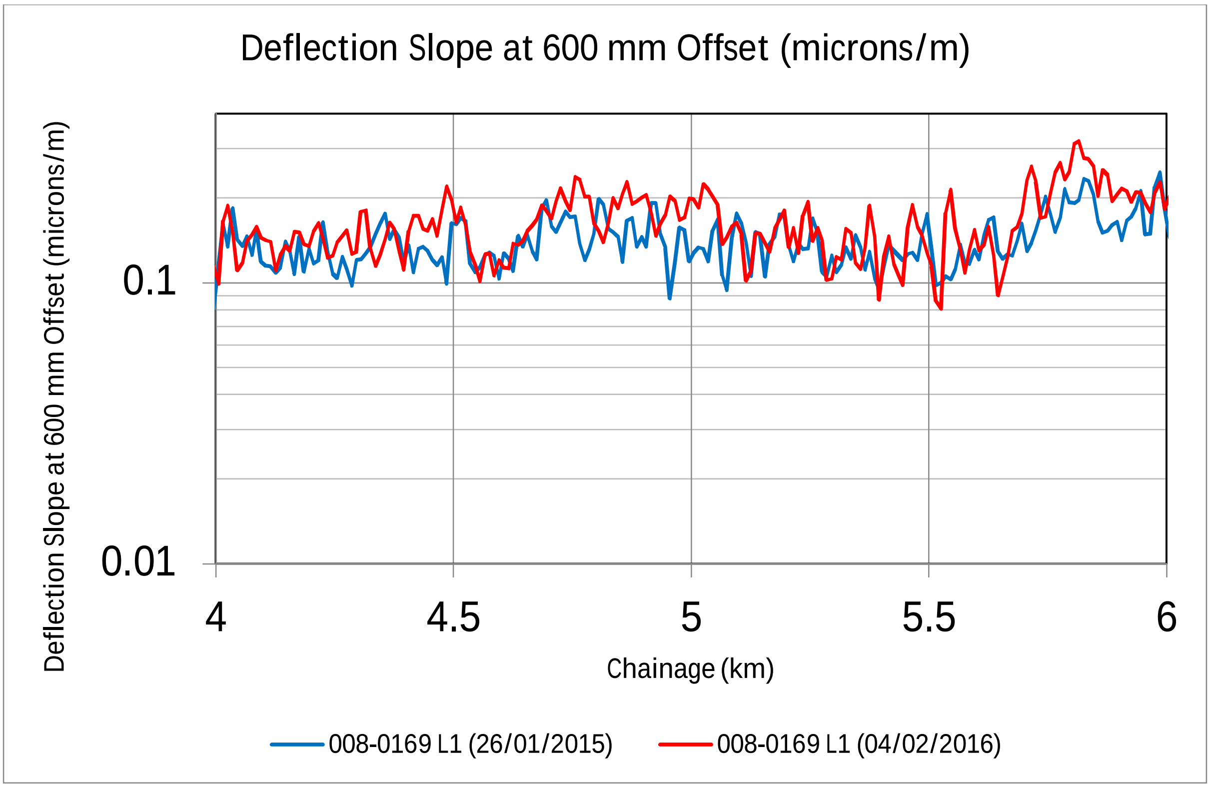


Figure A3: Deflection Slope at 600 mm offset plot comparing TSD data for 2015 and 2016 for SH8 RS169

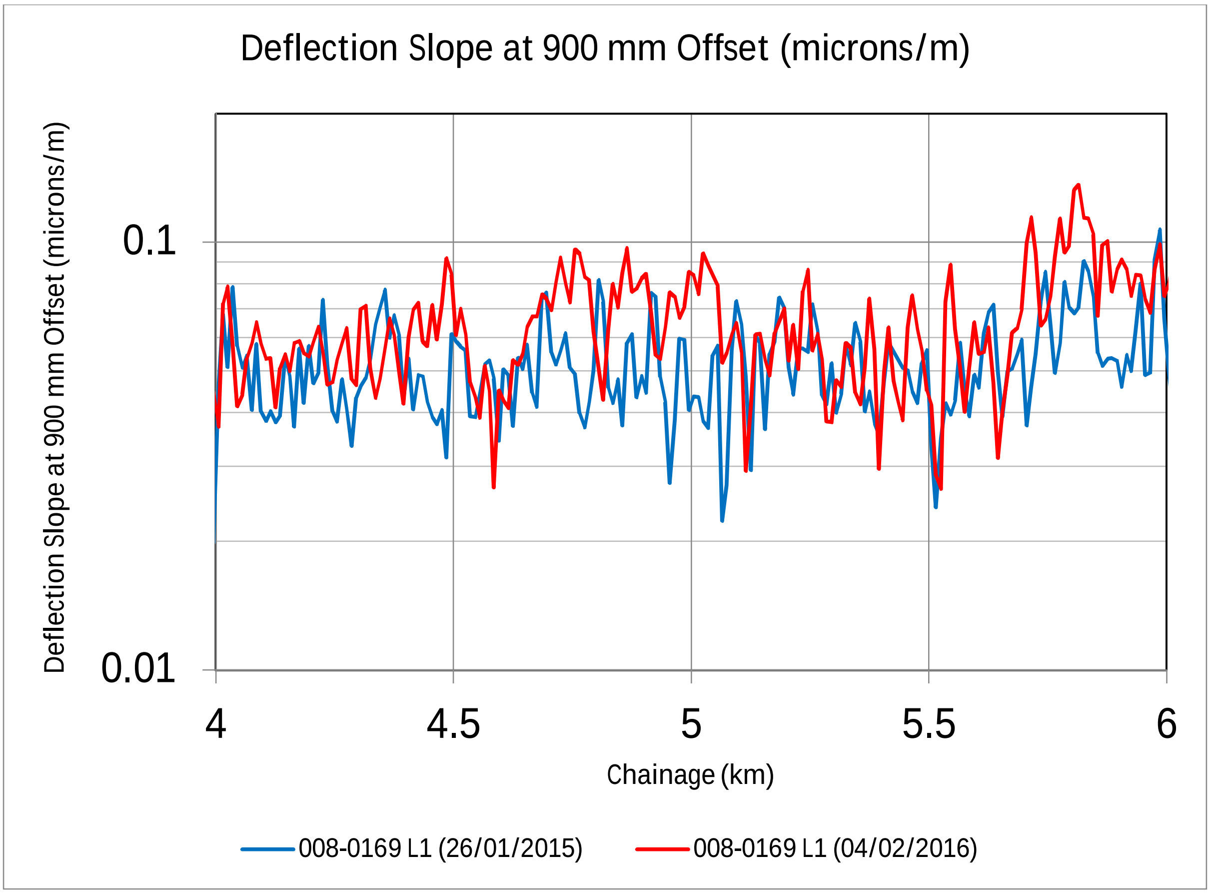


Figure A4: Deflection Slope at 900 mm offset plot comparing TSD data for 2015 and 2016 for SH8 RS169

Appendix B

SH90 RS35 L1 comparing 2015 and 2016 TSD datasets

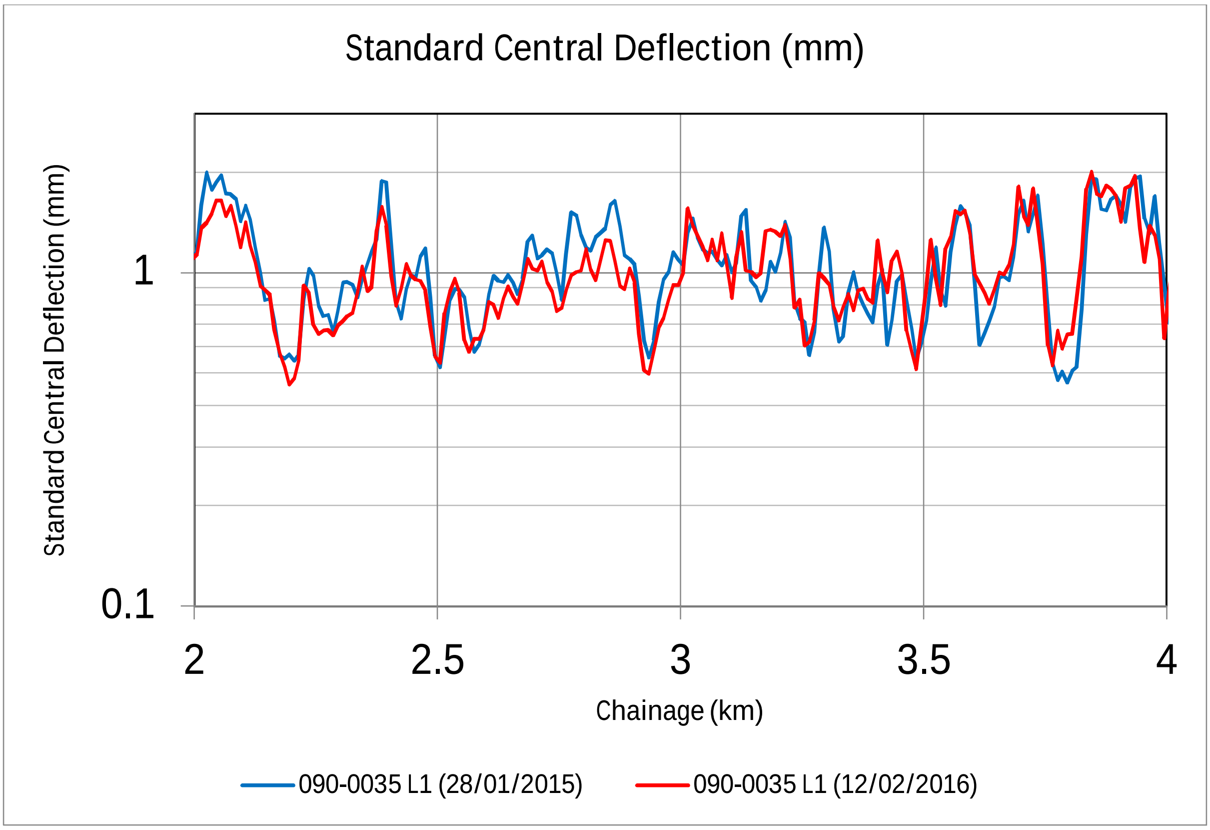


Figure B1: Standard Central Deflection plot comparing TSD data for 2015 and 2016 for SH90 RS35

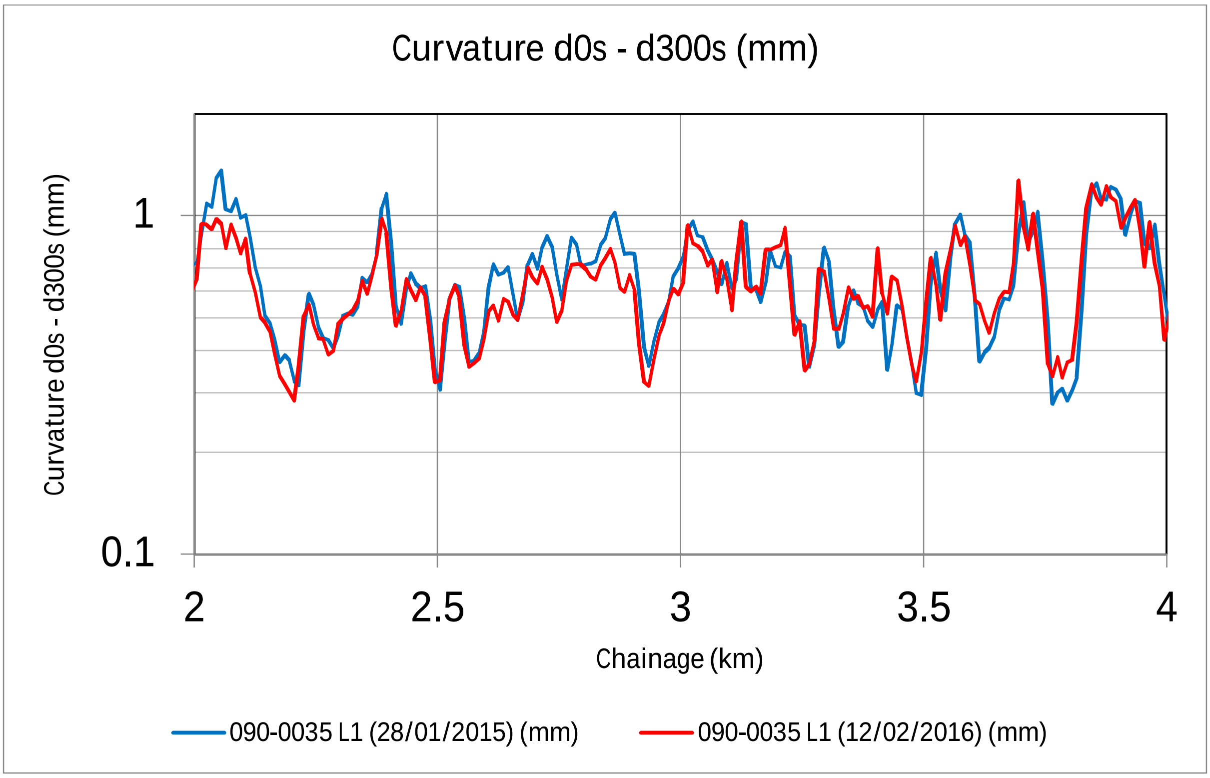


Figure B2: Curvature d0s – d300s plot comparing TSD data for 2015 and 2016 for SH90 RS35

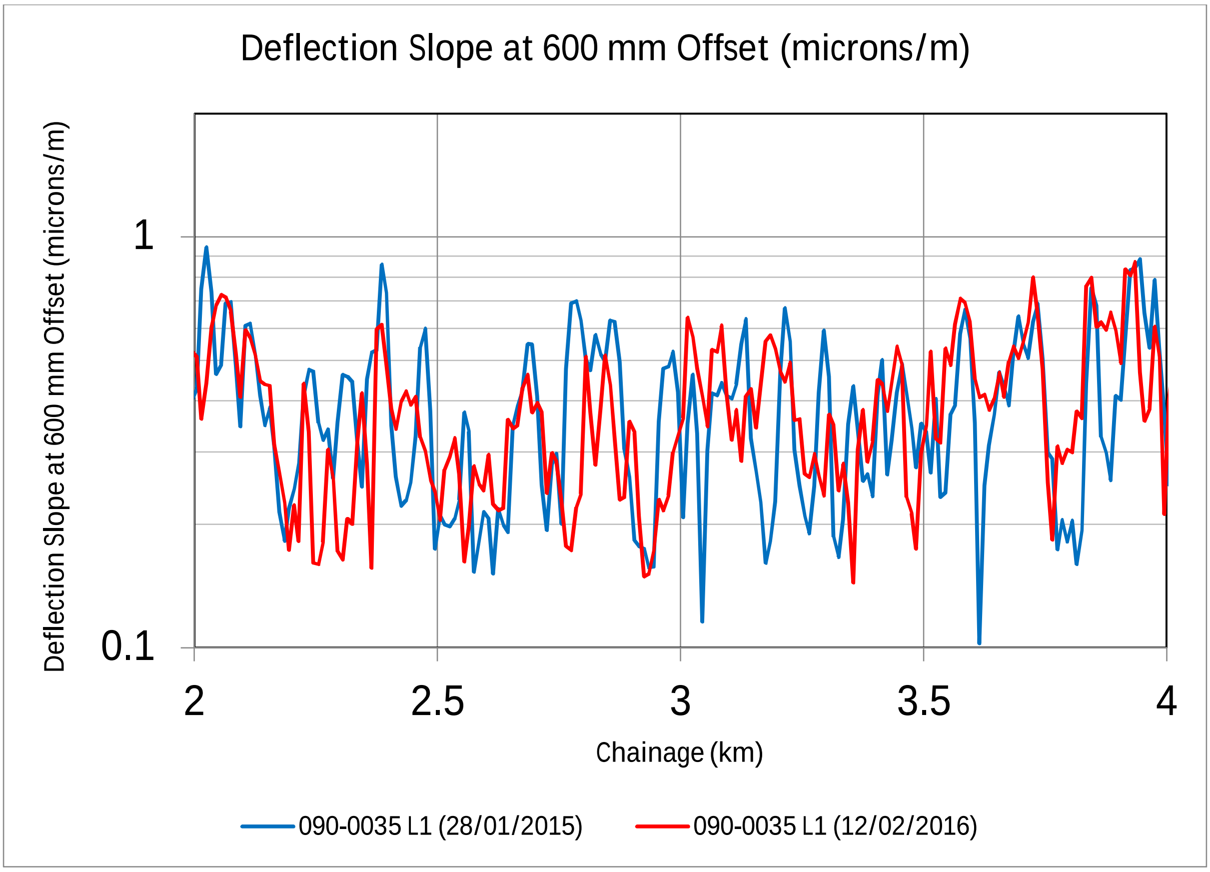


Figure B3: Deflection Slope at 600 mm Offset plot comparing TSD data for 2015 and 2016 for SH90 RS35

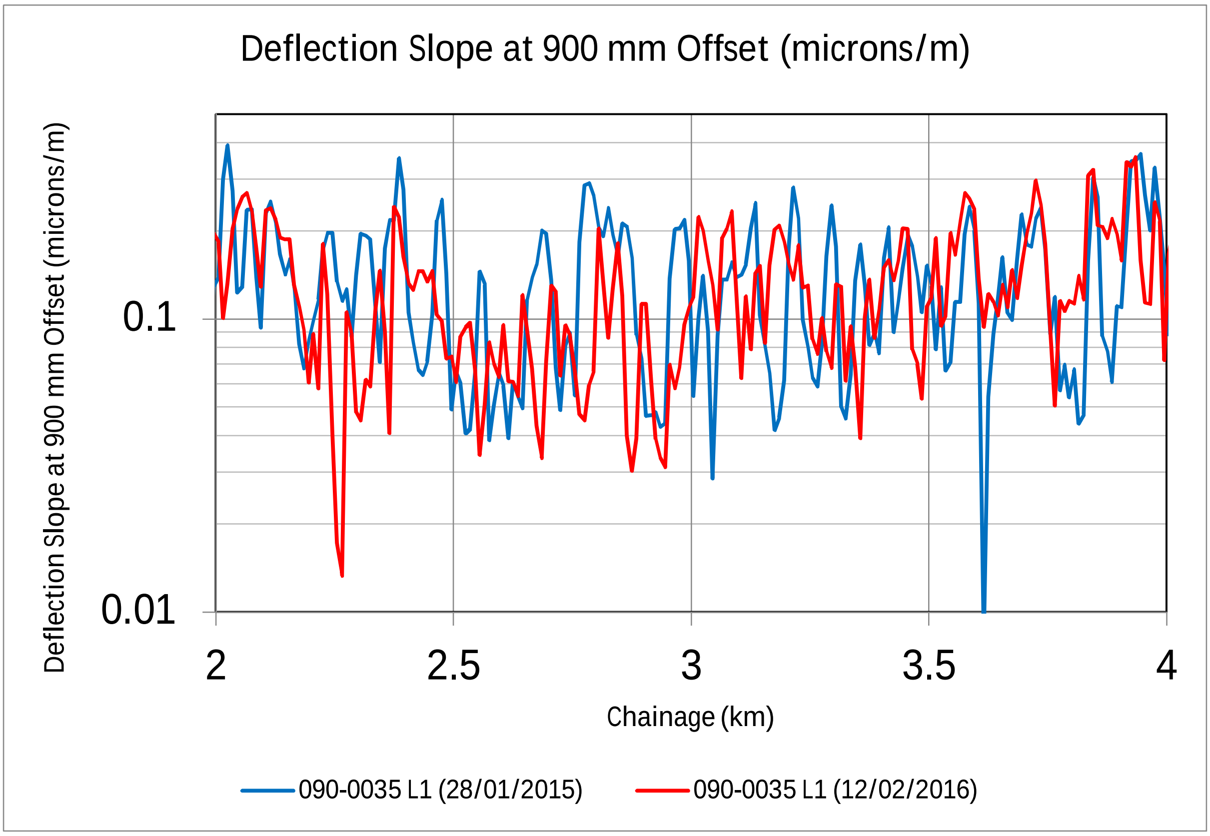


Figure B4: Deflection Slope at 900 mm Offset plot comparing TSD data for 2015 and 2016 for SH90 RS35

