Harmonising Automated Rut Depth Measurements

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Christopher R. Bennett and Hanqing Wang
Data Collection Ltd.
Motueka

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

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An Important Note for the Reader

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Executive Summary

Ruts are permanent deformations of the pavement structure. They are an important indicator of the structural integrity of the pavement as well as having an impact on road user safety. For these reasons, most road agencies regularly monitor the levels of rut depths on their pavements.

Automated Rut Depth Systems

In NZ there are four different instruments used for automated measurement of rut depths:

- MWH 30-Sensor Ultrasonic System
- WDM 16-Sensor Laser System
- PMS 15-Sensor Laser System
- ARRB 13-Sensor Laser System

Each system collects and processes data using proprietary algorithms, usually reporting the rut depth under a simulated 2 m straight-edge to be consistent with manual measurements.

Harmonising Rut Depths

This project considered the feasibility of harmonising the measurements of the different automated measurement systems as well as other operational issues. The goal was to confirm whether outputs from the different systems were compatible with each other and could be referenced back to a single 'standard' value. This was done by developing a computer simulation program which would predict the rut measurements from profilometers on a series of road profiles. These profiles were supplied by Transit NZ from their recent calibration section data collection project.

The software developed allows the following factors to be considered:

- the number of sensors and their spacings;
- the position of the vehicle relative to the kerb;
- the effects of randomly varying the lateral placement along the road;
- calculation of the rut depths using three different algorithms: user defined straight-edge; wire model; and pseudo-ruts;
- the effects of changing the datum for the rut depth measurements (measuring perpendicular to the straight-edge or perpendicular to the elevation datum); and
- smoothing the reference profiles using polynomial or spline curve fitting.

Effect of Number of Sensors

Profilometers sample the transverse profile at discrete points. Since the ability to correctly measure the rut depth depends upon the ability to locate the high and low points of the profile, the number of sensors and their spacing—hereinafter referred to as 'sampling'—will have an impact on the results.

The reference profiles were analysed using different numbers of sensors **at even spacings** and the standard error of the measurements was calculated. As shown below, this error was non-linearly related to the number of sensors.

Kerb	$ERROR = 14.39\ SENSORS^{-0.5770}$	$R^2 = 0.94$
Centre	$ERROR = 11.40\ SENSORS^{-0.3831}$	$R^2 = 0.90$

where ERROR is the standard error in mm
SENSORS is the number of sensors

The results indicate that there are significant improvements made in accuracy by increasing the number of sensors, but the marginal benefits decline with increasing sensor numbers. From 25 sensors there are much less benefits from adding additional sensors.

An assessment of the mean rut depth showed that with less than approximately 15 sensors, there can be a significant under-estimation of the true rut depth. It is notable that even with 60 sensors the rut depth would still be underestimated by approximately 1 mm.

The accuracy of a profilometer measurement depends upon two operational factors:

- its position on the road (lateral placement); and
- its ability to locate the high and low points in the profile measured.

Even when the profile is being very accurately measured, if the vehicle is not positioned in such a way that the true high and low points are being sampled, there will be an error. Not surprisingly, the greater the number of sensors the greater the probability of locating the high and low points so the lower the error. A continuous sample (such as that provided by a scanning laser) would in theory give the same results as the 'true' profile.

The findings suggest that there will be underestimation errors of 2-4 mm with operational profilometers in New Zealand (13 to 30 sensors). They also show why the 16, 15 and 13 laser systems have lasers at irregular spacings; this assists in locating the high and low points by focusing the measurements where they are most relevant.

Rut Depth Algorithms

A comparison of the pseudo-rut measurements with the 2 m straight-edge measurements for the same profiles showed that pseudo-ruts are a very poor descriptor of rut depths and should not be used.

The wire model and the 2 m straight-edge model will give the same results when the high points are spaced at 2 m intervals or less. The reference profiles all fell into this category so it was not possible to compare the predictions of the two models.

