EVALUATION OF A HIGH SPEED TRANSVERSE PROFILE LOGGER

Christopher R. Bennett

Highway and Traffic Consultants Ltd.
P.O. Box 177
Kumeu, Auckland 1250, NEW ZEALAND

ABSTRACT

Transverse profile data are increasingly being collected using high speed data acquisition vehicles. This paper presents the results of a technical evaluation of the ROMDAS Transverse Profile Logger. A series of laboratory and field experiments were conducted to establish the capabilities and limitations of the instrument. The tests covered areas such as the accuracy of the measurements, effects of temperature, and the ability to measure transverse profiles. The types of testing are those that should be conducted by any organisation considering adopting any type of high speed data collection equipment.

INTRODUCTION

An essential element of any pavement management system (PMS) is the availability of accurate and reliable data. For many administrators, the cost of data collection is the largest single component of the cost for the PMS. Because of this, there has been a trend towards automated data collection equipment. These allow for a significant volume of data to be collected and processed rapidly, often at high speeds with little disruption to traffic.

The most common items collected this way for flexible pavements are roughness, rutting and texture. The administrator or consultant has a number of different instruments produced in several countries to choose from using a variety of different technologies. There is a wide range in costs between the various instruments, and also a range of capabilities and features.

The problem faced by all users lies in evaluating and verifying the claimed performance of these instruments, and identifying any shortcomings. It is only by being completely familiar with the capabilities of the instrument that one can use them correctly in the PMS decision making process.

This paper describes a technical evaluation that was made of one such instrument: the ROad Measurement Data Acquisition System (ROMDAS) Transverse Profile Logger (TPL). It outlines a series of laboratory and field tests that were conducted to evaluate the suitability of the ROMDAS TPL for measuring the transverse profile of a pavement and calculating rutting. The procedures followed here should apply to other similar instruments, and could also be extended to other measurement devices.

THE ROMDAS TRANSVERSE PROFILE LOGGER

The ROMDAS transverse profile logger (TPL) is designed to measure the transverse profile of the pavement. It is a component of the ROMDAS system which also measures roughness, visual condition and right-of-way video (HTC, 1996).

The TPL uses ultrasonic sensors to establish the transverse profile. Five sensors at 100 mm spacings are contained in a single enclosure called the ‘ultrasonic measurement system array’ (UMSA). The main section of the TPL contains four arrays (20 sensors) while there are two detachable ‘wings’ with one array each (five sensors). A ‘master controller’ connected to a personal computer (PC) fires the sensors and stores the data.

Based on a sampling interval defined by the user, the computer sends a trigger signal to the master controller consisting of the current chainage (in m). To avoid interference effects between adjacent sensors, the same sensor is fired in all UMSA at the same time. This is then followed by a firing of the other sensors until all five sensors in the UMSA have been fired. The raw data are stored in the master controller along with the chainage where the measurements were taken.

The staggering of the firings complicates the dynamic testing of the TPL. The resulting transverse profile is not from the same point in space but are instead a composite formed from the five firings. This is illustrated in Figure 1. The firing of all sensors in all UMSA takes approximately 0.125 s. The total longitudinal distance between sensors 1 and 5 in each array therefore depends upon the speed of the vehicle.

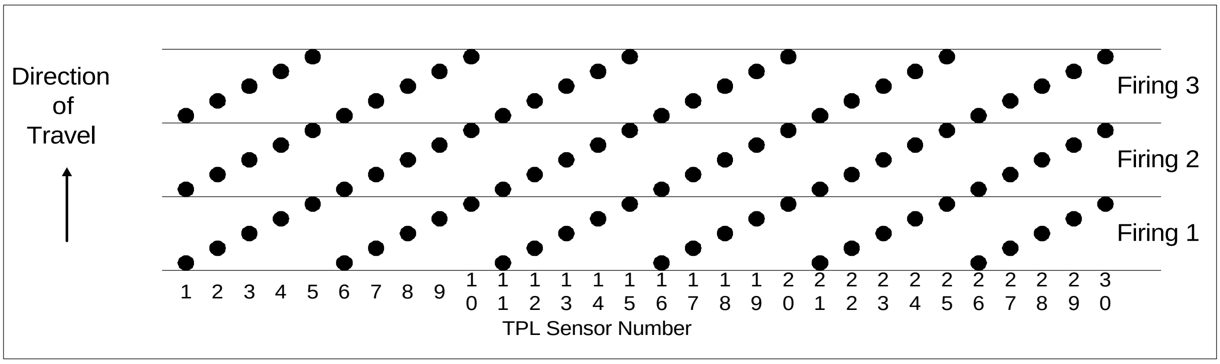

Figure 1: Transverse Profile Measurement Locations

EFFECT OF DISTANCE TO ROAD ON MEASUREMENTS

The first set of tests conducted were into the effect of distance to the road on the sensor output. These were done by operating a UMSA in the laboratory. Starting at 100 mm, an object was moved a 5 mm intervals away from the UMSA and the measurements were recorded. The measurements were made with only a single sensor transmitting so as to eliminate any effects of interference from the other sensors.

Figure 2 shows the results of the tests for 3 sensors. It will be observed that there are 3 'zones' for the readings:

- initially, the readings increase with increasing distance, however, the relationship is unstable;
- there is a second zone where the output is not influenced by the object;
- above 200 mm there is a strongly linear relationship between the distance and the readings.