Appendix C

Example applications of TSD Data

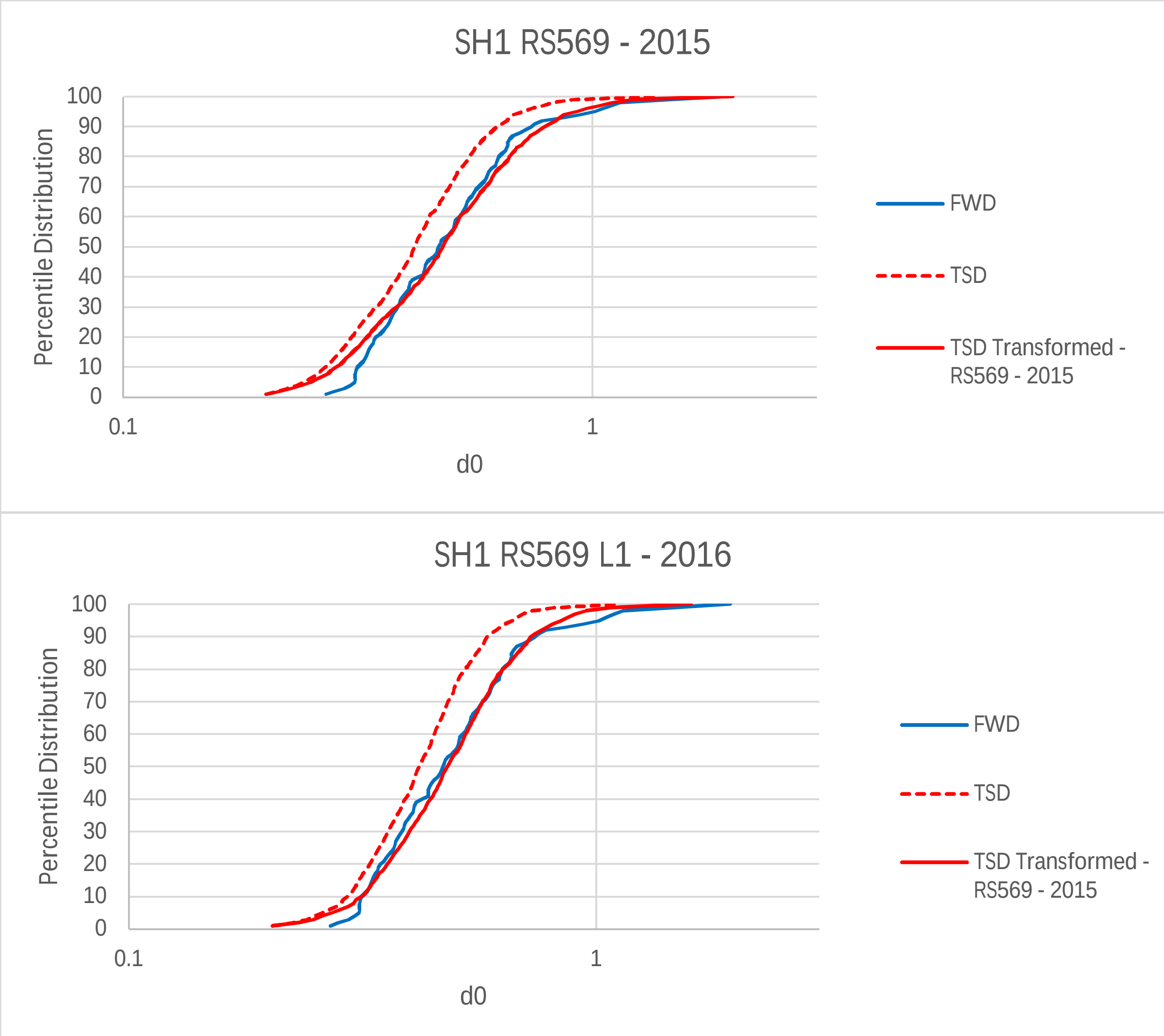


Figure C1: Transfer function generated from 2015 TSD/FWD data applied to 2015 and 2016 data

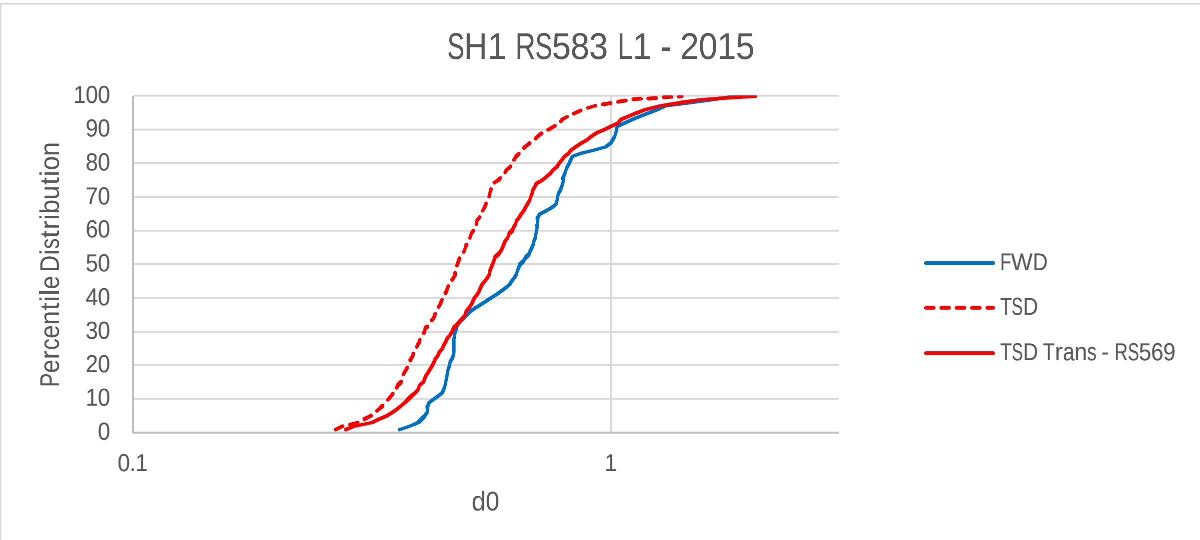


Figure C2: Transfer function generated from 2015 TSD/FWD data RS569 applied to RS583

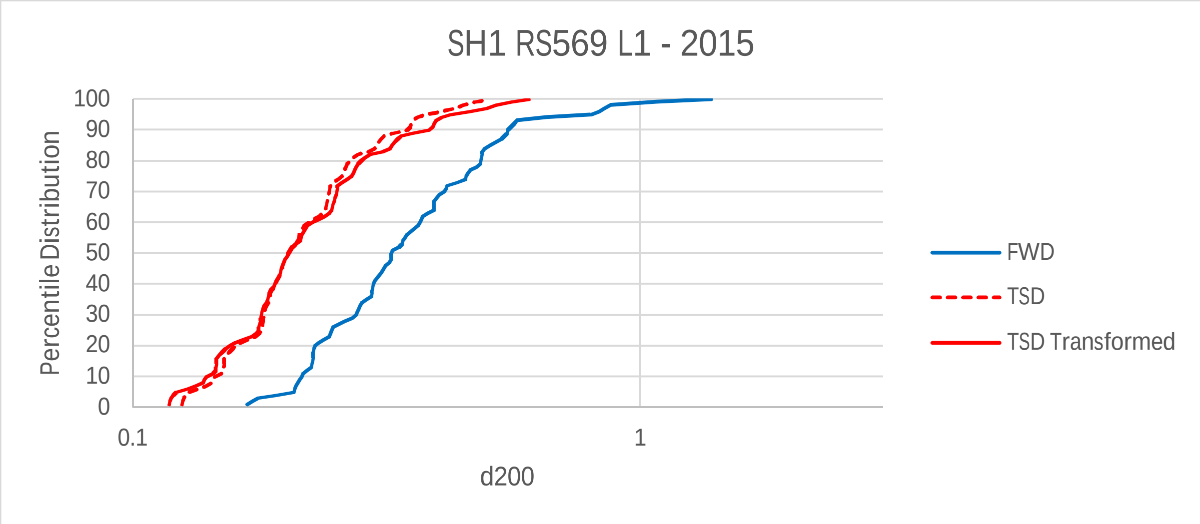


Figure C3: Transfer function generated from RS569 d0 applied to RS569 d200

Appendix D

QMR Method (Additional Notes)

The transfer at D_0 proves to be somewhat effective for this specific case as shown in Figure D2, but due to the method generating deflections for offsets based solely on the central deflection, the method does not hold as the deflection offset increases.

Figure D3 shows the QMR method transformation at D_{600} using the set "k" factor - this proves to be a very ineffective transformation from TSD to an equivalent FWD deflection. To improve the transformation at D_{600}, the "k" factor was calibrated to the specific Route Station. A linear trend was generated for the input "k" factor, this allowed an increasing "k" factor to be applied across the Route station as the deflection reading increased. This addition improves the ability to fit the transformed TSD deflections to an equivalent FWD deflection.

The trendline generated for the calibration is shown in Figure D1, where the resulting calibrated transformation using the increasing value for "k" is shown in Figure D4. This proves effective but requires too specific calibration (each route station) and therefore has been left out of the Network Specific Individual Offset Method.

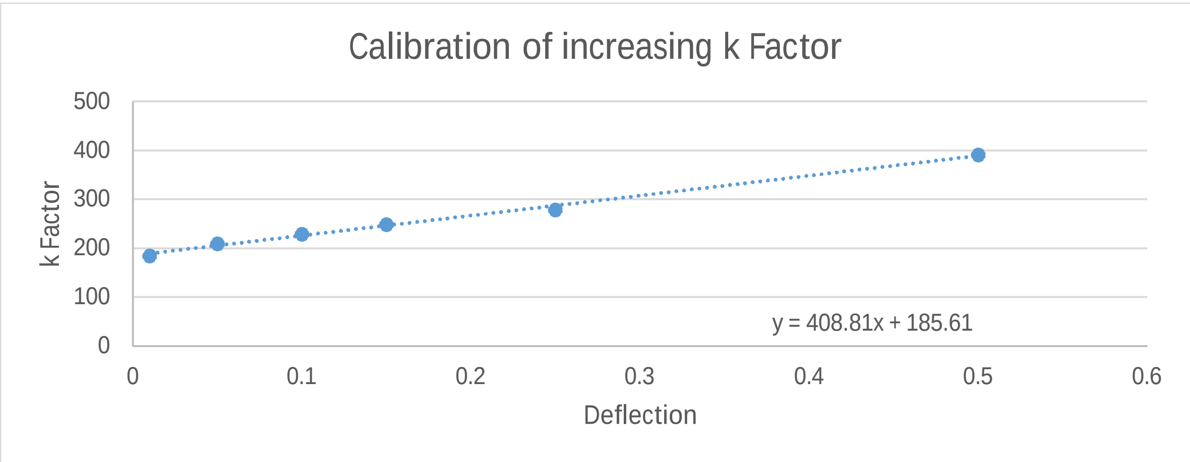


Figure D1: Calibration for k value increase as deflection increases

Using the modified concept for the k_x factor the equation becomes:

$$D_{0\,(FWD)} = \frac{40.129 + D_{0\,TSD}}{0.9845}$$

$$D_{x\,(FWD)} = D_{0\,(FWD)} e^{\left(-\frac{x}{slope_x * D_{0\,(FWD)} + intercept_x}\right)}$$

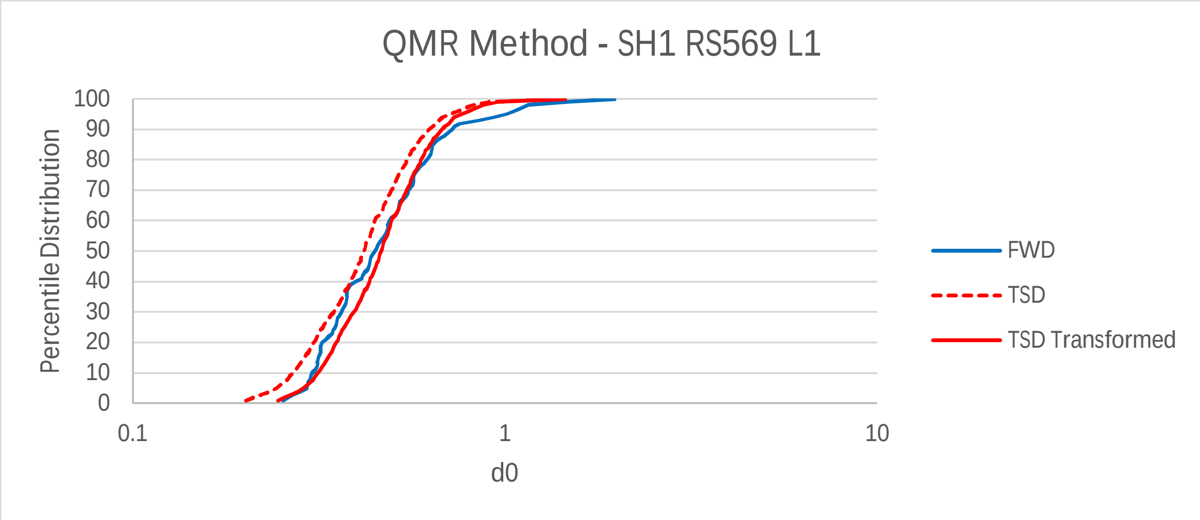


Figure D2: QMR method, transformation for central deflection, d0

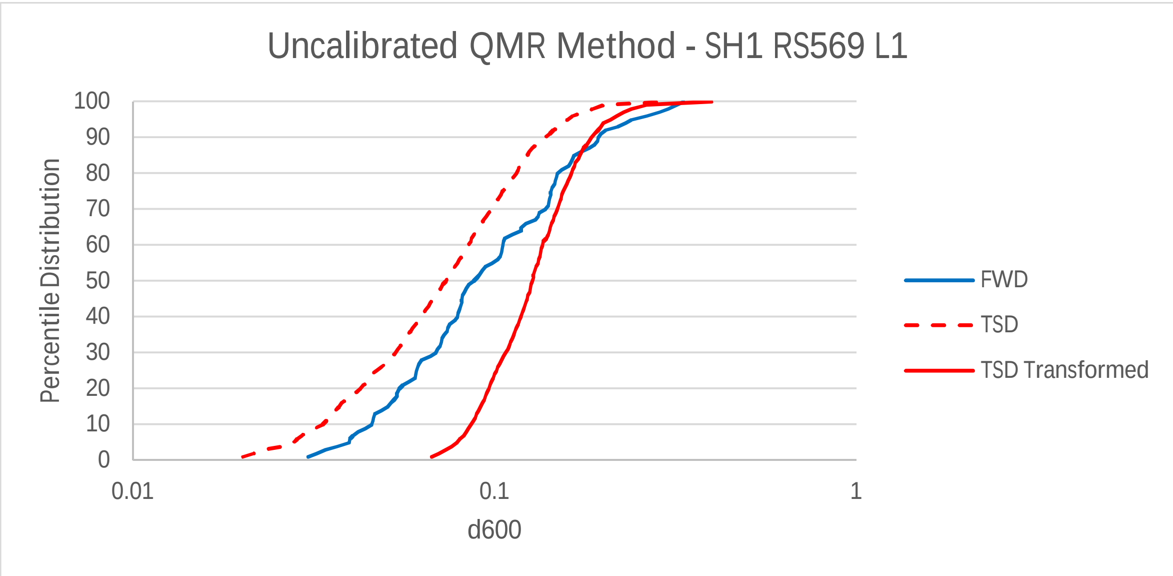


Figure D3: Uncalibrated QMR method, provided k value

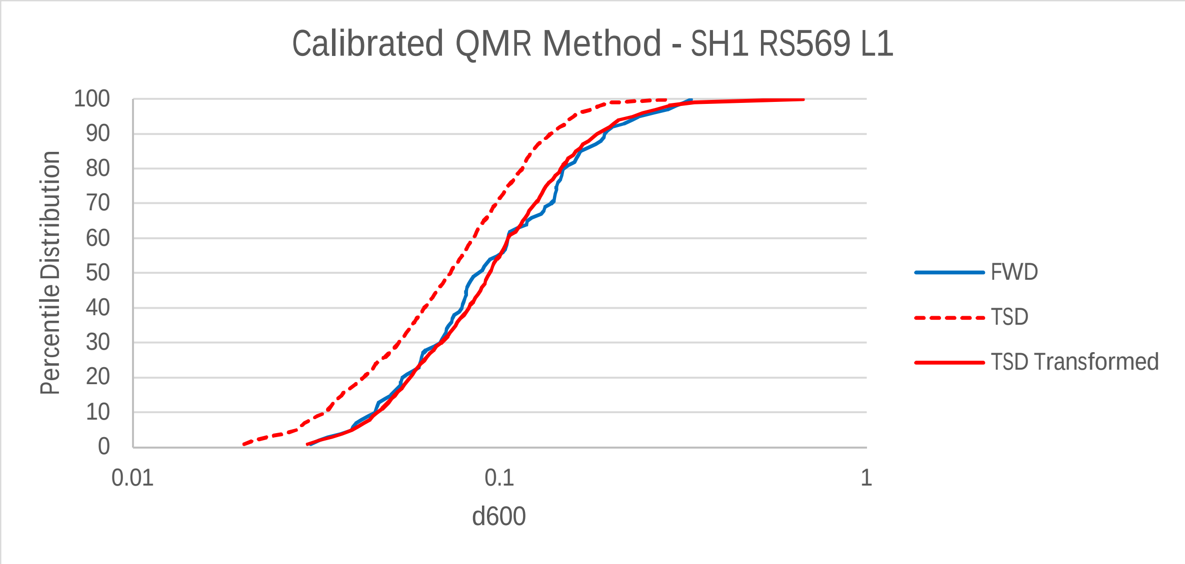


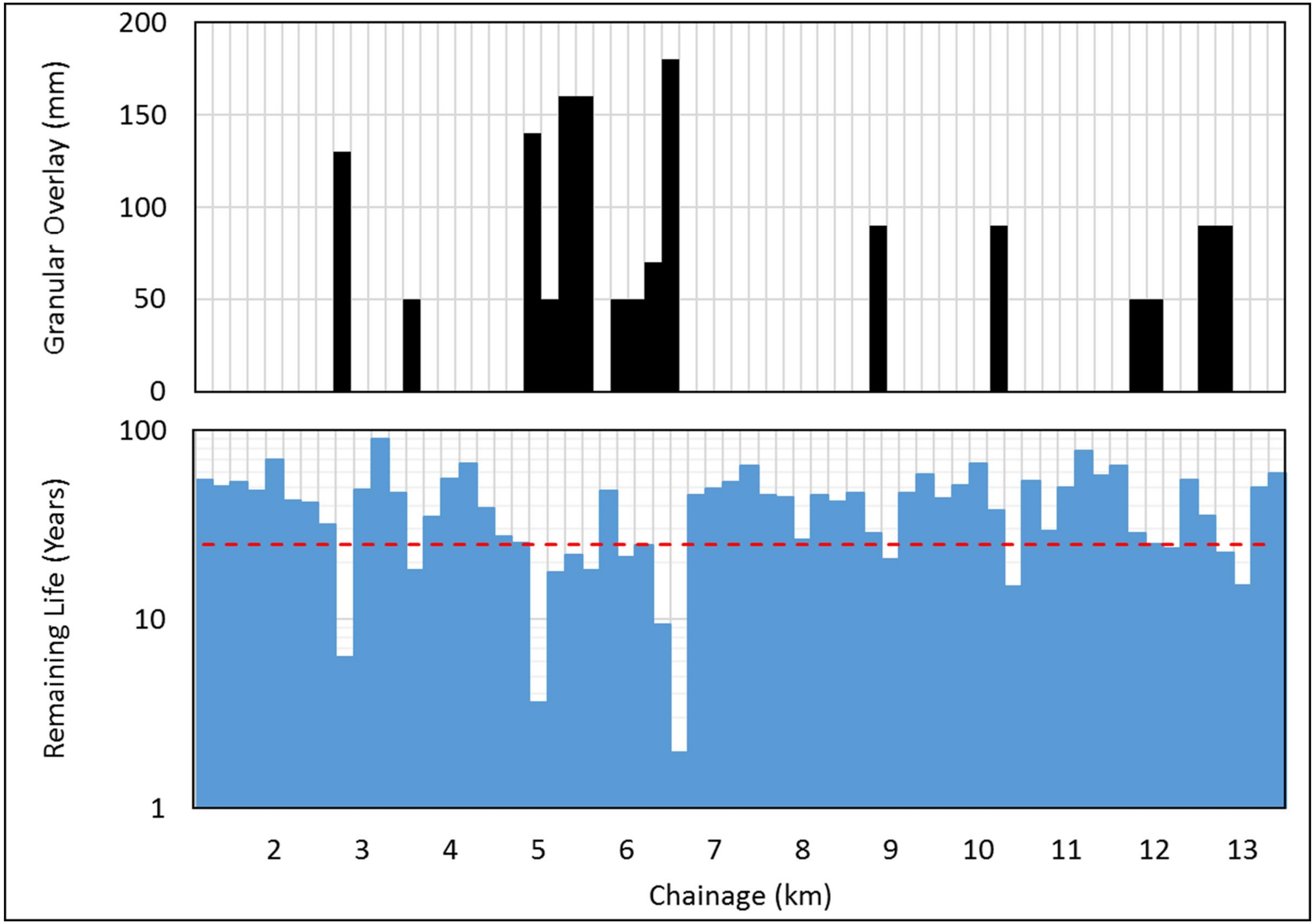
Figure D4: Calibrated QMR method, with k value increasing with deflection

