Comparison of Roughness Calibration Equipment - with a View to Increased Confidence in Network Level Data

G. Morrow, A. Francis, S.B. Costello, R.C.M. Dunn

Abstract
With the advent of key performance indicators and performance specified maintenance contracts (PSMC), both in New Zealand and abroad, the accuracy, repeatability and reproducibility of roughness data is coming under increased scrutiny. Continuity of the service provider and their equipment has proven to assist in obtaining repeatable results. However, in some circumstances a change in the service provider has lead to a significant change in the average overall network figures, which appears largely unsubstantiated to the road controlling authority (RCA).

Roughness is measured in network surveys using either profilometers or response type road roughness measuring systems (RTRRMS). Responsibility for calibration of the equipment resides with the service provider. Checks are often performed throughout the duration of the survey to ensure the vehicle stays within accepted bounds, specifically for RTRRMS. It is usual to have the vehicle run over the same section of road and compare the results with those obtained from previous runs. This provides the road controlling authority with some assurance of data repeatability, but does not provide assurance that the machine was correctly calibrated to begin with.

For calibration it is necessary to provide a reference roughness. This provides the road controlling authority with confidence that the equipment is calibrated correctly prior to the roughness survey being undertaken on their network. There are a variety of instruments available for calibration level surveys, each with different levels of accuracy and precision. This research assesses and evaluates the accuracy of these different instruments, which range from low to high cost methods, for establishing the reference roughness on selected calibration sites.

INTRODUCTION

With the advent of key performance indicators and performance specified maintenance contracts (PSMC), both in New Zealand and abroad, the accuracy, repeatability and reproducibility of roughness data is coming under increased scrutiny. In addition, pavement deterioration modelling, an integral part of such contracts, relies on historical data to predict future trends with accuracy. Clearly, any irregularities in the data will be reflected in the accuracy of the resulting deterioration models.

On more conventional contracts in New Zealand, roughness is a key trigger in determining maintenance treatments for sections using the treatment selection algorithm (TSA) in the Road Assessment and Maintenance Management (RAMM) database. In addition, roughness data is used to support Land Transport New Zealand applications for shape correction works, and is a component of vehicle operating cost for submissions made in accordance with the Project Evaluation Manual (Transfund, 2004).

Continuity of the service provider and their equipment has proven to assist in obtaining repeatability of results. However, in some circumstances a change in the service provider has lead to a significant change in the average overall network figures, which appears largely unsubstantiated to the road controlling authority (RCA). Austroads (1999), for example, reported a 14% change in network roughness when the service provider and equipment manufacturer was changed, even though the contract specification remained the same.

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INTERNATIONAL ROUGHNESS INDEX

Although historically, in New Zealand and Australia, the measure for roughness has been NAASRA counts/km (National Association of Australian State Road Authorities), the accepted world standard is the International Roughness Index (IRI). The IRI was an outcome of the International Road Roughness Experiment conducted in Brazil (Sayers et al., 1986) and is reproducible, portable and stable with time. This allows data from different instruments and different countries to be directly compared and enables historical trends to be determined with confidence.

IRI is calculated as follows (Sayers, 1995):

- The IRI is computed from a single longitudinal wheelpath profile. The sample interval should be no larger than 300 mm for accurate calculations. The required resolution depends on the roughness level, with finer resolution being needed for smooth roads. A resolution of 0.5 mm is suitable for all conditions.
- The profile is assumed to have a constant slope between sampled elevation points.
- The profile is smoothed with a moving average whose baselength is 250 mm.
- The smoothed profile is filtered using a quarter-car simulation, with specific parameter values (Golden Car), at a simulated speed of 80 km/h.
- The simulated suspension motion is linearly accumulated and divided by the length of the profile to yield IRI. Thus, IRI has units of slope (m/km).