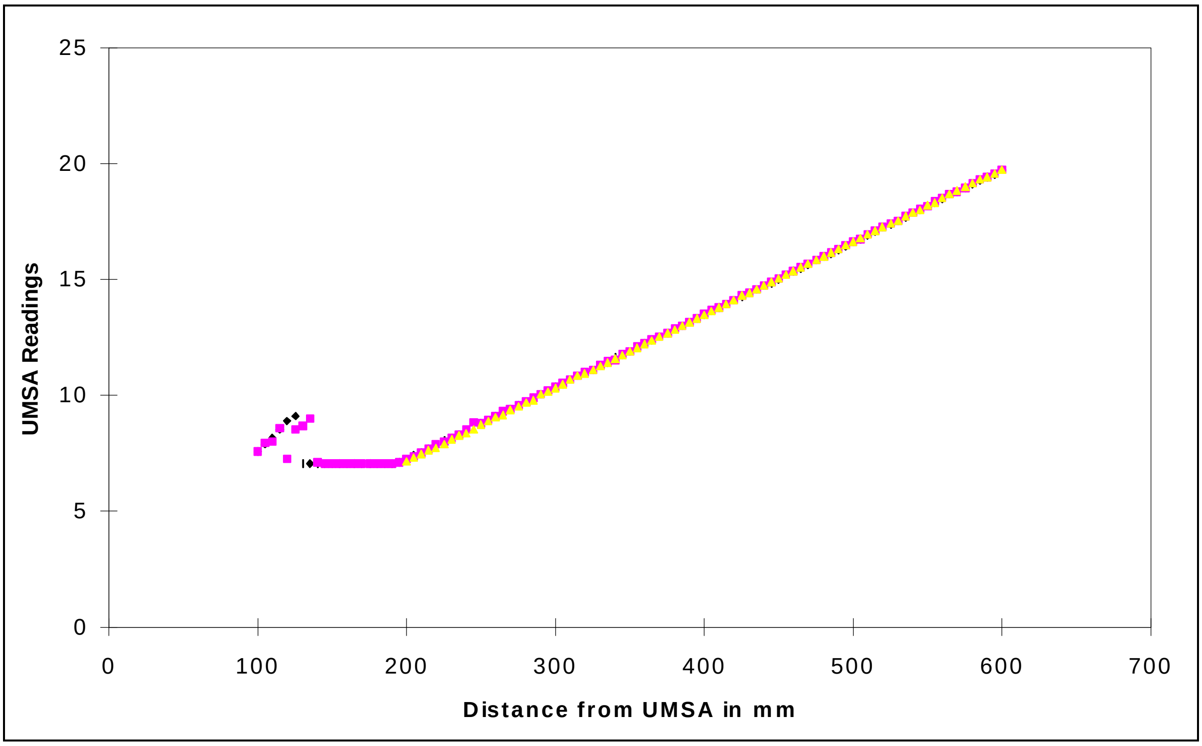

Figure 2: Effect of Distance on Measurements

For each sensor, a linear regression equation was fitted to the data above 200 mm. The coefficients of determination were 1.0 and the standard errors < 1.0 mm. There were different constants which were probably a reflection that the ultrasonic sensors are recessed from the front plate of the UMSA and are not at a constant distance from the plate. The slopes of the equations were approximately equal. The mean slope was 31.90 mm/UMSA measurement. Over the range of UMSA data (7 - 20), using this mean slope instead of the actual regressed slope resulted in an error of less than 1 mm. Given the method of measurement – which was of a similar accuracy – this indicated that a single conversion factor can be used for all sensors to convert the UMSA readings to the distance in mm.

INTERFERENCE FROM ADJACENT SENSORS

The UMSA is designed to fire sensors 1 to 5 sequentially. The delay between each firing is required to eliminate any interference from adjacent sensors on the readings. To test the effects of interference on adjacent sensors the same series of measurements described in Section 0 were repeated. However, whereas previously only a single sensor was uncovered, in this test all sensors were uncovered. It was found that there was no interference in the readings.

TIME STABILITY OF READINGS

The system was set up 400 mm from a plate and initialised. The readings were checked over a period of 6 hours on an hourly basis in a room with constant temperature. There were no significant changes to the readings over this time. This indicates that the output is stable with respect to time.

EFFECTS OF TEMPERATURE AND HUMIDITY

Introduction

The speed of sound is a function of the air temperature and humidity. A series of experiments were therefore conducted to investigate these effects on the measurements.

The experiments were made using a climate chamber. This allowed both the temperature and relative humidity to be varied over a wide range of conditions. A UMSA was installed in the chamber with the cable connected to the PC via an access port to the chamber. The UMSA was set on the floor of the chamber facing the ceiling. The measurements recorded were therefore the distance from the UMSA to the ceiling. Owing to the size of the chamber the UMSA was not perfectly flat and the ceiling was also irregular. These two factors led to variations in the final measured distances. The data were recorded using three UMSA sensors since the remaining two suffered from interference due to protrusions from the chamber sides.

The chamber had both heating and refrigeration available so the temperature was varied over the range of 4 - 40 °C. The ’dry’ temperature was displayed on a thermometer outside of the chamber, graduated in 1 °C intervals. The humidity was supplied via a mister which was provided with water from a beaker tube. A second graduated thermometer was used to monitor the ‘wet’ temperature. The relative humidity was calculated based on the difference between the dry and wet temperatures using a chart supplied by the manufacturer of the climate chamber.

Effects of Temperature on Measurements

Finch (1988) reported that the effect of temperature on sound is 0.69 m/s/°C. It was concluded by Finch (1988) that temperature had a limited effect on the measurements and when evaluating rut depths this was further reduced.

The effects of temperature on the measurements was investigated by holding the relative humidity constant at 100 per cent and varying the temperature between 4 and 40 °C.