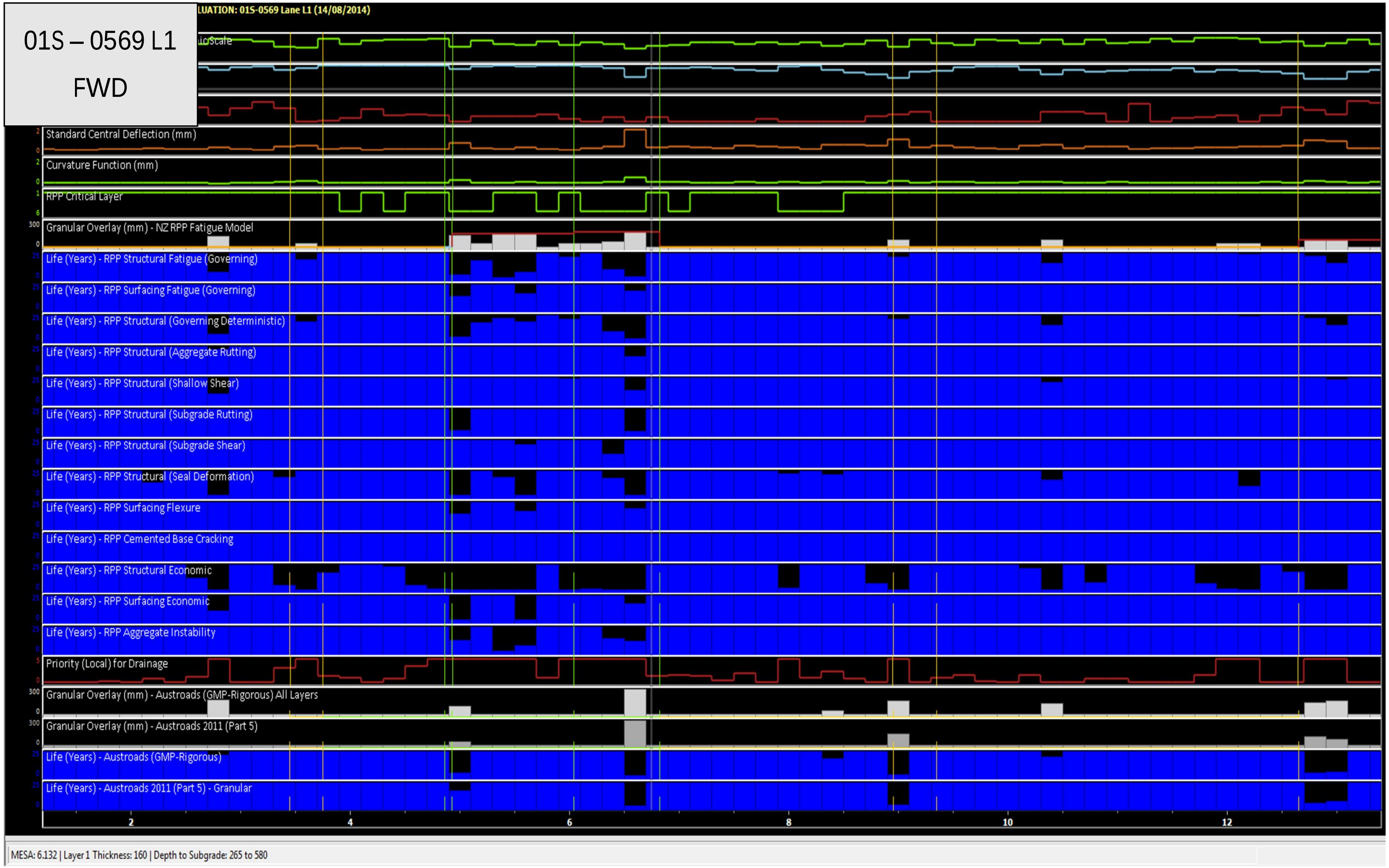
Appendix E

Coastal Otago 50 km Pilot Sections
01S RS569 & SH90 RS0 – Both Lanes

Summary Plot: 01S – 0569 L1 FWD

Granular Overlay and Remaining Life

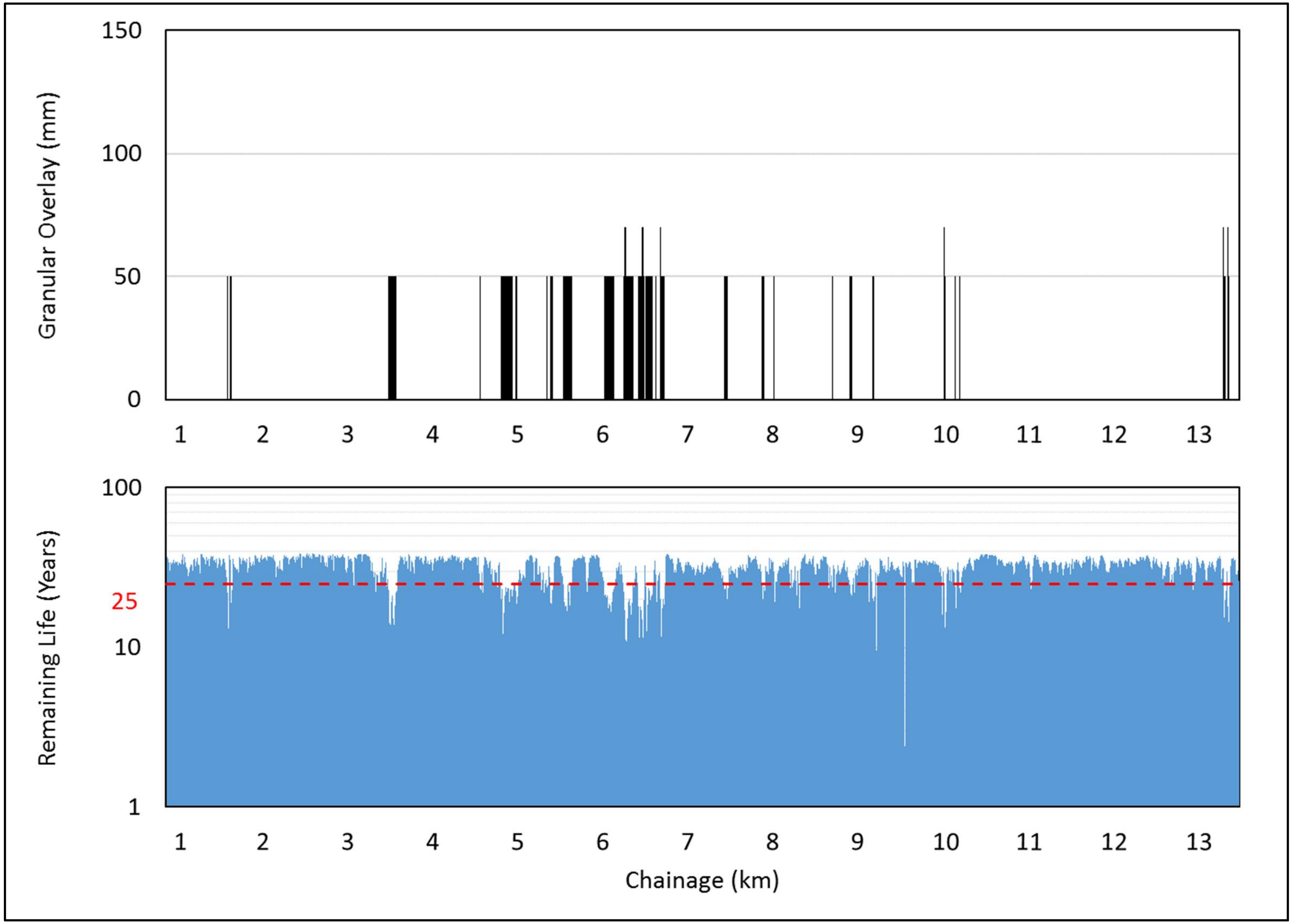




01S – 0569 L1
FWD
LUATION: 01S-0569 Lane L1 (14/08/2014)
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Governing Deterministic)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Structural (Seal Deformation)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Cemented Base Cracking
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Aggregate Instability
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
2
4
6
8
10
12
MESA: 6.132 | Layer 1 Thickness: 160 | Depth to Subgrade: 265 to 580

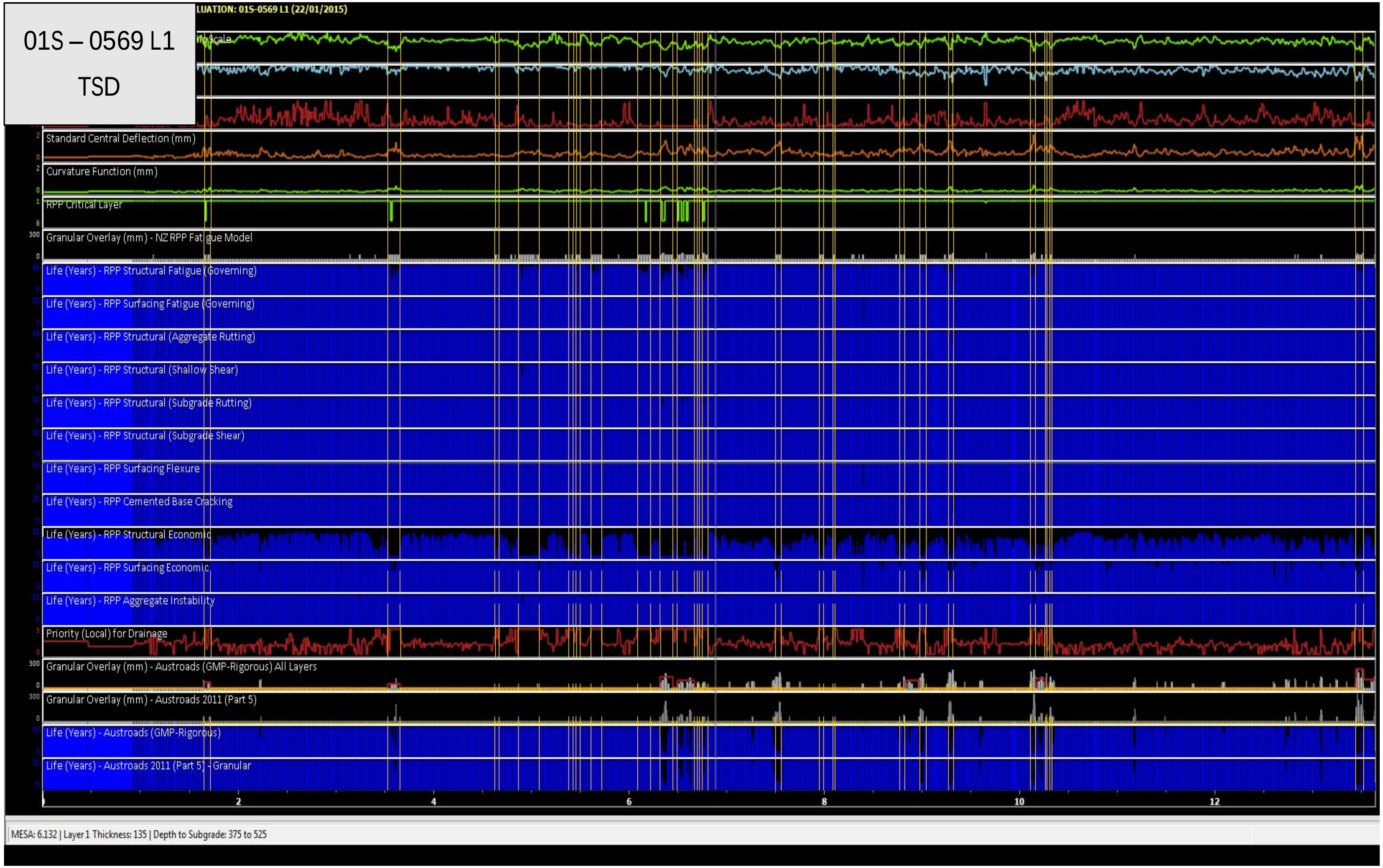
Summary Plot: 01S – 0569 L1 TSD

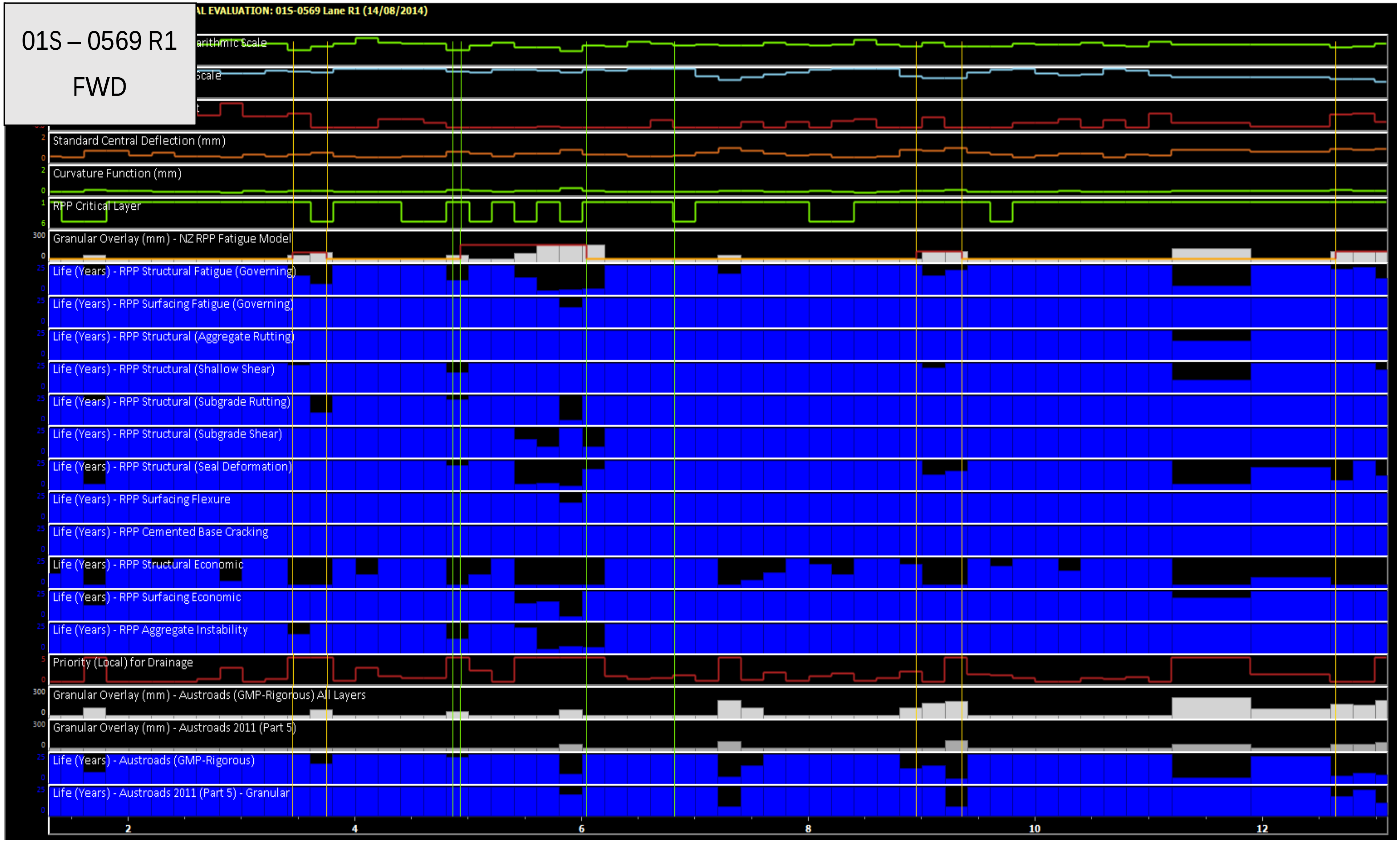
Granular Overlay and Remaining Life



01S – 0569 L1

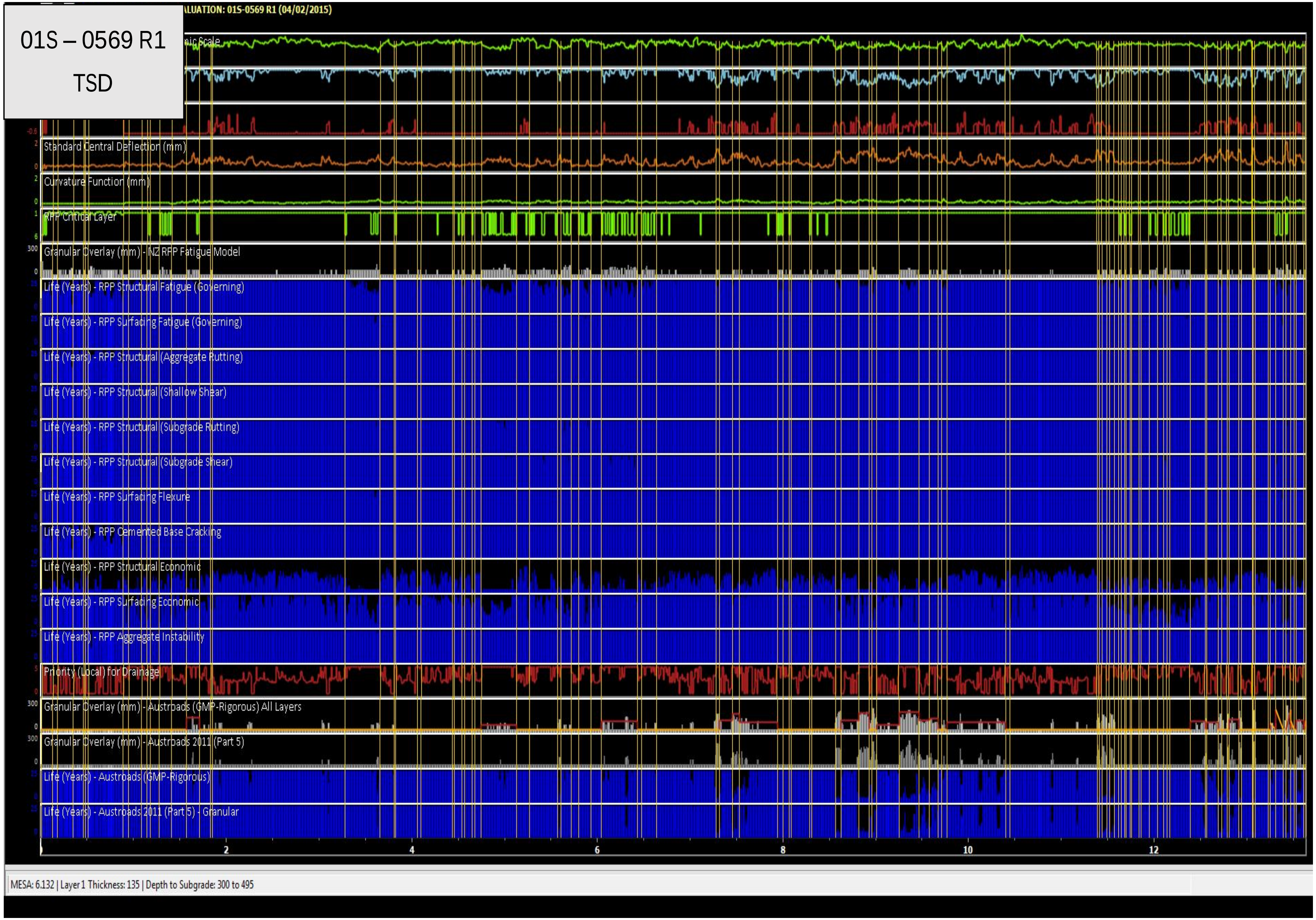
TSD




01S – 0569 R1
FWD
AL EVALUATION: 01S-0569 Lane R1 (14/08/2014)
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Structural (Seal Deformation)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Cemented Base Cracking
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Aggregate Instability
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
2
4
6
8
10
12

