Reference Road Profiles for Profiler Validation

Transfund New Zealand Research Report No. 247

Reference Road Profiles for Profiler Validation

S. Fong
Opus International Consultants Ltd
Opus Central Laboratories, PO Box 30 845, Lower Hutt

Transfund New Zealand Research Report No. 247

ISBN 0-478-25357-5
ISSN 1174-0574

PO Box 2331, Lambton Quay, Wellington, New Zealand
Telephone 64-4 473-0220; Facsimile 64-4 499-0733

Fong, S. 2003. Reference Road Profiles for Profiler Validation. *Transfund New Zealand Research Report No 247.* 57pp.

Keywords: chipseals, inertial, longitudinal, New Zealand, profiler, roads, roughness, rutting, static, tracking, transverse, validation

An Important Note for the Reader

The research detailed in this report was commissioned by Transfund New Zealand. Transfund New Zealand is a Crown entity established under the Transit New Zealand Act 1989. Its principal objective is to allocate resources to achieve a safe and efficient roading system. Each year, Transfund New Zealand invests a portion of its funds on research that contributes to this objective.

Contents

Executive Summary

This study seeks to produce statistically sound procedures for determining reference transverse and longitudinal road profiles against which non-contact vehicle based profilers can be validated on highly textured chipseal road surfaces.

It was found that:

- Researchers, practitioners and end users internationally have identified problems with the interaction of highly textured surfaces and different designs of profiler devices.

- These difficulties are caused by differences in the size of the measuring footprint and sampling distance of static contact and non-contact vehicle based profilers.

- Chipseal road surfaces have high texture levels that cause problems when comparing profile measurements between current static contact and non-contact vehicle based profilers.

- Up to 10% difference at 3.0 mm Mean Profile Depth in derived roughness can result from static contact and non-contact vehicle based profiler systems that produce highly repeatable measurements.

- In most countries these differences are accepted as they have road networks mainly comprised of low texture surfaces.

- Tracking variations in roughness measurements are more dependent on the condition of the pavement and sensor configuration rather than the amount of tracking error.

- Tracking variations in rutting have been quantified in various rutting bands for an idealised survey system that measures the complete transverse profile so that the variability is due to tracking position errors alone, rather than sensor configuration.

- Rutting validation should be conducted by comparing measurements at matching transverse spacing.

These differences between the reference and vehicle profile measurement have become contentious issues during the validation of network survey equipment in Australasia. Road networks in these countries have a large proportion of medium to high textured surfaces. Therefore a specification has been developed that can resolve the differences between the two measurement technologies, allowing valid comparisons to be made. In deriving this specification, profile errors due to factors such as texture effect, tracking, profiler design and operation, have to be quantified so that they can be accounted for appropriately.

Abstract

Obtaining a reference road profile is vital for the validation of profiling devices. The accuracy of network survey profiles affects important pavement performance indices such as roughness and rutting. Various international researchers have identified problems with the interaction of road surface macrotexture, sensor footprint size and sample spacing of different types of profiler. Inherent measurement errors are associated with profiler devices and their operation on road surfaces with high levels of macrotexture. This presents difficulties in countries with predominantly chipseal surfaces,such as Australia and New Zealand, when making valid comparisons between profiler systems. The errors caused by large footprint size and high texture interaction have been identified and quantified. Validation criteria addressing these errors have been proposed. Measurement errors in roughness due to tracking or off-line surveying are more influenced by the transverse variability of the pavement condition rather than the transverse position of the survey vehicle. Measurement errors in rutting due to tracking or off line surveying have been quantified in various rutting bands for an idealised survey system that can reproduce the full transverse profile.

1. Introduction

A research programme was submitted to Transfund New Zealand in the 2001-2002 round to establish a statistically sound procedure for determining reference transverse and longitudinal road profiles. The purpose of these reference profiles is to allow validation of non-contact, vehicle based profilers on moderate to high-textured chipseal road surfaces that are prevalent in New Zealand.

An experimental study of the factors that affect profile measurement was conducted. The main factor for New Zealand road surfaces was highly textured surfaces that cause measurement bias on profilers with large measurement footprint. The current static profilers used for establishing reference validation measurements have large measurement footprints in comparison with the vehicle mounted inertial laser profilers. The effect of the interaction between footprint size and texture needs to be quantified to allow for robust validation procedures so that comparisons can be made between static and vehicle profilers.

The cause and effect of tracking errors due to transverse variability in instrument position need to be identified as they can have an adverse effect on the validation of roughness and rutting measurements.

2. Background

The reason for obtaining valid profiles for road networks is that they provide basic inputs to the condition monitoring of pavement management systems.

The condition monitoring of pavements is important for:

- Asset managers, to give accurate statistics on the state of the network.
- Pavement deterioration modelling to track changes in sections of the network.
- Performance based maintenance contracts to ensure the specified performance levels are met.

To be successful the profiler must be capable of sensing the relevant information present in the "true" profile and the data processing must produce a valid set of profile statistics. Profilers must be validated against a reference measurement. It is generally considered that the most accurate profiles are obtained from static contact devices. The most widely known devices of this type are the FACE Corporation Dipstick and ARRB Walking Profiler. These two devices operate by accumulating profile height differences between a rear and front foot that is progressively stepped forward over the road surface.

Opus Central Laboratories had been working with AUSTROADS during 1999 to develop guidelines for the validation of roughness measurements (AUSTROADS 2001a). During the development of these guidelines, problems were identified with the current static contact devices used for profile validation on highly textured surfaces. These guidelines expressly exclude the validation of roughness with static instruments on sites with medium to high levels of texture.

At the same time, Transit New Zealand also found that the large contact footprint and stepping effect of the current static profiler devices was creating measurement difficulties on chipseal surfaces. The predominant road surface used on the New Zealand state highway network is chipseal, which has high levels of texture.

The difference in size between the measuring "footprint" of static contact and non-contact devices is causing problems on highly textured surfaces. The small footprint of non-contact laser sensors on vehicle based high-speed data collection (HSDC) vehicles sees texture elements, while static contact devices ride over the texture. A 30% difference in roughness derived from the longitudinal profile is possible from different profilers (VicRoads, 1999).

Existing Transit New Zealand specifications for profiler validation are based on the 1999 tender documents for TNZ 2069: Road Condition Surveys: Roughness and Rutting. Validation of two HSDC profilers in New Zealand (WDM SCRIM+ and Greenwood Profilograph) has shown that these systems are capable of producing profile measurements that are more repeatable than static methods.

3. The "True" Profile

To measure the "true" road profile an infinite number of points would be required. What needs to be determined is the purpose of measuring the road profile from which the required level of accuracy can be defined. There will never be a measured "true" road profile but achievable limits of accuracy need to be defined to allow for comparisons between profiler devices.

Road profile accuracy is important, as there is a move away from response type systems for roughness measurement and from manual rating methods for rutting. Instead, the road profile is measured and processed to yield a roughness or rutting statistic.

In New Zealand the standard measure of roughness is the NAASRA count, which response type vehicles historically measured. These vehicles have been replaced by profilometric methods where a measured longitudinal road profile is processed through the International Roughness Index (Sayers, 1995) to yield a roughness statistic. The conversion between roughness in NAASRA and the International Roughness Index (IRI) is defined by Prem (1989).

The World Bank developed IRI (Sayers, et al. 1986) to standardise roughness measurements throughout the world. To achieve compatibility with a wide range of equipment, including response type systems, it was defined as a mathematical transformation of a measured road profile. The IRI acts as a filter on the measured road profile, which simulates the response of a Golden Car (Sayers, 1995) travelling over the road profile at 80 km/h. The road profile needs to be accurate between the wavelength ranges of 0.2 to 200 m, although the significant wavelengths are between 0.3 to 100 m. There are two resonant wavelengths of the car's suspension, wheel hop (2.4 m) and body bounce (16 m). The contributions from the wavelength range are summarised into one IRI value.

4. Selection of Reference Instrument

To collect profile reference validation data for the roughness calibration the selected reference profiler device must have a wavelength response that is uniform over the range of wavelengths that are important in the derivation of the roughness index. A uniform wavelength response means that the profiler reads consistently over the wavelength range with no significant amplification or attenuation of the profile variations. A profile can be mathematically broken down into a series of profile variations, each being described by a wavelength and amplitude. The wavelength is the longitudinal distance at which the profile variation occurs and the amplitude is the vertical distance.

In the specific case of the International Roughness Index (IRI), in New Zealand and Australia the wavelength range is between 0.3 to 100 m. PIARC (Europe) and ASTM (USA) have differing requirements for the maximum and minimum wavelengththat affects IRI. PIARC sets the minimum wavelength at 0.3 m that under sampling theory defines a maximum sampling distance of 0.15 m. ASTM specifies a minimum sampling distance of 0.3 m (they do note that a shorter interval will improve precision) that means that sampling theory will define a minimum wavelength of 0.6 m. The maximum wavelength influencing IRI was arbitrarily defined by PIARC at 50 m where ASTM defines a maximum of 100 m. Studies conducted in New Zealand (Fong and Brown, 1997) and Australia (Prem, 1998) show that the upper limit needs to be set at 100 m as the IRI computation still exhibits some sensitivity to wavelengths between 50 to 100 m. A good introduction to roughness measurement, the influence of profile wavelength, amplitude, and how IRI was developed and calculated is contained in The Little Book of Profiling by Sayers and Karamihas, 1998.

Given the limitations of current technology, only direct static measurement of the profile from a fixed reference can achieve the requirement for the flat wavelength response. The reference profiler must have a vertical resolution of better than 0.125 mm and maximum longitudinal sampling distance of 305 mm to follow ASTM E 1364-95 Class 1 criteria.

4.1 Instrument Descriptions

Instrument specifications are summarised in table 4.6.

4.1.1 Rod and Level

This is the most accessible device available for profiling but also the most labour intensive and time consuming. Full details concerning the operation of the rod and level for profiling are contained in ASTM E 1364-95. A minimum of two operators is required, with ASTM E 1364-95 recommending four operators to speed the measuring process; the third operator recording the profile heights and a fourth operator acting as relief to preserve accuracy by reducing fatigue. With three operators, each profile point can be measured in less than ten seconds. On a flat site, taking profile points every 300 mm, the measuring speed is just over 0.1 km/h, taking 4.5 hours to measure a 500 m long profile. Depending on the level used, profile height accuracy will be within 0.125 mm. Digital levels have height accuracies of 0.030 mm. To reduce variability on highly textured surfaces ASTM E 1364-95 recommends that a foot of at least 20 mm diameter be used on the rod. With large elevation changes the measuring speed will be slower as new levels have to be established more often. The data has to be tabulated to produce a continuous longitudinal profile.

Figure 4.1 Rod and Level Road Profiling.

4.1.2 TRL Beam

The TRL (Transport Research Laboratory, UK) beam consists of a linear vertical displacement transducer (LVDT) that is driven by a motor across a 3.6 m long horizontal beam. The beam is supported at the ends and levelled to produce a fixed horizontal reference. The LVDT is vertical to the road surface and has a 50 mm diameter by 6.5 mm wide wheel that follows the undulations of the ground. Profile points are collected at every 100 mm to a displayed accuracy of 0.1 mm. The beam is then repositioned along the site for the next 3.6 m segment. Two operators are required to move the beam because of its length and weight. The traverse speed along the site is 0.1 km/h, taking 4.5 hours to measure 500 m. The data has to be tabulated to produce a continuous longitudinal profile. The price to construct a TRL beam is approximately NZ$35,000.

Figure 4.2 TRL Beam and Measuring Wheel Detail (Photo courtesy Transit CAPTIF).

4.1.3 Dipstick

The Face Corporation (USA) Dipstick (DIP = Digital Incremental Profiler) is a precision inclinometer that measures the height difference between a pair of feet mounted on the end of a handle. The feet spacing can be altered from various spacing ranging from 100 mm to 300 mm. For profiling on highly textured surfaces 63.5 mm (2.5 in) diameter feet are used. The Dipstick is manually walked along the site by rotating the feet so that one foot is always in contact with the ground and the height differences accumulated to produce the road profile. Data is collected using a palmtop computer mounted on the Dipstick handle. This accumulates the height differences to produce a continuous profile. The palmtop emits a beep when it has taken a reading so that the Dipstick can be moved to the next position. A time delay is required when recording the data as this allows the inclinometer reading to stabilise before moving to the next position. The time constraint is a feature of all inclinometers as they are sensitive to background or residual vibrations that can cause measurement error. This time delay at each reading limits the Dipstick to a maximum survey speed of 0.2 km/h, taking 2.5 hours to measure 500 m. Only one operator is required but operator fatigue can lead to biased results so a relief operator should be used for profiling lengths greater than 500 m. Software provided with the Dipstick has routines that can be used to edit the profiles and generate IRI roughness values. The 2002 price for the Dipstick is US$15,000 (NZ$27,000) for the basic manual operation Dipstick and an additional US$5,000 (NZ$9,000) for the automated palmtop data acquisition system.

Figure 4.3 Dipstick in use (Photo from FACE Corporation).

4.1.4 ARRB Walking Profiler

The ARRB (Australian Road Research Board) Walking Profiler is also a precision inclinometer but a mechanism is used to step a 241.3 mm (9.5 in) long beam along the direction of travel. The mechanism is built into a wheeled unit that is manually pushed at a maximum speed of 0.8 km/h before an audible warning is sounded. At the maximum speed, it takes 40 minutes to measure 500 m. The inclinometer is mounted in the middle of the beam that is allowed to twist in the middle and has two feet at each end. Each foot is 80 mm square with three rubber pads 20 mm in diameter in a triangular arrangement. Packaged software with the ARRB WP automates all the data collection and processing. One operator can comfortably use the ARRB WP for extended periods, as it does not require great levels of concentration, just a steady pushing pace. The 2002 price for the ARRB WP is approximately NZ$32,000.

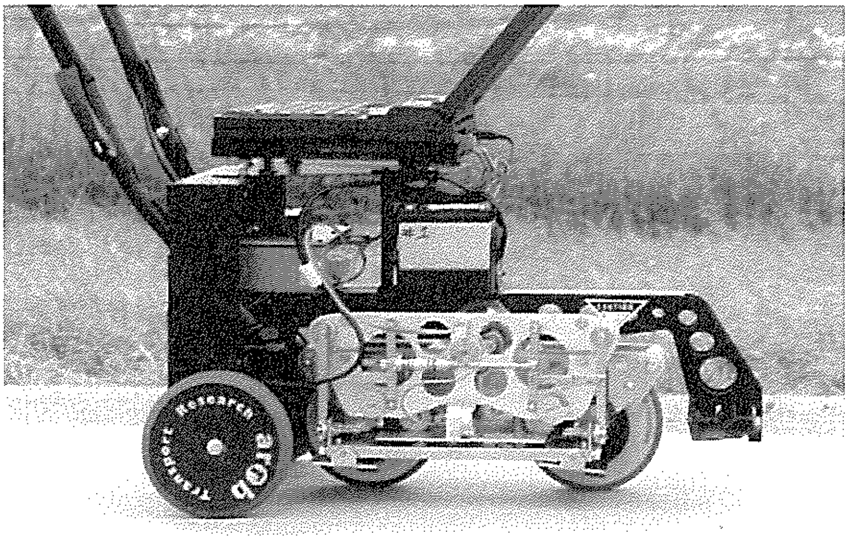

Figure 4.4 ARRB Walking Profiler without cowling (Photo courtesy Fernando, 1999).