The underlying IRI algorithm is a series of differential equations, which relate the motion of a simulated quarter-car to the road profile. The IRI is the accumulation of the motion between the sprung and unsprung masses in the quarter-car model, normalised by the length of the profile. Mathematically this is expressed as:

$$IRI = \frac{1}{L}\int_{0}^{L/S} \left| z_s - z_u \right| dt$$

where IRI is the roughness in IRI m/km, L is the length of the profile in km, S is the simulated speed (80 km/h), z_s is the time derivative of the height of the sprung mass and z_u is the time derivative of the height of the unsprung mass.

SITE SETUP

Considerable effort was devoted to the selection and setting out of the sites. Issues, such as the safety of the survey team, required traffic management, homogeneity of roughness within each site, variability between sites and how to mark out the sites, were all considered.

Site Selection Criteria

The following site selection criteria were used when looking for candidate sites on which to undertake roughness data collection:

- The sites had to be generally on flat terrain, or at a constant grade.
- The sites had to be at least 300m in length.
- A lead in and run out length of road was required in addition to the length of the survey section. This was to provide for safe stopping distance for traffic.
- The sites had to be of fairly uniform roughness over their length.
- Variability in roughness levels between sites was required so the equipment could be tested throughout the roughness range.
- Travel time between sites should be minimised to reduce lost time.
- Identify more sites than required with the expectation that some would be lost due to maintenance or rehabilitation work.

Preliminary Screening

Preliminary screening of possible site locations was carried out using the ROMDAS Vehicle Mounted Bump Integrator, which measures the relative displacement of the vehicle suspension to the floor of the vehicle (DCL, 2004). The relative displacement is recorded in pulses, with each pulse equivalent to 0.8mm suspension movement. The data was collected at a sampling interval of 50m and then summed to intervals of 300m. Sections were selected based on the total roughness. A number of sites were eliminated due to limited approach sight distance and a short list of seven sites was obtained. The locations of the sites were marked with paint and digital photographs taken of the area. It was decided to survey all sites with the expectation that some would be lost during the research period due to maintenance or rehabilitation work.

The test vehicle was driven up to speed (50 km/hr) in advance of the start of the calibration section. At the start of the section, the ROMDAS software was initiated and commenced recording. The software automatically stopped recording at the end of the 300m and the data was saved to disk. The procedure was repeated several times and, as can be seen in Table 1, the resulting standard errors (SE) as a percentage of the mean are almost all below 1%. The means range from 2016 to 5013 thereby ensuring a good spread of roughness between sites.

Site	Run 1	Run 2	Run 3	Mean	Std Dev.	SE	SE(%)
1	4144	4067	-	4106	54	38.5	0.94
2	3907	3898	-	3903	6	4.5	0.12
3	3285	3117	3173	3192	86	49.4	1.55
4	2890	2946	2961	2932	37	21.6	0.74
5	2002	1993	2053	2016	32	18.7	0.93
6	2351	2333	-	2342	13	9.0	0.38
7	5019	5007	-	5013	8	6.0	0.12

Table 1: Preliminary Screening of Survey Sites (HTC, 2000)

Traffic Management

The extent of traffic management required generally depends on the average daily traffic (ADT) traveling through the survey site. The higher the traffic volume, the higher the level of traffic management required. A traffic management plan (TMP) was required to be submitted to the RCA for approval prior to undertaking any survey work on the road. In New Zealand, many RCAs have adopted the “Code of Practice for Temporary Traffic Management”, or COPTTM (Transit, 2004). Guidance is provided in this manual as to the appropriate level of traffic management required for surveying activities, and the traffic management devices required to be used. In accordance with the COPTTM, the person preparing the TMP must have the required qualification as should the person tasked with setting up and management of the site.