Figure 3 illustrates the relationship between distance and temperature, where the data have been normalised relative to the measurement at 4 °C. It can be observed that the data exhibited a strong linear relationship, although there was some scatter. This scatter is due in part to the measurement technique wherein it was difficult to (a) hold a constant temperature and humidity and (b) read the dial gauges accurately. A linear regression was fitted to the data from the three sensors which resulted in the following equation ($R^2 = 0.98$; S.E. = 0.89):

$$\underset{(10.0)}{dDIST = 2.84} - \underset{(-56.2)}{0.6927}\ TEMP \qquad \ldots\ldots\ldots\ldots \qquad \text{(Eq. 1)}$$

where dDIST is the change in measured distance relative to the distance at 4 °C

TEMP is the temperature in °C

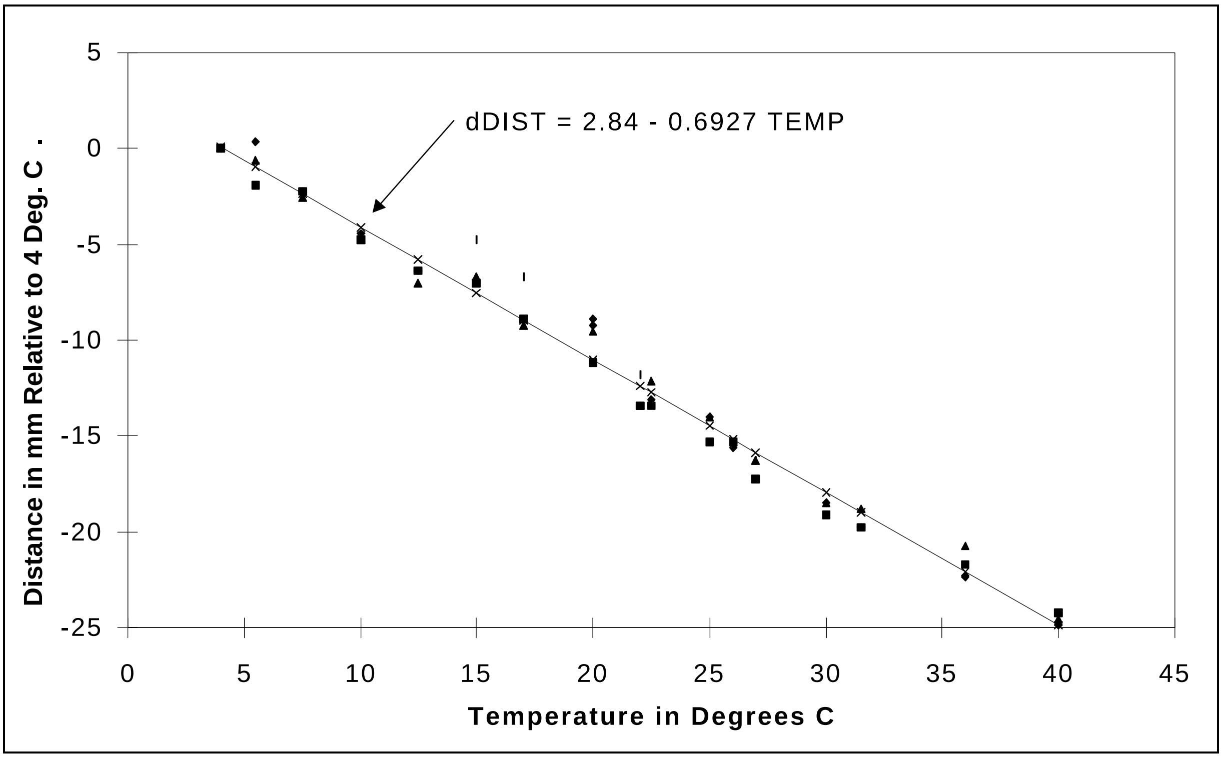

Figure 3: Effect of Temperature on Relative Distance

The ‘t’ statistics are shown under each coefficient. These show that the coefficients are well determined, particularly the temperature coefficient.

The equation confirms that there is a variation in height of 0.69 mm/°C. This suggests that it would be desirable to include a temperature monitor with the TPL so that the data can be corrected to a standard temperature.

Effect of Humidity on Measurements

Finch (1988) indicates that there is limited data available on the effects of humidity on ultrasonic signals. It is reported that the literature considered the effects to be negligible and that at 10 °C the difference between the velocity of sound in saturated and dry air was from 0.6 - 0.9 m/s – a change of about 0.3 per cent. It was therefore concluded by Finch (1988) that humidity would not be significant over the short distances measured by a TPL.

To test this conclusion, a series of measurements were taken at a constant temperature with varying humidity. It proved difficult to hold a constant temperature and vary the humidity with the climate chamber. However, a number of readings were made at a temperature of 20°C and these showed that the distance was effectively independent of the relative humidity. The variation in distance in the range of 44 - 100 per cent relative humidity was between 0.09 - 0.28 per cent. This supports the conclusion by Finch (1988) that it is not necessary to consider humidity with the TPL.

ACCURACY OF TPL MEASUREMENTS

Testing Procedure

The UMSA was installed vertically pointing down at a flat surface. All sensors except the centre sensor were blocked. A 3 mm circular shim (22.3 mm diameter) was fixed to the surface directly below the centre of the sensor. This was done to eliminate any effects of the surface not being perfectly flat.

A stack of 8 shims of approximately the same diameter with a total height of 25.0 mm were placed on top of the fixed shim. The UMSA output was then established as the shims were individually removed from the stack. The tests were done twice to ensure that the results were consistent. No major differences in readings were found between tests.

Upon testing a stack, the height of the UMSA was changed. The process was then repeated. This resulted in measurements being taken at heights of 205 - 597 mm. Heights below 200 mm were not tested due to the inability of the UMSA to record data at these heights.

