DETERMINATION OF RUT DEPTHS FROM MULTI-POINT TRANSVERSE PROFILE FILTERING OF LASER PROJECTION SYSTEMS

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ABSTRACT

This paper presents the findings of an alternate multi-point filtering method for transverse profile data collected by the INO Laser Rut Measurement System (LRMS) aimed at mirroring traditional multiple non-contact laser profilometer systems. The LRMS is capable of measuring the transverse profile of a road up to a resolution of 1280 points across a 4 m profile, providing more accurately measured rut depths. The development of this alternate filtering method was initiated in recognition of the effect that the higher resolution of the LRMS has on the accuracy of rutting determined over traditional methods. The corresponding impact that having more accurate rut depths has on pavement management decisions is also profound, affecting deterioration rates and key performance indicators.

The principal objective of this new filtering process was to provide a means by which the bias between traditional non-contact laser systems and the LRMS could be quantified at the data collection level. In doing so it is anticipated that road agencies progressing from multiple non-contact laser systems to LRMS or equivalent technology will be able to do so without the need to undertake large scale tandem surveys to quantify this bias. By measuring the bias at the data collection level, road agencies will have more information available with which to justify changes to their pavement management system such as adjusting intervention levels (IL) or key performance indicators (KPI) to accommodate the higher measured ruts.

The development and validation of this alternate filtering method was undertaken based on testing with the ARAN 800 with LRMS subsystem and Greenwood Laser Profilometer with 13 lasers completed in tandem. Testing was undertaken across six sites having different surface types, geometry and age. The sites exhibited rutting characteristics ranging from low < 5 mm to high > 20 mm and surface texture characteristics ranging from < 0.5 mm to > 2 mm.

The results of this multi-point transverse profile filtering process demonstrate that it is possible to produce rut depths from the LRMS that are equivalent to traditional multiple non-contact laser profilometer systems, eliminating the need to undertake extensive and expensive correlation studies. In demonstrating this correlation, road agencies are not only able to transition to more accurate profile systems with minimum expense but also able to adjust their KPI's accordingly and still utilise their historical rut data to predict deterioration rates for their road network.

INTRODUCTION AND BACKGROUND

Technology for the collection of High Speed Data (HSD) has changed dramatically in recent years, from the introduction of Inertial Measurement Units (IMU's) that accurately measure a vehicles dynamics to determine pitch, roll and heading in order to correct for poor GPS signals to projection lasers which measure the longitudinal profile of the road more representative of a tyre footprint. This laser projection technology has been around for sometime and has also been incorporated in systems designed to measure the transverse profile of the road for the calculation of rutting as well as more advanced profiling algorithms such as volumetric rut fill quantities.

The introduction of technologies that offer either in isolation or as a combination, higher resolution and precision or more representative measurements, will lead to challenges with incorporating this new data within the existing business practices of an organization. These

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challenges impact on decisions of what to do with the historical data that has already been collected and the performance criteria and business rules that have been established based on this historical data. Ideally any new technology should be backwards compatible, as is often the case with software; however this is rarely possible owing to the differing means by which old and new technologies measure the same condition. This desired backwards compatibility, is often achieved through the development of new algorithms, however these need to be validated against historically relevant data and methods.

This paper explores the development of one such algorithm which provides Multi-point Transverse Profile (MPTP) filtering of data collected by the Laser Rut Measurement System (LRMS) that is backwards compatible with traditional non contact laser system. The LRMS was developed by INO in Quebec, Canada and the MPTP algorithm was developed by Fugro PMS in Australia to filter the LRMS transverse profile for the height measurements at offsets (transverse locations) equivalent to traditional non contact point laser systems. The LRMS utilises two synchronised pulsed laser projectors to measure and record the transverse profiles of a road up to 4 m wide with a resolution of 1280 points at highway speeds.

The validation of the transverse profiles and rut depths was undertaken using data collected by a static Transverse Profile Beam (TPB) as well as an ARAN 8000 manufactured by Fugro Roadware and Greenwood Laser Profilometer (GLP) both of which are owned by Fugro PMS. Fugro Roadware were one of the first suppliers of HSD survey vehicles incorporating the LRMS technology and have since been the largest integrator of the LRMS both within their own fleet of ARAN's and those sold internationally. The more recent updates of the ARAN operating system do not calculate rutting at the time of acquisition, rather, this process is completed using Fugro Roadware's processing and production software Vision.

Validation of the LRMS transverse profiles and rut value was initially undertaken against the TPB to ensure suitability of the transverse profiles to undertake additional MPTP filtering. Subsequently validation of the MPTP algorithm was completed using rut depths derived from the GLP containing 13 non-contact lasers operated in tandem with the ARAN across six sites which exhibited rut depths from low < 5 mm to high > 20 mm and surface texture ranging from < 0.5 mm to > 2 mm.