When calculating rut depths it is possible to reference the rut depths as perpendicular to the elevation datum - the standard method - or perpendicular to the straight-edge. An analysis of the implications of these two methods showed that for rut depths below 50 mm there is no impact on the result; and even for 250 mm rut depths the difference is less than 3 per cent. Thus, this effect can be ignored.

Rut Depth Transfer Functions

The rut depths under a 2 m straight-edge predicted from the configuration of each profilometer were compared to the rut depth for the reference profile as well as to each other. It was found that there was a strong linear relationship in all instances, with R^2 above 0.88 standard errors below 1.5 mm, and many below 1.0 mm.

This confirms that it is practicable to develop transfer functions to convert rut depths from automated systems back to a reference standard.

Implications of Lateral Placement

When conducting a survey the lateral placement of the survey vehicle will have a significant impact on the validity of the measurements, particularly when trying to monitor rut depths between years. The impact will depend upon the shape of the profile, the amount of lateral variation as the vehicle drives down the road, and the number of sensors on the vehicle. The more sensors, and the closer they sample, the less the impact of lateral variations in position.

The analysis showed that increasing the amount of lateral variation significantly impacts on the accuracy of the predicted rut depth. There were different trends observed with the four profilometer configurations tested, reflecting the positioning of the sensors. The results suggested that the 16- and 15-sensor units may need to reposition their sensors to take additional readings towards the kerb, due to the potential for measurements to occur outside the pavement area. When this happens, the spacing to the next sensor is so large that key profile data are missed.

The variable effects of lateral placement on rut depth measurement may be one reason why it has not proved possible to use profilometer rut depth data for monitoring pavement deterioration trends. The variation in rut depths due to different lateral placement can be greater than the change in rut depth due to pavement deterioration.

Extending the Results

The study showed that the objective of developing functions for harmonising profilometer rut depth measurements could be realised. It was proposed to extend the results by:

- measuring additional transverse profiles so that the full range of pavement shapes in NZ are considered;

- working with profilometer suppliers to test their algorithms. This would be done by supplying a sample of profile data to them and analysing the resulting rut depths;
- investigating the optimal spacings of sensors so that providers are given guidance on how to configure their systems;
- considering the impact of measurement precision on the rut depth accuracy and transfer functions.

The HRD software should also be enhanced so that it can form the basis of a stable procedure that can continue to be used for harmonising rut depths. This procedure would be applicable to future instruments and technologies that may be implemented in NZ for measuring rut depths.

Abstract

A computer simulation study was conducted to investigate the viability of harmonising rut depth measurements from different automated rut depth measurement profilometers. A computer program was written which allowed for a standard reference transverse profile to be analysed by any number of profilometer sensors and spacings. The software generated a variety of rut depth statistics. The software was used to investigate the effect of the number of sensors on the predicted rut depth. It was found that the accuracy of the rut depth was proportional to the number of sensors and that this sampling effect results in an underestimation of 2-4 mm for the profilometers used in NZ. The pseudo-rut model was found to be inappropriate for predicting rut depth. It did not prove possible to test the wire model due to the shape of the reference profiles. There are limited differences between the rut depths when referencing perpendicular to the straight-edge as opposed to perpendicular to the elevation datum, so this factor does not need to be considered. Strong linear relationships were found between the rut depth measurements from all instruments, both with each other and with the reference profiles. It is therefore practicable to develop a standard methodology and transfer functions for rut depths. The lateral variation of profilometers has a significant impact on the accuracy of rut depth measurements. Some profilometer configurations appear to have inadequate coverage towards the kerb and so may miss important data if the first sensor measures outside the pavement area. The variation in rut depth which arises from lateral placement can be greater than the change due to pavement deterioration between years, which may account for the problems found when trying to use profilometer rut depth data for monitoring pavement deterioration trends.

1. Introduction

Ruts are permanent deformations of the pavement structure. They are an important indicator of the structural integrity of the pavement as well as having an impact on road user safety. For these reasons, most road agencies regularly monitor the levels of rut depths on their pavements.