It was found that when the UMSA was above 479 mm the spread of the beam gave unreliable readings with only one shim. The data points above this distance were therefore eliminated from the analysis.

UMSA Height Measurements

The data collected consisted of a series of 86 elevation measurements of known heights. In the first tests a relationship between height and the UMSA output was investigated by moving an object away from the UMSA and noting its distance from a tape measure. Since the shims offered a more accurate quantification of the distances, an analysis was made of the relationship between the UMSA readings and the height.

As in the earlier test, the data followed a strongly linear trend. A regression line was fitted to the data which resulted in the following equation ($R^2 = 1.00$; S.E.=1.08):

$$\begin{array}{l} DIST = -19.42 + 31.70\ UMSA \qquad . . . . \qquad (Eq.\ 2) \\ \qquad\qquad (-46.4)\ (1030.0) \end{array}$$

The slopes for sensor 3 were identical in the two tests. The only significant differences was with the constants. These may be due to difficulties in accurately establishing the vertical height of the sensor relative to the flat surface or else the measurement target in the earlier test not being perfectly vertical.

Accuracy of Measurements

The objective of the tests was to verify the accuracy of the UMSA measurements. For each test height, the data were reduced to obtain two values: the height of each individual shim and the height of the stack with different number of shims. Table 1 and Table 2 give the summary statistics for these data calculated from the measurements made at the different UMSA heights.

Table 1
Shim Height Statistics

Shim	Shim Height in mm							t	Number
Number	Actual	Measured	S.Dev	Min.	Max.	S.E.	C.I.		of Obs.
1	3.2	3.2	0.77	2.2	4.4	0.28	0.63	0.12	10
2	3.1	2.6	0.74	1.9	4.1	0.27	0.62	-1.83	10
3	3.1	3.7	0.82	2.2	4.4	0.29	0.65	1.90	10
4	3.1	3.0	0.70	2.2	4.1	0.26	0.60	-0.57	10
5	3.2	3.1	0.87	2.2	4.4	0.30	0.67	-0.42	10
6	3.3	3.4	0.70	2.2	4.1	0.26	0.60	0.47	10
7	3.0	2.7	0.58	1.9	3.8	0.24	0.55	-1.40	10
8	3.0	2.9	0.79	1.9	3.8	0.36	0.93	-0.26	6
All	3.13	3.07	0.79	1.9	4.4	0.10	0.20	-0.54	76

NOTES: 1/ S.E. = Standard Error; C.I. = Confidence Interval; t = t statistic for means (Z test used with 'All' data due to larger sample)

2/ The highlighted cell had a significantly different mean at 95% confidence.

The data in Table 1 show the following:

- for 7 of the 8 shims the mean predicted shim thicknesses from the different heights were not significantly different to the actual thickness at a confidence of 95% using a ‘t’ test. The one shim where there was a difference was approximately 3% outside of the acceptable limits.
- using a ‘Z’ test, the mean thicknesses of all shims were not significantly different to the mean predicted thickness.
- the standard errors are in the range of 0.24 - 0.36 mm for each of the shims, and 0.10 mm for the measurements of all the shims. This corresponds to confidence intervals of 0.55 - 0.93 mm for the individual shims; 0.20 mm for all shims.

Table 2
Stack Height Statistics

Number of Shims	Stack Height in mm							t	Number of Obs.
	Actual	Measured	S.Dev	Min.	Max.	S.E.	C.I.		
1	3.2	3.2	0.77	2.2	4.4	0.28	0.63	0.12	10
2	6.3	5.8	0.81	4.8	6.7	0.28	0.64	-1.64	10
3	9.4	9.5	0.84	8.2	10.8	0.29	0.65	0.27	10
4	12.5	12.4	0.97	11.1	13.6	0.31	0.70	-0.24	10
5	15.7	15.5	0.43	14.6	15.9	0.21	0.47	-0.95	10
6	19.0	18.9	0.79	18.1	20.0	0.28	0.64	-0.26	10
7	22.0	21.6	0.82	20.6	22.5	0.29	0.65	-1.43	10
8	25.0	24.7	0.28	24.4	25.0	0.22	0.56	-1.26	6

NOTES: 1/ S.E. = Standard Error; C.I. = Confidence Interval; t = t statistic for means

The data in Table 2 for the stack height indicate:

- at 95% confidence there was no statistically significant differences in the actual versus predicted mean heights.
- the confidence intervals for the means were in the range 0.47 - 0.70 mm.
- the stack height data appear to have a downward bias in that the predicted mean in 6 out of the 8 cases was lower than the actual height. However, there was no evidence of a systematic bias in the raw data.

MEASUREMENT OF TRANSVERSE PROFILES

Data Collection Technique

To evaluate the ability of the TPL to measure transverse profiles, field tests were conducted on a public road crossing several farm paddocks in the U.K. Built to a low standard, it suffered severe rutting and deformation.

A TRL Beam was used to collect data on the transverse profiles. This instrument consists of a 3.6 m long beam which is fixed at either end. The beam is levelled to give a horizontal datum. A linear vertical displacement transducer is connected to a wheel below the beam. As the wheel is moved along the ground the transducer is moved relative to the beam and the vertical displacement of the wheel is recorded. The data are displayed to an accuracy of 0.1 mm. The instrument was run in ‘Test’ mode which meant that the data were displayed continuously instead of at the 100 mm intervals which are usual with the TRL Beam.

Before the beam was operated a calibration test was conducted as per the manufacturer’s recommendations. This entailed setting up the instrument on a level floor and placing a calibration stand under the wheel. The heights from the TRL Beam were the same as those corresponding to the calibration stand. The instrument was further checked using the same shims as used in the earlier TPL calibration. It was found to give readings to within ± 0.1 mm of the known shim thickness.