Objective

The objective of this paper is to demonstrate that it is possible to achieve backwards compatibility of rut depths calculated from the higher resolution transverse profile measured by the LRMS. Furthermore this backwards compatibility can quantify the real deterioration in rutting which would otherwise not be possible when shifting from traditional non contact lasers to laser projection systems for the measurement of rutting.

METHODOLOGY

The development of the Multi-Point Transverse Profile (MPTP) filter involved modifying the existing rut processor within Vision in order to provide an additional processing option without having to rewrite the existing rut depth algorithm. Instead, the rut processor filters the profile and sends this to the existing rut algorithms after which the rut depths are determined as would otherwise be the case if using the full transverse profile from the LRMS. This algorithm is capable of calculating rut depths by way of the straight edge or catenary (wire) methods. The existing rut processor has options to include either or both the straight edge and catenary rut models, the width of lane to be analysed, filtering of cracks and edge effects e.g. kerb. The use of the MPTP filter ignores most of these settings with the exception of those applicable to the length of straight edge and catenary models as well as edge filters. The MPTP filter includes an additional option to allow the use of either pre-defined industry laser positions as defined by an offset from the centre of the vehicle, user-defined or manufacturer specific non-contact laser offsets. The MPTP filter selects from the available height readings, just those locations that coincide with the laser positions of the specified traditional non-contact laser system.

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When using LRMS measured transverse profile data to determine rut depths it is common but not mandatory to apply an initial filtering to 'smooth' the transverse profile to fewer than the 1280 points measured. This is for the most part in order to minimise the affect of surface texture depth on the derived rut depths. At present there is not an industry wide accepted standard for the number of resulting points from this initial filtering process, however 100 points was found to be used regularly and has been adopted by Fugro PMS. The result of this smoothing process means profile heights are only available every 40 mm across the width of the measured profile. As such it is likely that the offsets defined in the MPTP may not coincide with those of the initial filtered profile but be out slightly. For this reason a search radius was included within the MPTP to look for the nearest available offset with a height measurement. This search radius is also applicable for instances where the initial filtering of the profile data has not been undertaken or in cases where there are invalid height readings recorded by the LRMS.

In validating the rut depths derived after the MPTP filter has been applied, it is important to recognize the differences in the frequency of measurements from the LRMS and traditional non contact laser systems. These traditional laser systems operate at 16 kHz while the LRMS operates depending on the model, at either 30 Hz, 100 Hz or 250 Hz. Road Agency and National Specifications for the frequency of profile sampling vary internationally with 250 mm adopted in Australia and 100 mm required in parts of the United States of America. Furthermore each manufacturer of HSD equipment have their own proprietary algorithms for calculating rut depths, as such small differences can be expected in how the ruts derived from both laser technologies and algorithms of each piece of equipment are calculated.

Validation

The validation of the rut depths derived from the multi-point transverse profile (MPTP) filtering was completed using data collected as part of a wider equipment validation exercise for the ARAN. This validation exercise was undertaken with the ARAN in January and February 2011 across six sites. In addition, the GLP surveyed the same sites in tandem with the ARAN in order to capture reference data for validation of the MPTP filter. The ARAN and LRMS subsystem was validated against the TPB under both static and dynamic conditions at three separate survey speeds. The rut depth characteristics determined from the reference TPB at the six sites are summarised in Table 1 following. The texture depth characteristics at the six sites are summarised in Table 2 following and were determined by a Stationary Laser Profiler.

Table 1: Reference rut depth characteristics at each site

Site	Site name	Percentage of rut depth (mm)			
		0.0 - 5.0	5.0 - 15.0	15.0 - 25.0	> 25.0
3	SH1B	63.3	36.7	0.0	0.0
4	Woodlands Road	86.7	13.3	0.0	0.0
6	SH05 Cal59 Rotorua	0.0	63.3	16.7	20.0
7	SH30 CS56 Rotorua	0.0	3.3	96.7	0.0
13	Law Road	61.3	35.5	3.2	0.0
14	Whitikahu Road	23.3	70.0	6.7	0.0

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Table 2: Reference texture depth characteristics at each site

Site	Site name	Percentage of texture depth (mm)			
		0.0 – 1.0	1.0 – 1.5	1.5 – 2.0	> 2.0
3	SH1B	0.0	0.0	0.0	100.0
4	Woodlands Road	0.0	0.0	0.0	100.0
6	SH05 Cal59 Rotorua	100.0	0.0	0.0	0.0
7	SH30 CS56 Rotorua	N/A	N/A	N/A	N/A
13	Law Road	0.0	0.0	85.0	15.0
14	Whitikahu Road	0.0	0.0	0.0	100.0