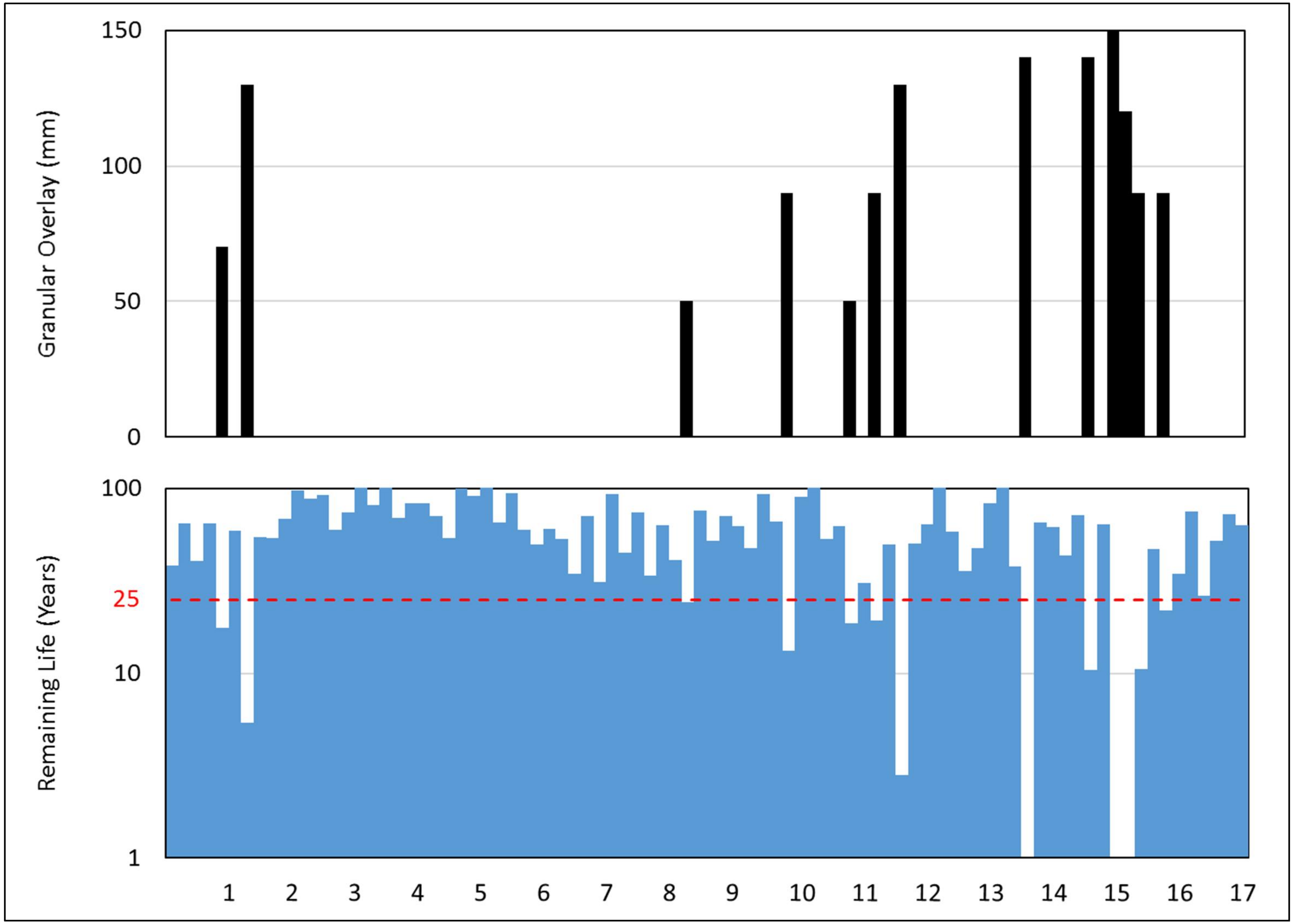
01S – 0569 R1

TSD



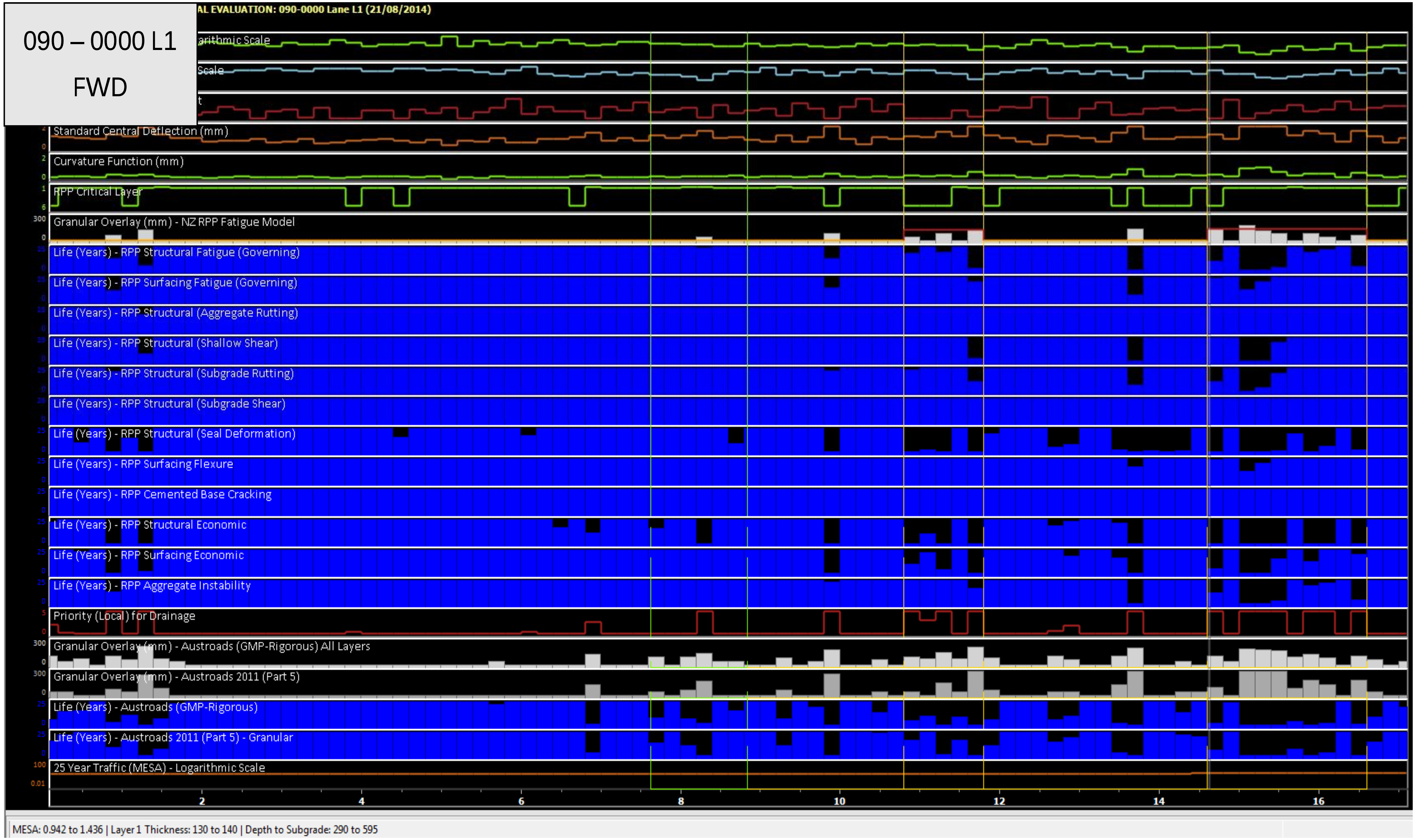
Summary Plot: 090 – 0000 L1 FWD

Granular Overlay and Remaining Life



090 – 0000 L1

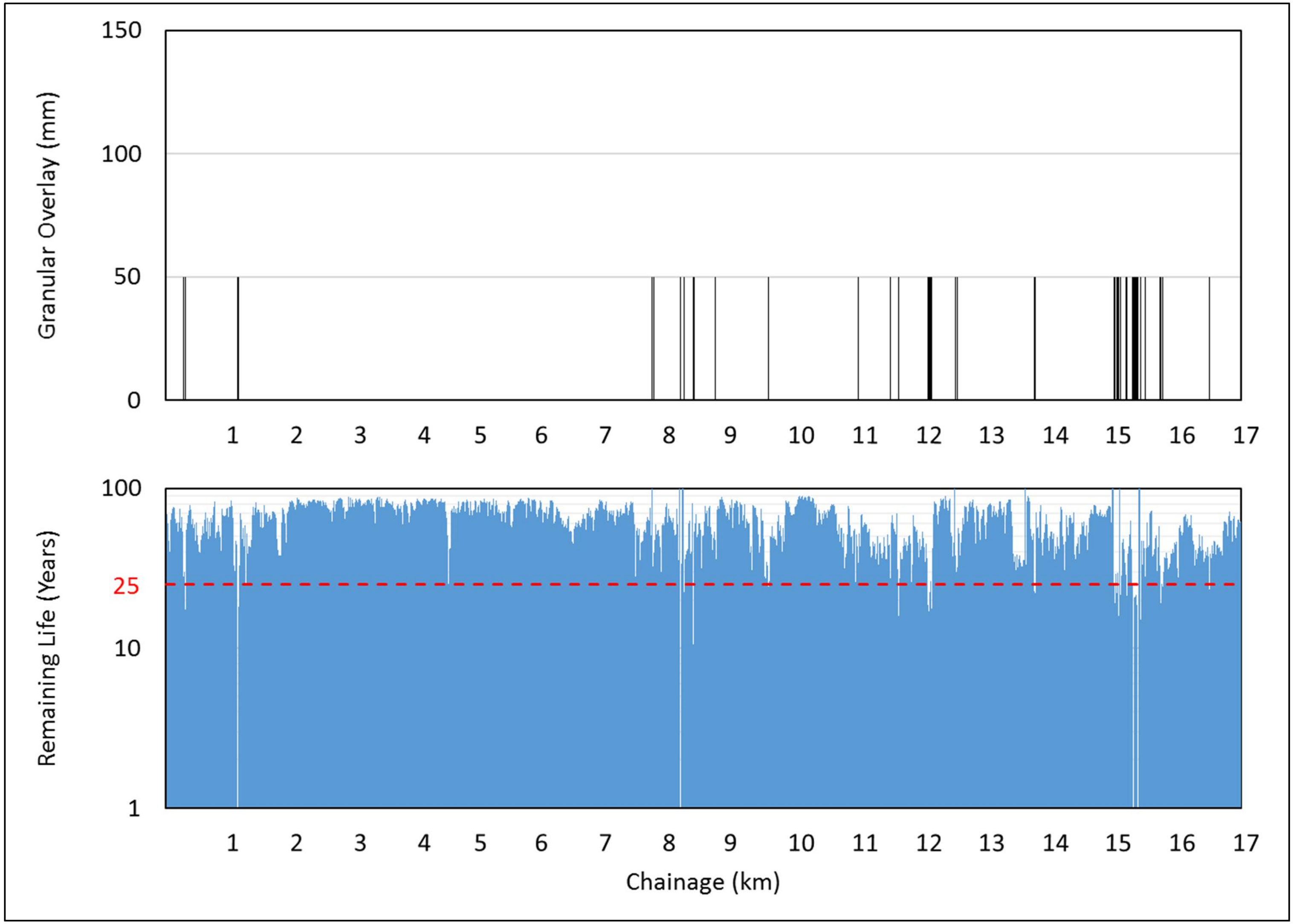
FWD

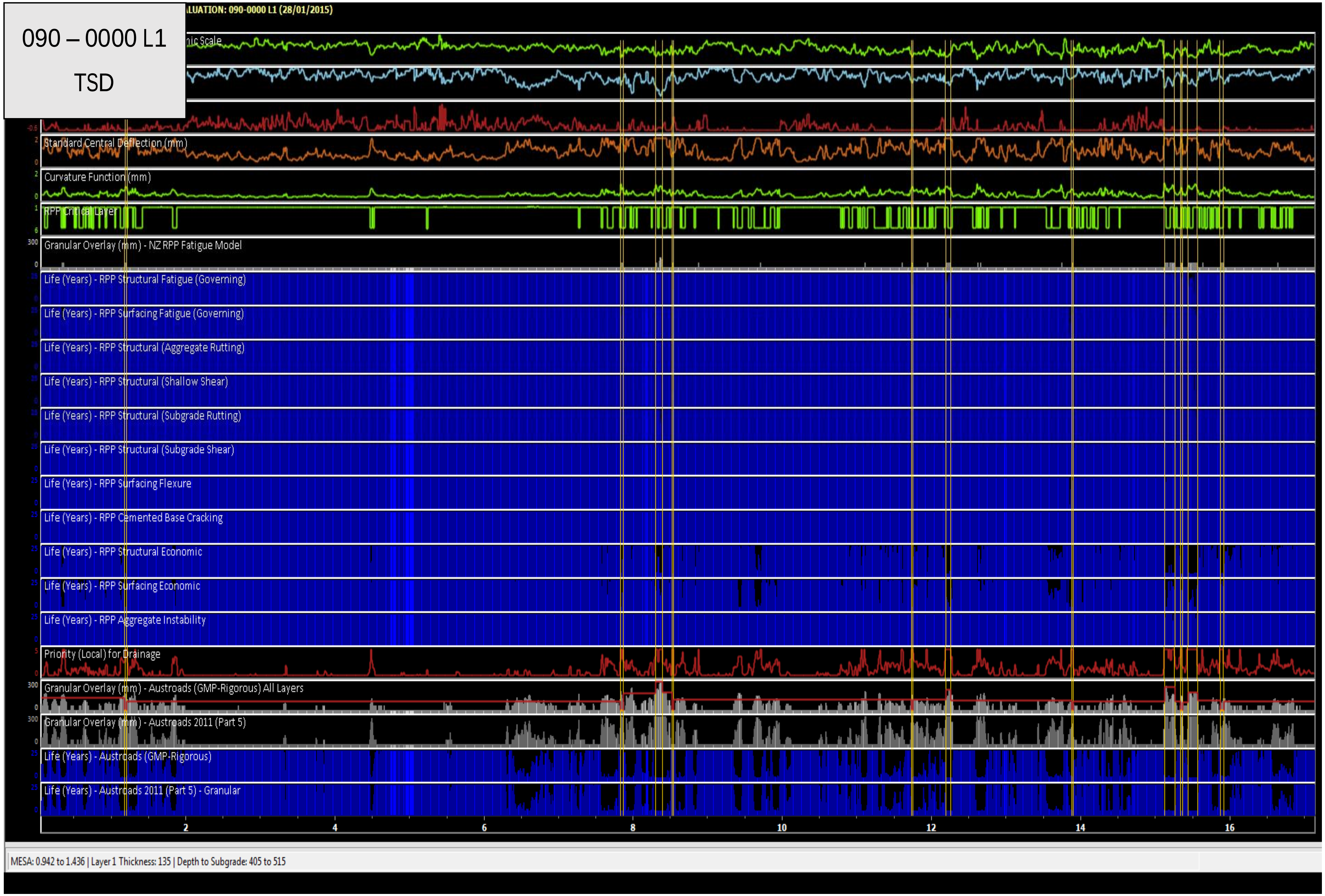


MESA: 0.942 to 1.436 | Layer 1 Thickness: 130 to 140 | Depth to Subgrade: 290 to 595

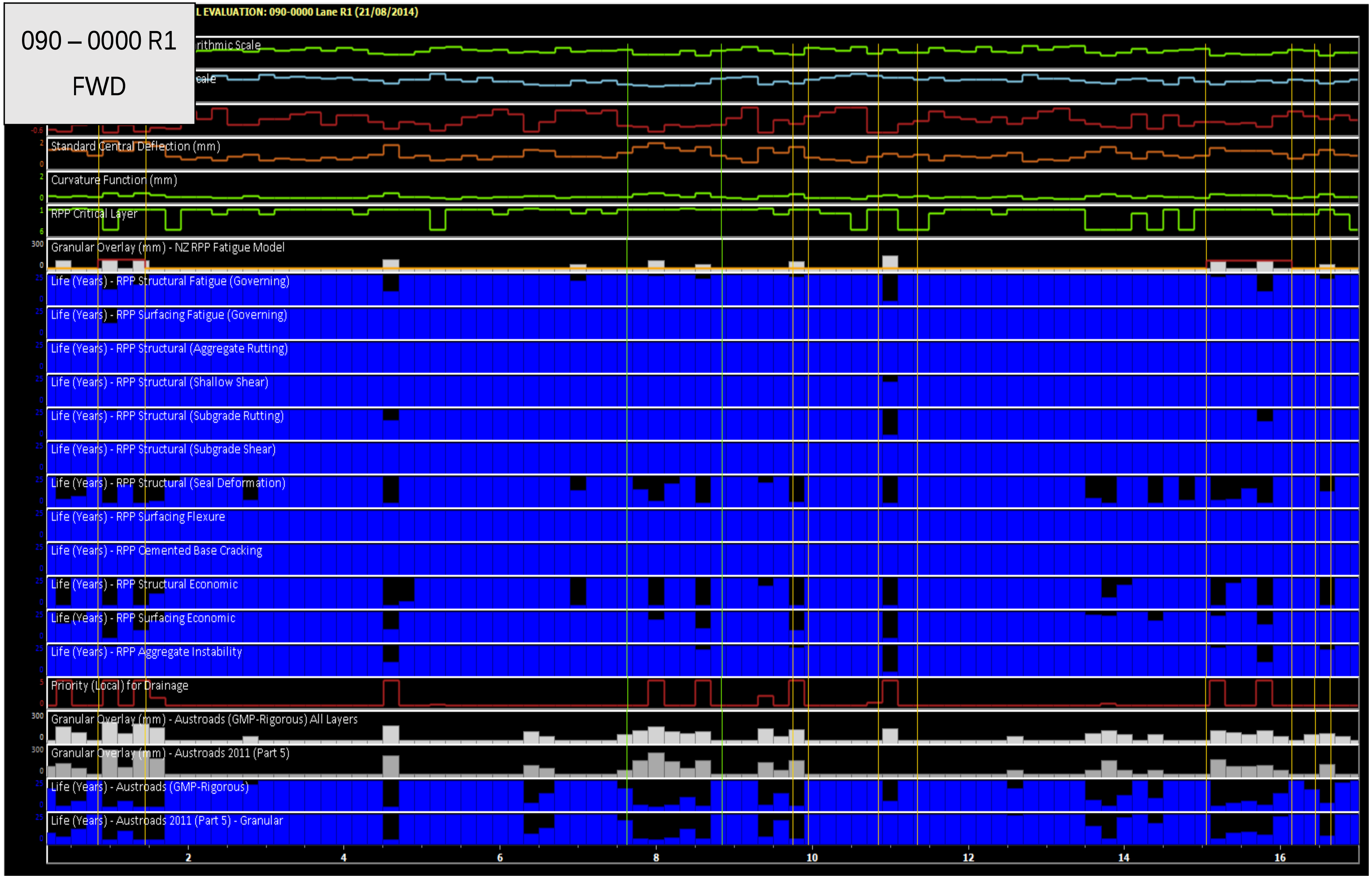
Summary Plot: 090 – 0000 L1 TSD

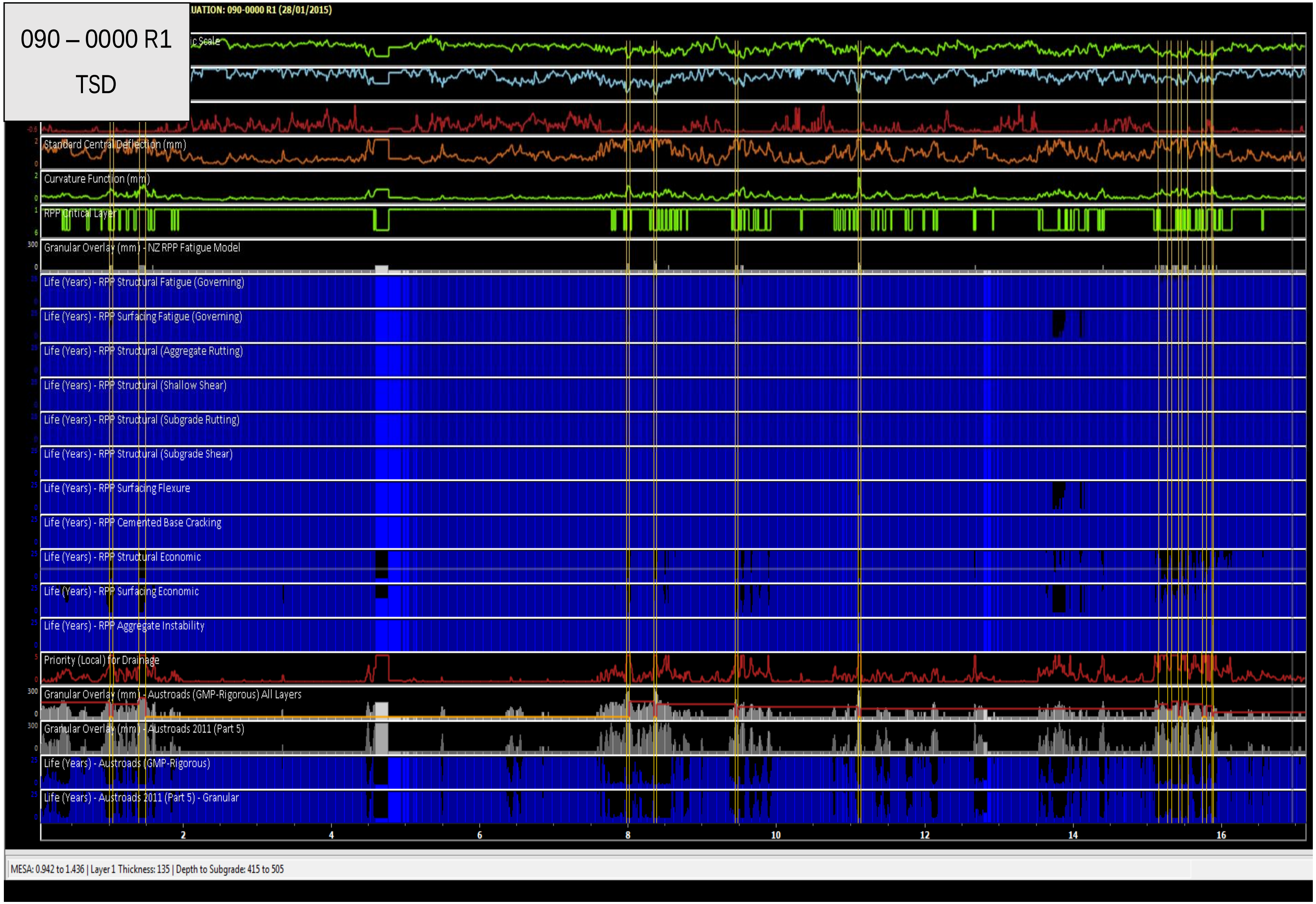
Granular Overlay and Remaining Life





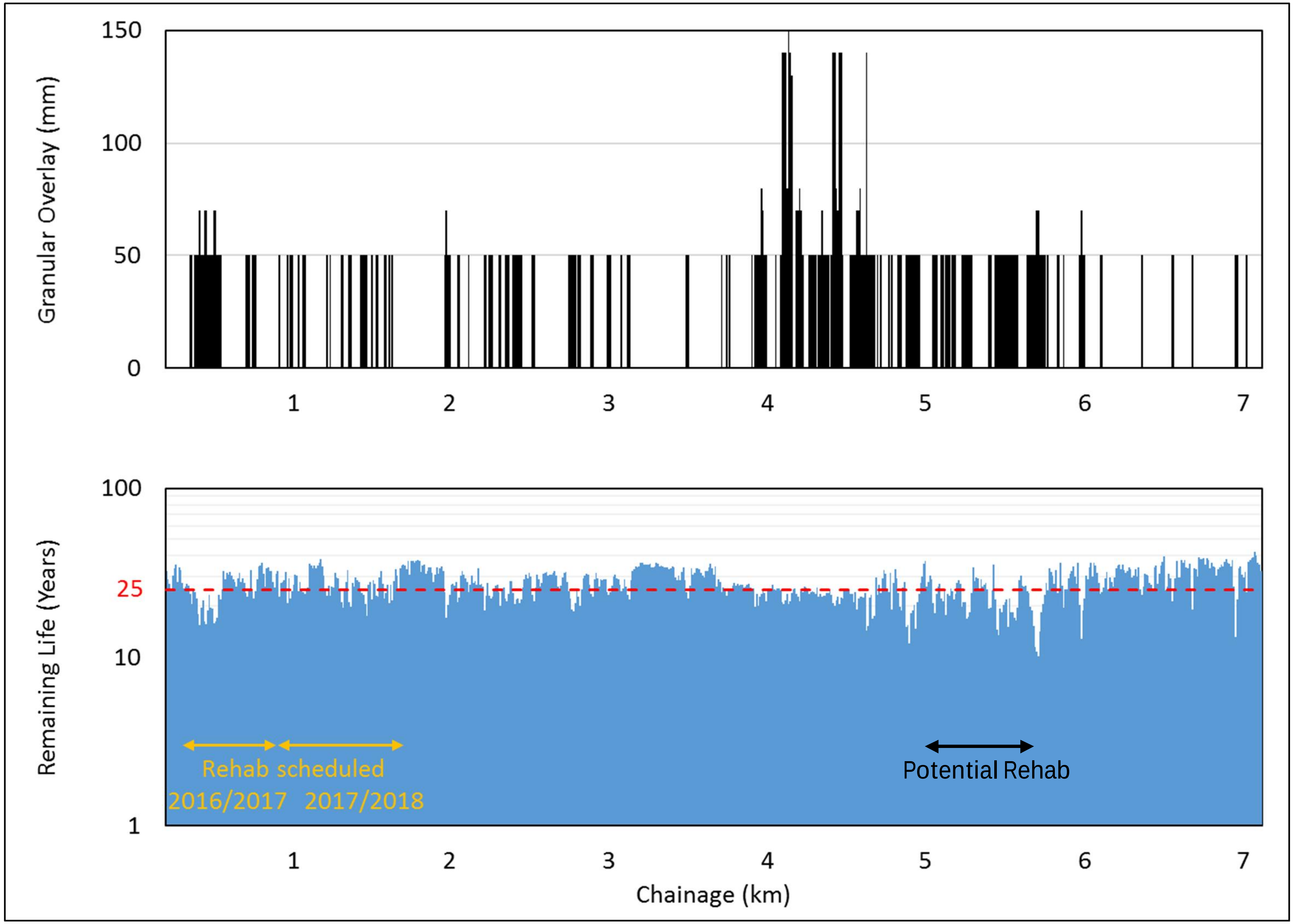
090 – 0000 L1
TSD
…LUATION: 090-0000 L1 (28/01/2015)
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Cemented Base Cracking
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Aggregate Instability
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
2
4
6
8
10
12
14
16
MESA: 0.942 to 1.436 | Layer 1 Thickness: 135 | Depth to Subgrade: 405 to 515