A series of 20 transverse profile measurement sites were selected at nominal 12.5 m intervals along the test section. The TPL was mounted on a vehicle and parked over the measurement site. A total of 25 UMSA sensors were used (i.e. the main bar and one wing) since the road was only 2.6 m wide. The TPL measurements were recorded for a period of 60 s. The start and end points of the TPL beam were painted on the road surface.

The TRL Beam was then used to record the transverse profile at 25 mm intervals. A tape measure was placed on the pavement surface zeroed at the left edge of the pavement. The TRL Beam wheel was then moved across to the right hand edge with the values displayed every 25 mm being recorded on data collection forms. At 5 sites two sets of TRL Beam readings were taken, however, it was found that the values were effectively identical so only one set was taken at the remaining sites.

Data Reduction

Due to interference caused by a power inverter, a number of inconsistent readings – essentially consisting of 0 elevations – were obtained from the TPL. The data were edited to remove these readings.

The TRL Beam gave the change in elevation relative to a horizontal datum. The TPL gave the distance to the surface from the TPL bar which will seldom be horizontal. It was therefore necessary to make a number of adjustments to the data to make them comparable.

Figure 4 shows the TRL Beam profile data and the raw TPL data. The TRL Beam data were recorded at 25 mm intervals; the TPL data at 100 mm intervals. It can be observed that the TPL data profile is a ‘mirror’ of the TRL Beam profile. This is because of the different datUMSA used by the two instruments. The first adjustment was thus to invert the TPL data so that it had a similar datum to the TRL Beam data.

The data were inverted as follows:

1. The UMSA data were converted to mm.
2. The data were normalised to an elevation of 100 mm by subtracting the difference between the start UMSA elevation and 100 mm from each reading.

3. The elevation of each point relative to the minimum elevation was calculated as RELEVi = min(ELEVi to ELEVn) - ELEVi
4. The data were then inverted using the equation:
   INVi = ELEV1 - RELEV1 + RELEVi

Figure 4 shows the results of this for Site 2 as the 'Uncorrected TPL Data'.

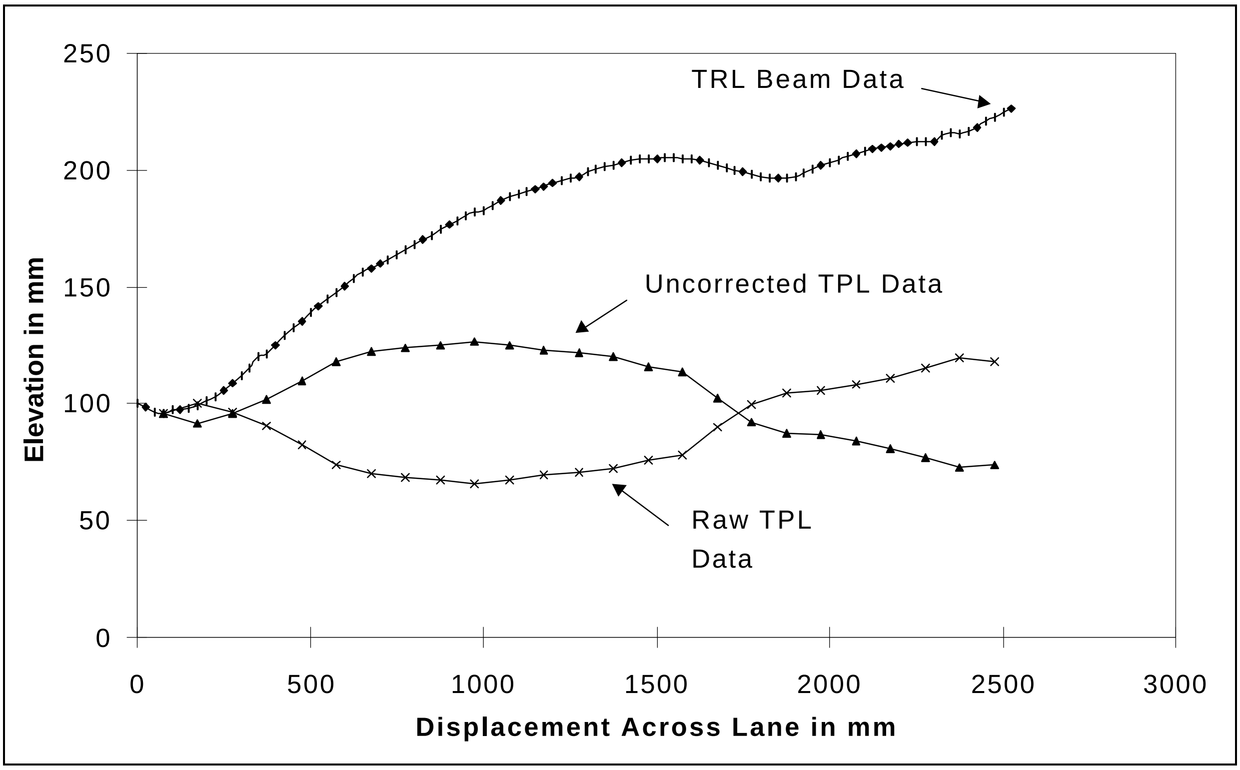

Figure 4: Inverted Raw TPL Data

It will be noted from Figure 4 that although the inverted TPL data has a similar profile to the TRL Beam data, the measurements have different slopes. This is due to the TRL Beam being horizontal and the TPL following the cross-fall of the pavement. To make the two sets of data coincident the following was done:

1. The point where the TRL Beam and TPL data coincided at the left of the pavement was established.
2. The point where the TRL Beam and the TPL data should coincide at the right of the pavement was established.
3. The data were 'rotated' around the left point by adding a value proportional to the difference in TPL and TRL Beam right point elevations to each reading. This value was calculated as:

ADJi = CHAINi (TRLe - TPLe) /CHAINDIFF . . . . (Eq. 3)

where ADJi	is the adjustment for chainage I in mm
CHAINDIFF	is the distance between the left and right readings in mm
CHAINi	is the displacement in mm

TRLe	is the TRL Beam elevation at the end point in mm
TPLe	is the TPL elevation at the end point in mm

In practice it was often necessary to test several start and end points to obtain a good correlation between the two profiles.
Figure 5 shows the final corrected data for Site 2.