Setting Out

Setting out and marking of the sites is extremely important to ensure all surveys start at exactly the same location and that the same line is followed. This avoids introducing differences in profiles due to different wheelpaths being surveyed. The process undertaken is detailed below:

- The middle of the lane was defined as being halfway between the centreline and the left hand edge of seal. The wheel paths were then spot marked every 50m at 0.8m each side of the middle of the lane. This reflects the 90%ile car width of 1.750m in New Zealand less approximately 180mm for tyre width to give an approximate width of 1.6m (LTSA, 1994). Install road nails at 50m intervals once the spot marks have been checked for correct alignment.
- Once the 50m interval marks were established, the 25m and 5m points were marked. Initially the 25m points were marked with chalk to make sure the alignment of the wheel path was smooth and not becoming jagged. When the alignment was considered correct the 25m points were marked with paint. Infill marking was then completed between the 25m points at 5m intervals. Once the 5m intervals were established, individual points were marked every 250mm, using a fibreglass tape.

INSTRUMENT SELECTION

A variety of instruments exist for calibration level surveys, each with different levels of accuracy and precision, represented by their "Class" (Sayers et al., 1986), and each with different cost, time and effort implications. Consequently, a selection of roughness calibration equipment ranging from high to low cost and with varying degrees of accuracy and precision were chosen. Firstly, a Class 1 profilometer, to be used as a reference instrument, would be required. Ideally this should be the Face Technologies Dipstick, with a reported accuracy of approximately 0.01mm, as this is the most widely used and accepted Class 1 profiler for calibration purposes. However, issues with availability resulted in the z-250, developed by Data Collection Limited (DCL), being used for this purpose. The z-250 operates on the same principles as the Dipstick and has the same sampling interval. The z-250 has been calibrated against the Dipstick resulting in an R^2 valued of 0.9958. The other instruments selected needed to offer either an increase in speed of operation or provide a lower cost option. The Walking Profilometer developed by the Australian Road Research Board (ARRB) offered a quicker operational speed to the Dipstick and is also a Class 1 instrument. The rod and level, popular in developing countries for calibrating roughness meters, because of its almost universal availability, can be classified as a Class 1 or Class 2 instrument depending on the sampling interval used. Finally, the Merlin, developed by the Transport Research Laboratory (TRL), and the Riley or mini-Merlin, offered lower specification alternatives. Both are considered Class 3 instruments and are cheap and simple to use. Plans for the construction of the Merlin (Mark 1) and Riley were obtained and the instruments fabricated locally.

Stationary Inclinometer (z-250)

The ROMDAS z-250 reference profiler, shown in Figure 1, was developed for measuring accurate reference profiles of pavements and, as noted earlier, is similar in design to the Dipstick. The z-250 consists of a measurement unit and a hand-held pocket PC, as the data logger. The measurement unit contains a battery and precision inclinometer along with a power circuitry. The inclinometer outputs a serial signal that is recorded and processed by the data logger (DCL, 2002). To collect profile information for a wheel path the z-250 is 'walked' along the road. The distance between the centre of the two moon feet on its base is 250mm. The data interval for the collected data is therefore 250mm.

Figure 1: ROMDAS z-250 Stationary Inclinometer.

Figure 2 shows the z-250 in operation. The 'walking' process consists of rotating the unit on each foot in turn along the marked wheelpath. The unit is placed at the start of the calibration section and kept stationary, to allow the slope of the profile to be recorded. The unit is then rotated about the front foot, with the rear foot brought forward in a clockwise rotation. The rear foot is then placed forward of the front foot along the line of the wheelpath, with the centre handle held vertical. The operator then pauses until the instrument beeps to indicate that a reading has been taken. The unit is then rotated in a clockwise direction anchoring around the 'new' front foot, to bring the 'new' rear foot to the front. This 'walking' action is continued until the end of the wheelpath to be profiled is reached, where 'end' is pressed on the hand-held PC. The roughness in IRI m/km will be displayed, and optionally a graph can be produced.

Figure 2: ROMDAS z-250 walking process

The instrument complies with the World Bank requirements for a Class 1 profilometer. It has a step size corresponding to a sampling interval of 250mm and is capable of measuring a height measurement resolution of ± 0.1mm. This meets the Class 1 requirements of 300mm and 0.5mm respectively.