As described in Chapter 2, rut depths are measured either manually or using non-contact techniques. The latter involves an instrumented vehicle travelling over a section of road using lasers or ultrasonics to measure the transverse profile of the pavement. From this, the rut depths are estimated. Depending on the instrument used and its analysis technique the resulting rut depths can vary significantly between vehicles.

There is no standardisation of measurement or analysis techniques between manufacturers. This results in measurements being made at different sampling intervals longitudinally along the pavement, and with a different number of sensors and spacings of locations across the pavement. The data are also analysed using algorithms which, although they generally reference back to a 2 m straight-edge, may in fact not be compatible.

The objective of the research was to investigate the feasibility of harmonising rut depth measurements from different automated systems. The work was broken into two phases:

- **Phase I: Feasibility of Harmonising Measurements**. Preliminary work aimed at confirming that it was indeed possible to harmonise the measurements; and,
- **Phase II: Development of Standard Procedures**. Development of standard procedures and functions to ensure measurements from different instruments can be related to one another.

Phase II would depend upon the success of Phase I.

This report presents the results of Phase I. The feasibility of harmonising measurements was investigated by developing a computer simulation program which enabled the rut depths measured with different types of instrument configurations to be compared as if they had all measured the same transverse profile. The data were then analysed using the same algorithm to calculate the rut depths. This meant that the only differences between the instrument outputs were due to the number of sensors and their spacings.

An important consideration in any rut depth survey is the location of the vehicle on the road. Often, data between successive runs may be poorly correlated. To consider this an analysis was made, using the software, of the implications of lateral placement on measurements.

The software also allowed for the implications of the number of sensors and their spacings to be made. This provided valuable insight into the systematic

underestimation of the 'true' rut depth caused by taking measurements at discrete points across the transverse profile.
The outcome of this research is a set of preliminary transfer functions between four different rut depth systems used in New Zealand.

As described in Chapter 9, additional work is required to enhance the range and applicability of these values.

The authors would like to express their appreciation to the following individuals and organisations whose support made the project possible:

- DCL's software team at Captorsoft Software Development (www.captorsoft.com) who developed the initial version of the harmonisation of rut depth software package;
- Transit New Zealand who provided a sample of transverse profile data from their calibration sections for analysis;
- Mr. Theuns Henning of HTC Infrastructure Management Ltd. for his technical reviews and comments; and
- Mr. Dave Robertson of Transit New Zealand for his technical reviews and comments.

2. Measuring Rut Depths

2.1 Introduction

Regular data collection is essential for the proper monitoring of road condition, and thus the asset value. Accordingly, many road controlling authorities have annual data collection programmes. Data is collected using one of two methods:

- **Manual Data.** This is a visual assessment of the pavement condition collected in accordance with the RAMM Rating Guide (Transfund, 1997). The pavement distresses are recorded along a 'Rating Length'.
- **Automated Data.** Roughness is collected either using a laser profilometer or a response-type meter (e.g. NAASRA meter). State Highways are only measured with profilometers, while response-type meters or profilometers are used for local authority roads. Rut depths are collected with lasers or ultrasonics. Texture is collected with lasers, although mainly only on State Highways.

2.2 Manual Rut Depths

As illustrated in Figure 2.1, rutting in RAMM is defined as the length of individual wheel path in metres where rutting (wheel tracking) exceeds 30 mm in depth measured from a 2 m straight-edge laid transversely across the wheel path. Only the length where rutting exceeds 30 mm is measured. Since there are 4 x 50 m lengths over a 50 m rating section (that is, two wheel tracks in each direction on a 2-lane road), there is a maximum possible value of 200 m for this measure.