090 – 0000 R1
FWD
L EVALUATION: 090-0000 Lane R1 (21/08/2014)
rithmic Scale
cale
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Structural (Seal Deformation)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Cemented Base Cracking
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Aggregate Instability
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
2
4
6
8
10
12
14
16


090 – 0000 R1
TSD
UATION: 090-0000 R1 (28/01/2015)
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Cemented Base Cracking
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Aggregate Instability
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
2
4
6
8
10
12
14
16
MESA: 0.942 to 1.436 | Layer 1 Thickness: 135 | Depth to Subgrade: 415 to 505

Summary Plot: 01S – 0583 L1 TSD

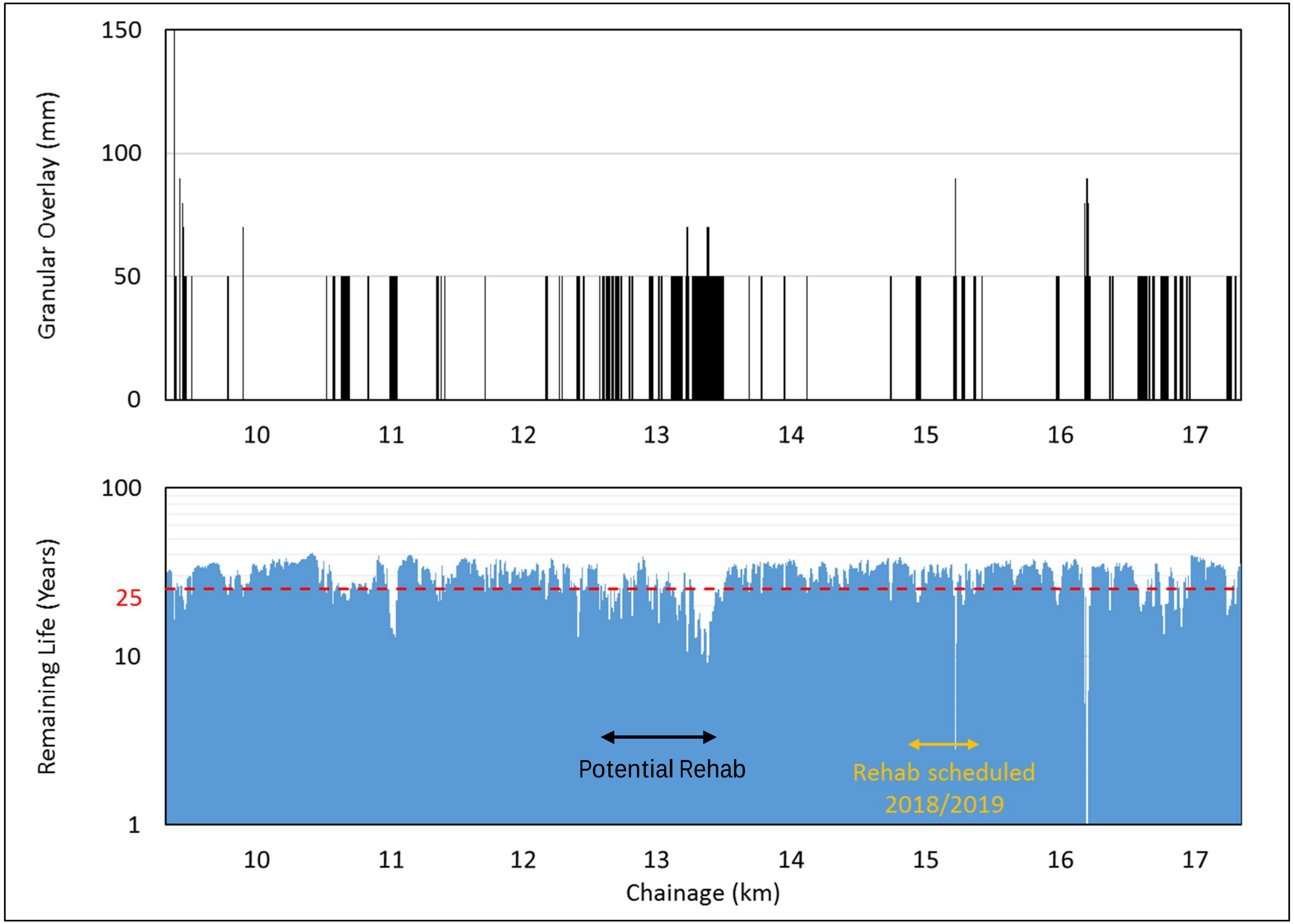
Granular Overlay and Remaining Life



Visually, the above TSD identified site is comparable to programmed sites.

Summary Plot: 01S – 0583 08.36 L1 TSD

Granular Overlay and Remaining Life



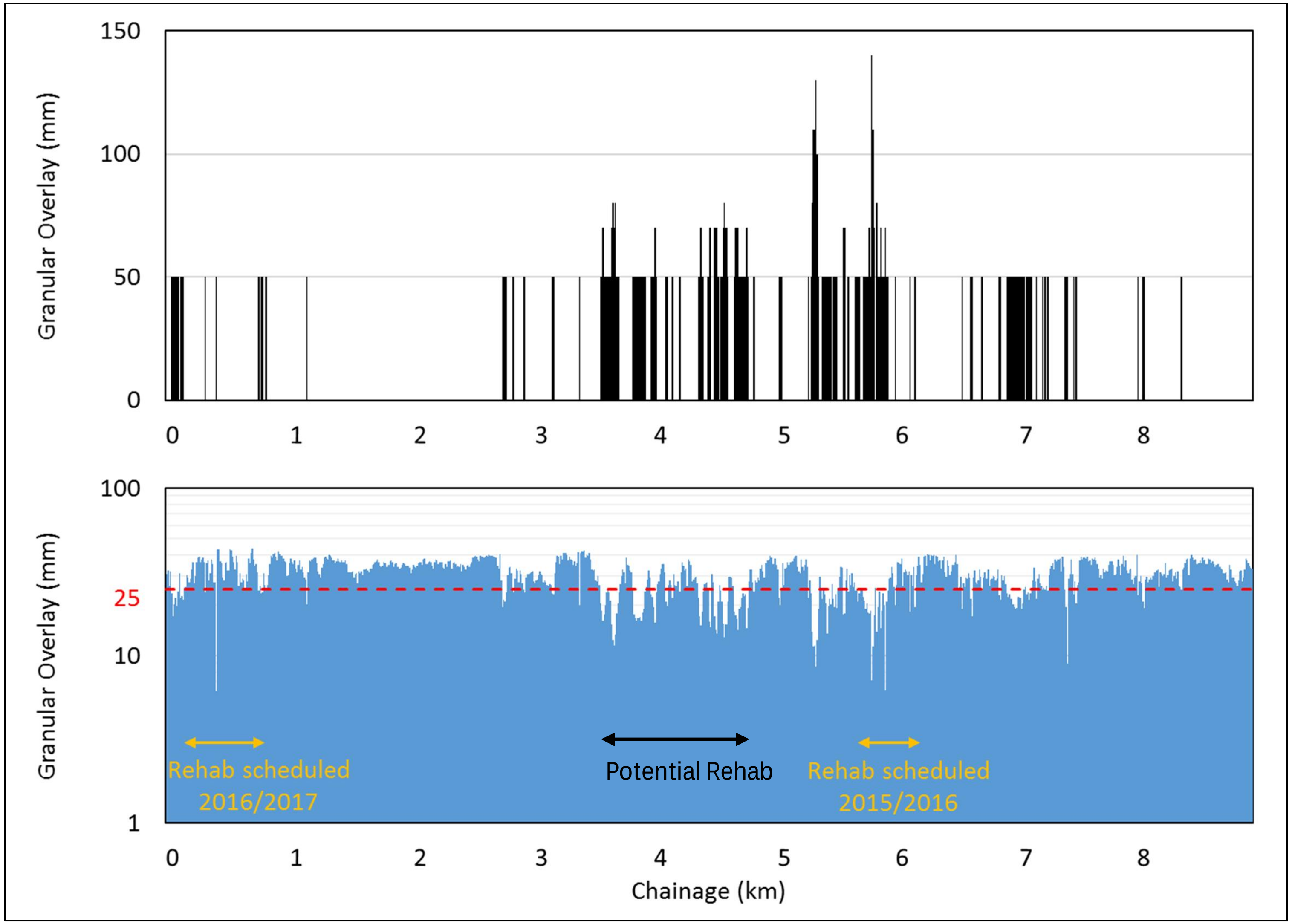
01S – 0583 08.36 L1
CH 13027

01S – 0583 08.36 L1
CH 15224

TSD identified site above, is structurally inferior to the programmed site. Unless other factors are involved, prioritisation may need to be re-considered.