Transverse profile beam

The Transverse Profile Beam (TPB) is a static device capable of measuring the transverse profile at intervals of approximately 3 mm across the road and has a vertical resolution of ±0.5 mm. The TPB measures the transverse profile by measuring the change in elevation of a wheel as it moves across the road or profile being measured, see Figure 1 following. The wheel is mounted on a moveable carriage, which is driven along a precision ground track mounted and supported on a 4 m long rail. To minimise sag at the centre of the measuring beam the rail is suspended at 2 m centres on a supporting superstructure. The wheel is mounted on a carriage that can move freely up and down and hence follow the true road profile as it moves across the road. The TPB was used to provide reference transverse profiles and rut depths in the left and right wheelpaths for every 10 m at each of the validation sites.

Figure 1: Transverse Profile Beam (TPB)

ARAN

For each of the validation sites, the ARAN undertook a total of ten repeat runs at each speed across the two days, five on each day of the validation. Three survey speeds of 40 km/hr, 60 km/hr and 80 km/hr were carried out to simulate the range of trafficable conditions expected during survey conditions. The ARAN LRMS subsystem which operated at a frequency of 250 Hz was also used to record stationary or static transverse profiles at the same locations as those recorded by the TPB in order to validate its ability to measure the Transverse Profile and Rutting. The LRMS on the ARAN was calibrated using a horizontal surface as per the manufacturer's specification prior to the validation site testing.

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Figure 2: ARAN 8000 with LRMS

GLP

For each of the validation sites, the GLP undertook the same number of repeat runs at each of the survey speeds as that of the ARAN. The GLP was calibrated using a milk test as per the manufacturer's specification prior to survey of the validation sites to ensure the lasers record from the same datum. The use of milk with a full fat content placed in a trough placed under the lasers ensures a flat opaque surface to calibrate the laser heights. The results from the five repeat runs over each of the two days was used to ensure internal repeatability of the GLP and suitability of this data for correlation against the MPTP derived ruts.

Validation results

The validation of the rut depth results derived from the ARAN and LRMS subsystem involved two parts, validation of the transverse profile and rut depths against the TPB and validation of the MPTP rut depths against the GLP.

Validation of ARAN LRMS vs. TPB

To enable comparison of the ARAN 4.0 m transverse profiles and TPB 3.4 m reference profiles, the results were reduced to a common resolution. As both devices record in excess of 1000 transverse points, each set of data was aggregated to an interval of 0.01 m across the transverse profile. The TPB, being a mechanical device, measures the profile from a traversed wheel at the top of any stone chip while the ARAN LRMS lasers report the profile based on the point of incidence, which may be anywhere between the embedded base and top of the stone chip, a distance of potentially some millimetres. While there is a minor smoothing of these texture effects when aggregating the data to 0.01 m it was still expected the ARAN LRMS would exhibit more localised variability than the profiles of the TPB. Therefore on sites where the texture depth is at a minimum, the differences between survey and reference measurements were expected to be lower than on high texture sites.

As the ARAN LRMS measures a wider profile than the TPB and includes the contribution of cross-fall in the height measurements, the two profiles were not immediately compatible for comparison. Under ideal conditions the TPB will have a zero profile height at either edge of the profile, or zero cross-fall, in reality this was not the case. The starting relative height was for all intents and purposes zero but the relative height at the opposite edge of the profile varied up to 20 mm from zero, see the blue line and left scale of Figure 3 following. Further to this, as the

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profile widths were not the same the ARAN LRMS needed to be aligned to the TPB. This alignment was not constant but rather varied depending on vehicle placement under static conditions and minor fluctuations in drive line under dynamic survey speeds. This transverse offset can be more clearly seen between the blue and red lines in Figure 3 following which shows an offset of approximately 60 mm, that is, by sliding the red profile 60 mm to the left, the profiles would be in alignment albeit with different slopes.