4.1.5 CSC Profilair

The CSC (Civil Structural Consultants Canada) Profilair is an interesting device that uses two methods of measuring the road profile. It consists of two beams joined and pivoted together, and it rides along on wheels at the pivot and the ends of the beam. One part has an inclinometer mounted on it to measure, much like the Dipstick and ARRB WP. At the pivot between the beams is a rotary encoder, which is used to very accurately measure the relative rotation of the beam halves. The road profile can be measured using the two sensors, although the inclinometer needs time to settle to give accurate readings and is used to give an update or correction when the Profilair is stationary or being pushed at low speed. The 1997 price for the CSC Profilair was US$31,400+ (NZ$56,000+) excluding the notebook PC for data acquisition.

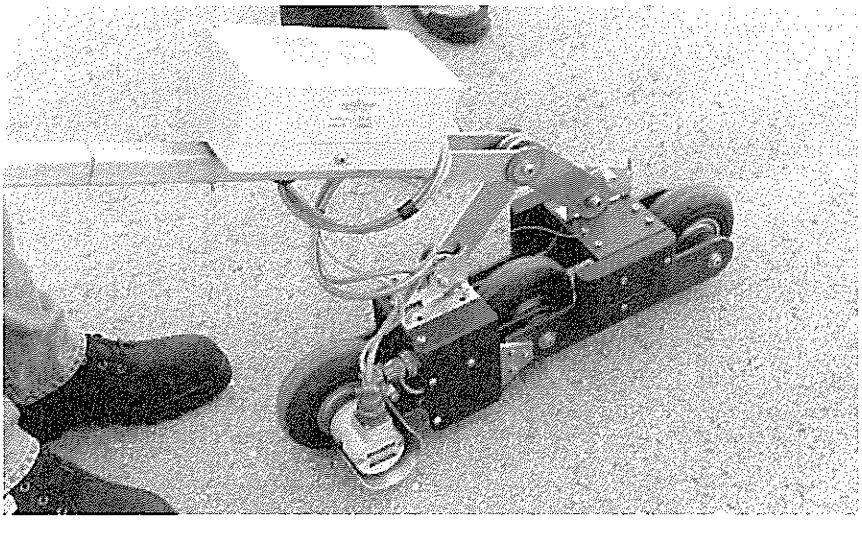

Figure 4.5 CSC Profilair (Photo courtesy Fernando, 1999).

4.1.6 Transit New Zealand SLP

The Transit New Zealand Stationary Laser Profiler (Transit SLP, Cenek et al. 1997) is the only non-contact profiling device here. It is based on the VTI (Sweden) stationary laser profiler that was originally designed for measuring high definition profiles for texture measurement. It has a height-measuring laser that transverses across a 1.7 m long rigid frame. The horizontal and vertical resolution of the laser is a magnitude above that required by ASTM E 1364-95 at 0.3 mm and 0.008 mm respectively. The inclination of the frame is measured as the SLP is moved along the site. With one operator to control the data acquisition and one to move the SLP a measuring speed of 0.12 km/h can be achieved, taking 4.2 hours to measure 500 m. The 2002 price to construct a SLP is in the region of NZ$75,000.

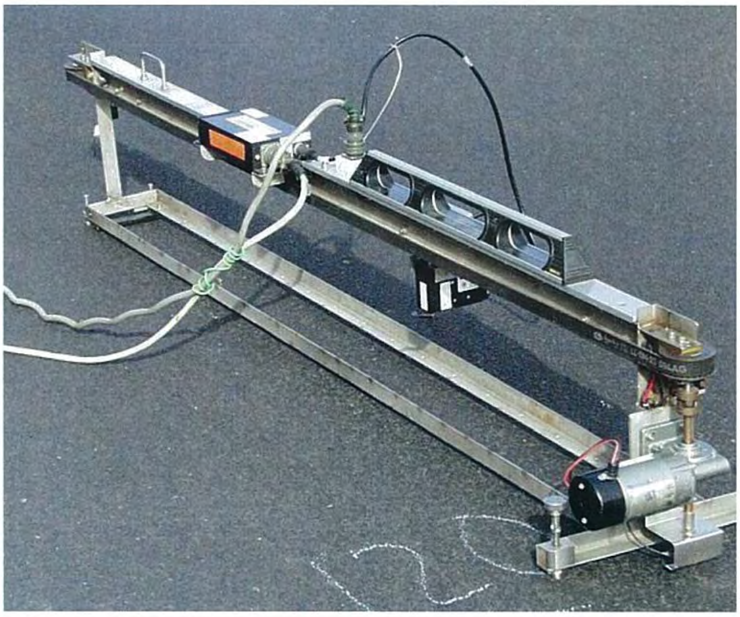

Figure 4.6 Transit New Zealand Stationary Laser Profiler.

4.2 Accuracy

Height accuracy figures are quoted by the manufacturers of the profiling equipment but other factors can affect the real accuracy achieved during on-site measurement. The profilers have quoted static accuracy that is degraded during the continuous measurement process, sampling interval and footprint configurations.

All of the instruments have static accuracy figures that are indicative of the ability to achieve a repeatable measurement at a single position, but a profile has to be defined over a series of positions. With each successive moveent to a new position the total measurement accuracy is degraded from the static accuracy. A large measurement footprint is used to reduce the variability and to ease placement on highly textured surfaces but, in turn, reduces the height accuracy. A different measurement footprint on each of the devices complicates profile comparisons as the pads or wheels ride over the highest texture features of the road surface.

A ranking of the profilers in terms of height accuracy only would place the Transit SLP first as it has the highest resolution in profile height, followed by digital rod and level, ARRB WP, Dipstick, CSC Profilair and TRL Beam last.

Including the sampling interval and footprint effects would change the ranking order: Transit SLP first, followed by the digital rod and level at 100 mm spacing, Dipstick with 100 mm foot spacing, TRL Beam, ARRB WP, and CSC Profilair last.

The low ranking given to the CSC Profilair is based on the findings of a report (Fernando and Leong, 1997) comparing the performance of the CSC Profilair, ARRB WP and a digital rod and level. The ARRB WP was found to be at least five times more accurate than the CSC Profilair in terms of deviation from the profile measured by rod and level.

For general road profiling for roughness the only two suitable instruments are the Dipstick and ARRB WP as they have automated profile collection systems and can survey at reasonable speeds at good vertical resolution and with reasonable horizontal sampling frequency.

4.3 Evaluation

Transit New Zealand owns a Dipstick that is available for hire and Info2000 have an ARRB WP available for hire. Both instruments were rented for evaluation purposes. The evaluation was conducted over three spray seal sites: one fine, one coarse textured and one worn and flushed. Each was 500 m in length and straight with no significant gradient. Table 4.1gives the IRI roughness and Mean Profile Depth (MPD, as defined by ISO 13473-1:1997(E)) range and site mean values. Repeat measurements (table 4.2) were conducted with each instrument at each site. The sites were also surveyed by rod and level.

Table 4.1 Site Characteristics.

Site	Surface Texture	MPD Range 10m averages	Site Mean MPD	IRI Range 100m averages	Site Mean IRI
SH53	Fine Chip	0.7 to 1.6	1.3	1.14 to 2.56	1.89
Paekakariki Hill Rd	Fine Chip. Worn and Flushed	0.5 to 1.6	1.1	3.50 to 6.15	4.68
Alexander Rd	Coarse Chip	1.5 to 3.7	2.9	1.94 to 3.52	2.82

Table 4.2 Profiler Runs.

Site	Wheelpath	ARRB WP Total	ARRB WP Rejected	Dipstick Total	Dipstick Rejected
SH53	Left	8	1	4	0
SH53	Right	8	0	4	1
Paekarakiki	Left	8	0	4	0
Paekarakiki	Right	14	1	4	0
Alexander	Left	12	2	4	1
Alexander	Right	13	0	4	1

Each instrument was calibrated prior to use according to the manufacturer's instructions. Both instruments are supplied with comprehensive instructions for operation and survey procedure. Additional literature for survey procedure is available for the ARRB WP (AUSTROADS 2001). Both the Dipstick and ARRB WP utilise inclinometers to measure the height differences between the front and rear feet and accumulate these differences to produce a total profile. The inclinometers can be laboratory calibrated by placing the feet on a level surface and introducing a block of known height under one of the feet to scale the voltage output of the inclinometer to the known height difference between the front and rear foot. Each instrument needs to be powered on for at least 30 minutes before use in the ambient conditions of calibration or survey to allow the electronics at inclinometers to reach a stable operating condition.

4.3.1 Dipstick

The Dipstick is a very simple and compact instrument;the entire package fitting into a large briefcase weighing approximately 11 kg. The Dipstick itself weighs approximately 4 kg with palmtop and batteries, most of the weight being concentrated at the foot of the unit. When unpacked, the Dipstick must be assembled with a two-part handle, palmtop bracket, base unit and feet. Batteries need to inserted into the palmtop, handle and base unit. The main Dipstick unit is powered by eight AA size batteries contained in the base and the palmtop is powered by six C size batteries in the Dipstick handle with six backup AA batteries in the palmtop itself. A new set of alkaline batteries provides power for over eight hours of operation. The alkaline batteries can be substituted with rechargeable cells with a trade off of less operation time.

The small palmtop computer runs a simple DOS menu-driven program for data collection through the serial port, and limited data processing can also be performed with the same software. Both the palmtop and software are antiquated being of early 1990's vintage, but are still capable of accomplishing the task.

No moving parts are required for the operation of the Dipstick, which is why it is so simple and compact. The acquisition of profile data is initiated by priming the software into action and lifting and swivelling the foot incrementally down the site. The software triggers a data profile point by sensing that the inclinometer reading has changed and settled to a steady value for a set number of successive readings. A beep sounds to indicate that the unit is ready to be swivelled through to the next profile point. The profile data is incrementally recorded in a binary database type format, which is compact in size as the storage media on the palmtop is limited in capacity. The software does not require any user input during the survey until survey finish. The data collection can be interrupted and resumed if the exact position of the feet is marked on the road surface.

The Dipstick does not require any calibration once in the field and is not sensitive to temperature changes once the unit has been switched on for 20 minutes prior to surveying.

The Dipstick, as tested, has two 63.5 mm diameter feet spaced 250 mm apart. There are alternative pointed feet, extensions for extra height clearance and alternative mounting points for feet spacing of 100, 150 and 300 mm. Transit NZ also has an adaptor plate for 241.3 mm foot spacing, the same as the ARRB WP, although the data has to be post processed to correct the profile height points as this spacing is not coded into the Dipstick processing software.

The collected data can be processed on the palmtop to produce the raw accumulated profile or IRI roughness at 30 m intervals. These can be displayed as a table, graphed or printed. Collected data must be downloaded from the palmtop to another computer through a parallel RS232 cable null modem, as the palmtop does not have a floppy disc drive. Alternatively, the data saved on the PCMCIA memory card can be loaded onto another computer that can accept that type of card, once the correct drivers are loaded on the host computer.

Occasionally, the unit would not trigger automatically to collect a profile point but this was easily remedied by lifting the foot to deliberately change the inclinometer reading and placing it down again for the steady state reading so that a reading would be triggered.

The use of the palmtop to collect data is optional as the Dipstick can be operated by manual reading of the two LCD height displays on the foot of the unit. There is one display at each end of the foot, so that when the Dipstick is rotated the height can be easily seen on the forward facing foot. These height differences must be noted down and accumulated post survey to produce the complete profile. Using the palmtop removes the need to record the height differences on paper and reduces the possibility of transcription errors. If the foot spacing is different from the standard 300 mm the transcribed heights must be corrected proportionally.

The Dipstick is easy to use, but slow - survey speeds are typically no greater than 200 m per hour. For sites over 300 m long this makes surveying a very monotonous task. The differing height of operators can introduce a user bias that produces a slight off vertical component on the inclinometer. This can be compensated for in the survey software set-up or post survey.

4.3.2 ARRB WP

The ARRB WP is a much larger package than the Dipstick. It comes in a sturdy packing case approximately 1.2x0.6x0.6 m and weighs 40 kg. The ARRB WP with laptop and battery weighs approximately 30 kg and is about the size of a lawnmower. The added weight and size over the Dipstick is due to the mechanism to automatically step the profile beam forward as the unit is pushed like a lawnmower. There is a main motorcycle type 12V lead acid battery that can be recharged in the WP by attaching the supplied battery charger. The laptop computer used for data acquisition through the serial port can also be powered off the main battery or its own internal battery. As most laptops have limited operating time off internal batteries (typically less than two hours) it is safer to take power off the main battery. A battery with full charge will power the WP and laptop for about six to eight hours, depending on the power requirements of the laptop. There is a low battery warning in the unit that will sound if the main battery requires recharging or changing.

A handle must be held in to release a brake on the stepping mechanism for surveying. Chain driven cams and pins are used to lift the profile beam using drive from the road wheels as the WP is pushed forward. There is an upper speed limit for pushing as the mechanism places the beam on the ground, completely releasing the beam structurally from the rest of the WP to isolate it from any vibration. There is a time allowed for any residual vibration to subside and a profile reading is taken before the beam is picked up by the mechanism and stepped forward again. A speed alarm will beep if the pushing speed is near the allowable limit and will sound continuously if the limit is exceeded. On the unit rented from Info2000 the speed alarm started operating erratically and eventually failed. This was traced to a break in the electrical connection to the speaker and appears to be a common fault with other WP units.

The ARRB WP requires a field calibration over a level 20 m closed loop (20 m out and 20 m back) to adjust the laboratory calibration to compensate for temperature effects on site.

The WP software is easy to use and, once set running, does not require any further user intervention until finishing the survey. Surveying can be interrupted by releasing the brake handle, the WP will collect a profile point and apply the brake with the profile beam held off the road surface. Pulling the brake handle in will resume the survey. It is not possible to move the WP from the interrupted position as it is difficult to mark the last exact position of the profile beam on the road, and the software does not allow a previously collected profile to be resumed after powering off.

In the specifications the maximum gradient that the WP can be operated is 9.5°. A similar limitation should be applied to the maximum camber or cross fall. If the cross fall exceeds 9.5° the profile measurement can be influenced by the tilt introduced by the slope left to right across the WP chassis. This is measured by the inclinometer as a fore and aft inclination adding false profile height. This is because the inclinometer is mounted on the profiler beam rigidly so that the angle measured is relative to the road surface which maybe itself at a significant camber or cross fall angle.