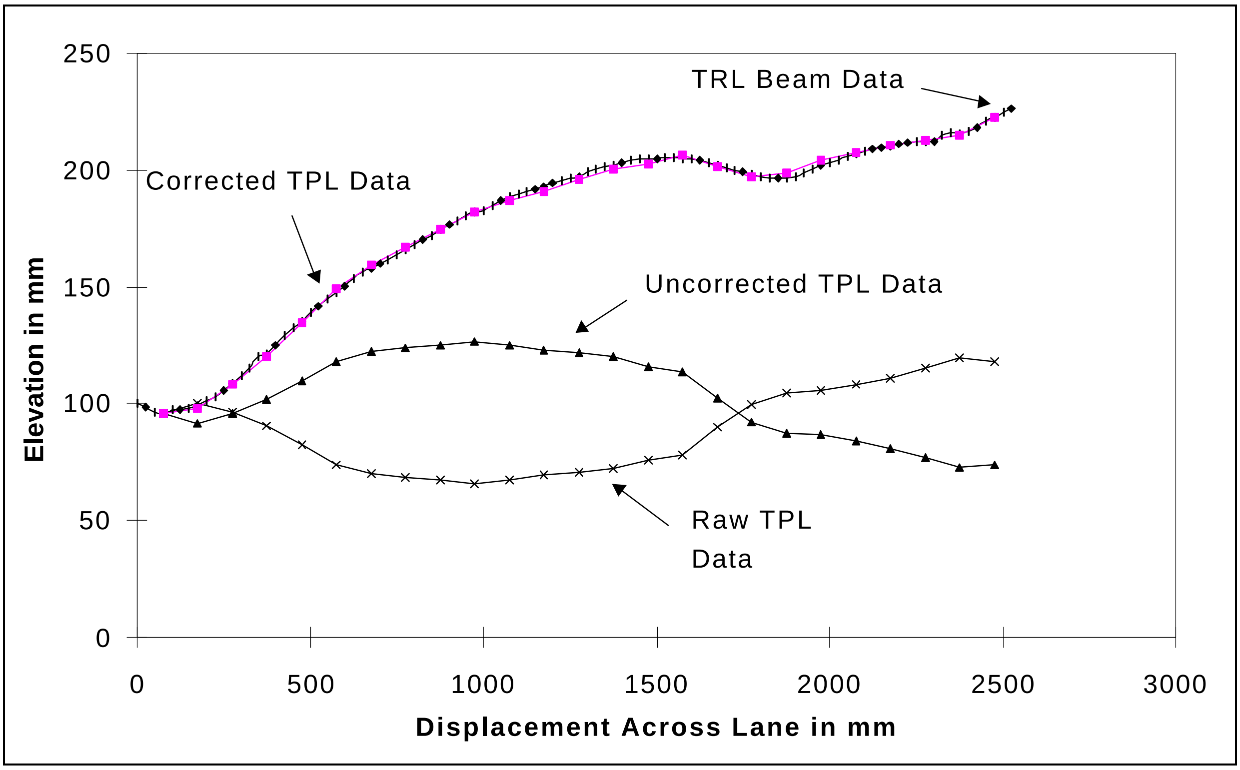

Figure 5: Final Corrected Data

Using this data reduction process, the data were reduced for each of the test sites. The correlations between the TPL profile data and the TRL Beam data were > 0.96 at every site, and most were > 0.99.

This analysis has shown that the TPL can give a reliable representation of the transverse profile when the vehicle is stationary.

MOVING TEST

The final field test was to verify the ability of the TPL to measure while moving. Although measurements were planned at the same site as the stationary test, the power inverter problems made this impossible. The moving test was therefore conducted at a later date using a large, newly surfaced parking lot.

A target consisting of a 4 m long rectangular section of size 200 mm x 200 mm was placed on the surface. The TPL was mounted on a vehicle which was driven at different speeds over the section. It was found that the TPL was able to accurately measure the height of the section and that the measurements were not influenced by speed.

A second test was conducted where it was driven along a road and the height of kerb was measured. This was found to agree with the standard kerb height for the road.

RUT DEPTH CALCULATIONS

The statistic which is most often used for characterising the transverse profile is the rut depth. As described in NDLI (1995), there are two methods commonly used with automated data acquisition systems for expressing rut depths: the wire model and the distance under a straight-edge. The ROMDAS system uses the latter so the rutting was evaluated using this method.
Two sets of analyses were conducted using the stationary field test data:

- **TPL versus TRL Beam at 100 mm Intervals.** The objective of this analysis was to compare the rut depths that arose with the TPL readings with those for the TRL Beam at the same locations. Since the measurements were from the same location on the road, any differences would be due to the different instrument measurements.
- **TPL and TRL Beam at 100 mm Intervals versus TRL Beam Profile.** The objective of this analysis was to compare the rutting from discrete measurements – 100 mm – with that from a more continuous measurement interval (25 mm). Any differences here are due to the use of a larger measurement interval.