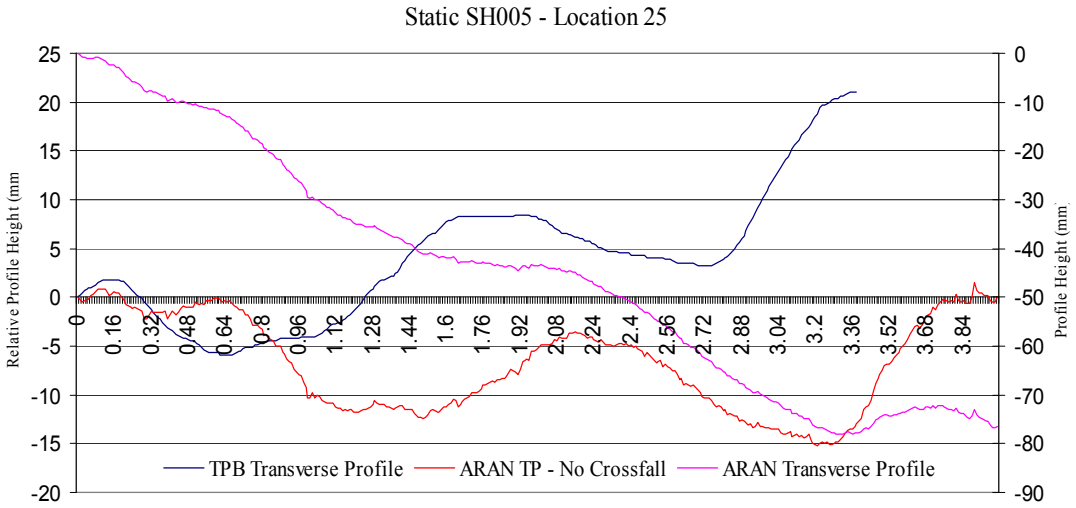

Figure 3: Raw transverse profile comparisons

While the cross-fall of the ARAN transverse profile was known at each location and its effect could be removed, as shown by the red line in Figure 3, there was still a significant discrepancy between the two profiles, including the unknown and variable transverse offset between the ARAN and TPB. As such a macro was written in excel to automate the task of adjusting the ARAN measured profile to match the pseudo cross-fall of the TPB while at the same time offsetting the ARAN profile until the best relative match was reached. This relative match was considered to have been reached when the statistical r^2 of the two profiles was at its greatest and was the basis for assessing how well the ARAN LRMS measured the true transverse profile of the road. The end result of matching the two profiles is shown in Figure 4 following and represents an r^2 of 99%.

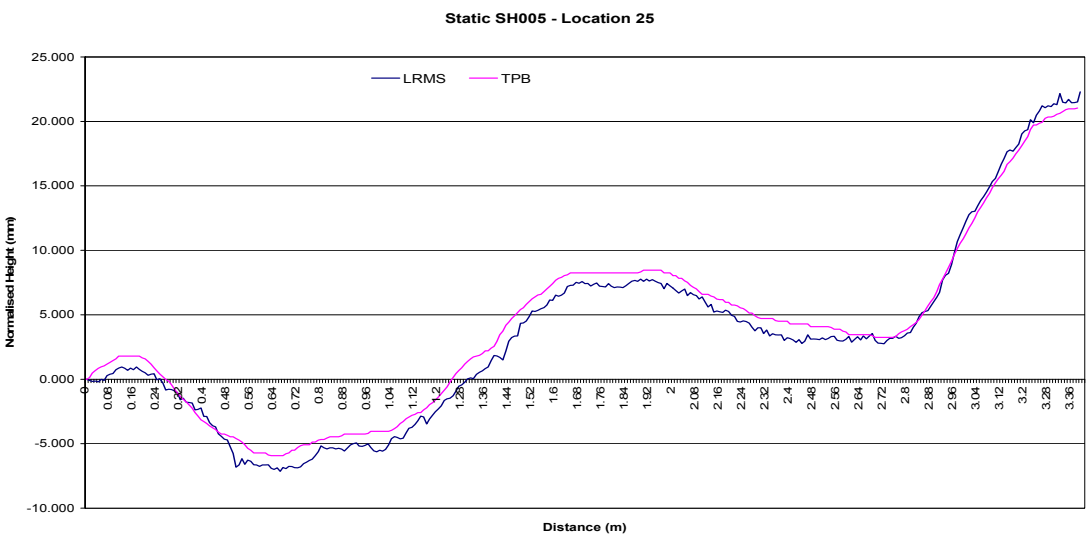

Figure 4: Final matched profile

After alignment of the two profiles across the six sites the ARAN transverse profiles achieved an r^2 greater than 0.9 for all sites with the exception of Site 14, see Table 3 following. This site had a very high texture depth close to 3.0 mm and as such the texture affects in the ARAN profiles were more pronounced.

Table 3: Transverse profile correlation

Site	Speed (km/hr)	r^2	Site	Speed (km/hr)	r^2
3	0	0.95	7	0	0.96
	40	0.96		40	0.96
	60	0.96		60	0.96
	80	0.96		80	0.96
4	0	0.94	13	0	0.98
	40	0.99		40	0.98
	60	0.98		60	0.98
	80	0.96		80	0.99
6	0	0.99	14	0	0.74
	40	0.98		40	0.84
	60	0.95		60	0.82
	80	N/A		80	0.82

Figure 5 to Figure 8 following provide examples of the transverse profiles representative of the correlation between the ARAN LRMS and reference TPB device for each site.