Summary Plot: 01S – 0651 L1 TSD

Granular Overlay and Remaining Life



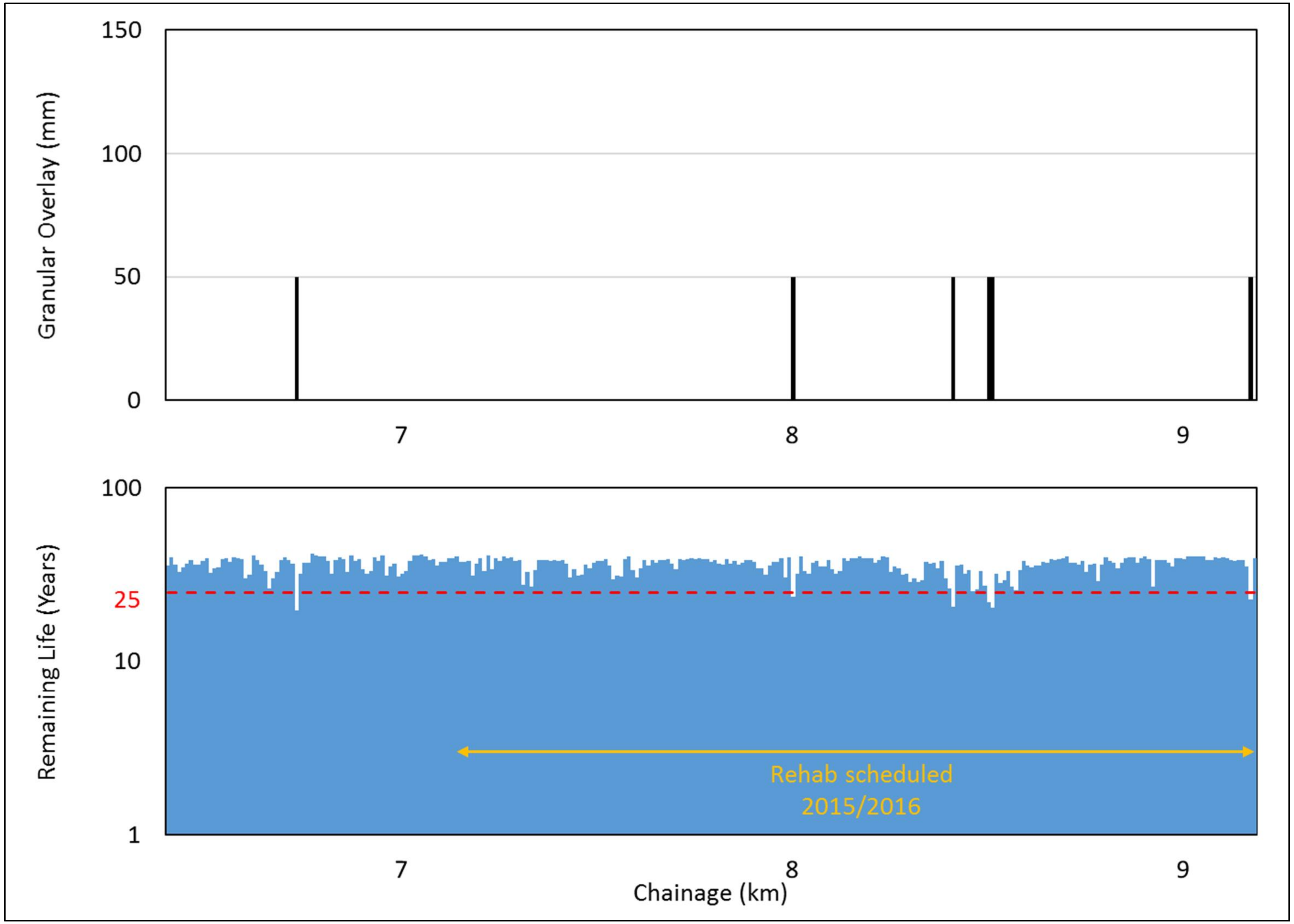

01S – 0651 L1
CH 413


01S – 0651 L1
CH 3523


01S – 0651 L1
CH 5817

Summary Plot: 01S – 0683 L1 TSD

Granular Overlay and Remaining Life



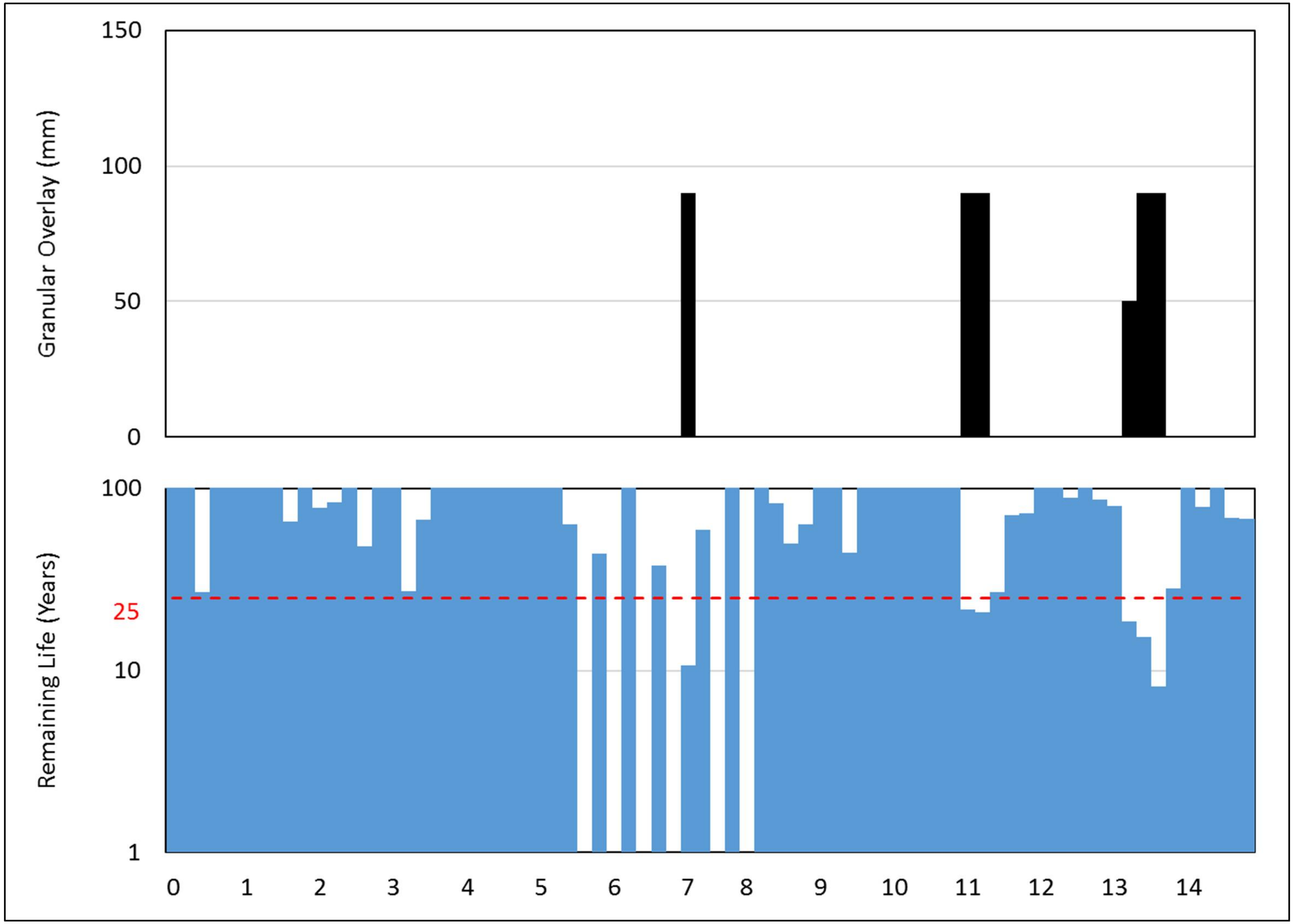
01S – 0683 L1
CH 8431

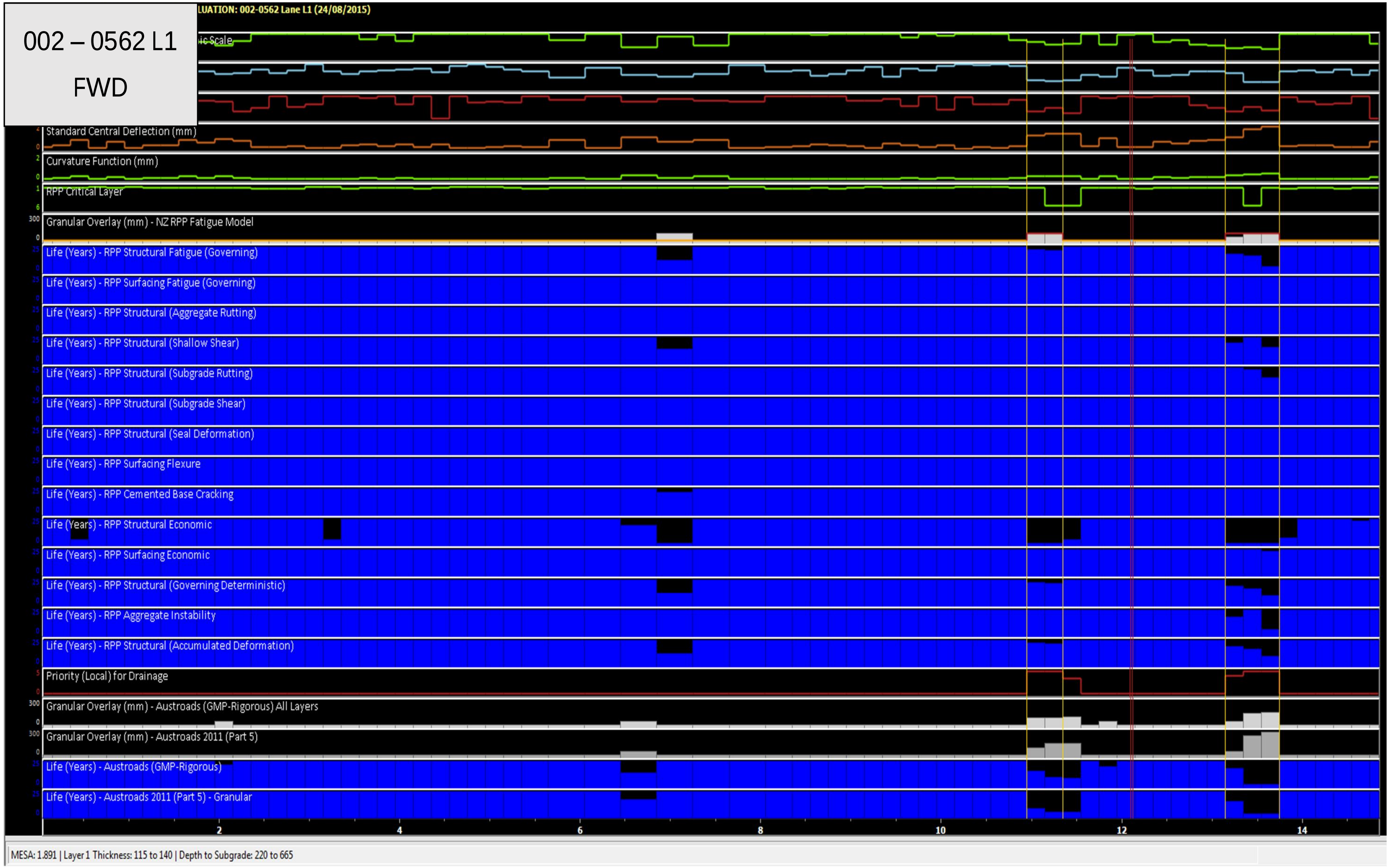
Appendix F

Hawke's Bay 50 km Pilot Sections
SH2 RS483 & SH2 RS562 – Both Lanes

Summary Plot: 002 – 0562 L1 FWD

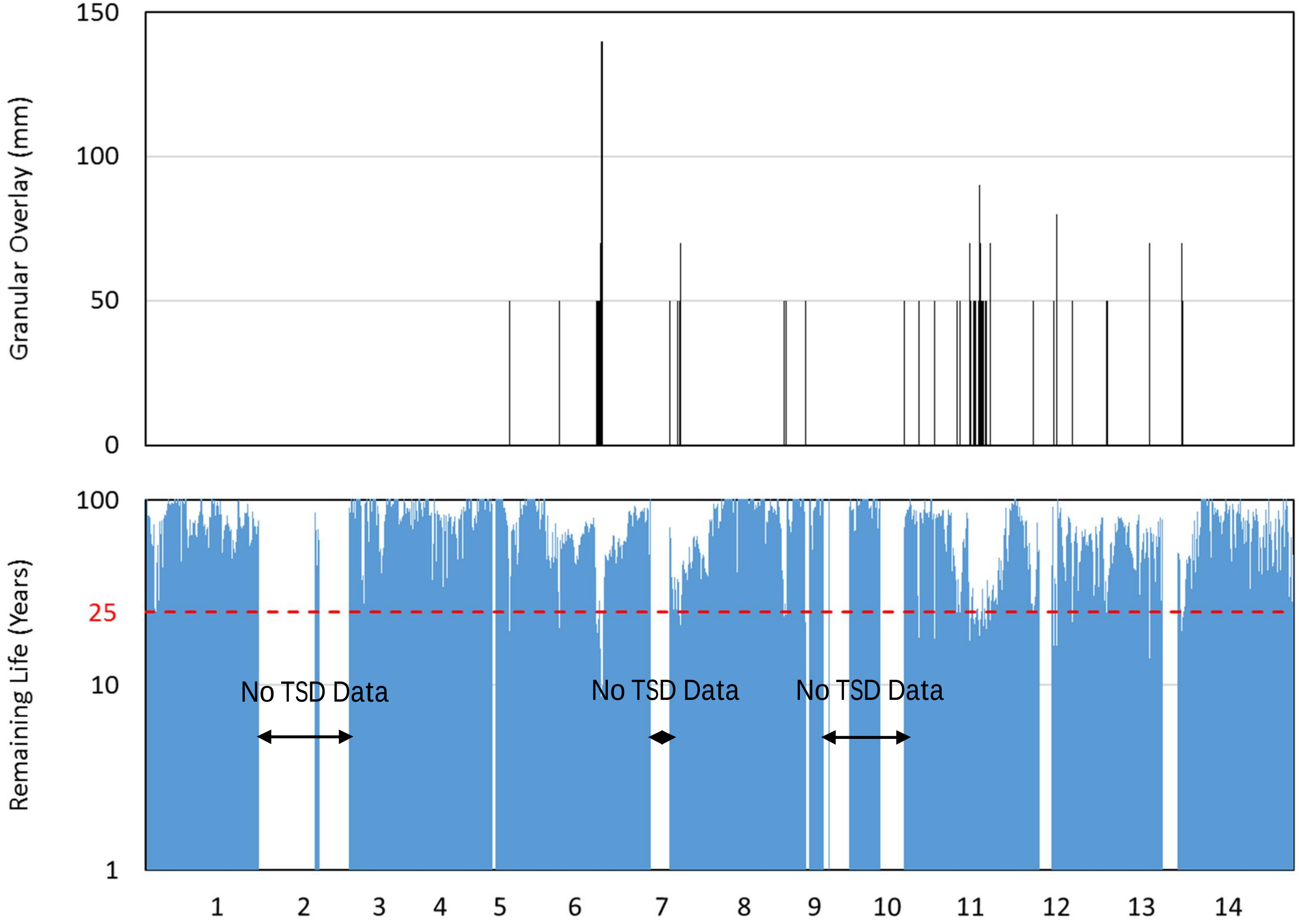
Granular Overlay and Remaining Life

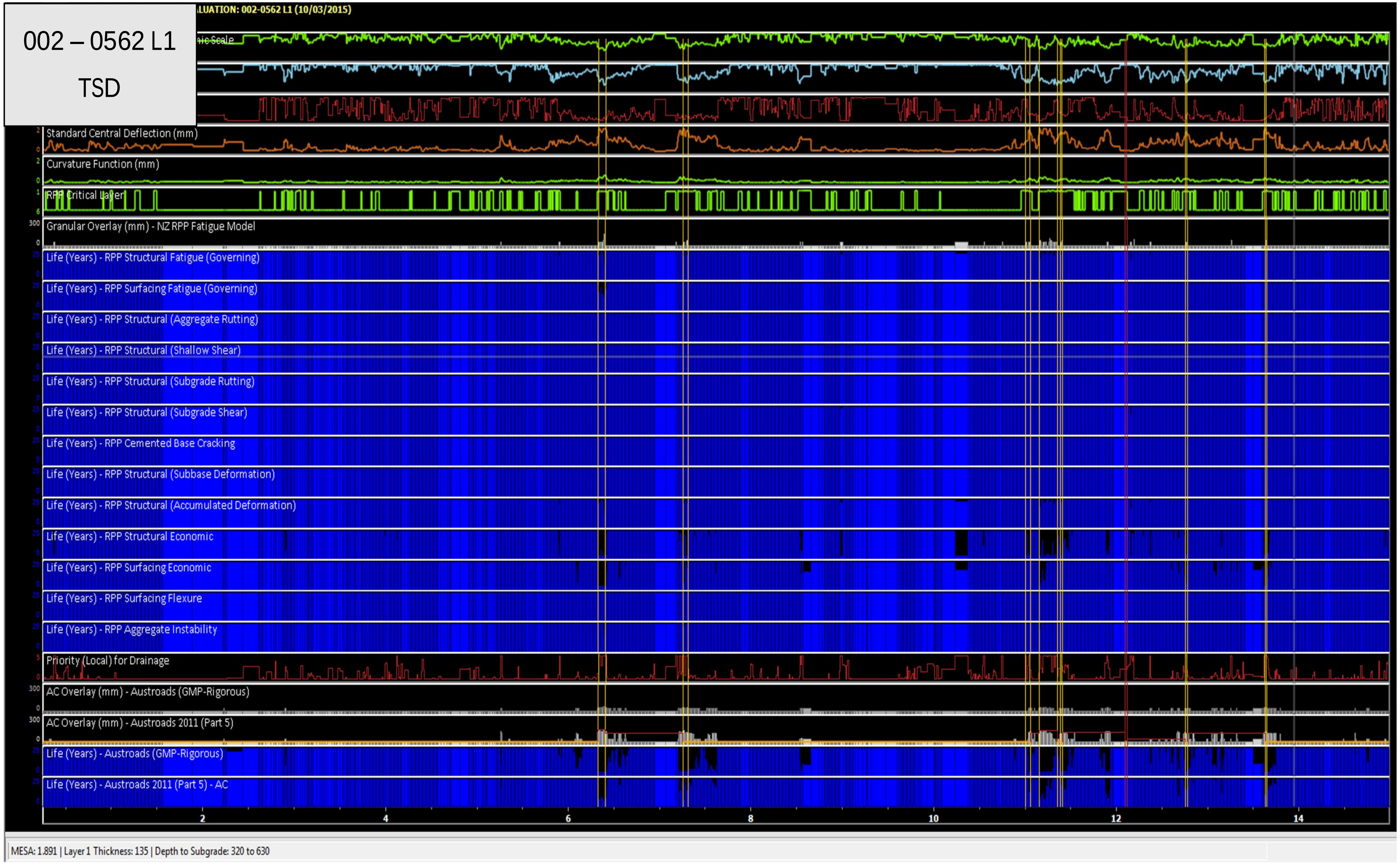



002 – 0562 L1
FWD
LUATION: 002-0562 Lane L1 (24/08/2015)
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Structural (Seal Deformation)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Cemented Base Cracking
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Structural (Governing Deterministic)
Life (Years) - RPP Aggregate Instability
Life (Years) - RPP Structural (Accumulated Deformation)
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
2
4
6
8
10
12
14
MESA: 1.891 | Layer 1 Thickness: 115 to 140 | Depth to Subgrade: 220 to 665