4.3.3 Comparisons

Both instruments are easy to use. The Dipstick is easy to transport, being lighter and more compact. The WP has a mechanism to perform automated stepping of the profile beam that makes the unit larger and heavier, but physically less demanding to use and faster. The Dipstick has to be manually stepped along the site, the maximum survey speed of the Dipstick being 200 m/hour compared with 800 m/hour for the WP.

The Dipstick has a lower height resolution (0.025 mm) than the WP (0.005 mm), which has a more sensitive inclinometer that is also more sensitive to changes in ambient temperature. The temperature sensitivity of the WP is pointed out in AUSTROADS (2001) where a field recalibration is recommended if the ambient temperature around the inclinometer changes by more than ±10°C. They have different beam and foot configurations. The WP has a 241.3 mm long beam with rectangular pivoting feet, each with a triangular arrangement of three 20 mm diameter rubber pads. The Dipstick can have variable foot spacing between 100 to 300 mm and different feet from points to large 63.5 mm diameter feet.

The Dipstick, being compact, can negotiate corners better than the WP, and the WP is limited to radii greater than 15 m. The Dipstick is also better at negotiating highly distressed sites where the manual stepping gives much more positive location of the feet. The WP wheel arrangement, low-slung front fender and low clearance of profile beam occasionally get caught in potholes that can only be cleared by forceful pushing.

Sites with high or variable camber or cross fall should be profiled with the Dipstick as the WP adds the road surface camber to the profile measurement as the inclinometer is mounted on a profiler beam that always measures relative to the road surface. The Dipstick can be held vertical by the operator to compensate for camber.

For sites less than 100 m in length the speed differences between the two instruments is not great as the WP requires a field calibration while the Dipstick does not. As the site length increases the slow speed of the Dipstick becomes a problem as only a limited number of repeat runs can be collected. Repeat runs are the best way to ensure that good profile data is collected and the comparative speed advantage of the WP allows more profiles to be collected while on site.

4.3.4 Relative Accuracy

A rod and level was used to survey in each wheelpath of each site every 10 m to provide a fixed reference for the profiler measurements. To gauge the accuracy of the WP and Dipstick, comparisons were made with the rod and level survey (table 4.3). As the Dipstick measures a profile point every 0.25 m and the WP every 0.24 m, the profile points nearest to the 10 m intervals of the rod and level were used for the comparison. Also, there were less repeat surveys with the Dipstick so the number of comparison points was proportionally less than for the WP. The results listed in table 4.3 show that the two devices gave nearly the same percentage of points within ±5 mm of the rod and level survey, with a slight advantage to the Dipstick.

Table 4.3 Relative Accuracy to Rod and Level.

Site	Surface Texture	Dipstick Points	Dipstick within ±5 mm	ARRB WP Points	ARRB WP within ±5 mm
SH53	Fine Chip	350	90 %	750	91 %
Paekakariki	Fine Chip. Worn and Flushed	400	66 %	1050	62 %
Alexander	Coarse Chip	300	82 %	1150	75 %

4.3.5 Repeatability

The repeatability of the two instruments was tested using procedures described in AUSTROADS (2001a). Averaged 100 m IRI roughness from individual runs was used to produce linear regressions to the averaged IRI from all runs combined in each 100 m segment at each site. The resulting regression statistics are listed in table 4.4. AUSTROADS (2001a) defines complying performance when the regression constant is greater than 0.95 (final two columns in table 4.4) based on five repeat runs of any 100 m segment of road. Given the greater number of runs conducted with the WP (seven toten) compared with the Dipstick (three tofour) both devices performed well, with a slight advantage to the WP. The WP has R^2 values all exceeding 0.95 while the Dipstick has a few non-complying sections on SH53. There were only 3 repeat runs on SH53 instead of the five required so some sections have R^2 below 0.95, as shown by the mean and minimum values.

Table 4.4 Mean Roughness Regression Statistics.

		Slope		Offset		R^2	
Site	Data	WP	Dipstick	WP	Dipstick	WP	Dipstick
SH53	Maximum	0.993	1.005	0.019	0.124	0.991	0.952
	Mean	0.991	0.977	0.016	0.062	0.990	0.925
	Minimum	0.990	0.949	0.013	0.000	0.988	0.898
	Runs	7	3	7	3	7	3
Paekakariki	Maximum	0.999	1.025	0.006	0.027	0.995	0.984
	Mean	0.999	1.010	0.005	-0.038	0.983	0.982
	Minimum	0.998	0.996	0.004	-0.103	0.971	0.980
	Runs	8	4	8	4	8	4
Alexander	Maximum	0.994	1.014	0.024	0.076	0.986	0.997
	Mean	0.993	0.998	0.022	0.040	0.986	0.988
	Minimum	0.993	0.982	0.019	0.004	0.985	0.979
	Runs	10	3	10	3	10	3
Site Maximum		0.999	1.025	0.024	0.124	0.995	0.997
Site Mean		0.994	0.995	0.014	0.021	0.986	0.965
Site Minimum		0.990	0.949	0.004	-0.103	0.971	0.898
Site Minimum Runs		7	3	7	3	7	3

Another measure of repeatability in AUSTROADS (2001a) is the Coefficient of Variation (CoV, table 4.5) calculated for each 100 m segment. The criteria requirethe CoV of individual 100 m segments to be less than 5% and a site average CoV less than 3%. Both devices showed excellent repeatability under these requirements. The test procedure requires five repeat runs when the WP has seven to ten repeats and the Dipstick has three to four repeats. The low number of repeats for the Dipstick produced a marginal failure on SH53 with a 5.5% CoV against the required 5%.

Table 4.5 IRI Roughness Variability and Coefficient of Variation.

		IRI		CoV	
Site	Data	WP	Dipstick	WP	Dipstick
SH53	Maximum	2.36	2.56	1.4	5.5
	Mean	1.82	1.97	0.9	3.3
	Minimum	1.14	1.27	0.5	0.8
	Runs	7	3	7	3
Paekakariki	Maximum	6.10	6.15	0.6	2.3
	Mean	4.71	4.65	0.4	1.1
	Minimum	3.50	3.50	0.2	0.2
	Runs	8	4	8	4
Alexander	Maximum	3.46	3.52	1.7	5.4
	Mean	2.81	2.83	0.8	1.9
	Minimum	1.94	2.02	0.3	0.5
	Runs	10	3	10	3
Site Maximum		6.10	6.15	1.7	5.5
Site Mean		3.11	3.15	0.7	2.1
Site Minimum		1.14	1.27	0.2	0.2
Site Minimum Runs		7	3	7	3

Given that only three repeat survey runs were conducted with the Dipstick compared with seven with the WP, the repeatability of the two devices can be considered to be identical.

4.3.6 Summary

In terms of accuracy and repeatability, both the ARRB WP and Dipstick give the same performance on the road, with a very slight advantage to the WP. Each device has its advantages and disadvantages.

The advantages of the Dipstick are: small size, light weight, compactness, no moving parts, more stable in changing ambient temperatures, easier to manipulate over difficult surfaces, and ability to negotiate tight corners. Its disadvantages are: slow survey speed, tedious manual stepping, dated computer hardware and software, and data transfer is more difficult. Updated computer hardware and software is available but is costly (more than $US 5000 = NZ$9000).

The WP has fully automated stepping, so that only pushing at a fairly constant speed is required. The greatest advantage of the ARRB WP is the higher survey speed, generally four times faster than the Dipstick. This allows more repeat survey runs. Having repeat surveys improves the accuracy of the profiling by taking the averaged profile or profile statistic. Comparative disadvantages of the Dipstick are: heavy, large, less manoeuvrable, and difficult to use on highly distressed surfaces.

Table 4.2 Reference Profiler Comparison.

Device	Principalof Operation	Measurement Footprint	Operators	Speed [km/h]	Time to survey 500 m [hours]	Automatic Profile Collection	Automatic IRI Processing	Static Vertical Resolution [mm]	Horizontal Resolution [mm]
Rod & Level	Direct Height	20 mm diameter pad	2	0.1	4.5	No	No	< 0.125	Variable
TRL Beam	Direct Height	50 mm diameter x 6.5 mm wide wheel	2	0.1	4.5	Semi	No	0.1	100
Transit SLP	Direct Height	0.8 mm diameter laser spot	2	0.12	4.2	Semi	No	0.008	0.3
Dipstick	Inclinometer	2 x 63.5 mm diameter pads	1	0.2	2.5	Yes	Yes	0.025	100 to 300
ARRB WP	Inclinometer	2 x 80 mm square feet each with 3 x 20 mm diameter rubber pads	1	0.8	0.6	Yes	Yes	0.005	241.3
CSC Profilair	Inclinometer and Angle	3 x 85 mm diameter x 15 mm wide wheels	1	2.0	0.25	Yes	Yes	0.008	250

5. Tracking Ability of Vehicle Based Profilers

Two 1000 metre long sites were used to investigate the degree of transverse wander during typical survey conditions of an HSDC vehicle. Both sites have corners and road features that make the task of following a given track difficult. The resulting roughness gives a repeatability measure of the profiler. No special instructions were given to the driver of the HSDC vehicle. The surveys were conducted in excellent visibility during off peak traffic flows of a mid morning working day.

The driven line taken by the HSDC vehicle was tracked by laying a paint line. A paint mixture was made from water, plaster and different coloured chalk. This paint mixture put down a faint line that would not distract other road users and wear away with successive vehicle passes or wash away in the next wet weather. This paint was dispensed from a tube mounted on the front passenger side door.

5.1 Tracking Sites

These tests were conducted to determine the amount of wander in the wheelpath and the effect on the derived roughness. The surface condition of the sites was generally good with localised small areas of pavement distress. Some localised scabbing and patching were present at both sites. There were no visible wheelpaths caused by trafficking at the sites, so the profiler operator was left to choose the driven line. Paint lines laid during previous runs were visible to the driver, but offset to the far left so were difficult to use as an aid to tracking. Table 5.1 lists the main characteristics of the two sites.

Table 5.1 Tracking Sites.

Site	Surface Texture	Lane Width [m]	IRI Range 100m averages	Site Mean IRI
Harcourt Werry Drive	Coarse Chip and OGPA	3.7 to 5.3	2.89 to 5.59	3.79
Raiha St	Coarse Chip and OGPA	6.2 to 6.4	1.42 to 6.78	3.07

5.1.1 Harcourt Werry Drive

Harcourt Werry Drive starts in a built up urban area with narrow lane width and 50 km/h speed limit. It enters a tight left right curve and opens out to a wider lane without kerb and channels. The lane is marked with edge lines and a double yellow centreline up to 300 m. The centreline changes to a single yellow line for the oncoming lane up to 400 m where the speed limit rises to 70 km/h. The survey was conducted at 50 km/h.

The overall impression is that of a narrow lane that is reinforced by the surroundings, trees and fences bordering the oncoming lane, and trees and grassy riverbank on the edge line. Figure 5.2 is the view from the start of the site with traffic control cones in place just before measuring the paint lines that can be seen in the LWP. There is a seal patch in the LWP alongside the first cone that runs across from the kerb (a darker surface strip just after the measuring tape). There is some scabbing in the right wheelpath on a right hand corner at 300 m (figure 5.3) along the site.

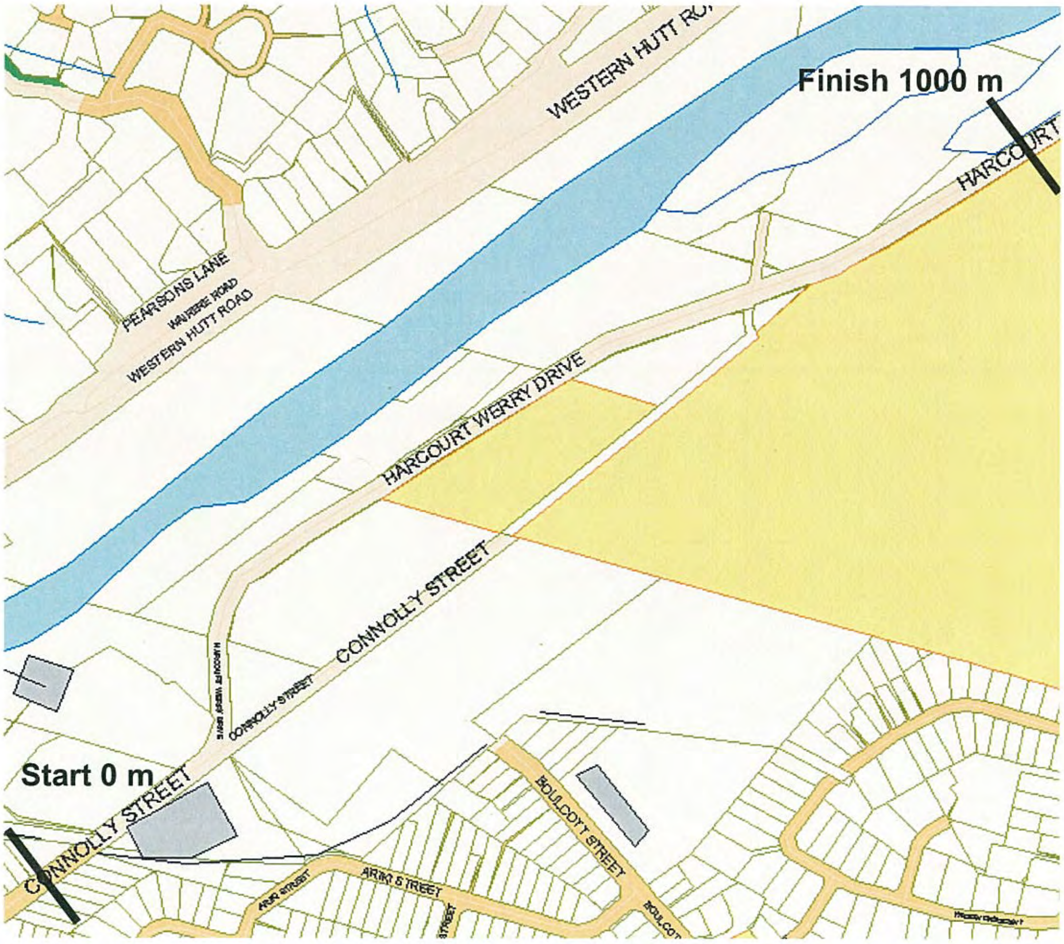

Figure 5.1 Harcourt Werry Drive.

Figure 5.2 Site start, approach to first corner on Harcourt Werry Drive. Note seal patch from kerb.

Figure 5.3 Scabbing on Harcourt Werry Drive at 300 m in the RWP.