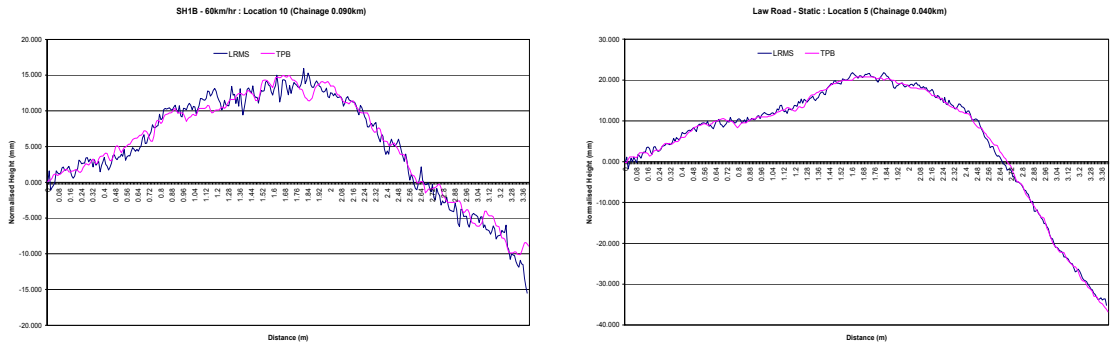

Figure 5: Site 3 (SH1B) & Site 13 (Law Road) – Example static comparison

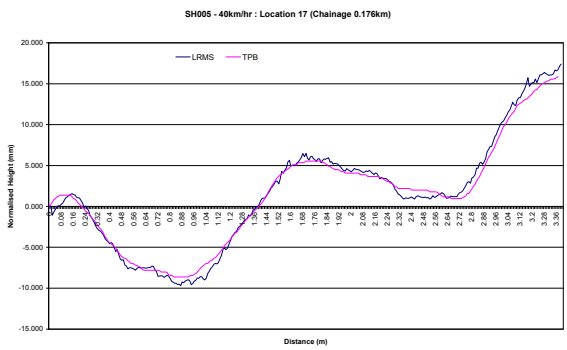

Figure 6: Site 6 (SH005) – Dynamic 40 km/hr transverse profile comparison

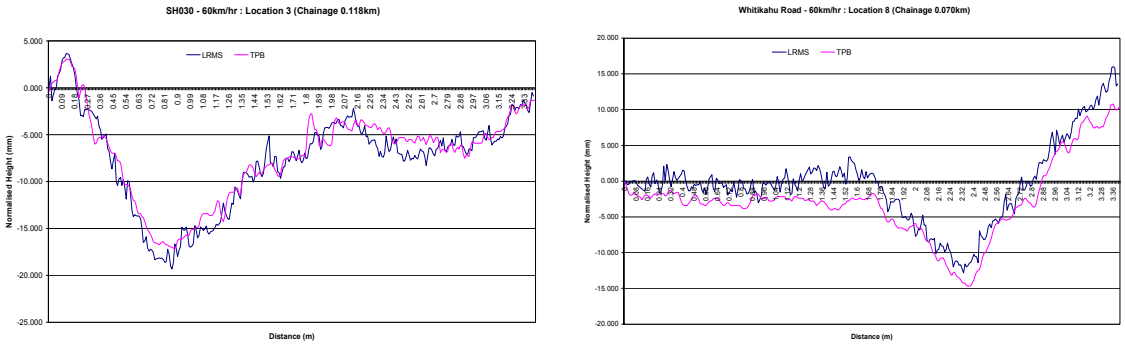

Figure 7: Site 7 (SH030) & Site 14 (Whitikahu Rd) – 60 km/hr transverse profile comparison

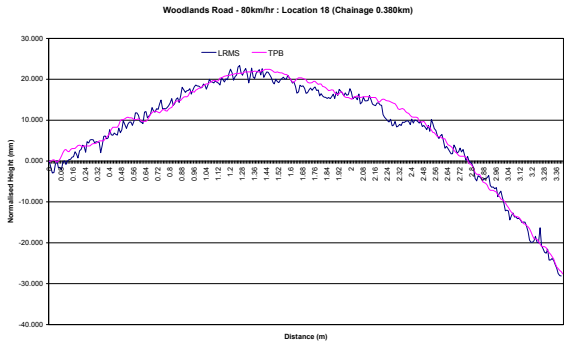

Figure 8: Site 4 (Woodlands Road) – Dynamic 80 km/hr transverse profile comparison