Summary Plot: 002 – 0562 L1 TSD

Granular Overlay and Remaining Life

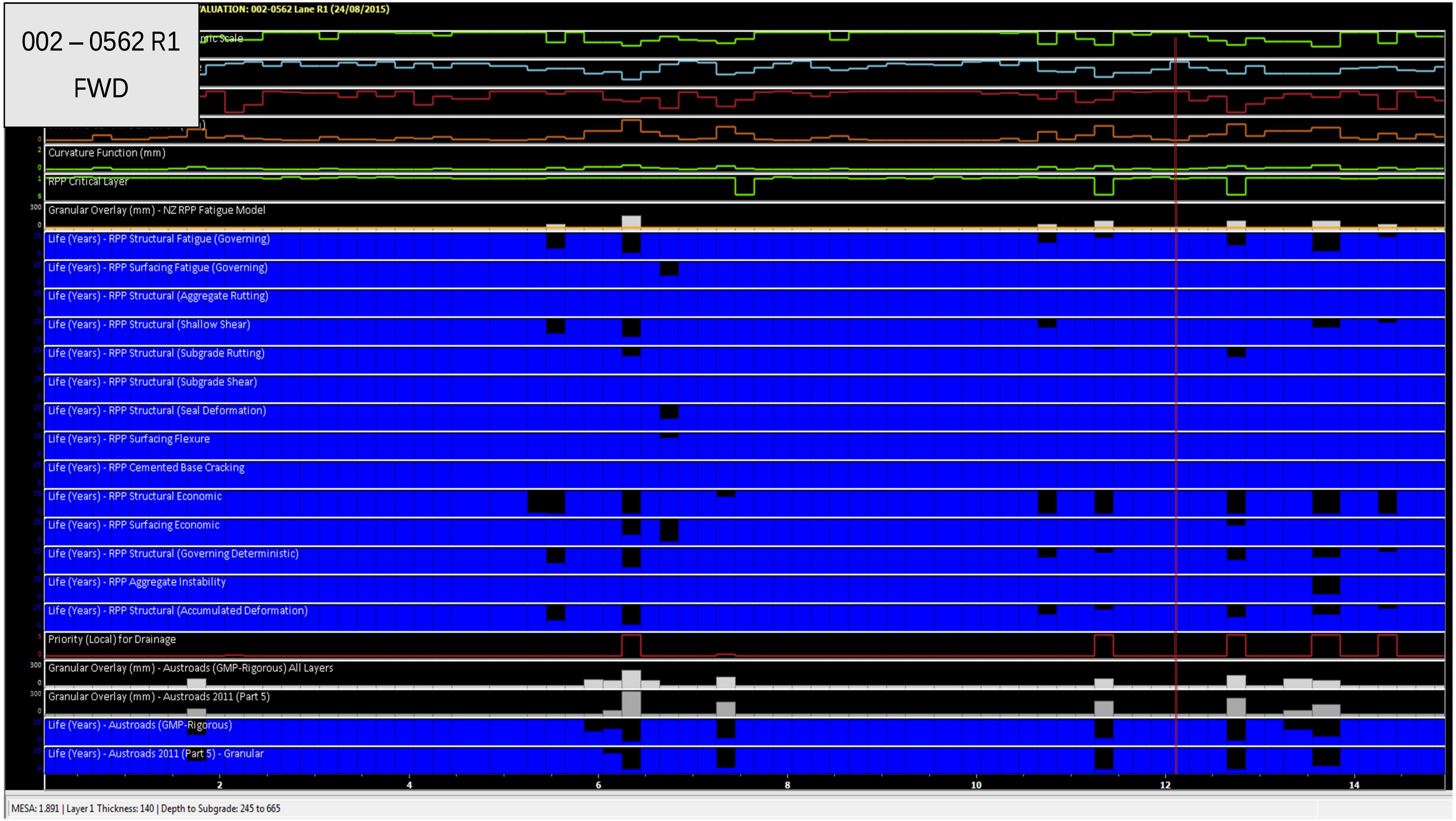


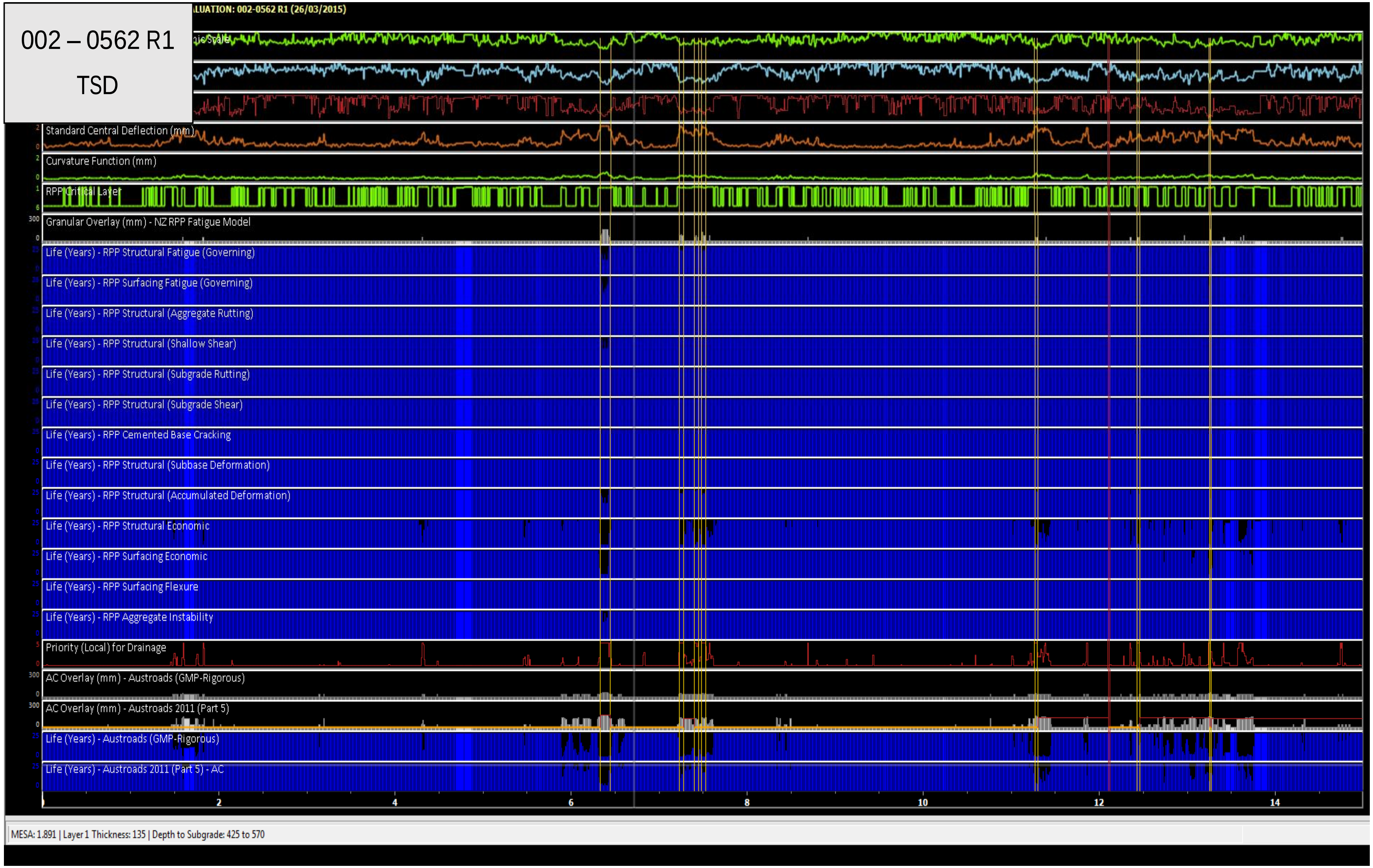


Good consistency between FWD and TSD

002 – 0562 R1

FWD

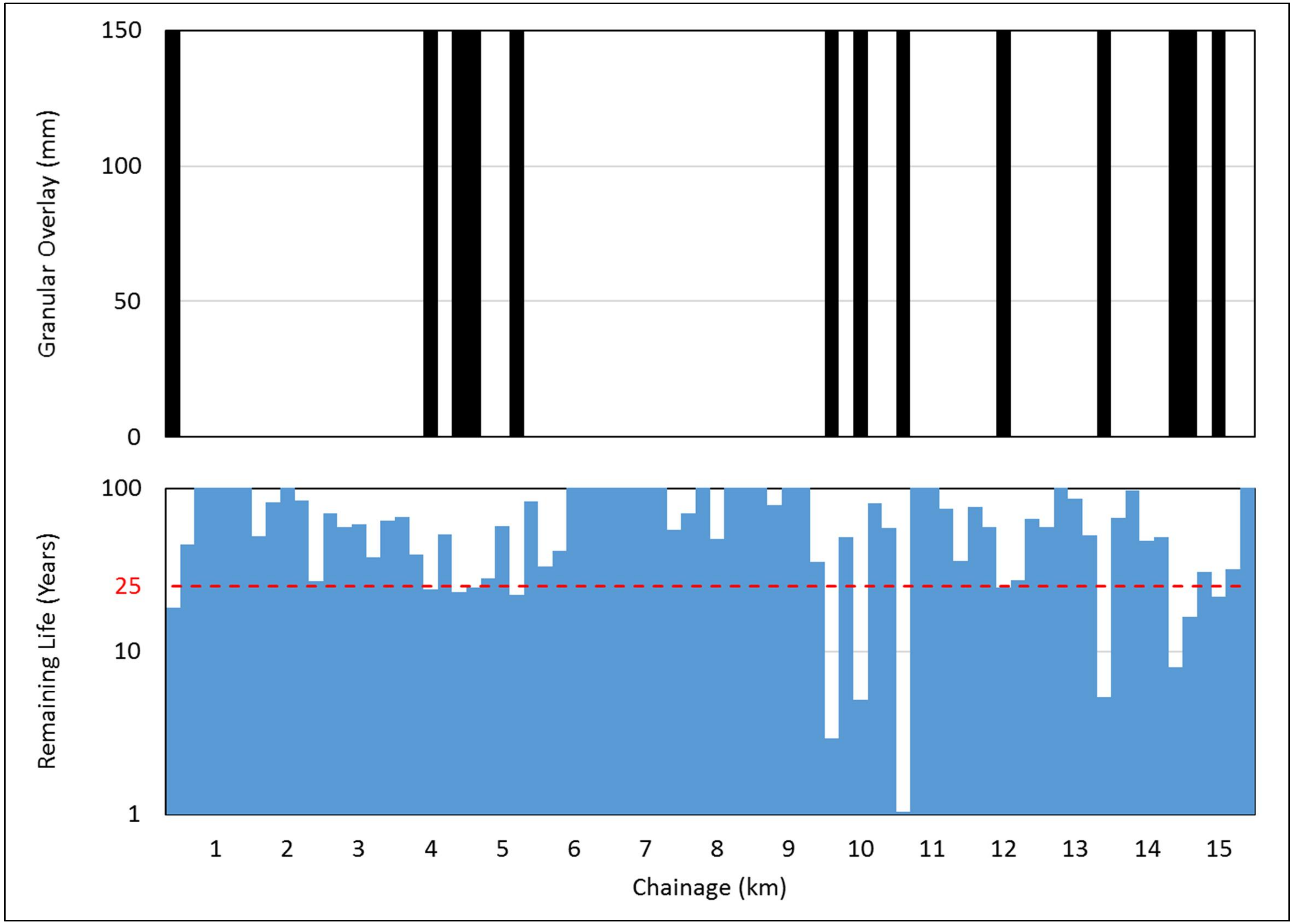


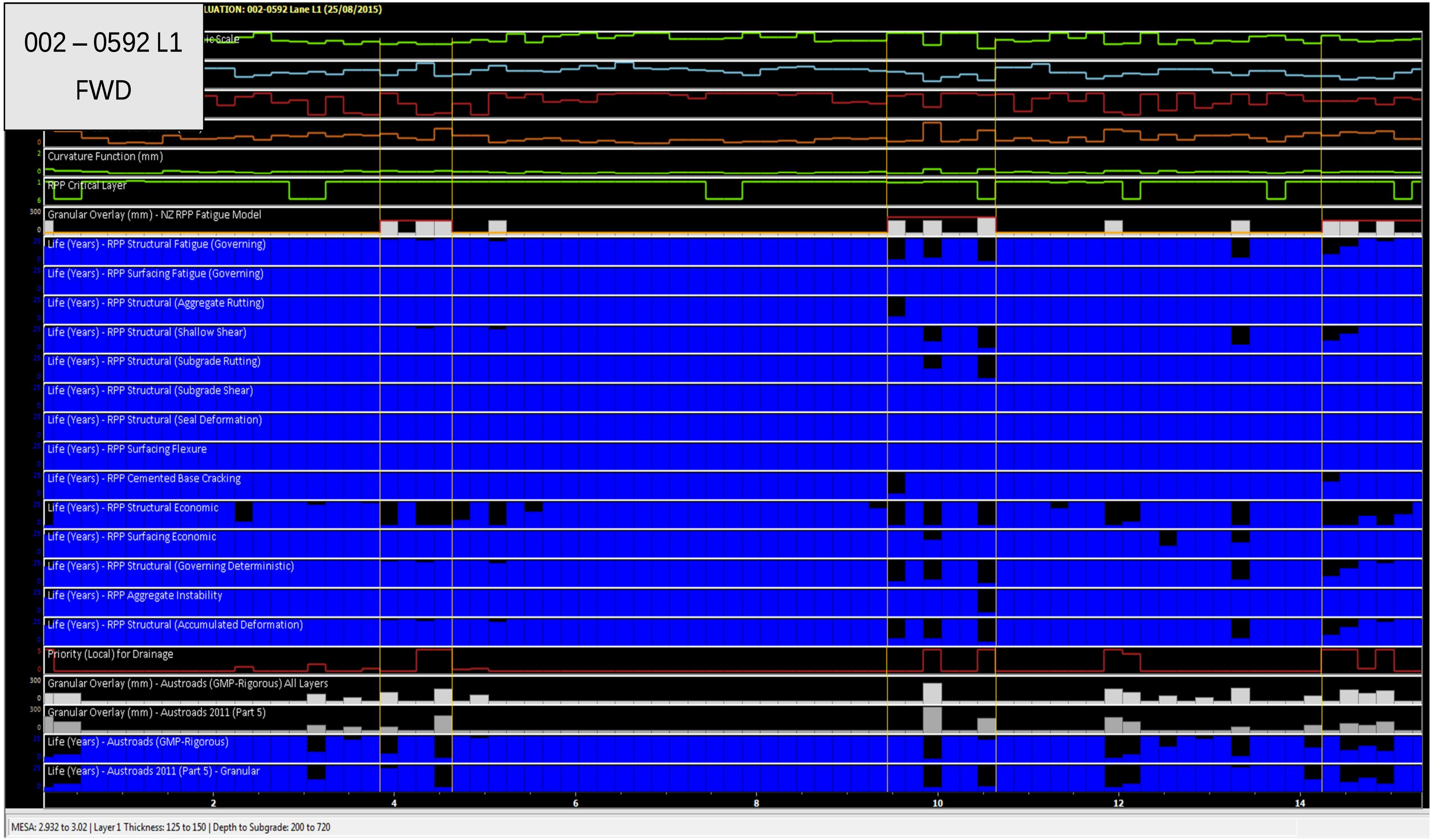


Good consistency between FWD and TSD

Summary Plot: 002 – 0592 L1 FWD

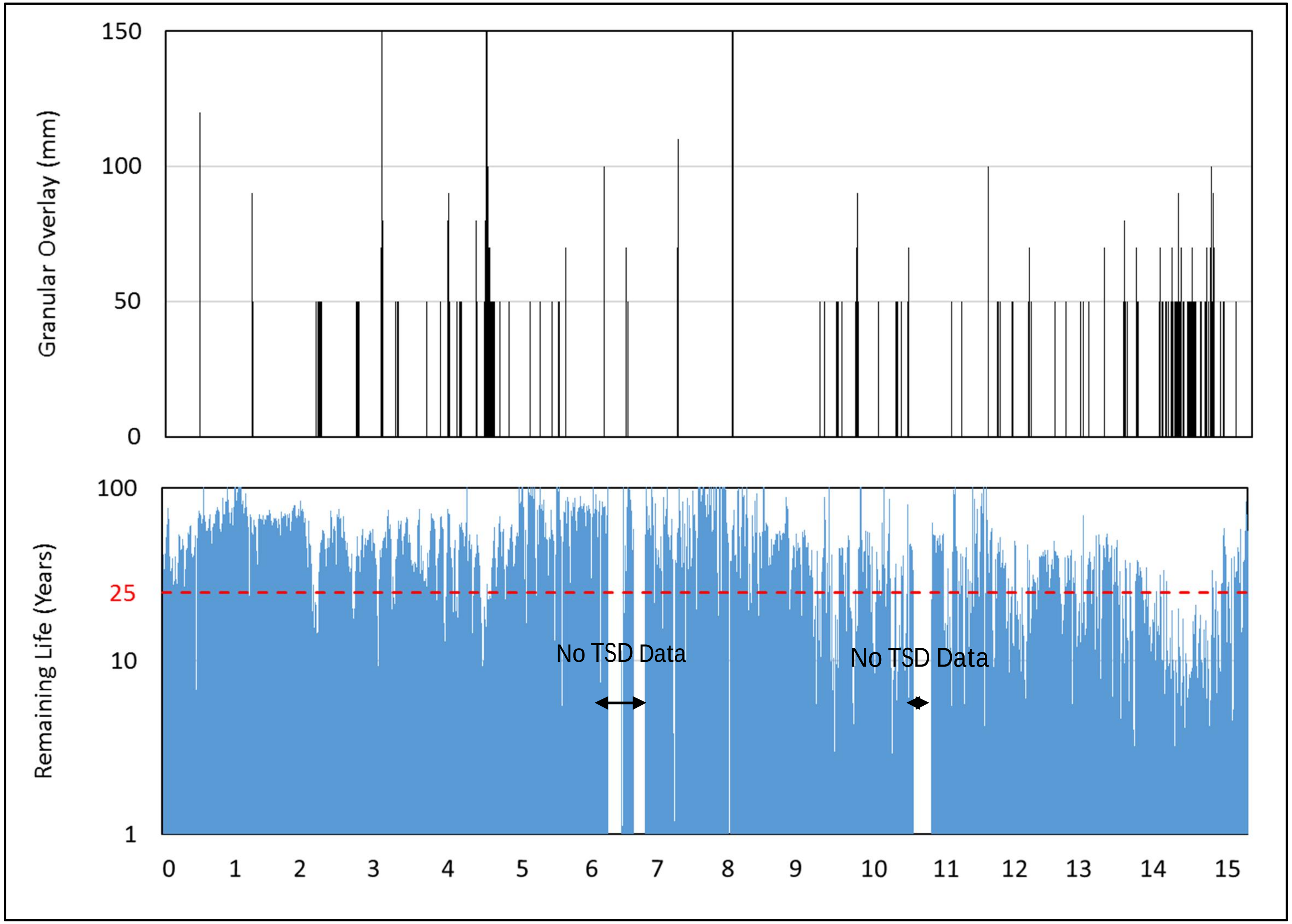
Granular Overlay and Remaining Life

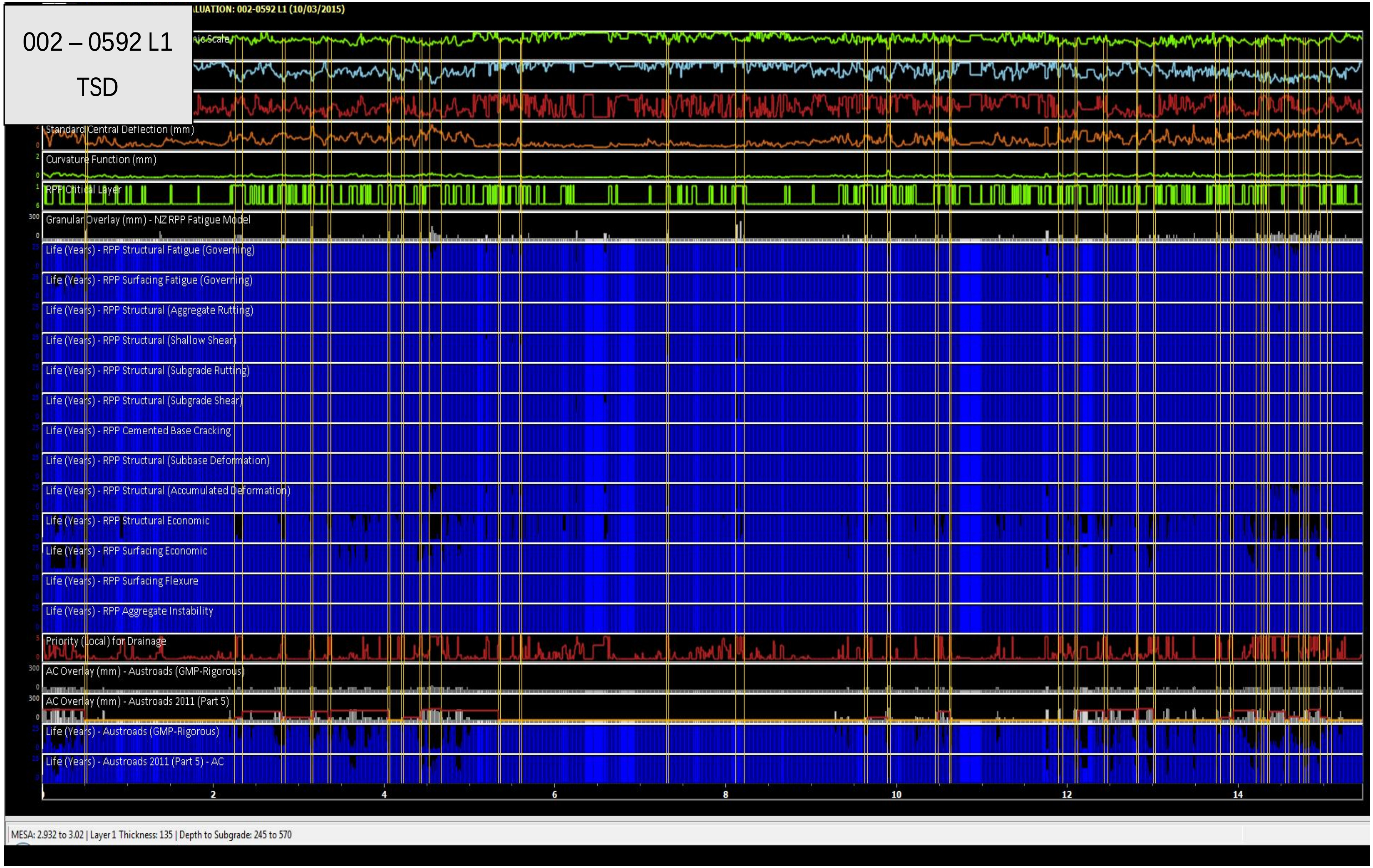



002 – 0592 L1
FWD
LUATION: 002-0592 Lane L1 (25/08/2015)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Structural (Seal Deformation)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Cemented Base Cracking
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Structural (Governing Deterministic)
Life (Years) - RPP Aggregate Instability
Life (Years) - RPP Structural (Accumulated Deformation)
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
2
4
6
8
10
12
14
MESA: 2.932 to 3.02 | Layer 1 Thickness: 125 to 150 | Depth to Subgrade: 200 to 720

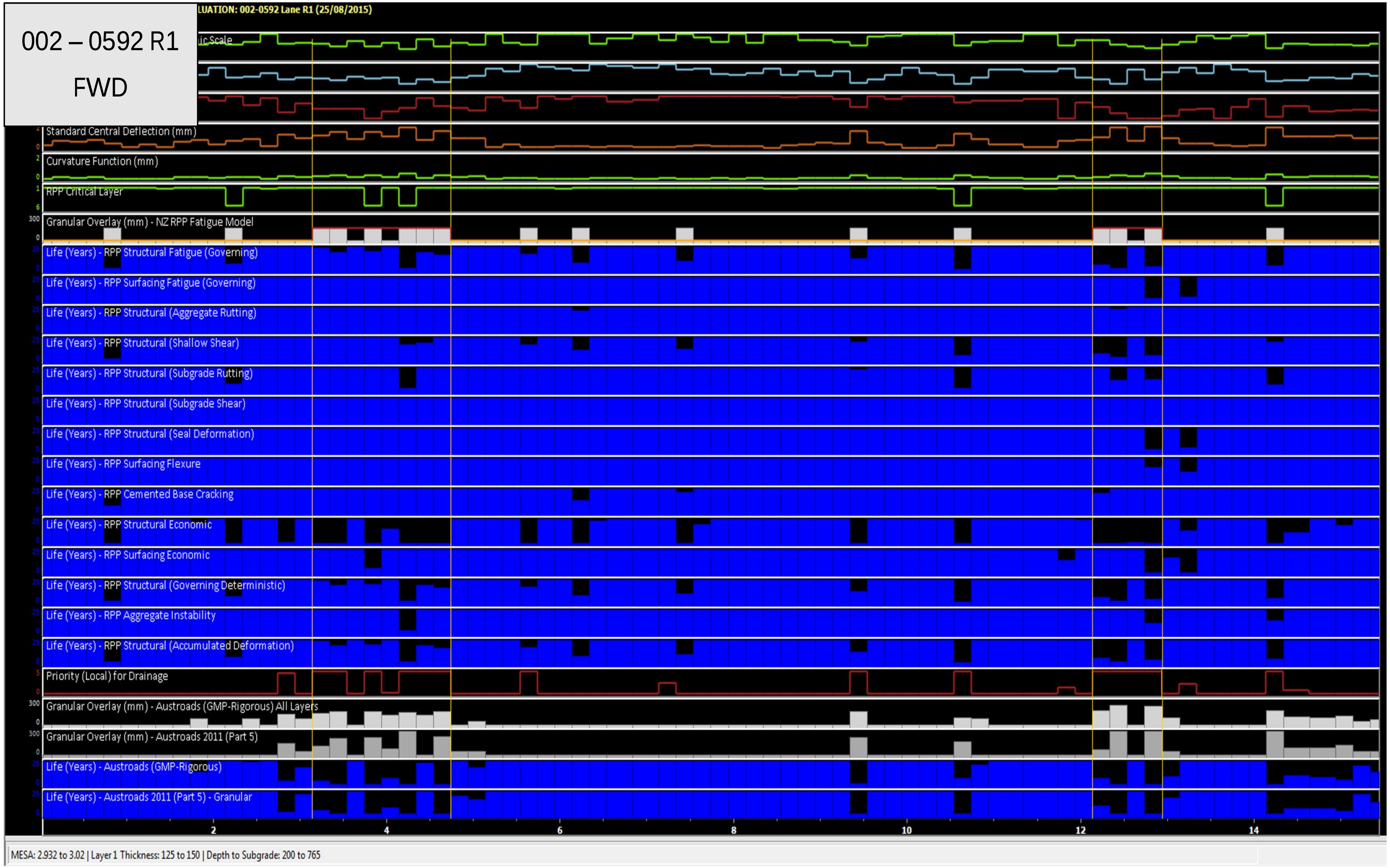
Summary Plot: 002 – 0592 L1 TSD

Granular Overlay and Remaining Life

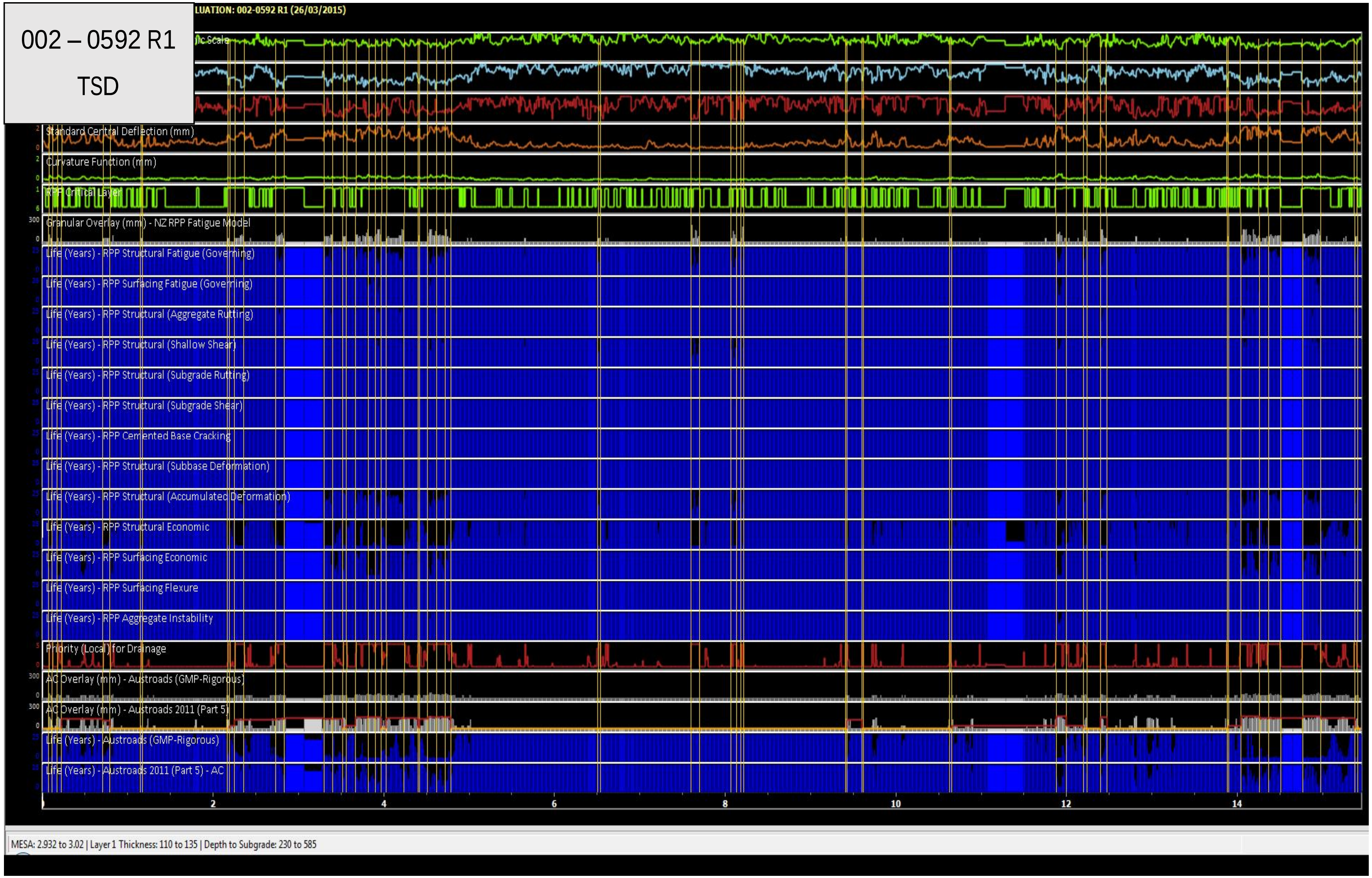




Good consistency between FWD and TSD



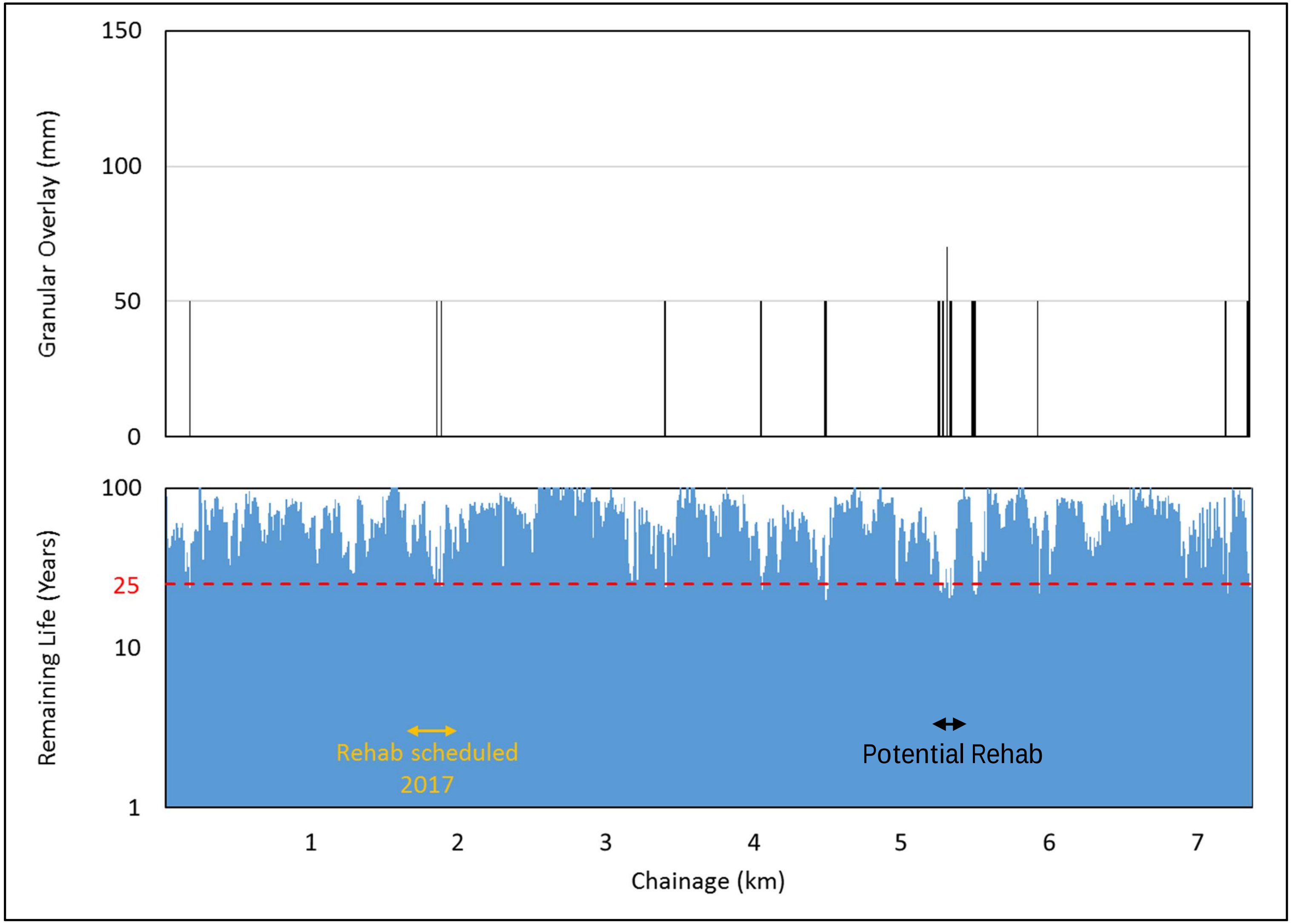
002 – 0592 R1
FWD
LUATION: 002-0592 Lane R1 (25/08/2015)
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Structural (Seal Deformation)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Cemented Base Cracking
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Structural (Governing Deterministic)
Life (Years) - RPP Aggregate Instability
Life (Years) - RPP Structural (Accumulated Deformation)
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
2
4
6
8
10
12
14
MESA: 2.932 to 3.02 | Layer 1 Thickness: 125 to 150 | Depth to Subgrade: 200 to 765