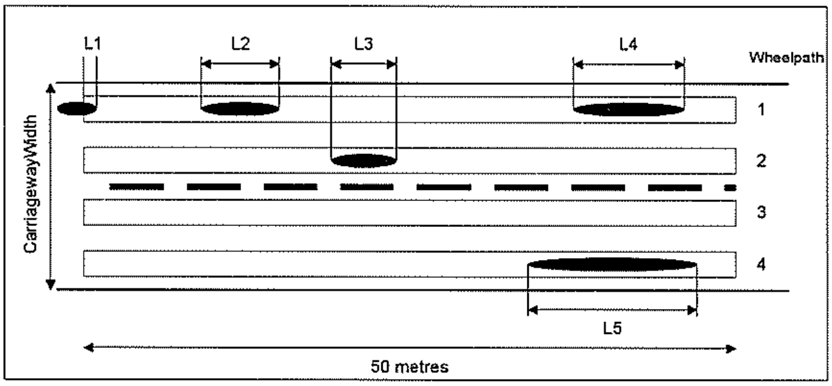


Figure 2.1 RAMM Rut Depth Rating

Instead of 30 mm, Transit New Zealand uses a 20 mm criteria for defining rut depth on State Highways. Since 1998 rut depths have been measured using high speed data acquisition vehicles (see Section 2.3) instead of manually. The RAMM criteria is calculated from the high speed measurements.

With the implementation of predictive modelling for pavement deterioration there has been a shift of emphasis away from the RAMM approach (i.e., the length of pavement with rut depths greater than 20/30 mm) to the use of the mean rut depth. This trend is likely to continue as it is consistent with the output from the predictive modelling.

2.3 Automated Rut Depths

Automated measurements are made using lasers or ultrasonic transducers to measure the transverse profile of a pavement as a vehicle travels over it at highway speeds. There are various terms for the equipment depending upon the manufacturer but for simplicity they will be referred to in this report as 'profilometers'.

2.3.1 Technology

There are four technologies used for estimating rut depths:

- **Ultrasonics**. Ultrasonic sensors are the lowest cost sensors and are used in systems like ROMDAS and ARAN. These have sensors at approximately 100 mm intervals which measure up to 3 m across the pavement. Due to the speed of ultrasonics these systems typically sample at every 2.5 – 5 m along the road. Figure 2.2 is an example of the MWH 30 sensor ultrasonic profilometer operated in NZ.

Figure 2.2 MWH ROMDAS Ultrasonic Profilometer

- **Point Lasers**. Point lasers give the elevation at a point. The number of lasers varies, with the WDM profilometer using 16 while the ARRB TR profilometer uses 13. Much faster than ultrasonics, these record the transverse profile at intervals as close as every 10 mm along the road. Figure 2.3 is an example of the WDM laser profilometer.

Figure 2.3 WDM Laser Profilometer

- **Scanning Lasers**. This is a new technology not currently used in NZ. These lasers measure what is almost a continuous profile. An example of such a system is the Phoenix Science 'Ladar' which samples a 3.5 m pavement width from a single scanning laser mounted 2.3m above the ground. 950 points are sampled across the transverse profile, every 25 mm along the pavement.

- **Optical**. Not used in NZ, these use digitised images of the transverse profile which are analysed to estimate rut depths. These images may be produced using various photographic techniques, often supplemented by lasers. An example of such a system is the INO rut system which uses two lasers to project lines to the pavements and a special camera to measure deformations of the laser line.

Since scanning lasers and optical systems are not in use in NZ, the focus of this project was on ultrasonic and point laser systems. The configurations of four different profilometers were considered:

- 30 Sensor MWH ultrasonic system;
- 16 Sensor WDM point laser system;
- 15 Sensor PMS point laser system; and,
- 13 Sensor ARRB TR point laser system.

2.3.2 Sensor Positioning

Each profilometer has its own unique configuration for the positioning of the elevation sensors. Figure 2.4 shows the positioning for the ARRB TR multilaser profilometer where the sensors are positioned at different spacings. By comparison, the MWH ROMDAS profilometer has 30 sensors at 100 mm equal spacings.