While the rut depth algorithms of the Vision software allow for the width of the transverse profiles to be reduced by narrowing the measured profile by equal amounts from both sides or as a transverse offset as mentioned earlier, this acts as a constant offset. As such this will not guarantee that the same 3.4 m footprint is achieved as that of the TPB for the derived rut depths. As discussed previously this is associated with static vehicle placement and fluctuations in drive line at survey speeds. As such the algorithms used to calculate the rut depths from these transverse profiles will not utilise exactly the same profile footprints as those compared and shown in Figure 5 to Figure 8 previously and some variability in the rut depths determined can be expected. As a result of this, the average rut depth across each of the validation sites was assessed rather than each individual location within the sites. The results show a good correlation after a constant transverse offset of 50 mm to align the ARAN LRMS profile to the TPB has been applied see Table 4 and Figure 9 following. This 50 mm offset was found to best represent the shift in the LRMS profiles needed to match the profiles of the two devices as discussed in §3.1 previously. It is important to note that the ARAN LRMS Static ruts were determined based on 100 point smoothing of the transverse profile data and not the 400 points used in the transverse profile validation.

Table 4: ARAN LRMS vs. TPB calculated rut depths

Site	Wheelpath	TPB (mm)	ARAN LRMS static (mm)	Difference (mm)
3	Left	4.60	5.53	0.93
	Right	5.32	5.42	0.10
4	Left	3.44	3.67	0.23
	Right	3.11	3.02	-0.09
6	Left	17.08	17.30	0.22
	Right	13.89	12.75	-1.14
7	Left	19.82	19.06	-0.76
	Right	9.53	9.89	0.36
13	Left	5.75	5.95	0.20
	Right	3.97	3.92	-0.05
14	Left	7.44	8.13	1.69
	Right	9.39	9.55	0.16

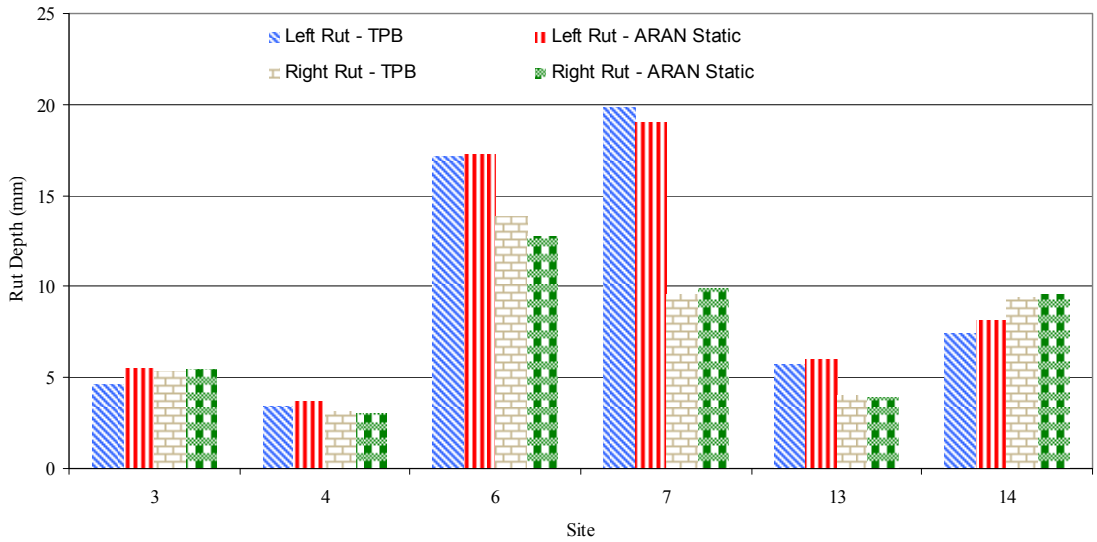

Figure 9: ARAN LRMS vs. TPB calculated rut depths

Validation of MPTP filtered rut depths vs. GLP

Having verified the transverse profiles and rut depths of the ARAN LRMS against the reference device there now exists a strong case for undertaking MPTP filtering of the LRMS data. Applying the MPTP filtering to the ARAN LRMS profiles using the laser positions of the GLP, the rut depth results were analysed. Figure 10 and Figure 11 following, present the rut depth results pre (green line) and post MPTP filtering (blue line). By applying MPTP filtering and only using 13 points from the LRMS transverse profile there is a significant reduction in the rut depths measured. These rut depths are also more closely aligned with those of the GLP as can be seen by the Blue and Brown lines with the blue line representing the ruts calculated after MPTP filtering.

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It is important to note that the Green line representing the 100 point rut depth is based on a 3.4 m profile footprint equivalent to the TPB, whereas the GLP and MPTP filtered rut depths are based only on 3 m. The effect of this wider footprint is most clearly illustrated in Figure 7 shown previously, where the profile peaks occur at the edge of the profile which for the GLP and MPTP filtered profiles would be 0.2 m inside this. As a result the rut depths from a narrower profile would be lower, furthermore the results shown following were determined from the average of the 10 runs completed at 60 km/hr over the two days.