Walking Profilometer

The ARRB Walking Profilometer, shown in Figure 3, is a high quality precision instrument designed to facilitate the efficient collection and presentation of continuous paved surface information, including distance, profile and grade (ARRB, 2001). The Walking Profilometer measures road profiles in a similar way to the z-250, except the walking process is automated by the operator pushing the machine along a wheelpath at walking speed, hence the name walking profilometer. As this is done at a slow continuous walking speed the time taken to profile the wheelpaths is considerably less than for the z-250.

The instrument records profile elevation data by measuring the output of an accelerometer that is fixed between two contacts points, as the device steps along the road surface (Fong and Brown, 1997). The step length or data sample interval is 0.2413m, with a height measurement precision of ± 0.01mm per step. Hence, this instrument also complies with the World Bank requirements for a Class 1 profilometer.

Figure 3: ARRB Walking Profilometer

Merlin

The TRL Merlin (Machine for Evaluating Roughness using Low-cost Instrumentation) is a simple roughness measuring machine designed for use in developing countries (Cundill, 1991). As shown in Figure 4, the device consists of a metal frame 1.8m in length, a bicycle tyre at the front, a foot at the rear, and a moving foot mid way to record the mid-chord deflection. The centre foot for recording the mid-chord deflection has a pointer at the other end, for use when manually recording the points onto a graph. For this research, an automated data logging system was utilised. This included the use of a digimatic indicator for recording the deflections at the base of the centre probe and a laptop for storing the data.

Figure 4: TRL Merlin (Mk 1)

The machine is pushed along the road and readings taken at regular intervals, typically one revolution of the wheel. For the purposes this research, it was decided to record data at half revolution intervals. The width of the histogram is obtained and used to calculate IRI by correlation, from published equations. There are a number of equations that can be used depending on the type of surface. For example, equations exist for asphaltic concrete, surface treated (chip seals), gravel and earth.

A general purpose equation, developed by Cundill (1991), exists for all road surfaces. This was carried out using computer simulations of its operation on road profiles measured in the 1982 International Road Roughness experiment. The relationship between the Merlin scale and the IRI scale for all road surfaces is:

$$IRI = 0.593 + 0.047D$$

where IRI is the roughness in terms of the International Roughness Index, measured in metres per kilometre (m/km), and D is the roughness in terms of the Merlin scale, measured in mm. The equation is valid for D greater than 42mm and less than 312mm, which equates to IRI greater than 2.4m/km and less than 15.9m/km. This equation was used to calculate IRI for the sites surveyed in this study.

Rod and Level

The rod and level are familiar surveying tools to most engineers. The level provides the elevation reference, the readings from the rod provide the height relative to the reference, and a tape measure provides the distance between individual elevation points. However, the requirements for obtaining a profile measure suitable for determining roughness are much more stringent than under normal operation. For example, Sayers et al. (1986) recommend that elevation measures be taken at intervals of 250 mm for Class 1 surveys and 500 mm for Class 2. In addition, the individual height measures must be accurate to 0.5mm or less. In contrast, the absolute height of the instrument is not a concern for roughness measurements, even though such information is imperative when using a rod and level for other applications. Readers are referred to Sayers et al. (1986) for a detailed description of the procedure.

Riley

Based on the same principles as the Merlin (mid-chord deviation), the Riley or mini-Merlin, shown in Figure 5, is a simpler and more portable device using a sectional beam and a dial gauge. The instrument is placed at the start of the calibration section and the dial gauge reading recorded. Moving the instrument to the next point, the instrument is again placed on the road and the dial gauge reading recorded. This is repeated until the end of the section.

Figure 5: Riley or mini-Merlin

The standard deviation of the readings is then recorded and the IRI, measured in metres per kilometre (m/km), is given by (Riley, undated):

$$IRI = 0.593 + 7.75 STD_{adi} \quad \text{where} \quad STD_{adj} = STD \frac{LAR}{5}$$

STD_{adi} is the standard deviation of the recorded values, adjusted to account for the lever arm ratio of the instrument. STD is the standard deviation calculated from the raw dial gauge readings and LAR is the actual lever arm ratio of the instrument as determined from the calibration. The denominator is the lever arm ratio used in deriving the conversion formula.