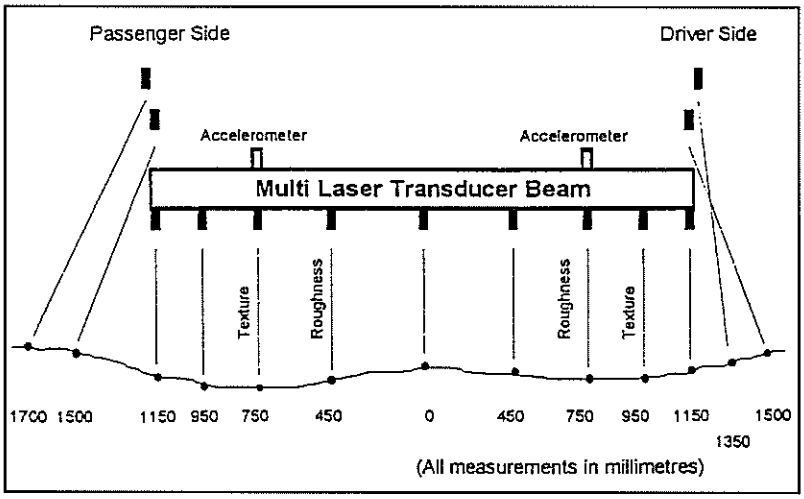


Figure 2.4 ARRB TR Multilaser Profilometer Laser Positioning

Irrespective of the technology used and the sensor spacing, the analytical approach is similar for all technologies. The elevations of each sensor result in the transverse profile being established. The data are analysed to determine the rut depths.

2.3.3 Analytical Process

There are three basic algorithms used for calculating rut depths.

- The **straight-edge** model emulates the manual method of placing a straight-edge across the pavement. Figure 2.5 is an example of the straight-edge model. In NZ all profilometers report the straight-edge rut depth.

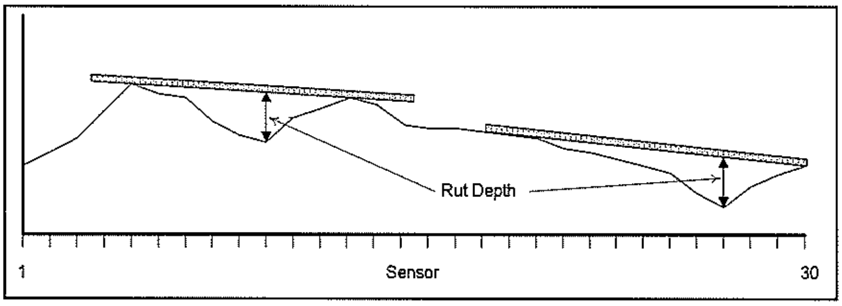


Figure 2.5 Example of Straight-Edge Simulation

- As described by Cenek, et al. (1994), the **wire model** is popular since it is very fast in performing its calculations. Figure 2.6 is an example of the wire model calculations. Unlike the straight-edge, the wire model expresses the rut depth based on a wire 'stretched' over the high points. The distance to the pavement from the wire is calculated, and the highest values constitute the rut depth. In NZ the PMS profilometer reports the wire model rut depth in addition to the straight-edge rut depth.

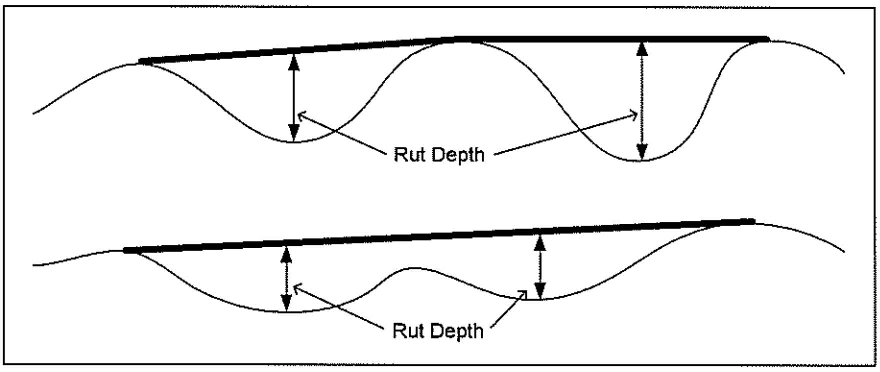


Figure 2.6 Example of Wire Model

- **Pseudo-ruts** are defined are as the difference (in mm) between the high point and the low points. It is used on systems with only a limited number of sensors and, while common in the USA, has not been applied in NZ.