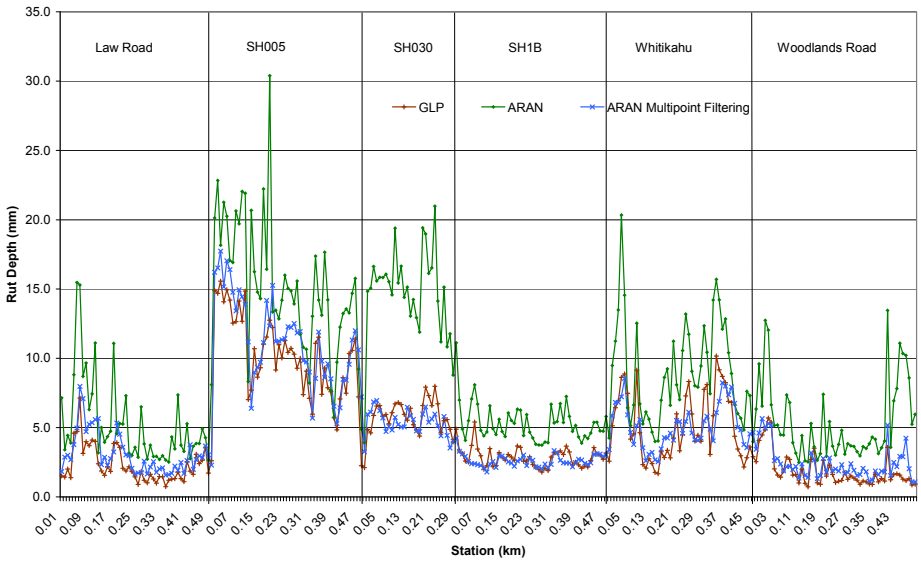

Figure 10: ARAN LRMS vs. GLP – Left wheelpath rut

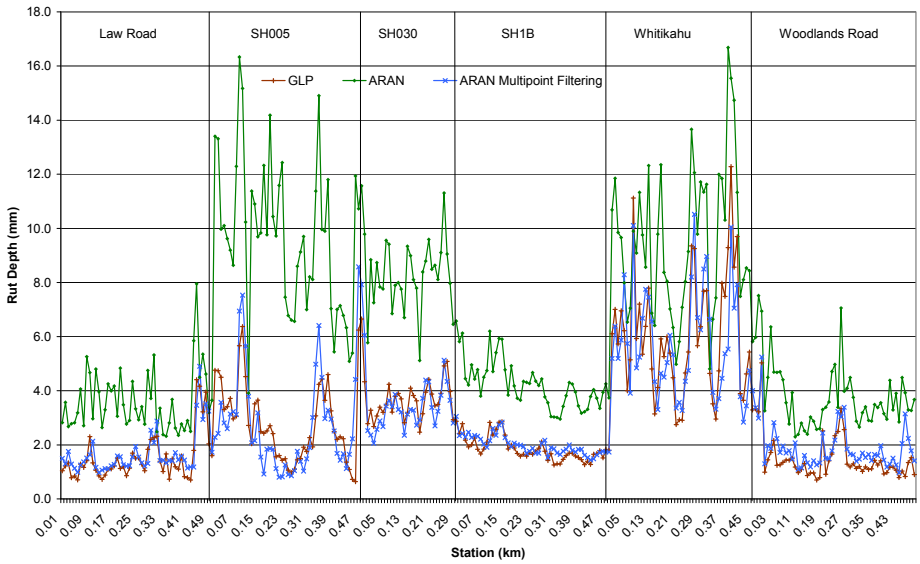

Figure 11: ARAN LRMS vs. GLP – Right wheelpath rut

Analysing the data further it can be seen in Table 5 following, the rut depths are, with the exception of the left wheelpath of site 6 within 1 mm of each other and for the most part within 0.5 mm. There is also generally a higher variance in the left wheelpath ruts which may be a result of differences in the edge filtering methods of the rut algorithms used by Greenwood and Fugro. It is important to note that both methods used the same 2 m straight edge settings to quantify the depth of rutting.

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Table 5: LRMS MPTP vs. GLP calculated rut depths

Site	Wheelpath	GLP (mm)	LRMS MPTP (mm)	Difference (mm)
3	Left	2.93	2.65	-0.28
	Right	1.93	2.06	0.13
4	Left	1.97	2.49	0.52
	Right	1.54	1.90	0.36
6	Left	10.94	12.10	1.16
	Right	2.81	2.67	-0.14
7	Left	5.84	5.31	-0.53
	Right	3.54	3.27	-0.27
13	Left	3.28	4.03	-0.75
	Right	2.03	1.98	-0.05
14	Left	5.03	5.08	0.05
	Right	5.74	5.51	-0.23

Looking at all sites combined Table 6 following, presents an overall summary of the correlation between the two systems. The left and right wheelpaths have an r^2 respectively of 0.89 and 0.83, and these results are based on 10 m data and subject to the associated higher variability which occurs from data reported at smaller intervals. The differences in the left wheelpath rut depths seen in Table 5 translates to a 0.4 mm difference in mean rut depth however the r and r^2 for the left wheelpath is higher than the right suggesting a greater correlation despite the right wheelpath mean being the same.