5.1.1.1 *Harcourt Werry Drive Tracking Results*

The tracking results are presented in two levels of detail at 20 m (figures 5.4 and 5.5) and 100 m (figures 5.6 and 5.7) averaging of roughness and the Coefficient of Variation (CoV) of the roughness measure as defined by AUSTROADS (2001a). CoV is based on the ratio of the standard deviation and mean of a single roughness segment. A segment is the roughness between two fixed distances. The 20 m level is used to show how the changes in tracking directly influence the roughness and the variability is accordingly higher. The 100 m averaging level is used to show the effects on the standard reporting distance for roughness. The 20 m level will show greater variability than the 100 m level but is useful in picking up the cause of variations at the larger level. Under AUSTROADS (2001a) guidelines, repeatability is acceptable when the individual 100 m averaged segments have CoV < 5%.

Roughness results are reported at the end of the segment, so that for 100 m averaging the roughness figure at 200 m relates to the road condition between 100 and 200 m. At the shorter averaging distance of 20 m, the roughness reported at 160 m will be influenced by the road condition 100 m before between 60 to 160 m.

In the first 100 m segment the CoV exceeds 5% at 8%. The tracking spread is very large at the start of the site where the lane width narrows down on the approach to the first corner. On the road surface there is a narrow seal patch at 0 m and manhole cover at 40 m that contributeto the variability, depending on the tracked path.

There is some scabbing at 300 m in the RWP of Harcourt Werry Drive (figure 5.3) that affects the roughness measurements, depending on the line taken through the corner. The corner is sweeping and the lane is opening up from widths of under 4 m to 5.3 m. This variability in roughness and tracking can be seen just after the 300 m mark in the RWP plots with 20 m (figure 5.5) and 100 m (figure 5.7) averaging, which exceed the 5% CoV limit.

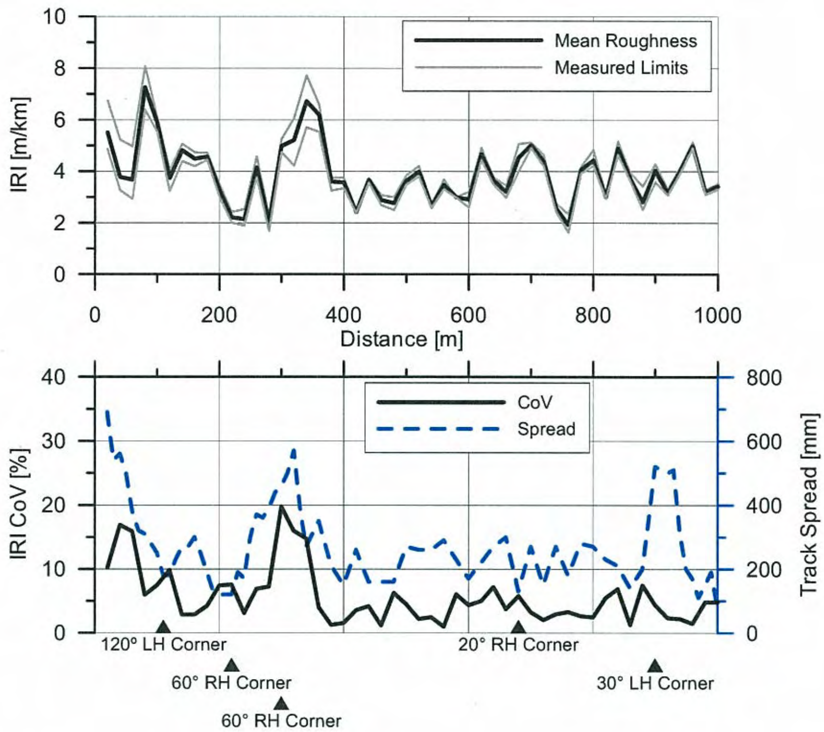

Figure 5.4 Harcourt Werry Drive LWP, 20 m averages.

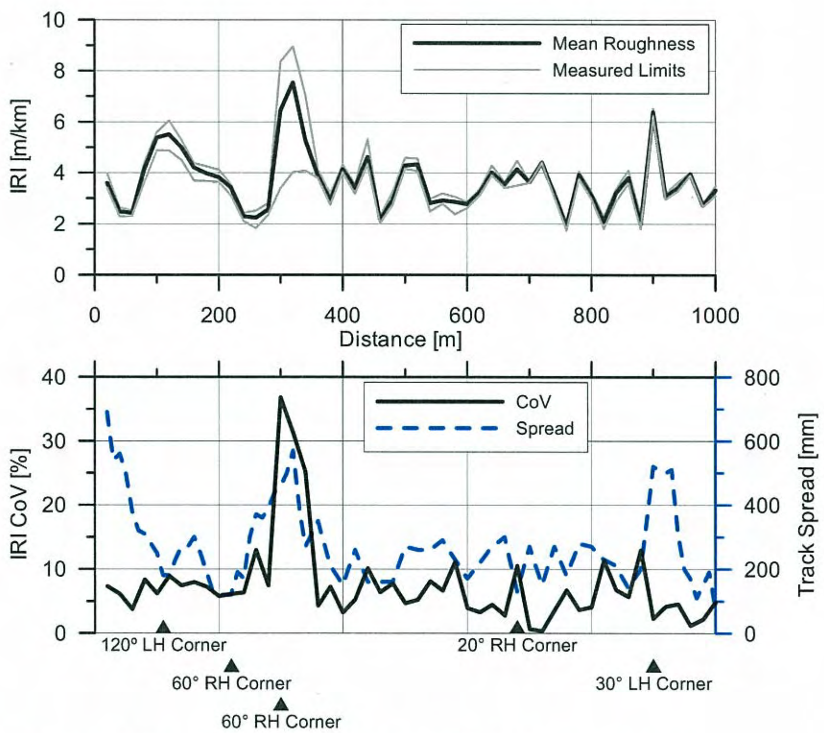

Figure 5.5 Harcourt Werry Drive RWP, 20 m averages.

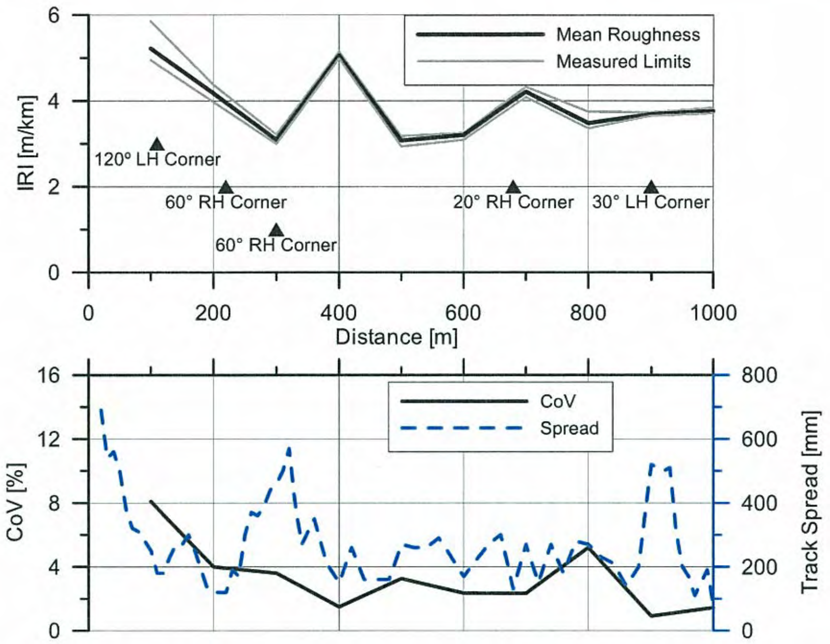

Figure 5.6 Harcourt Werry Drive LWP, 100 m averages.

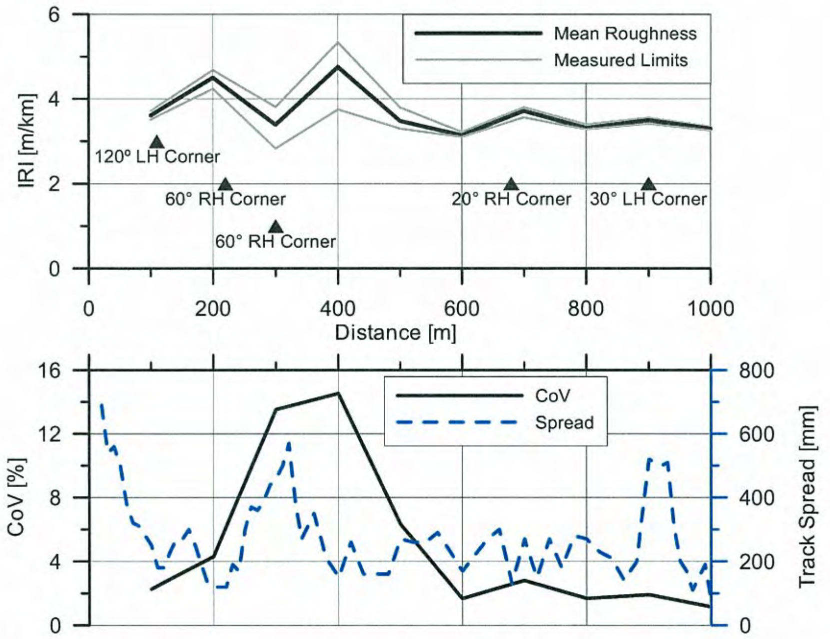

Figure 5.7 Harcourt Werry Drive RWP, 100 m averages.

The mean tracking spread on Harcourt Werry Drive is 286 mm, with high spreads at the start of the site, 300 m and 900 m. The high spread at the start is caused by the narrowing lane width. At 300 m the lane widens through a corner and at 900 m there is a semi-blind left corner. The high spread at the start and 300 m result in CoV greater than 5% due to localised roughness features in the left and right wheelpaths respectively. At 900 m the surface is homogenous across the lane so that the CoV is low. These effects are apparent in both the 20 and 100 m averaged results, although at the 100 m level, the actual CoV value is about half that of the 20 m level.

The CoV changes in a complex way related to the lane width, the sight distance and the actual variability of the roughness on the road. For homogeneous surfaces the 100 m averaged CoV is generally below 5%.

5.1.2 Raiha St

Raiha St is in an industrial area with very wide lanes (6.2 to 6.4 m). The street rises over a blind rise and falls over steadily. In contrast to Harcourt Werry Drive, Raiha St is wide and sweeping but with large elevation changes. The lane is wide enough to fit an additional temporary lane for traffic control and the centreline is marked with a white line. The posted speed limit on the site is 70 km/h although the surveys were conducted at 50 km/h.

Figure 5.8 Rahia St (Source: **NZTopo*Online*, extracted September 2002, Crown Copyright Reserved).**

Figure 5.9 View from the start of Raiha St.

Figure 5.10 Left hand corner at 500 m Raiha St.

At 500 m (figure 5.10) there is a driveway to a hospital site and there is some localised pavement distress caused by vehicles turning into the entrance. At 860 m there is a side road on the right.

5.1.2.1 *Raiha St Tracking Results*

The lane width on Raiha St is much wider than on Harcourt Werry Drive and the tracking spread is correspondingly greater with a mean of 336 mm compared with 286 mm. High CoV occurs between 500 to 600 m and at 880 m where there is localised roughness due to damage caused by heavy vehicles turning into side streets.

These two localised areas of comparatively high pavement distress result in 100 m CoV above 5%, when it is less than 4% on the rest of the site. As with Harcourt Werry Drive, the cause of high CoV is due to a mix of site geometry, sight distance, and localised pavement distress. The lane width on Raiha St is less of a factor as the lanes are so wide and the pavement distress is less localised than on Harcourt Werry Drive.

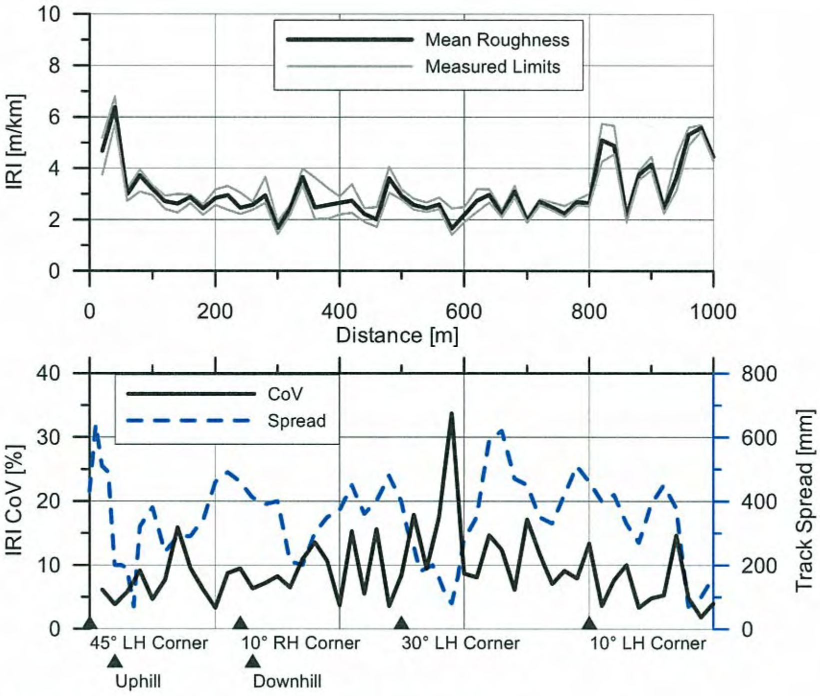

Figure 5.11 Raiha St LWP, 20 m averages.

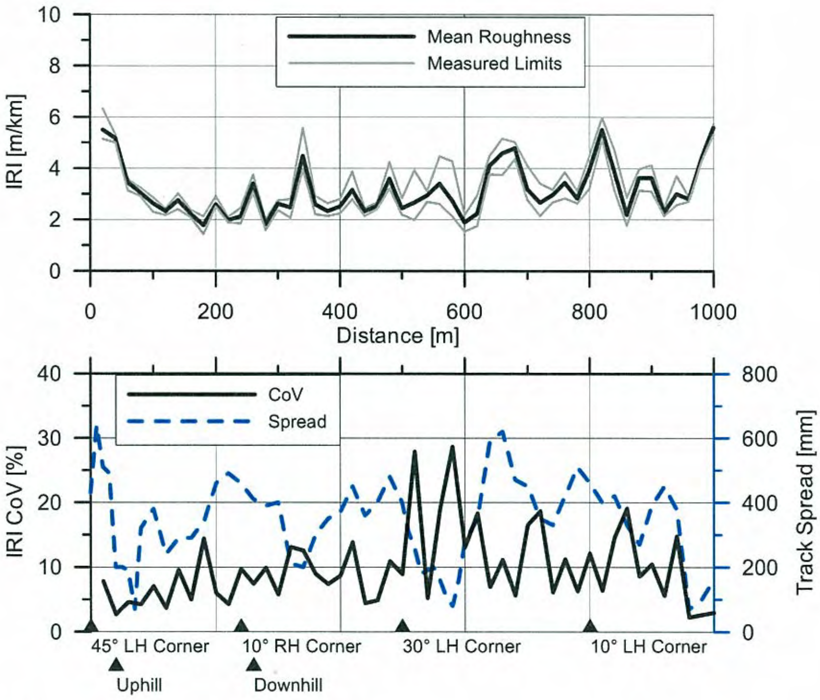

Figure 5.12 Raiha St RWP, 20 m averages.