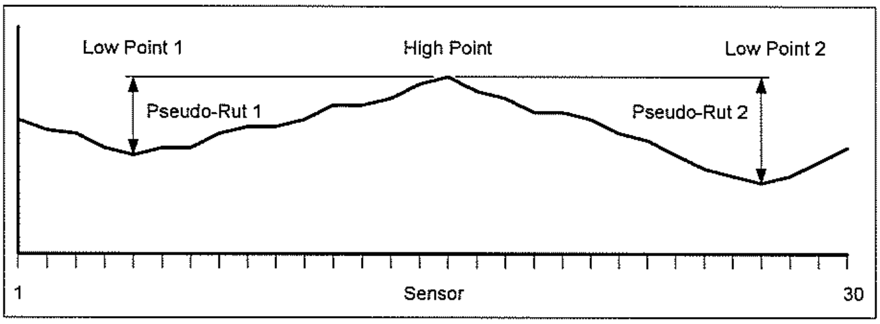


Figure 2.7 Definition of Pseudo-Ruts

2.4 Implications of Sampling

One feature of profilometer measurements of rut depth is that they **always** underestimate the true rut depth. The reason for this can be readily visualised from the straight-edge simulation example shown in Figure 2.5 above. For the measured rut depth to correspond to the actual rut depth, the sensors would need to record the high and low points in each wheelpath. Since the sensors are spaced at discrete intervals across the road, this is impossible.

Bennett (1998) tested the implications of discrete sampling of rut depth. The results are presented in Figure 2.8. The data were calculated by taking continuous transverse profiles (horizontal axis) and then calculating the rut depth as if the profile had been sampled at 100 mm intervals instead (vertical axis). The data clearly show the bias introduced from having discrete samples over the continuous sample.

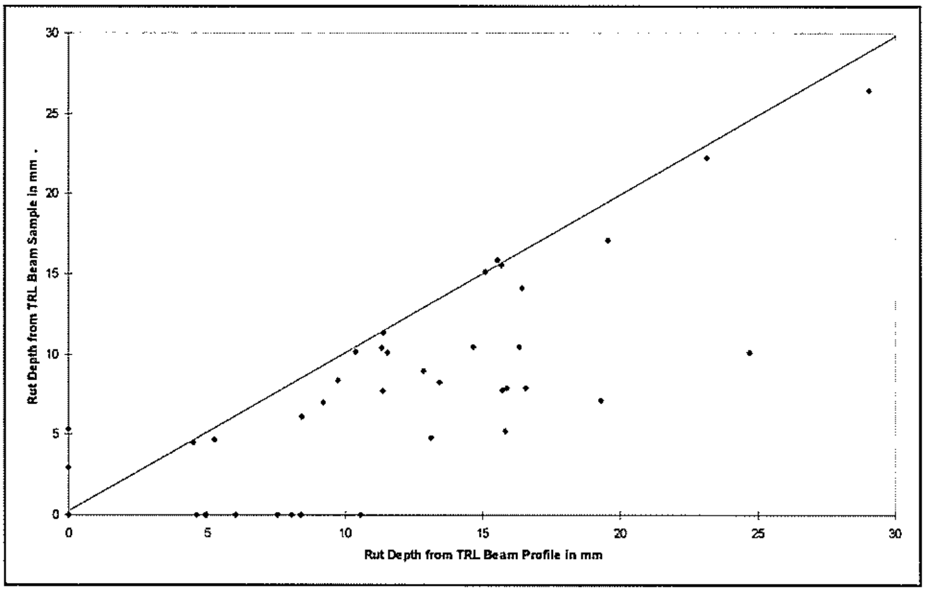


Figure 2.8 Effect of Sampling on Rut Depth from Continuous Samples

Discrete sampling also results in differences in rut measurements between systems. Figure 2.9 shows a hypothetical example of two different systems measuring the same profile. Each will result in different high and low point elevations and, thus, different estimates of rut depths.