The reason for this is associated with the left wheelpath ruts exhibiting a greater range of calculated rut depths (1.97 mm – 10.94 mm) than those of the right wheelpath which only vary on average between 1.54 mm – 5.74 mm. For this reason it is also necessary to consider that, while the left wheelpath ruts are higher than the right, they still do not cover the full range of possible rut depths measureable for each system. When using the statistical r^2 method of analysis it is important to consider where possible the full range of observable results.

Table 6: Summary statistical analysis

	GLP		LRMS MPTP	
	LWP	RWP	LWP	RWP
Mean	4.5	2.8	4.9	2.8
r			0.9429	0.9121
r^2			0.8891	0.8320
Slope			0.9097	0.9767
Intercept			0.0915	0.0178

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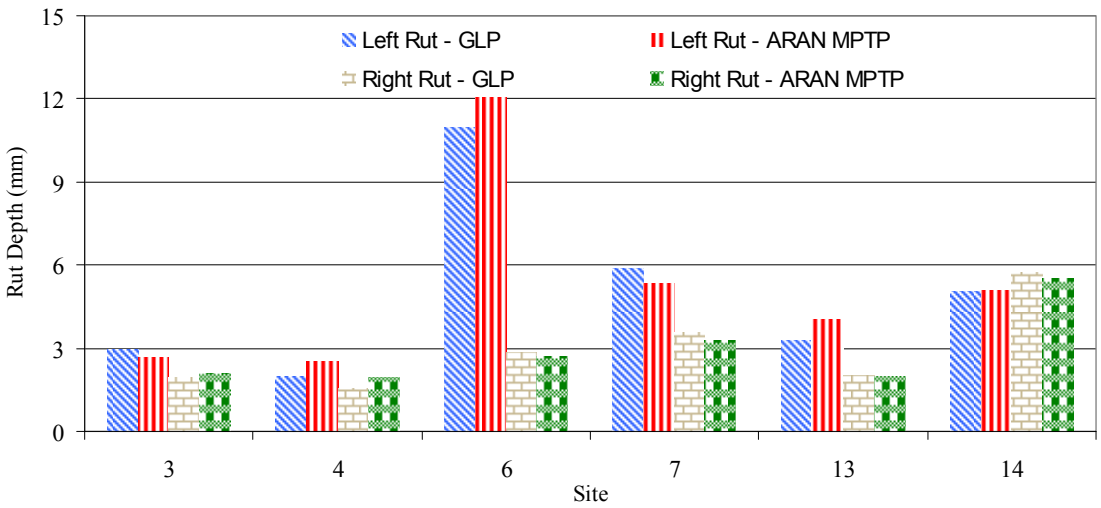

Figure 12: ARAN MPTP filtering vs. GLP calculated rut depths

CONCLUSIONS AND RECOMENDATION

The validation exercise completed with the LRMS against the TPB demonstrates the ARAN is capable of measuring the true profile of the road to a high level of precision. Furthermore the level of resolution achieved by the LRMS is sufficient to undertake additional Multipoint Transverse Profile (MPTP) filtering in order to calculate equivalent 13 point derived rut depths. The results of this MPTP filtering across six sites with rut depth characteristics ranging from low < 5 mm to high > 20 mm and surface texture characteristics ranging from < 0.5 mm to > 2 mm showed a very strong correlation. Some isolated minor differences were observed which are thought to be the result in differences between how each algorithm handles edge filtering.

Based on these results there is strong evidence to suggest that rutting derived from MPTP filtering is suitable for quantifying the change in rutting that has occurred since the last survey collected by traditional non contract laser systems. This can achieved without having to collect rutting data from both systems at the same time to quantify this change. At the same time Road Agencies have the information by which they can transition confidently to laser projection systems. This can be done while still making use of their historical data and if necessary adjusting their KPI's and intervention levels from those determined using traditional laser results.

Further investigation is planned to confirm the effectiveness of the MPTP filtering across a wider sample set. This will involve approximately 2500 km of road pavement that has been surveyed on an annual basis for the past five years. Using this data the historical trends will be analysed to determine if there are any quantifiable changes to the trend by introducing rutting derived by MPTP filtering. This is expected to confirm the suitability of using the difference between unfiltered and MPTP filtered ruts from the LRMS as justification for adjusting KPI's and Road Agency intervention levels.

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