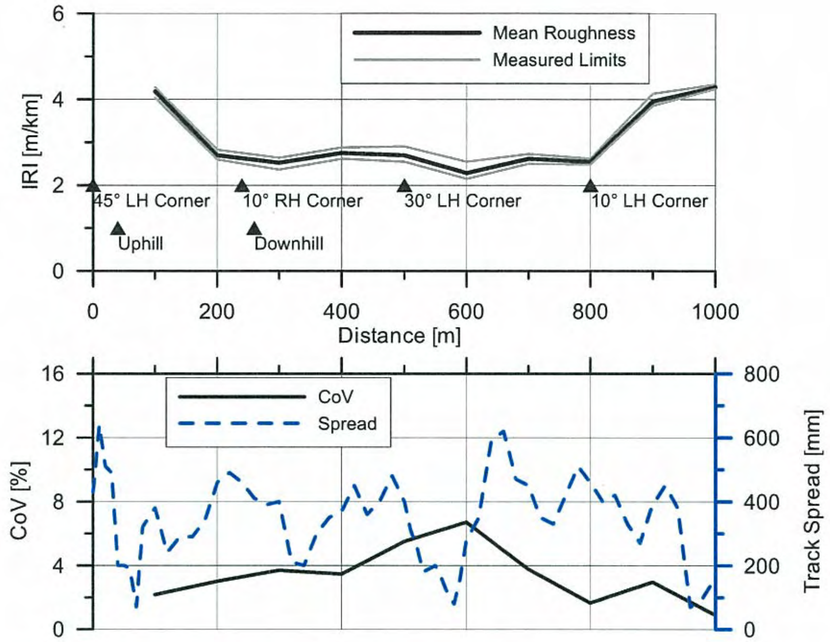

Figure 5.13 Raiha St LWP, 100 m averages.

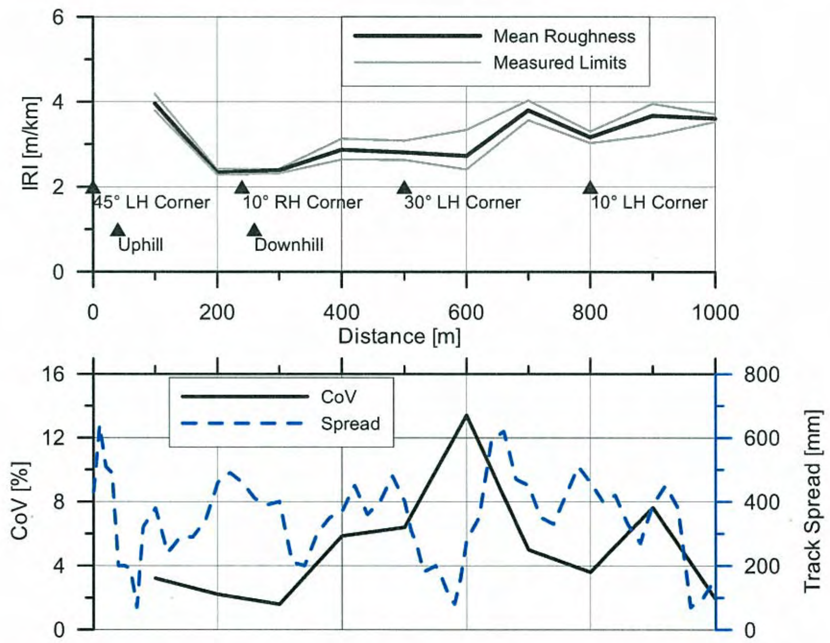

Figure 5.14 Raiha St RWP, 100 m averages.

Tracking factors in roughness measurements are only apparent when the pavement has localised distress such as scabbing or potholing.

6. Footprint Size Effect

Surface macrotexture (features with wavelength between 0.5 and 50 mm) can adversely influence the profile measurement. Not only can small features be missed out by a large sampling interval or large sensor footprint, but by the phenomenon of aliasing at small sampling intervals or small sensor footprint. Aliasing occurs when the very small variations in the surface macrotexture are mistakenly measured at higher wavelengths that may influence the computed roughness. Profiles are usually filtered to eliminate the macrotexture effect but the effectiveness of the filters is sometimes limited, depending on the degree of macrotexture.

On coarse, New Zealand chipseal surfaces the macrotexture effect can be significant. Introducing a standard deviation error into measured profiles on low, medium and high roughness profiles increases the error in roughness. The effect on roughness is dramatic. Introducing a standard deviation error of 2 mm, the roughness on the low, medium and high roughness profiles increased by 90%, 27% and 12% respectively (VicRoads, 1999).

Ultrasonic height sensors have a large measurement footprint that makes them unsuitable for use on coarse textured surfaces (Karamihas and Gillespie, 1999). They can produce roughness values of up to 55% high on chipseal. The main reasons are:

- Ultrasonic sensors detect the highest feature within their footprint, which on chipseal are the tops of the exposed aggregate.
- They have a large sampling distance of approximately 300 mm.

The ARRB WP and Dipstick effectively share the same measurement mechanism as ultrasonic height sensors so they can be expected to show the same limitations. A theoretical study with a limited amount of physical testing by the author (Fong, 1999) showed that the level of roughness error increases with increasing Mean Profile Depth (20% at MPD = 3.5 mm) when comparing large footprint profilers (63.5 mm diameter for the Dipstick) with inertial laser profilers, which have small footprints (up to 6 mm diameter).

A static inclinometer profiler like the Dipstick or ARRB WP incorporates measuring feet under the profiling beam to which the inclinometer is mounted. The feet are used to provide a stable platform for the profiling beam when stepping over textured surfaces. In comparison with HSDC profilers the static profilers footprint and beam length, which defines the sampling distance, is large. The large footprint and sampling distance can miss profile features that are measured by the HSDC systems.

6.1 Static Profiler Configuration

To investigate the effect of texture on profile measurements, high-resolution road profiles from texture validation sites were used. These texture validation profiles were measured with the Transit SLP (section 4.1.6) over 200 m in left and right wheelpaths, with additional in between wheelpath surveys at some sites. In total, 45 200 m long sites were used, with the texture and roughness ranges listed in table 6.1. Real and simulated surveys were performed on these sites with the ARRB WP and

Dipstick. 180 km of simulated profile surveys were generated, producing 1800 100 m IRI values. The simulations used high-resolution profiles measured with the SLP and modelled the beam and foot configuration of the ARRB WP and Dipstick. A small degree of foot placement error was modelled in the simulation to replicate the inability to place the profiler exactly in the same position during repeat survey runs.

Table 6.1 Footprint Sites.

45 × 200 m Sites	Surfaces	MPD [mm]	IRI [m/km]
Minimum	AC, Fine Chip	0.02	1.17
Maximum	Coarse Chip	2.92	3.16

The sample and footprint length of the ARRB WP (beam 0.2413 m and footprint 0.0720 m) and Dipstick (beam 0.250 m and footprint 0.0508 m) were used as the basis for the profiler configurations used in the tests and simulations. There was a change of 3.5% in sample length from 0.2413 to 0.250 m and a footprint change of 9% from 0.0720 to 0.0635 m. The specific dimensions are not necessarily important as this investigation is concerned with the differences due to increasing the sample length or footprint of the profiler.

Changes in the IRI roughness with increasing profiler sample length or footprint are shown in figure 6.1. The tests are summarised as the IRI roughness differences between alternative profiler configurations. Trend lines are added to the data although there is a large amount of scatter in the data as only a part of the roughness variation is due to texture, beam length and footprint interactions. The two negative gradient trend lines show the effect of changing the sample length. Increasing the sample length causes a decrease in IRI. The two positive gradient lines show that increasing the footprint increases IRI. In these tests the 9% difference in footprint causes a bigger change than the 3% increase in beam length.

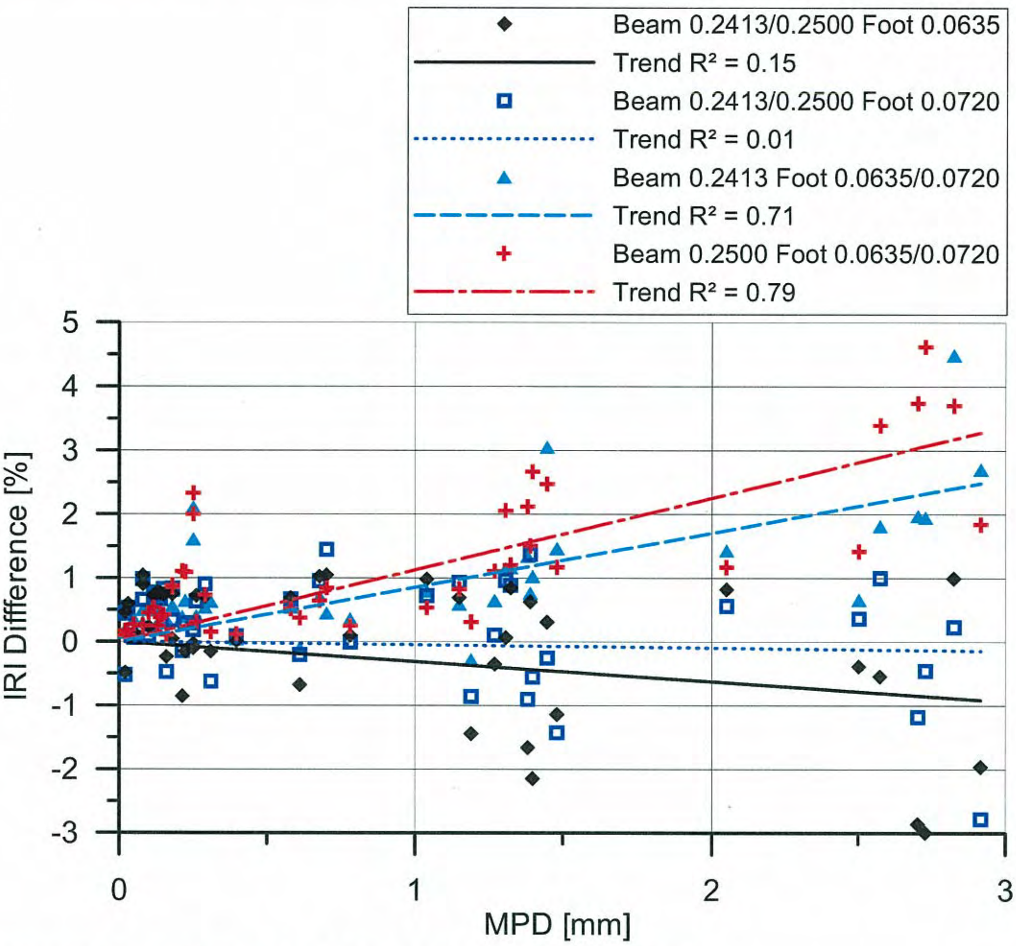

Figure 6.1 Profiler Beam and Foot Configuration Effects.

Figure 6.2 shows the effect of texture on the repeatability, as measured by the coefficient of variance (CoV) of the profiler configurations. Trend lines are shown for each profiler configuration although there is a large scatter of data as texture alone is not the only cause of variation. The trend lines indicate that texture causes approximately 1% variance in the 100 m IRI averaged repeat measurements at texture levels above 0.1 mm MPD rising to a constant 2% above 1 mm MPD.

Figure 6.3 shows much the same information as figure 6.2 as the change in the standard deviation of repeat roughness measurements with texture. The standard deviation of repeat roughness measurements being generally below 0.05 m/km IRI, reaching a limit of 0.05 at 3.0 mm MPD.

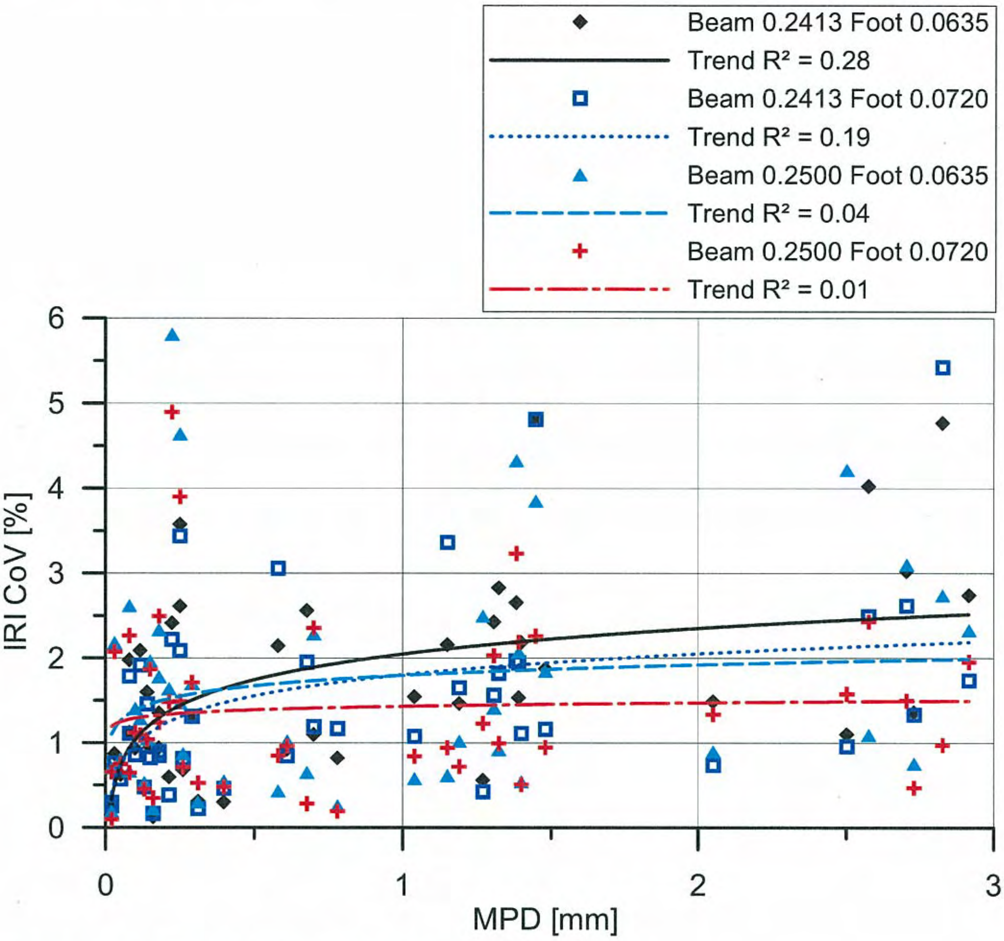

Figure 6.2 IRI CoV and Profiler Configuration.