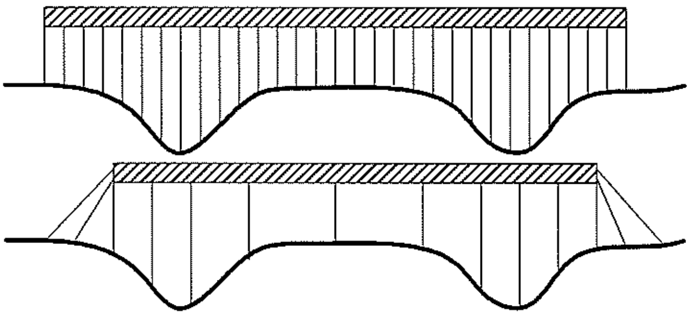


Figure 2.9: Example of Sensor Spacings on Transverse Profile

The sampling effect is important with a single instrument, but when several different instruments are used the need for harmonisation is highlighted still further. This need is illustrated in Figure 2.10 which shows the results from three different instruments, each with their own sensor spacing, when analysing the same profile. The values obtained for the kerb and centre rut depths were 6.8 – 7.4 mm and 2.6 – 3.5 mm respectively, which compared with the true values of 8.0 and 5.3 mm[1].

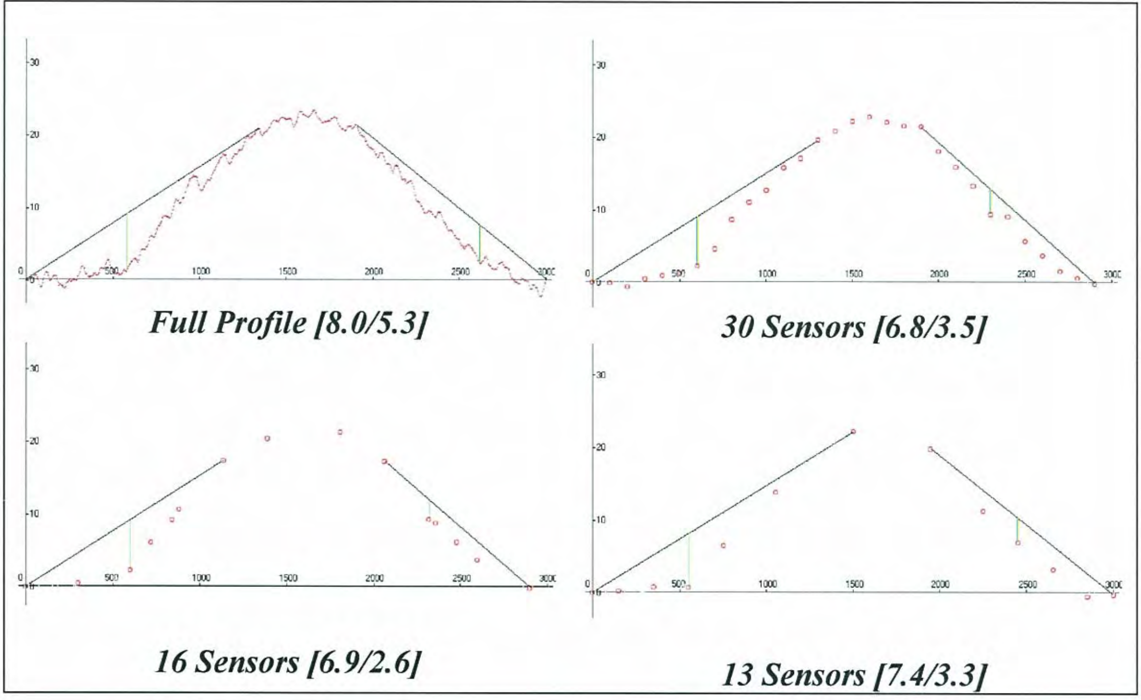


Figure 2.10: Effects of Sampling from Three Different Instruments

As will be shown in Chapter 4, the amount of the bias will depend principally upon the number of sensors and their spacing. The more sensors there are, and the closer they are together, the closer the readings will be to the true rut depth. However, it must be emphasised that a profilometer will never give the same rut depth as that recorded manually unless it samples the transverse profile in such a way that it correctly identifies the high and low points. Even then there will still be differences since the profilometer measurements are usually made with a greater precision than manual measurements (*eg* +/- 0.1 mm vs +/- 1 mm).