RESULTS AND ANALYSIS

The roughness at each site, both left and right wheelpaths, was measured using each of the instruments. Of the seven original sites surveyed, three were lost due to maintenance or rehabilitation work during the course of the research. The results from the four remaining sites are summarised in Table 2. The IRI obtained across the eight remaining wheelpaths, range from 7.24 down to 1.86 IRI m/km for the z-250, which covers almost the full spectrum of IRI for paved roads. Newly paved surfaces typically range from about 1.5 to 3 IRI m/km, older paved surfaces from 2.5 to 5.5 IRI m/km and damaged pavements as high as 11 IRI m/km.

	Site No. 3		**Site No. 5**		**Site No. 6**		**Site No. 7**	
	IRI (m/km)		**IRI (m/km)**		**IRI (m/km)**		**IRI (m/km)**	
Instrument	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
z-250	7.24	5.55	4.30	3.72	1.86	2.55	1.92	2.08
WP	7.38	5.31	4.27	3.46	1.79	2.12	1.74	2.06
Merlin	6.85	5.39	4.42	3.90	2.41	2.67	2.40	2.50
Riley	6.27	4.65	4.09	3.52	2.60	2.83	2.42	3.04
R&L (250mm)	7.18	5.19	4.39	3.67	2.21	2.85	2.45	2.77
R&L (500mm)	6.73	4.85	4.26	3.49	2.12	2.67	2.26	2.75

Table 2: Survey Summary Results for each instrument

These are shown graphically in Figure 6. It is noted, that the correct relative roughness between sites is maintained from instrument to instrument. In particular, the three Class 1 instruments produce very similar results, as would be expected, except on relatively smooth surfaces (below about 3 IRI m/km) where the rod and level overestimates the roughness. This is not altogether unexpected as the required resolution depends on the roughness level, with finer resolution needed for smooth pavements. When used as a Class 2 instrument the rod and level consistently produces lower estimates of roughness than its Class 1 equivalent. In addition, the Riley, a Class 3 instrument, significantly underestimates the roughness on rougher surfaces. Finally, for a Class 3 instrument the Merlin produces consistently accurate results when compared to the Class 1 instruments.