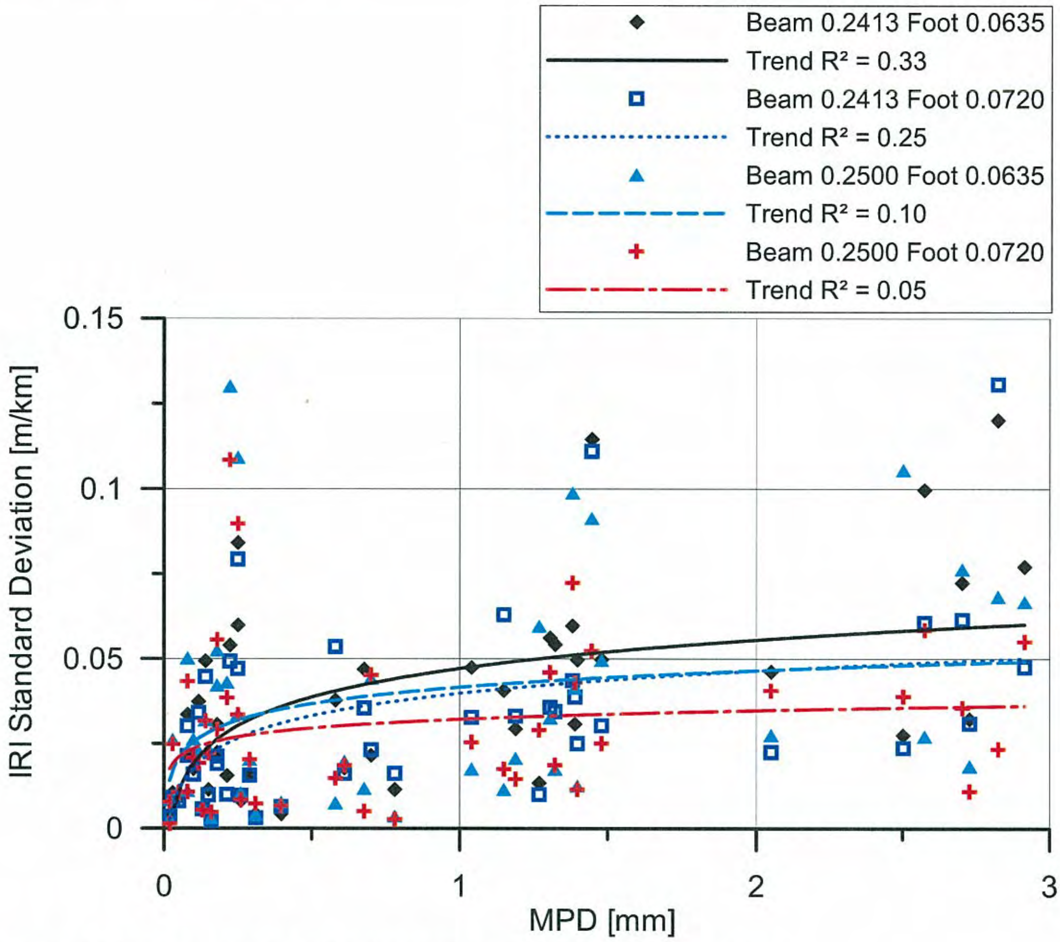

Figure 6.3 IRI Standard Deviation and Profiler Configuration.

6.2 Static and Non-Contact Profilers

There are large differences in the footprint of the reference static profilers, such as the Dipstick and WP, and the HSDC profilers. The large footprint of HSDC ultrasonic height sensors (about 50 mm diameter) is known to give IRI readings 55% higher than the true roughness on highly textured surfaces (Perera and Kohn, 1994, Karamihas and Gillespie, 1999). The similarity in measurement method and the associated limitations on highly textured surfaces, such as chipseal, between HSDC ultrasonic profilers and static profilers has been noted by Prem, 1999. McGhee (2000) found differences of 14% over a 30 m section between the IRI roughness from the static and laser based HSDC profilers.

Figure 6.4 compares the effects of different footprint between static profilers and laser HSDC profilers. There are two different non-contact laser HSDC profiler configurations;one represents the Transit SLP with a 0.3 mm diameter laser spot size and the other a typical laser HSDC profiler with a 6 mm spot size. The IRI difference between the two non-contact devices is less than 0.3% up to 3.0 mm MPD. Comparisons between the static and the laser HSDC profilers show a much greater difference that is dependent on the texture levels of the road surface. The differences rise from zero at low texture rising linearly to 10% at 3.0 mm MPD.

The static devices, with their large footprint, pick up the highest features on the road surface, which is the texture problem associated with ultrasonic sensors (Karamihas and Gillespie, 1999). The laser profilers are better at averaging the road profile as they are scanning the road surface continuously with a small measurement footprint, so that the survey contains more detailed profile information.

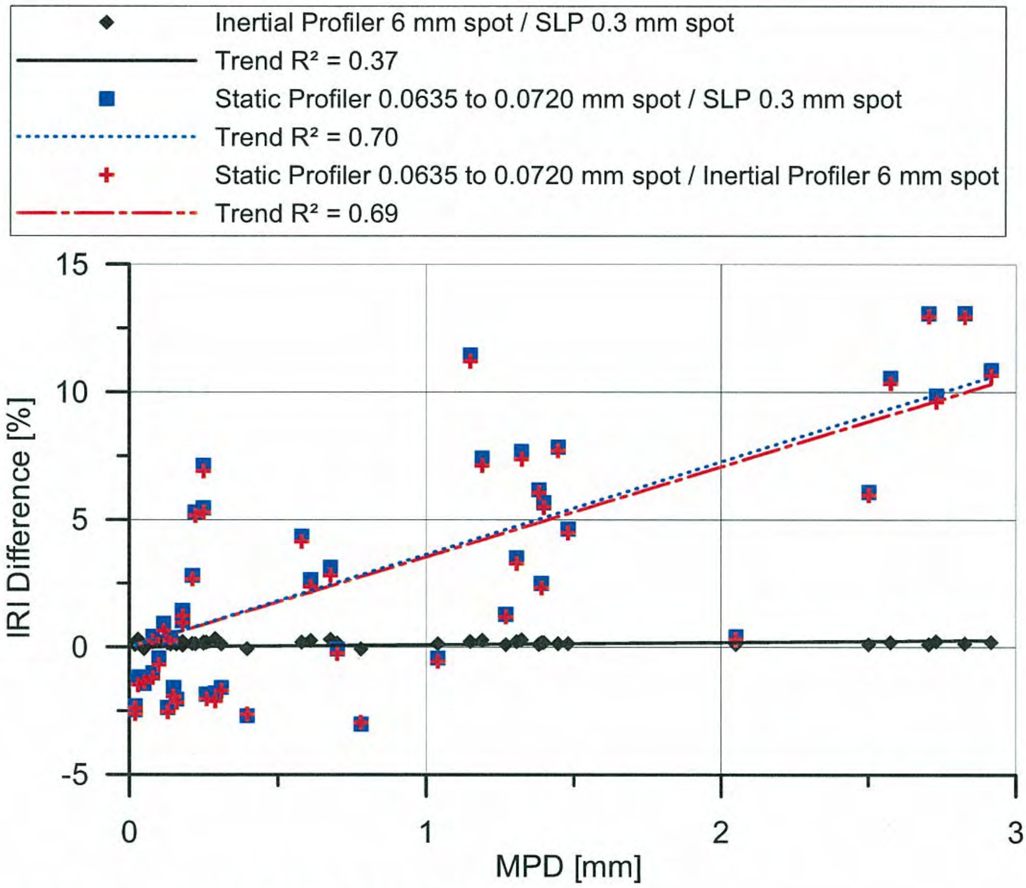

Figure 6.4 Footprint and Texture Effect.

The World Bank has specifications for reference profilers (Sayers et al. 1986). These are essentially hardware specifications with requirements for height resolution and repeatability that do not ensure accuracy. The World Bank specifications have been found to be lacking (Sayers, 1995) as a hardware specification cannot address the issues of the previous sections.

There are test methods for checking profiles with static methods (ASTM E1364-95) and inertial profilers (ASTM E950-94, 1994). Prem (1999) compared these methods and found that the specifications for height resolution for inertial profilers are more stringent than those required for static profilers. The sample intervals required in ASTM E1364 are also much larger than those for accurate profile collection for roughness. Under the ASTM documents, inertial profilers are calibrated against static methods that have lower levels of accuracy.

In his recommendations Prem (1999) states:

> Further research should be supported to establish a viable and practical method of measuring reference profiles that is suitable for the validation of laser and optical inertial profilers. The method should replicate the height sensor's footprint and the way small features in the road and surface texture are measured. This is especially important for validating profiler performance on all surface types, particularly highly textured surfaces and those with areas of localised roughness.

A better reference instrument would combine the accuracy and small measurement footprint of the Transit SLP and the measurement speed of the ARRB WP.

7. Effect of Vehicle Tracking on Transverse Profile Rutting Measure

Existing validation tests for rutting are conducted on straight and level sites where vehicle tracking is kept very carefully within tight tolerances. Visual alignment markings are applied to the road surface as an aid to keep consistent tracking. In real live survey conditions the tracking variability is much greater without any tracking aids. As presented in section 5, the tracking variability is affected by many site factors. Rutting measures are extremely sensitive to transverse location. HSDC systems derive rut depths by calculating the deviation from the straight edge or taut wire from measured profiles.

In most HSDC vehicles only a limited number (3 to 20) of sensors are used to measure the transverse profile. The height sensors on the HSDC vehicle are only able to measure a limited representation of the true profile over the full width of the road surface. When the transverse profile is uniform and flat, and the associated rutting is low, variability in transverse position is unimportant. When there is rutting or the profile is non-uniform, variability in transverse position can significantly affect the derived rutting measure.

Some new HSDC rutting systems are now being produced that scan a high-resolution transverse profile that can be considered essentially continuous. This investigation of tracking variability in rutting assumes that the transverse profile is being reproduced accurately and the change in derived rut depth is due to tracking errors only. In reality, with a discrete number of height sensors the tracking error will be higher as the misalignment of the sensors will not measure the true high and low profile points.

Table 7.1 Rutting Sites.

5 × 300 m Sites	Surfaces	Rutting [mm]	Tracking Error [mm]
Minimum	Fine Chip	0	±1
Maximum	Coarse Chip	65	±200

Five sites were used to investigate the rutting variability. The characteristics of the sites are summarised in table 7.1. A tracking error was introduced at each measurement position, ranging from 1 to 200 mm to both the left and the right. The reduction in rut depth with tracking error is calculated as the rut ratio between the true rut and measured rut, as shown in figure 7.1. The results are grouped into rut bins, shown in figures 7.2 to 7.7 and summarised in table 7.2. Best-fit lines are shown on the figures to indicate a general trend. The ratios for the lowest rut bins are low but the actual reduction in rut depth is small compared with the larger rut bins.

The loss or reduction in rut depth calculated here assumes that the full transverse profile is being measured. When there are a discrete number of sensors for measuring the transverse profile, the reduction in rut depth maybe greater. The reduction is dependent on the number and placement of sensors.

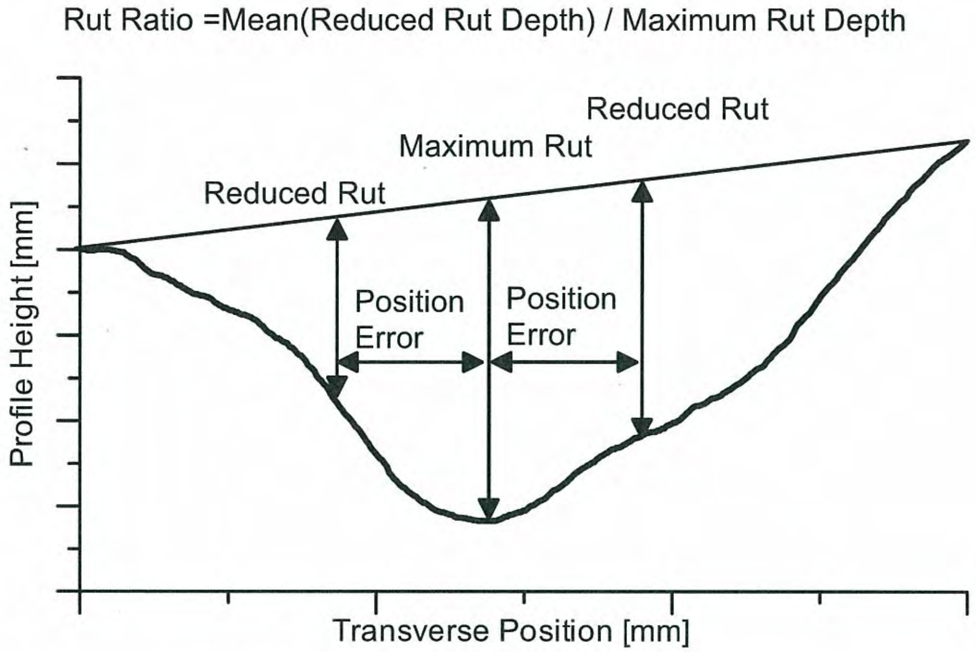

Figure 7.1 Rut Reduction Ratio.

Table 7.2 Tracking Rut Reduction.

Rut Bin	Ruts	Fit r^2	Ratio at ±100 mm	Reduction at ±100 mm	Ratio at ±200 mm	Reduction at ±200 mm
0 to 5	114	0.26	0.7	0 to 1.5	0.2	0 to 4
5 to 10	218	0.44	0.8	1.0 to 2.0	0.3	4 to 7
10 to 15	127	0.56	0.9	1.0 to 1.5	0.6	4 to 6
15 to 20	166	0.56	0.9	1.5 to 2.0	0.6	6 to 8
20 to 25	144	0.55	0.9	2.0 to 2.5	0.7	6 to 8
25 to 65	76	0.73	0.9	2.5 to 6.5	0.7	8 to 20
Total	845					

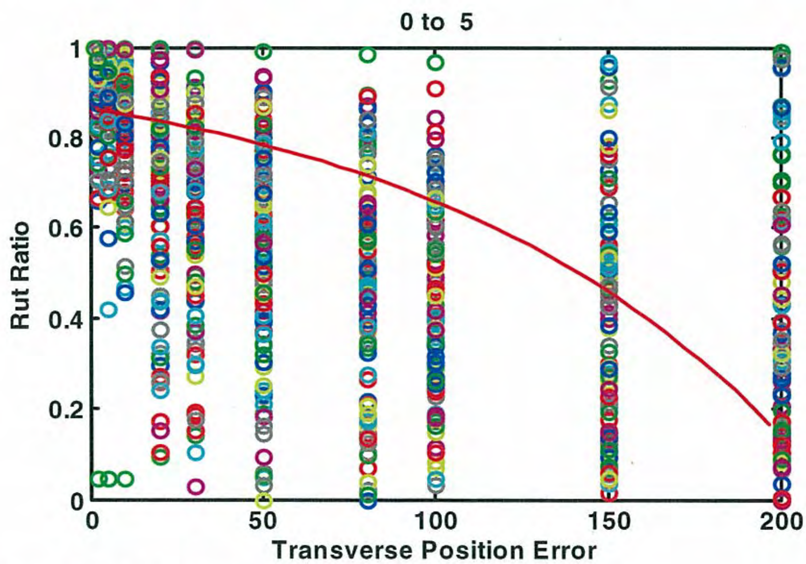

Figure 7.2 0 to 5 mm Rut Bin Tracking Variability.