The profiles for each site were plotted and the points where a 2.0 m straight edge would have rested on the pavement for the left and right wheelpaths were established using a ruler. The low point under this straight edge was also established. The rutting is defined as the difference in elevation between this low point and the straight edge. It was found that for some sections there was no discernible rutting in some wheelpaths, whereas in others there was significant rutting.

Figure 6 compares the rut depths calculated from the TPL data and the TRL Beam at the 100 mm spacing sample intervals. It can be observed that there is good agreement between the two sets of values. The correlation coefficient is 0.93 for these data.

The results from Figure 6 show that the rut depths calculated from the TPL agree with those which would have been established from taking measurements at the same locations using a static device. However, another issue which needs to be addressed is how these values compare with the true rut depth of the pavement.

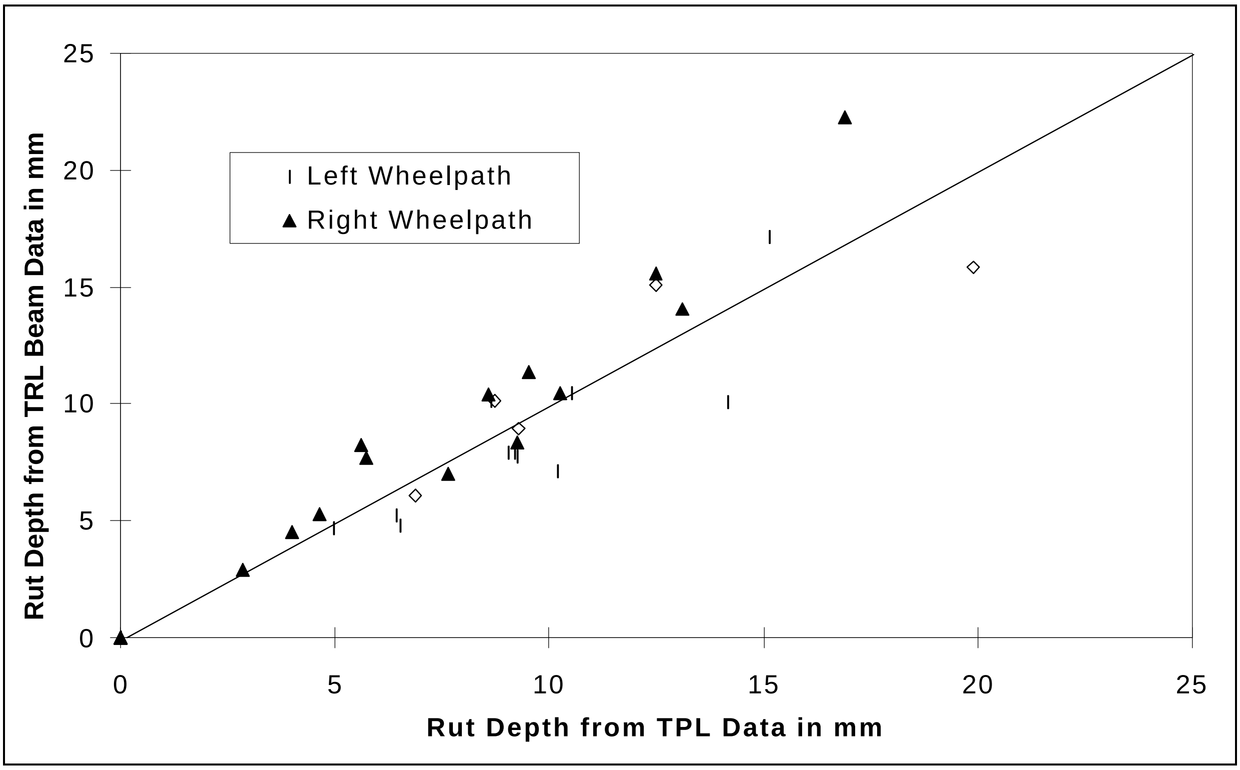

Figure 6: Comparison of 100 mm Interval TPL and TRL Beam Rutting

Rutting is defined as the difference in elevations between a straight edge resting on two high points to the lowest point under the straight edge. It is thus based on a continuous profile. The TPL, as with any vehicle mounted rut measurement device, does not measure the continuous profile. It instead takes samples of this profile at discrete intervals – in the TPL case 100 mm. Since is it unlikely that the TPL measurements will exactly coincide with the high and low points of the pavement, there will always be a difference between rutting when measured with samples versus that arising under a straight edge.

To investigate the magnitude of the errors, the rut depths were established using the 25 mm samples from the TRL Beam profile. Figure 7 compares these profile rut depths with the rut depths calculated from the same TRL Beam data but at 100 mm.

It will be observed that even though the same data set was used, the sample data underestimated the true rut depth. In some instances the sample data reported that there was no rutting when the profile indicated significant rutting. This was due to in part to the pavement having curvature at the very edge and the sampling measurements not extending this far.

Others (Cenek, et al., 1994; Jameson, et al., 1989) have found poor agreement between profilometer measurements and straight-edge rut depth and this sampling interval effect is undoubtedly a contributing factor. Hallett and Robieson (1996) compared the rutting under a straight-edge to that from a laser profilometer. Their data showed a similar trend to that in Figure 7 which suggests that the differences were due to sampling.