Good consistency between FWD and TSD

Summary Plot: 002 – 0544 L1 TSD

Granular Overlay and Remaining Life



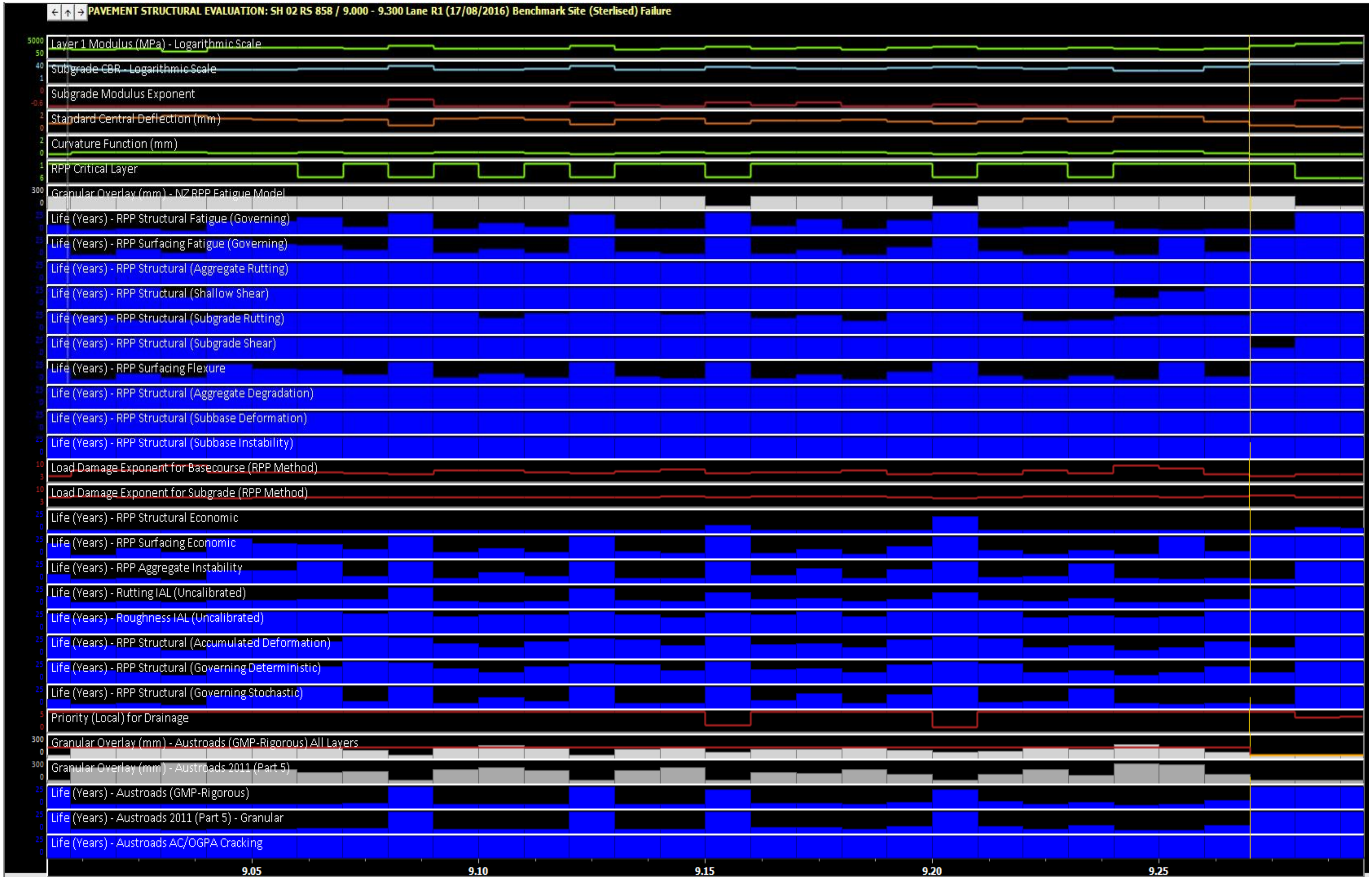
002 – 0544 L1
CH 1793

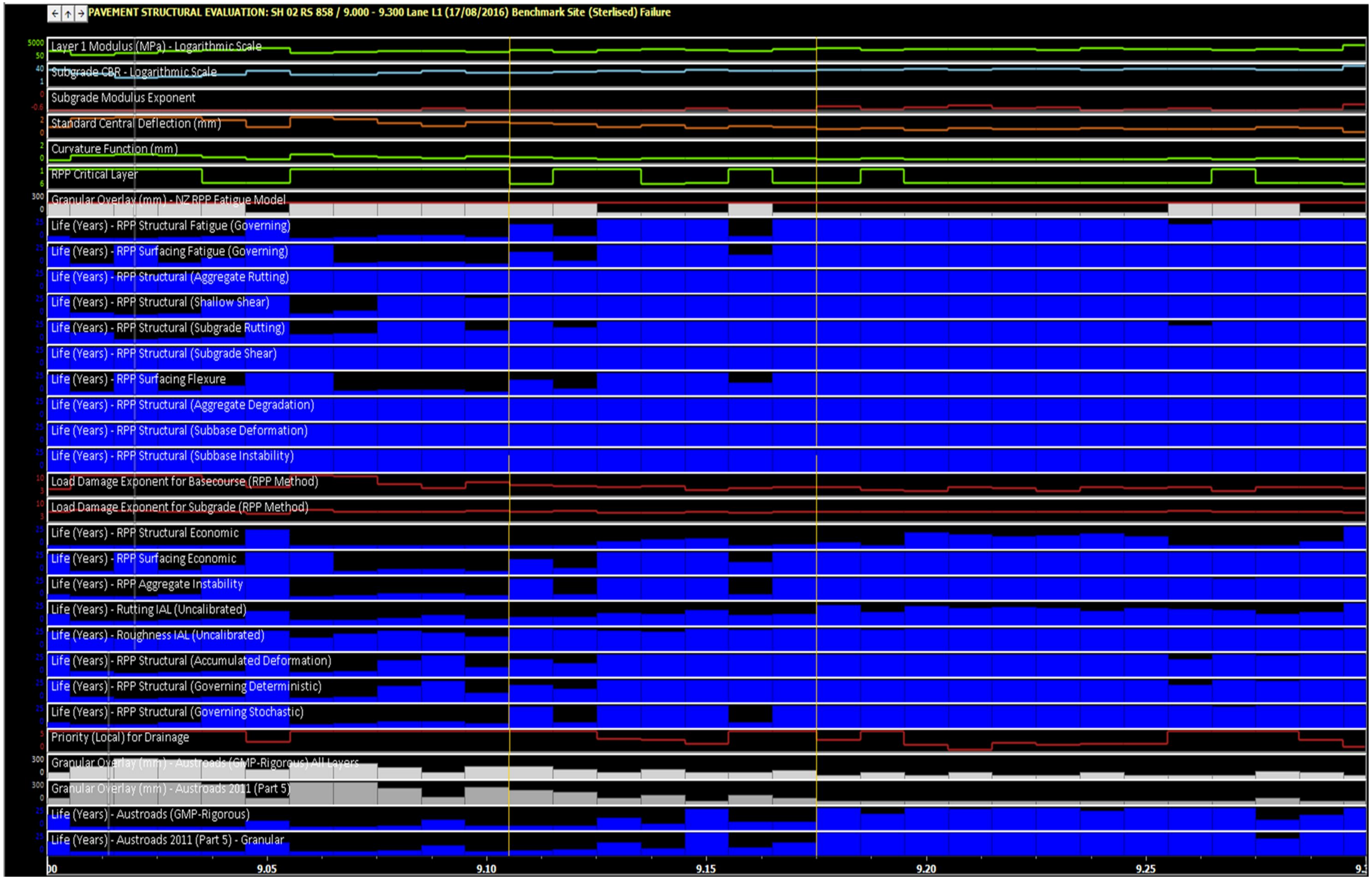
002 – 0544 L1
CH 5355

Visually, the above TSD identified site is comparable to programmed site.

Appendix G

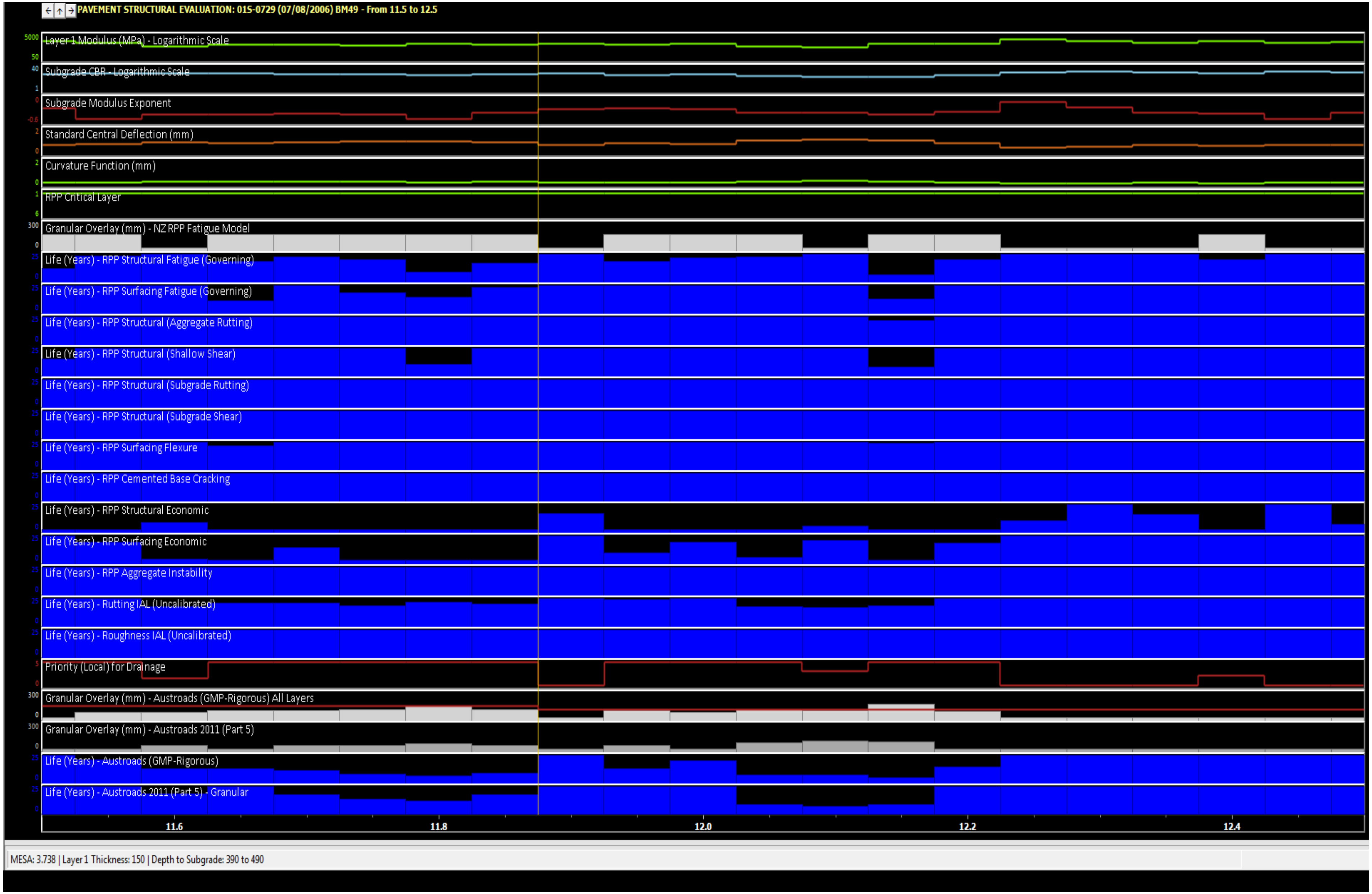
Terminal Failure Site Investigation

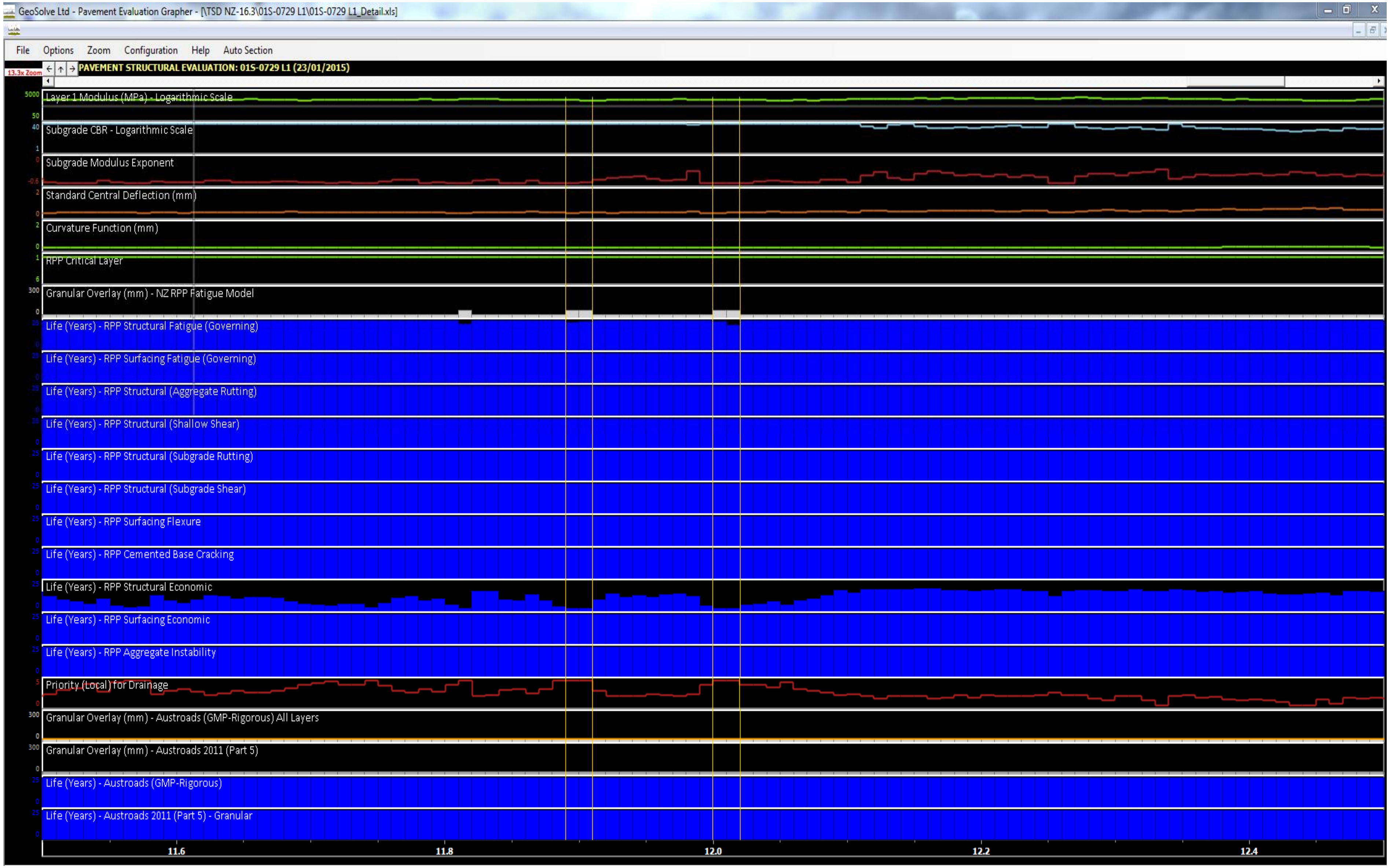

PAVEMENT STRUCTURAL EVALUATION: SH 02 RS 858 / 9.000 - 9.300 Lane R1 (17/08/2016) Benchmark Site (Sterlised) Failure
Layer 1 Modulus (MPa) - Logarithmic Scale
Subgrade CBR - Logarithmic Scale
Subgrade Modulus Exponent
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Structural (Aggregate Degradation)
Life (Years) - RPP Structural (Subbase Deformation)
Life (Years) - RPP Structural (Subbase Instability)
Load Damage Exponent for Basecourse (RPP Method)
Load Damage Exponent for Subgrade (RPP Method)
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Aggregate Instability
Life (Years) - Rutting IAL (Uncalibrated)
Life (Years) - Roughness IAL (Uncalibrated)
Life (Years) - RPP Structural (Accumulated Deformation)
Life (Years) - RPP Structural (Governing Deterministic)
Life (Years) - RPP Structural (Governing Stochastic)
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
Life (Years) - Austroads AC/OGPA Cracking
9.05
9.10
9.15
9.20
9.25


PAVEMENT STRUCTURAL EVALUATION: SH 02 RS 858 / 9.000 - 9.300 Lane L1 (17/08/2016) Benchmark Site (Sterlised) Failure
Layer 1 Modulus (MPa) - Logarithmic Scale
Subgrade CBR - Logarithmic Scale
Subgrade Modulus Exponent
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Structural (Aggregate Degradation)
Life (Years) - RPP Structural (Subbase Deformation)
Life (Years) - RPP Structural (Subbase Instability)
Load Damage Exponent for Basecourse (RPP Method)
Load Damage Exponent for Subgrade (RPP Method)
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Aggregate Instability
Life (Years) - Rutting IAL (Uncalibrated)
Life (Years) - Roughness IAL (Uncalibrated)
Life (Years) - RPP Structural (Accumulated Deformation)
Life (Years) - RPP Structural (Governing Deterministic)
Life (Years) - RPP Structural (Governing Stochastic)
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
9.05
9.10
9.15
9.20
9.25

Appendix H

LTPP Site Coastal Otago FWD – TSD Comparison


PAVEMENT STRUCTURAL EVALUATION: 01S-0729 (07/08/2006) BM49 - From 11.5 to 12.5
Layer 1 Modulus (MPa) - Logarithmic Scale
Subgrade CBR - Logarithmic Scale
Subgrade Modulus Exponent
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Cemented Base Cracking
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Aggregate Instability
Life (Years) - Rutting IAL (Uncalibrated)
Life (Years) - Roughness IAL (Uncalibrated)
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
11.6
11.8
12.0
12.2
12.4
MESA: 3.738 | Layer 1 Thickness: 150 | Depth to Subgrade: 390 to 490



GeoSolve Ltd - Pavement Evaluation Grapher - [\TSD NZ-16.3\01S-0729 L1\01S-0729 L1_Detail.xls]
File
Options
Zoom
Configuration
Help
Auto Section
13.3x Zoom
PAVEMENT STRUCTURAL EVALUATION: 01S-0729 L1 (23/01/2015)
Layer 1 Modulus (MPa) - Logarithmic Scale
Subgrade CBR - Logarithmic Scale
Subgrade Modulus Exponent
Standard Central Deflection (mm)
Curvature Function (mm)
RPP Critical Layer
Granular Overlay (mm) - NZ RPP Fatigue Model
Life (Years) - RPP Structural Fatigue (Governing)
Life (Years) - RPP Surfacing Fatigue (Governing)
Life (Years) - RPP Structural (Aggregate Rutting)
Life (Years) - RPP Structural (Shallow Shear)
Life (Years) - RPP Structural (Subgrade Rutting)
Life (Years) - RPP Structural (Subgrade Shear)
Life (Years) - RPP Surfacing Flexure
Life (Years) - RPP Cemented Base Cracking
Life (Years) - RPP Structural Economic
Life (Years) - RPP Surfacing Economic
Life (Years) - RPP Aggregate Instability
Priority (Local) for Drainage
Granular Overlay (mm) - Austroads (GMP-Rigorous) All Layers
Granular Overlay (mm) - Austroads 2011 (Part 5)
Life (Years) - Austroads (GMP-Rigorous)
Life (Years) - Austroads 2011 (Part 5) - Granular
11.6
11.8
12.0
12.2
12.4