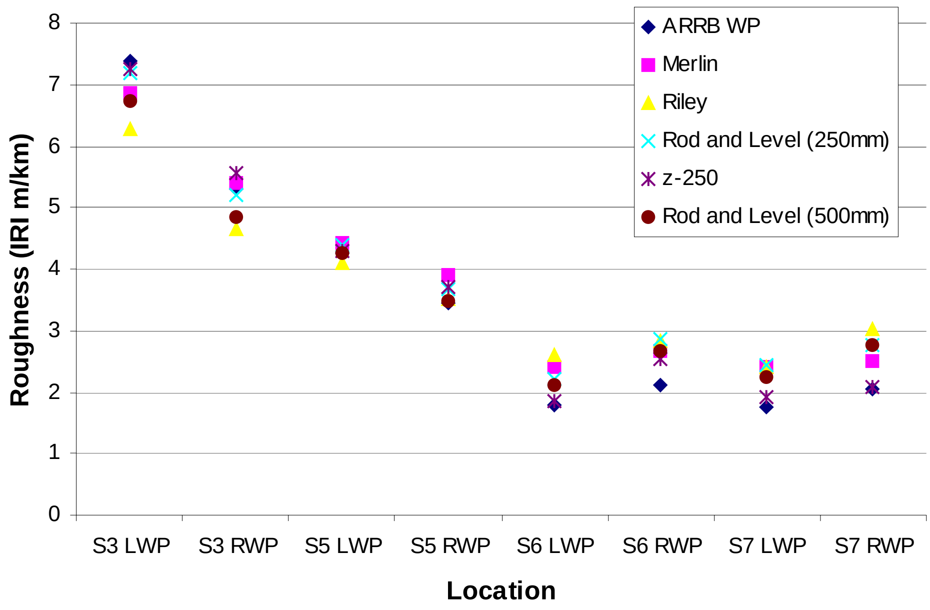

Figure 6: Wheel Path IRI for each Site

Repeatability and reproducibility of the Walking Profilometer, Merlin and z-250 were assessed on one wheelpath of a 50m section of road. Each instrument underwent five repeat runs with two different operators. The results of these multiple runs are displayed in Table 3 and graphically in Figure 7.

	Operator 1					Operator 2				
	Run Number					Run Number				
Instrument	1	2	3	4	5	1	2	3	4	5
ARRB WP	2.06	2.16	2.08	2.14	2.14	2.18	2.11	2.10	2.08	2.13
Merlin	2.95	2.48	2.48	2.71	2.81	2.46	2.59	2.44	2.67	2.71
z-250	2.23	2.19	2.22	1.94	2.15	2.19	2.13	2.23	2.21	2.19

Table 3: Multiple Run Results

Clearly, the variability of the Class 3 Merlin is greater than the two Class 1 instruments, both for the same operator and between operators. Both of the Class 1 instruments are relatively consistent when used by the same operator but some variability is noted between operators. This is further highlighted in Table 4 where the averages and standard deviations of the multiple runs are displayed.

It should be noted, however, that operator 1 was unfamiliar with the instruments whereas operator 2 was responsible for collecting the roughness data using all three instruments on the main sites. This introduces the question of operator error, particularly for those unfamiliar with the instruments. Referring to Table 3 it is noted that the standard deviation for operator 2 for the Class 1 instruments was very low, 0.04 for the Walking Profilometer and 0.04 for the z-250. For the Class 3 Merlin this increased to 0.12.