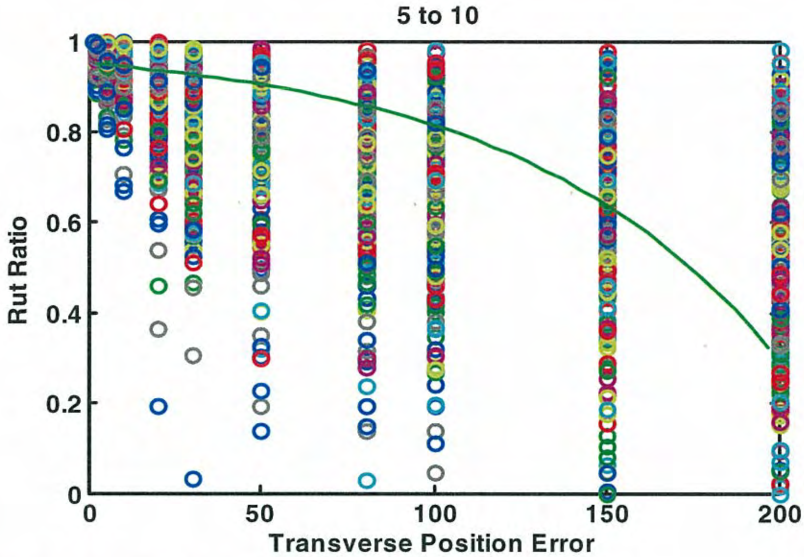

Figure 7.3 5 to 10 mm Rut Bin Tracking Variability.

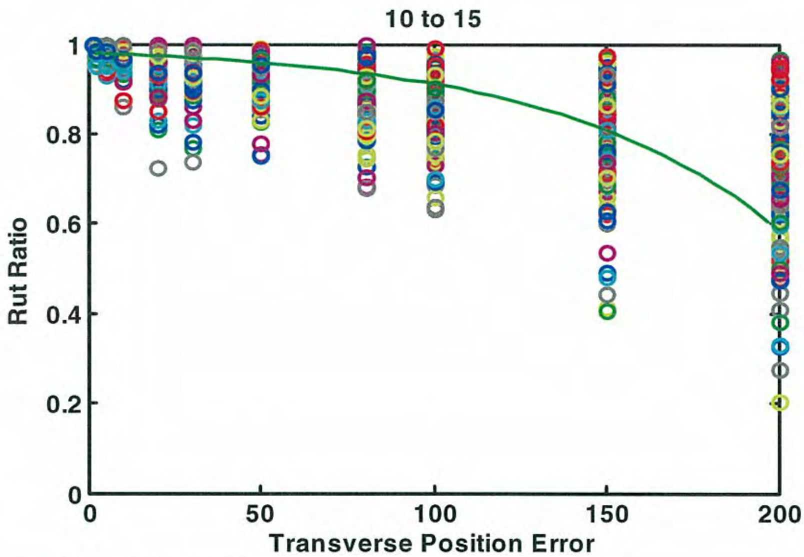

Figure 7.4 10 to 15 mm Rut Bin Tracking Variability.

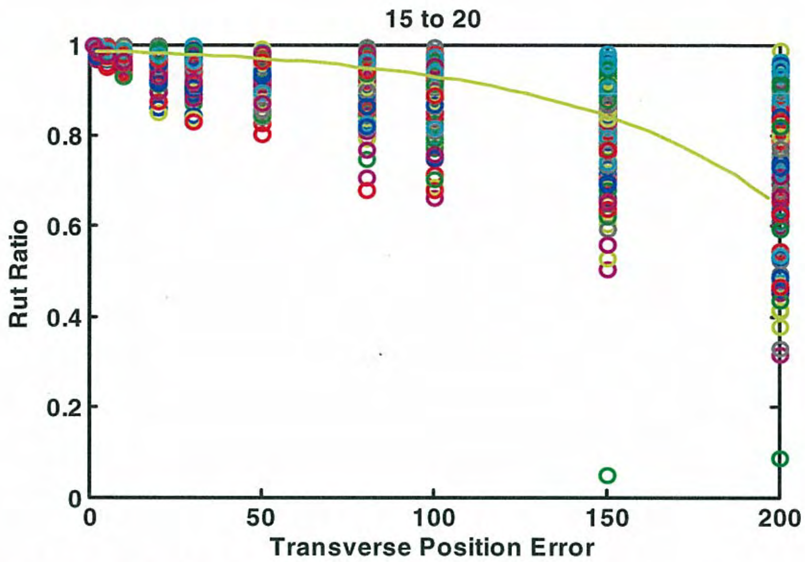

Figure 7.5 15 to 20 mm Rut Bin Tracking Variability.

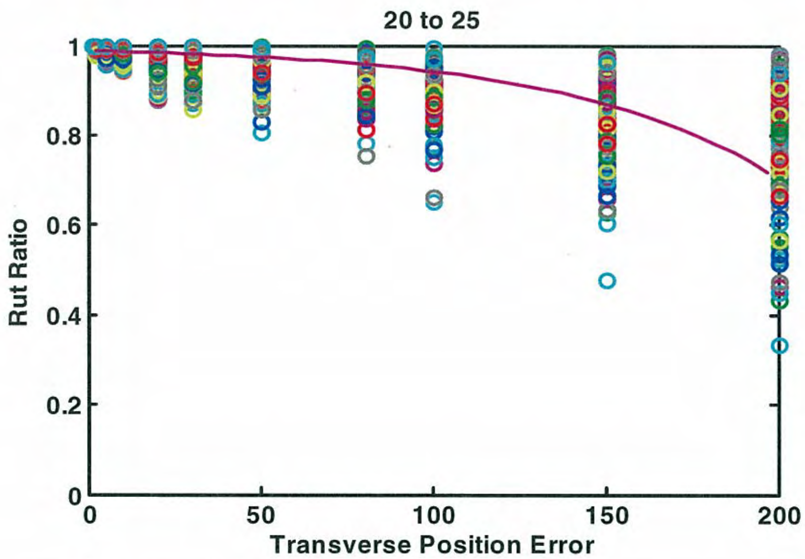

Figure 7.6 20 to 25 mm Rut Bin Tracking Variability.

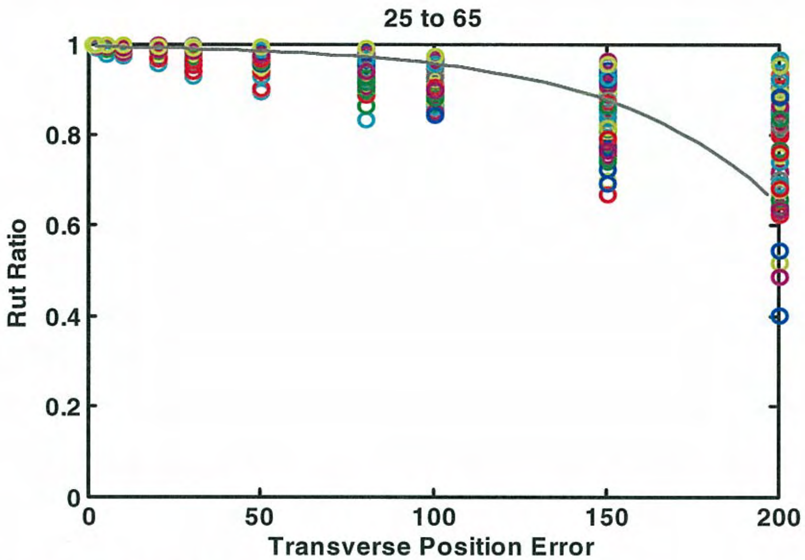

Figure 7.7 25 to 65 mm Rut Bin Tracking Variability.

A limited number of sensors on an HSDC transverse profile bar will never be able to fully reproduce the transverse road profile, so there is always the possibility that derived rut will be underestimated. The spacing of the height sensors on the HSDC rut bar can be optimised to minimise the loss of rut depth, but continuous transverse profile scanning is the only method to fully guarantee that the maximum rut depth can be measured.

8. Profile Validation Criteria

In previous sections we have investigated the repeatability, accuracy relative to rod and level measurements, and sensitivity to texture of reference profilers. The variability of inertial profiler measurements to tracking has also been examined.

8.1 Current AUSTROADS Criteria

The roughness validation specification used by Transit New Zealand for laser HSDC during the past decade has been based on linear regression of 100 m roughness values between a reference device and the inertial profiler. These specifications were incorporated in the Guidelines for Road Condition Monitoring, Part 1 – Pavement Roughness (AUSTROADS 2001a). The regression statistics are used as acceptance criteria. Limits are placed on the regression slope, offset and regression constant. In the Guidelines there are recommendations that medium to high textured surfaces be avoided when the method of profile measurement from the reference device and HSDC survey system differ. The Class 1 reference instruments generally used are the ARRB WP or the Dipstick - static inclinometers with large contact footprint and sampling distances. These are different in method of measurement to vehicle mounted HSDC systems that use laser height sensors and inertial accelerometer platforms. In the absence of other formal guidelines, the regression limits are used despite the limitations introduced by texture, footprint and sampling length differences.

8.1.1 IRI Verification

The Guidelines require test sites at least 500 m long. Multiple sites are required to make a total minimum combined length of 2500 m. The sites should cover the roughness ranges from 1.0 to 7.0 m/km IRI, based on 100 m segments. Multiple runs are required at three speeds of the HSDC between the minimum and maximum operational survey speeds. At each speed a minimum of 50 sets of 100 m averaged IRI values should be obtained.

The validation analysis requires least squares regression between the 100 m averaged reference IRI and surveyed IRI values at each site and speed to produce a best-fit line of the form below.

$\mathbf{IRI_{ref} = A \times IRI_{device} + B}$

Where $\mathbf{IRI_{ref}}$ = 100 m averaged IRI calculated from the reference device

$\mathbf{IRI_{device}}$ = 100 m averaged IRI calculated from the survey device

A = best fit linear regression slope

B = best fit linear regression offset

The validation criteria require that:

A is between 0.95 to 1.05 m/km IRI

B is between -0.25 to +0.25 m/km IRI

r^2, the regression coefficient is equal to or greater than 0.975

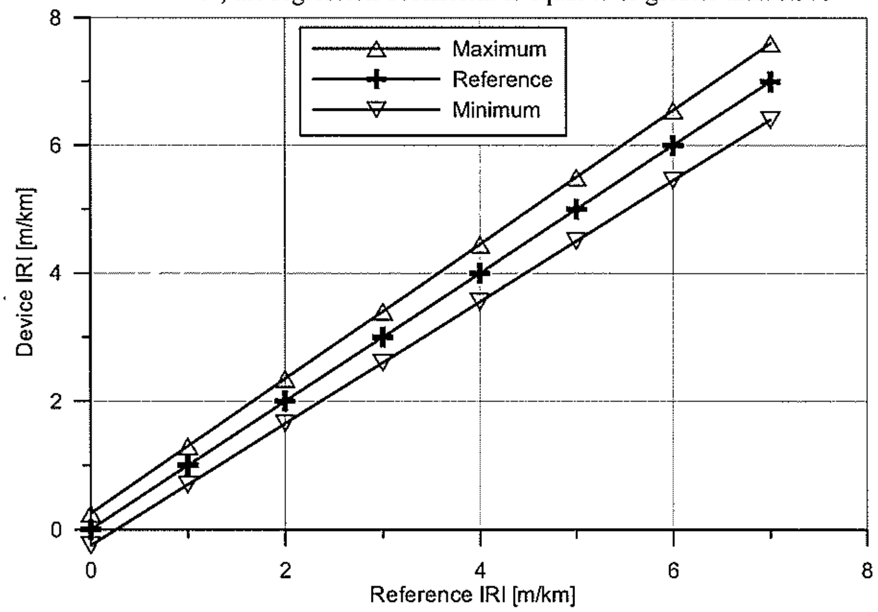

Figure 8.1 AUSTROADS Validation Criteria

8.1.1.1 *Limitations of Linear Regression*

There are limitations to the linear regression criteria. To take an extreme case, a device can pass the test on the upper limits of slope (A = 1.05) and offset (B = 0.25). At 7.0 m/km reference IRI the device is allowed 7.6 m/km IRI, a difference of 0.6 m/km IRI that is equal to 15 NAASRA. It is also difficult to achieve good regression results when the data range is small in relation to the absolute accuracy of the measurement.

A simulation of 1000 validation tests was conducted. Each test consisted of five 500 m sites at three different speeds over a good range of roughness values (3 to 6 m/km IRI). Simulated errors were added to the HSDC measures by increasing the standard deviation of the repeat 100 m IRI roughness values. The simulation results are summarised in table 8.1. The first column is the increasing standard deviation in the test device, followed by the effects on the mean slope, offset and r^2. The final two columns show the expected percentage of individual regression failures in the entire 1000 validation test set.

Table 8.1 Regression Simulation.

Device IRI standard deviation	Slope A	Offset B	r^2	Slope Fail [%]	Offset Fail [%]
0.00002	1.0017	-0.0031	0.9922	6	5
0.02	0.9979	0.0041	0.9910	4	5
0.05	0.9909	0.0159	0.9843	5	6
0.1	0.9734	0.0456	0.9599	5	5
0.2	0.8960	0.1854	0.8811	15	13
0.5	0.6043	0.7156	0.5909	52	49
1.0	0.2734	1.3134	0.3207	93	90
Criteria	$0.95 \geq A \geq 1.05$	$-0.25 \geq B \geq +0.25$	0.975		

The final two columns of table 8.1 show that even very low levels of variability in the test device will produce a 5% failure rate over the total number of sites and tests in the validation criteria. Table 8.1 shows that the device standard deviation should be less than 0.2 to pass the AUSTROADS (2001a) linear regression validation criteria.

8.1.1.2 *Normal Distribution*

If the IRI values from the test device are assumed to be normally distributed, which they usually are when the device is not biased by some systematic measurement error, then the distribution of IRI values varies about a mean value according to the standard deviation. With a normal distribution (figure 8.2) there is a 68% probability that the data lies within one standard deviation of the mean, about 95% lies within two standard deviations of the mean and 99% is found within three standard deviations from the mean.