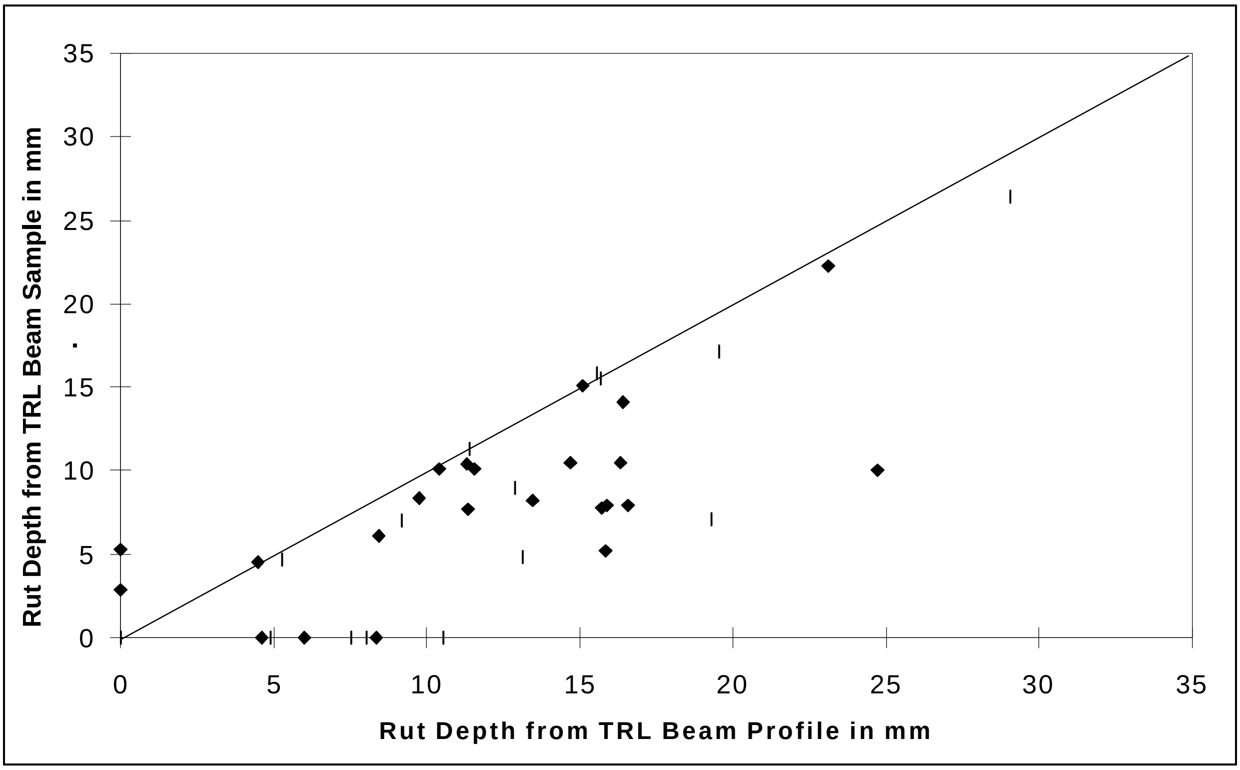

Figure 7: Rut Depths from TRL Beam Profile and TRL Beam Samples

This highlights the fundamental trade-off with any high-speed data acquisition. One obtains a representative sample of data at frequent intervals but it is only a sample. If more accurate data are required it is necessary to use a different type of data collection. It should be noted that the differences will be proportional to the spacing of the measurement sensors so these distances should be minimised. Furthermore, the total coverage of the device, in terms of the lane width measured, should also be as wide as practical.

Table 3 presents the summary statistics for the rut depth data over all sections. It will be noted that there is good agreement between the TPL and TRL Beam sample data. As suggested by the earlier analysis, the agreement with the profile based rutting is not as good.

Table 3
Statistics for Rut Depth Data

Statistic	Rut Depth Under 2.0 m Straight Edge in mm								
	Both Wheelpaths			Left Wheelpath			Right Wheelpath		
	TRL Beam Profile	TPL	TRL Beam Sample	TRL Beam Profile	TPL	TRL Beam Sample	TRL Beam Profile	TPL	TRL Beam Sample
Mean	12.0	7.7	8.0	13.2	8.5	7.8	10.8	6.9	8.1
S. Dev	6.6	5.6	6.3	5.8	5.1	4.9	7.2	6.1	7.5
Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	29.0	21.2	26.4	24.7	19.9	17.1	29.0	21.2	26.4

An evaluation was made of the impact of using the raw TPL data for calculating rutting instead of the data which had been corrected to have the same slope as the TRL Beam data. It was found that there were no differences in the calculated rut depths. This may initially appear to be counter intuitive, however, it is a reflection of the fact that the corrections made were linear and that there were no changes to the relative elevations. Thus, it is not necessary to take into account the road slope for calculating rut depths.

CONCLUSIONS

On the basis of the series of tests conducted with the ROMDAS TPL the following are the main conclusions with regard to the instrument:

- the UMSA height measurements are made with an accuracy better than 1.0 mm. This is based on the 95% confidence intervals for the measurement of the individual shims and the stack all of which were below 1.0 mm; eliminating the test with only 6 measurements, the data suggest an accuracy of better than 0.70 mm.
- there is no systematic bias evident in the height measurements with the measurements falling on either side of the actual height.
- there is a linear relationship between the UMSA measurements and distance. The slope of the relationship was identical using two different measurement methods.
- it is not necessary to account for humidity in the TPL measurements.
- it is desirable to account for temperature since the effect is a change in height of 0.69 mm/°C. Changes of this magnitude could lead to errors when comparing rutting on different sections measured at different temperatures.
- the TPL gives and accurate reflection of a road profile measured at 25 mm intervals;
- the rut depths calculated from the TPL data agree with those from the transverse profile measured at the same 100 mm intervals;
- there is a poor correlation between the 100 mm rut depths and those based on the 25 mm sample intervals. This will be a problem with any instrument similar to the TPL.

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