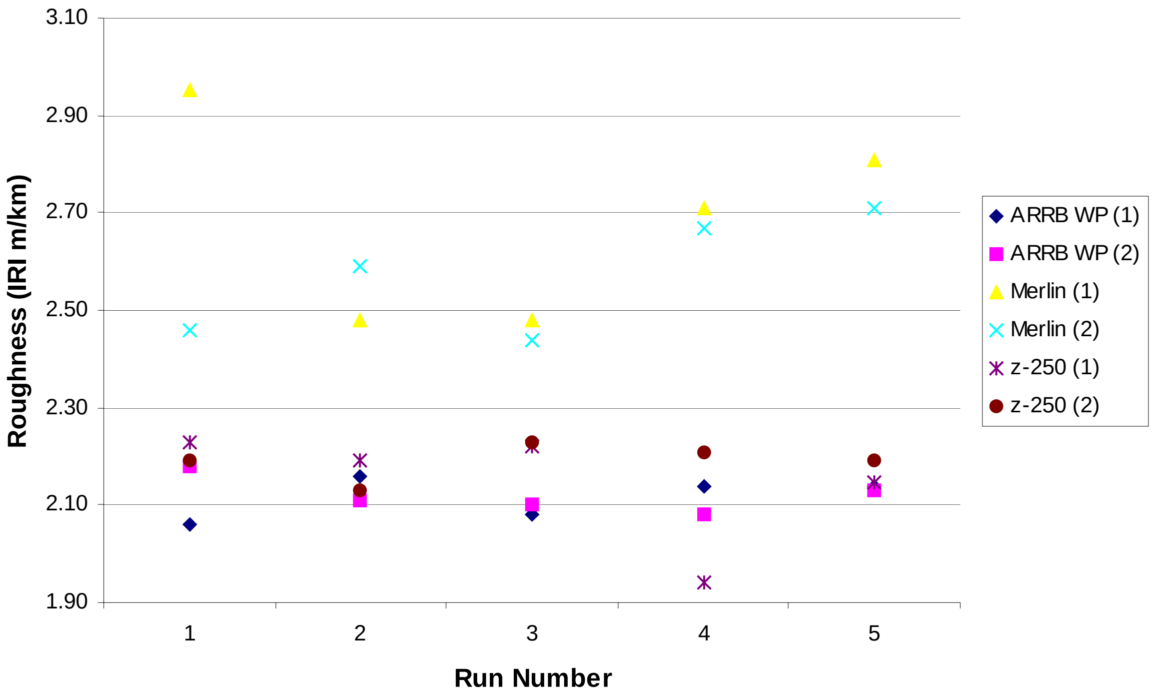

Figure 7: Multiple Run Results

In contrast, operator 1 returned a standard deviation almost twice that for the Merlin and three times that for the z-250. This would seem to reflect the operator dependence of stationary inclinometers. This observation is backed up by Bertrand et al. (1991), who indicated that although very accurate, stationary inclinometers are extremely sensitive to how they are operated. In contrast, the Walking Profilometer is relatively operator independent as the 'walking' is automated, with the operator responsible only for pushing the device. This is reflected in the fact that the average and standard deviation for the Walking Profilometer remained the same between operators, at 2.12 and 0.04 respectively.

	Operator 1		Operator 2	
Instrument	**Average**	**Std Dev.**	**Average**	**Std Dev.**
ARRB WP	2.12	0.04	2.12	0.04
Merlin	2.69	0.21	2.57	0.12
z-250	2.15	0.12	2.19	0.04

Table 4: Average and Standard Deviation of Multiple Runs

DISCUSSION AND CONCLUSIONS

The importance of calibrating high-speed data collection devices for the measurement of roughness, in particular RTRRMS, cannot be underestimated. The myriad of instruments available range from precision profilers, such as stationary inclinometers and walking profilometers, to lower specification alternatives, such as the Merlin or Riley. All such devices offer advantages over their competitors. The stationary inclinometer, the most widely used and accepted Class 1 profiler for calibration purposes, is relatively expensive and laborious to use. In addition, its operation is highly sensitive to how it is operated. The Walking Profilometer is both faster and easier to operate but is even more expensive, without delivering any increase in accuracy over the industry standard Face Technologies Dipstick. The Merlin, for a Class 3 instrument, performed extremely well and is easy to use. However, it lacks the portability of the Riley. The rod and level is probably the most familiar, and readily available, of all the instruments, however, it is extremely labour intensive and is really only suited to the developing world where labour is inexpensive.

In summary, it is clear that this is a case of "horses for courses" with Class 1 instruments remaining the choice for long-term pavement performance (LTPP) studies such as that reported by Henning et al. (2004) and low cost Class 3 or labour intensive instruments serving the developing world. In between these two extremes the right combination of cost and precision will dictate the engineer's choice, particularly as the correct relative roughness between sites is maintained for all instruments.

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AUTHOR INFORMATION

Gregg Morrow
Senior Engineer
Opus International Consultants Ltd
P.O. Box 272-1088, Papakura, New Zealand
Phone +64 9 296 9690, Fax +64 9 296 9699
Email gregg.morrow@opus.co.nz

Adam Francis
Senior Traffic Engineer
Beca Carter Hollings and Ferner
P.O. Box 6345, Auckland, New Zealand
Phone +64-9-300 9000, Fax +64-9-300 9300
Email afrancis@beca.co.nz

Seósamh B. Costello
Senior Lecturer
Department of Civil and Environmental Engineering
The University of Auckland, Private Bag 92019,
Auckland, New Zealand
Phone +64 9 373 7599, Fax +64 9 373 7462
Email s.costello@auckland.ac.nz

Roger C.M. Dunn
Associate Professor,
Department of Civil and Environmental Engineering
The University of Auckland, Private Bag 92019
Auckland, New Zealand
Phone +64 9 373 7599 Fax +64 9 373 7462
Email rcm.dunn@auckland.ac.nz