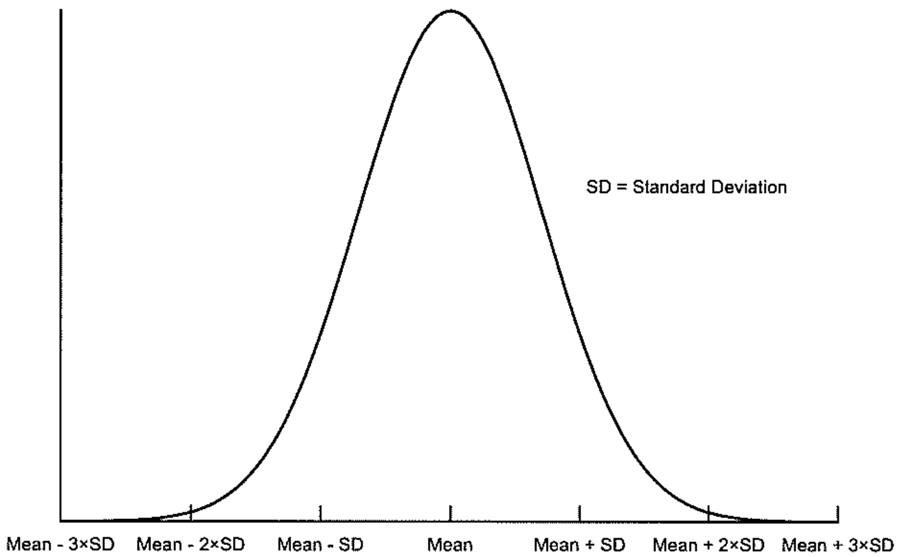

Figure 8.2 Normal Distribution.

Given that the test device standard deviation should be less than 0.2 IRI to pass the regression criteria, it is highly probable that 68% of the data will be within ±0.2 IRI (±4 NAASRA) of the reference value and 95% will be within ±0.4 IRI (±9 NAASRA). If 95% of the survey variation required is to be within 0.14 IRI (±2.5 NAASRA), the standard deviation of the device must be less than 0.07 IRI. Table 8.1 shows that to achieve this level of probability using regression requires very stringent criteria of better than 0.98 to 1.02 slope and less than ±0.04 offset. The current regression criteria will pass a device performing satisfactorily but cannot be used to guarantee an acceptable allowance of measurement variability.

8.1.2 Profile Verification

In the AUSTROADS (2001a) Guidelines there is an alternative verification procedure for profile measurement devices that compares the ability of the device to match the profile measurement of the reference device. This method is not recommended as a primary criterion for validation as footprint differences on highly textured surfaces can affect the results.

The profile comparison is performed by using spectral analysis techniques to quantify the ability of the profile measurement device in reproducing the profile of the reference device. Spectral analysis breaks down the profile information into components of profile variations at different wavelengths. In the case of roughness the wavelengths of interest are between 0.3 to 100 m. There are allowable tolerances for the profile variations at different wavelength bands based on the sensitivity of the IRI calculation. The IRI number itself is based on spectral functions where the measured profile is passed through a filter that represents the response of a "Golden Car" (Sayers and Karamihas, 1998). The Golden Car has filter parameters that represent the suspension spring and shock absorbers of a standardised car travelling at a fixed speed. The IRI value is an accumulation or sum of the filtered profile that relates to the car travelling over the road profile.

8.2 Profiler Variability

The reference devices of choice, the Dipstick and ARRB WP have demonstrated IRI CoV of 2% (figure 6.2) and standard deviation better than 0.05 IRI at texture levels up to 3.0 mm MPD (figure 6.3). Their variability is normally distributed (section 8.1.1.2) so that there is 95% probability that repeat measures are within ±0.1 IRI (±1 NAASRA). Inertial laser profilers are capable of equal and better levels of repeatability on validation sites.

8.3 Roughness Validation Criteria

The current AUSTROADS (2001a) IRI verification procedure (section 8.1.1) using linear regression is a test that does not differentiate between a profiler with good performance and another that can produce results within specified roughness tolerances without applying very tight requirements on the regression results (section 8.1.1.1). The alternative AUSTROADS (2001a) profile validation criteria (section 8.1.2) has problems with the differences in the measurement method and the comparative lower measurement accuracy of current reference devices (Dipstick and WP) on highly textured surfaces.

As an addition to the AUSTROADS (2001a) Guidelines, criteria should be added to ensure that the roughness measure tolerances are within acceptable limits, using the properties of the normal distribution (section 8.1.1.2) and the desired minimum absolute measurement accuracy of the profiler against that of the reference instrument. The mean roughness of the reference and profiler must agree to within some desired limit and the standard deviation of the profiler must meet the limits in table 8.2 for a desired accuracy or deviation from the reference instrument. To achieve the same level of roughness tolerance using linear regression would require very stringent criteria.

Table 8.2 Desired Accuracy and Standard Deviation.

Desired Accuracy		Standard Deviation Required	
IRI	NAASRA	IRI	NAASRA
±0.1	±1	0.04	0.2
±0.2	±4	0.08	0.8
±0.3	±7	0.11	1.6
±0.4	±9	0.15	2.7
±0.5	±12	0.18	3.5

- Use the criteria in the AUSTROADS (2001a) Guidelines as a starting point.

- Require regressions on a per site, wheelpath and speed basis, setting limits for slope offset and regression constant. The slope A should be between 0.9 to 1.1, offset between ±0.5 m/km, and r^2 greater than 0.90. The 95% confidence intervals for the slope should pass through 1.0 and the offset should pass through 0.0.

- Combine the results for all sites at each speed range and perform the regressions. The slope A should be between 0.98 to 1.02, offset between ±0.25 m/km, and r^2 greater than 0.90. The 95% confidence intervals for the slope should pass through 1.0 and the offset should pass through 0.0.

- Test the repeatability of the profiler at each speed using the Coefficient of Variance for each 100 m IRI segment the standard deviation divided by the mean should be less than or equal to 5%. The average of all segments at each site and speed should be less than or equal to 3%.

- Day to day repeatability can be tested using Bias Error (AUSTROADS, 2001a) where the percentage difference between the mean of five repeat measures separated by at least a day is within a nominated tolerance.

- For sites where the range of roughness values is small, the mean roughness of each segment for each wheelpath and speed should be within a nominated tolerance of the reference value and the repeat measures must have a standard deviation within a nominated tolerance. Allowance may be required for the percentage of values that are allowed to pass this test to account for the values that may fall outside tolerance.

- Repeatability between different speeds should be within a nominated tolerance value.

8.3.1 Site Selection

- A minimum of five sites should be established, each with a minimum length of 500 m and each representing a typical surface or pavement condition of the network.

- Sites with complex geometry, curvature or high pavement distress may be chosen, keeping in mind that the roughness measures accuracy and repeatability may be reduced by the site geometry or degree of distress.

- Sites with low roughness ranges will be difficult to validate with linear regression, the profile validation of normal distribution approach may be used as alternatives.

- Highly textured sites and the differences in footprint between static reference and HSDC profilers may cause the reference roughness values to be 10% higher than the profiler roughness.

- Figure 6.4 gives the footprint texture effect.

8.3.2 Establishing Reference Profiles

- Despite the limitations of the current reference devices (section 4.3.6) the best way to establish robust reference profiles is to perform repeat measurements. At least four repeat profiles should be surveyed so that any odd results can be removed. The repeat measures should produce 100 m IRI values within ±0.1 m/km if the road surface is not highly distressed.

- Consideration should be given to adding lead in and out lengths to the actual validation site length as the IRI calculation requires about 11 m to stabilise, increasing in length if there are high roughness features at the start and end of the site. A run in of 10 m should suffice on sites with smooth transitions on the start and end areas. These lead in and out areas can be added post survey by editing the collected data files.

- The values used for the IRI validation should be averaged from the repeat profiles removing any odd readings. For the profile validation criteria the profile spectra should be averaged together.

8.4 Rut Depth Validation

- For validating rut depth survey systems an allowance should be made for the sensor configuration. If there are a limited number of height sensors the maximum rut may not be accurately recorded. The spacing of the sensors has a critical effect on the ability of the survey vehicle to detect the ruts.

- The reference profiles should be established at the same sensor spacing as the HSDC vehicle and the rut depth derived from the measured reference profile. This will remove the variability caused by sensor spacing but may not necessarily represent the true rut depth. Requiring the profile points to be within a nominated tolerance of the reference profile should validate the transverse profile measurement system.

9. Conclusions

Published international literature has identified problems with profiler systems on high macrotexture road surfaces. These problems are caused by the different sensor footprint sizes and sample intervals used by different profiler systems. They are well known and accepted in many countries where the majority of the roads have low texture levels. In New Zealand and Australia, a high proportion of the road network has medium to high macrotexture levels.

Vehicle mounted inertial HSDC profilers used for network surveys of road roughness and rutting use laser or optical height sensors that have a small sensor footprint and small sampling distance.

Network survey profilers are validated against static profilers such as the Dipstick and ARRB Walking Profiler.

Validation studies in New Zealand and Australia have experienced problems on highly textured surfaces. The high texture level introduces errors in the profile measurement that makes it difficult to compare results from static and inertial profilers.

The texture effect has been found to add up to 10% IRI roughness at 3.0 mm MPD to static profiler measurements with large footprints in comparison with laser HSDC profilers with small measurement footprint.

Tracking errors are caused by a variety of factors that include lane width, curvature and sight distance. The deviation from a given track is influenced by a complex combination of these factors. On validation sites, aids such as additional temporary road markings can minimise tracking errors.

Roughness validation criteria using linear regression are not adequate for ensuring performance between nominated tolerances without being overly stringent.

Nominated tolerances to reference values and the standard deviation of a measurement are useful in validating a profiler to ensure performance within acceptable limits.

Rut depth measurements are strongly influenced by the sensor spacing.

Validation measurements for rut depth systems should match the sensor spacing and the rut depths should be derived from the reference profiles.

10. Recommendations

On the basis of this study, differences as large as 10% at 3.0 mm Mean Profile Depth in the calculated roughness values were identified between Class 1 static profilers, such as the Dipstick, and vehicle mounted HSDC profilers on coarse textured road surfaces, such as New Zealand chipseal surfaces. Class 1 profilers are generally used to obtain reference road profiles for roughness and rutting validation. The errors in road roughness measures are attributed to differences in the sensor footprint among the various static and inertial profilers. Validation specifications have been proposed that address the limitations of the current static reference profilers.

Future work will develop a better reference device to remove the texture and footprint interaction effect. The reference device should have a better measurement resolution and footprint comparable with the laser HSDC profilers. A better reference device will ensure that an accurate road surface profile can be measured, allowing for direct comparison of profilers. The road profile is important for asset management as it provides the basis for the calculation of roughness and rutting which impact on road user costs and safety.

Errors or underestimation of rutting from vehicle mounted HSDC profilers is mainly due to the inability of the limited number of height sensors to adequately reproduce the transverse profile. Ultrasonic sensors with large measurement footprint are adversely affected by highly textured surfaces.

Until survey systems measuring almost continuous transverse profiles become more widespread in use, the limitations of using a limited number of sensors must be addressed. The spacing of the height sensors should be optimised for the particular network or pavement type to make the best use of the limited number available.

11. References

ASTM E 1364-95. 1995. *Standard Test Method for Measuring Road Roughness by Static Level Method.* ASTM, USA.

ASTM E 950-94. 1994. *Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profile Reference.* ASTM, USA.

AUSTROADS. 2001. *Pavement Test PAT 01:2001. Determination of the International Roughness Index (IRI) using ARRB TR Walking Profiler.* AUSTROADS, Sydney, Australia.

AUSTROADS. 2001a. *Guidelines for Road Condition Monitoring. Part 1 – Pavement Roughness.* AUSTROADS, Sydney, Australia.

Cenek, P.D., Brown, D.N., Carpenter, P., Jamieson, N.J. and McLarin, M.W. 1997. *Replication of VTI's Stationary Laser Profilometer for Measuring Road Surface Profiles. Transfund New Zealand Research Report No. 84, 55pp.*

Fernando, E. 1999. Looking for a Smooth Ride. *Texas Transportation Researcher, Vol. 35, No.3, 1999.* Texas Transportation Institute, College Station, Texas, USA.

Fernando, E.G. and Leong, S.C. Profile Equipment Evaluation. *Research Report 1378-2. Texas Transportation Institute, College Station, TX, December 1997.* Texas Transportation Institute, College Station, Texas, USA.

Fong S. and Brown D.N. 1997. Transfer Function Based Performance Specifications for Inertial Profilometer Systems. *Central Laboratories Report 97-529351.*

Fong, S. 1999. Documentation of Work Conducted for Transit New Zealand on Roughness Validation, *Central Laboratories Report 99-529359.13.*

ISO 13473-1:1997(E). *Characterization of pavement texture by use of surface profiles – Part 1: Determination of Mean Profile Depth.* International Organization for Standardization.

Karamihas, S.M. and Gillespie, T.D. 1999. *NCHRP Report 434, Guidelines for Longitudinal Pavement Profile Measurement*, National Research Council, National Academy Press, Washington, D.C.

McGhee, K.K. 2000. *Quality Assurance of Road Roughness Measurement*, Virginia Transportation Research Council, VTRC 00-R20, May 2000.

Perera, R.W. and Kohn, S.D. 1994. Road Profiler User Group Fifth Annual Meeting. Road Profiler Data Analysis and Correlation. *Soil and Materials Engineering, Inc. Research Report No. 92-30, 87pp.*

Prem, H. 1989. NAASRA Roughness meter calibration via the road-profile-based International Roughness Index (IRI), Australian Road Research Board. *Research Report ARR 164.*

Prem, H. 1998. *Development and Evaluation of a Method for Validation of Pavement Roughness Measurements.* ARRB Transport Research Ltd. RE7135.

Prem, H. 1999. Measurement of reference profiles for high-speed profiler validation. ARRB Transport Research Ltd. *Road Transport and Research Vol. 8, No. 1, pp 84-91.*

Robertson, D.A. 1998. Towards a Specification for Validating IRI Measurements from Road Profilers, 9th REAAA Conference, Wellington, New Zealand, 3-8 May 1998.

Sayers, M.W. 1995. On the Calculation of International Roughness Index from Longitudinal Road Profile, *Transportation Research Record 1501.*

Sayers, M.W., and Karamihas, S.M. 1998. The Little Book of Profiling, The University of Michigan Transportation Research Institute, September 1998. Available from http://www.umtri.umich.edu/erd/roughness/litbook.html

Sayers, M.W., Gillespie, T.D., and Paterson, W.D. 1986. Guidelines for the Conduct and Calibration of Road Roughness Measurements, *World Bank Technical Paper 46. World Bank, Washington D.C.*

VicRoads, 1999. Technology Exchange Workshop, AUSTROADS BS.A.65 Roughness Guidelines, Validation of Roughness Measurements, VicRoads, Victoria, Australia, 4-5 March 1999.