2.5 Effect of Lateral Placement

In the context of rut depth measurements, the effects of sampling are exacerbated by lateral placement variations, i.e., when the operator does not position the vehicle in exactly the same wheeltrack between successive surveys. While this is typically not a problem during equipment validation, where the vehicles are operated in a very controlled manner over clearly marked wheelpaths, it becomes an issue during operational surveys.

[1] Throughout this report when reporting rut depth results the format will be [kerb,centre]. For example, [6.6/4.4] refers to a 6.6 mm rut depth at the kerb and a 4.4 mm rut depth in the centre of the road.

Simpson (2001) considered the two scenarios shown in Figure 2.11 for lateral placements. In the first there was no lateral variation in the position of the vehicle, while in the second there was completely random variation along the section. A value of 127 mm was used for the lateral standard deviation, a value determined "from field data collected at a limited number of sites". As shown in Chapter 8, this lateral placement variation has a significant impact on the rut depths resulting from any profilometer survey.

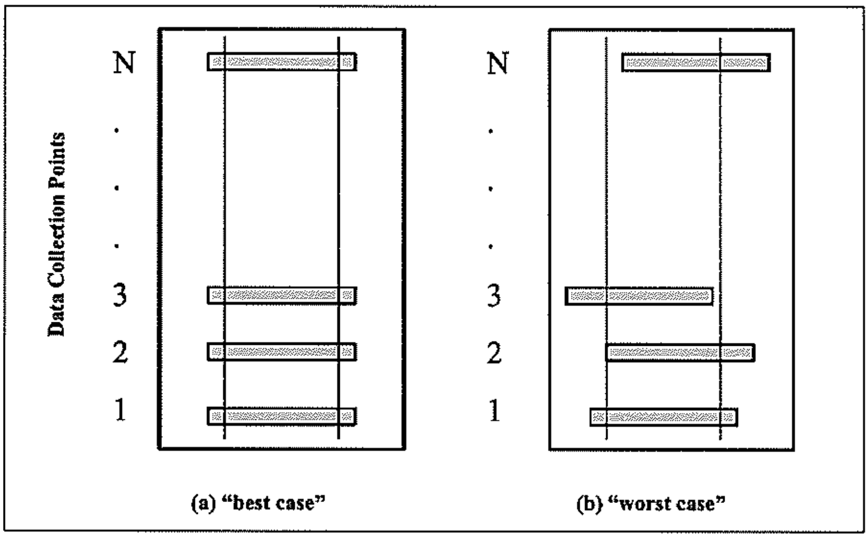


Figure 2.11: Simpson (2001) Lateral Placement Scenarios

2.6 Progressive Sampling

One feature of some ultrasonic profilometers (*e.g.* ROMDAS and ARAN) is their use of 'progressive sampling'. Unless ultrasonic sensors are placed at intervals of 300-500 mm, there will be interference from the sound signals from adjacent sensors. To get around this problem the measurements are made progressively along the road. For example, the MWH 30-sensor system records five sensors sequentially which results in a pattern such as that shown in Figure 2.12. Lasers are not influenced by adjacent sensors and so sample simultaneously.

Progressive sampling means that the transverse profile used in the analysis is a 'composite' profile which is constructed from the measurements of the individual sensors. This is illustrated in Figure 2.13. The profile is influenced by the speed at which the sensors are fired and the speed of the vehicle. Typically, this takes 3 – 5 m at speeds of 70 km/h; up to 10 m at higher speeds. When there is limited longitudinal variation in rut depths, there should not be a major difference between the laser and ultrasonic systems. The providers of ultrasonic systems argue that while their progressive sampling is inferior to lasers when there is a high degree of longitudinal variation, their use of more sensors (typically twice the number of lasers) offers improved results through better characterisation of the transverse profile.

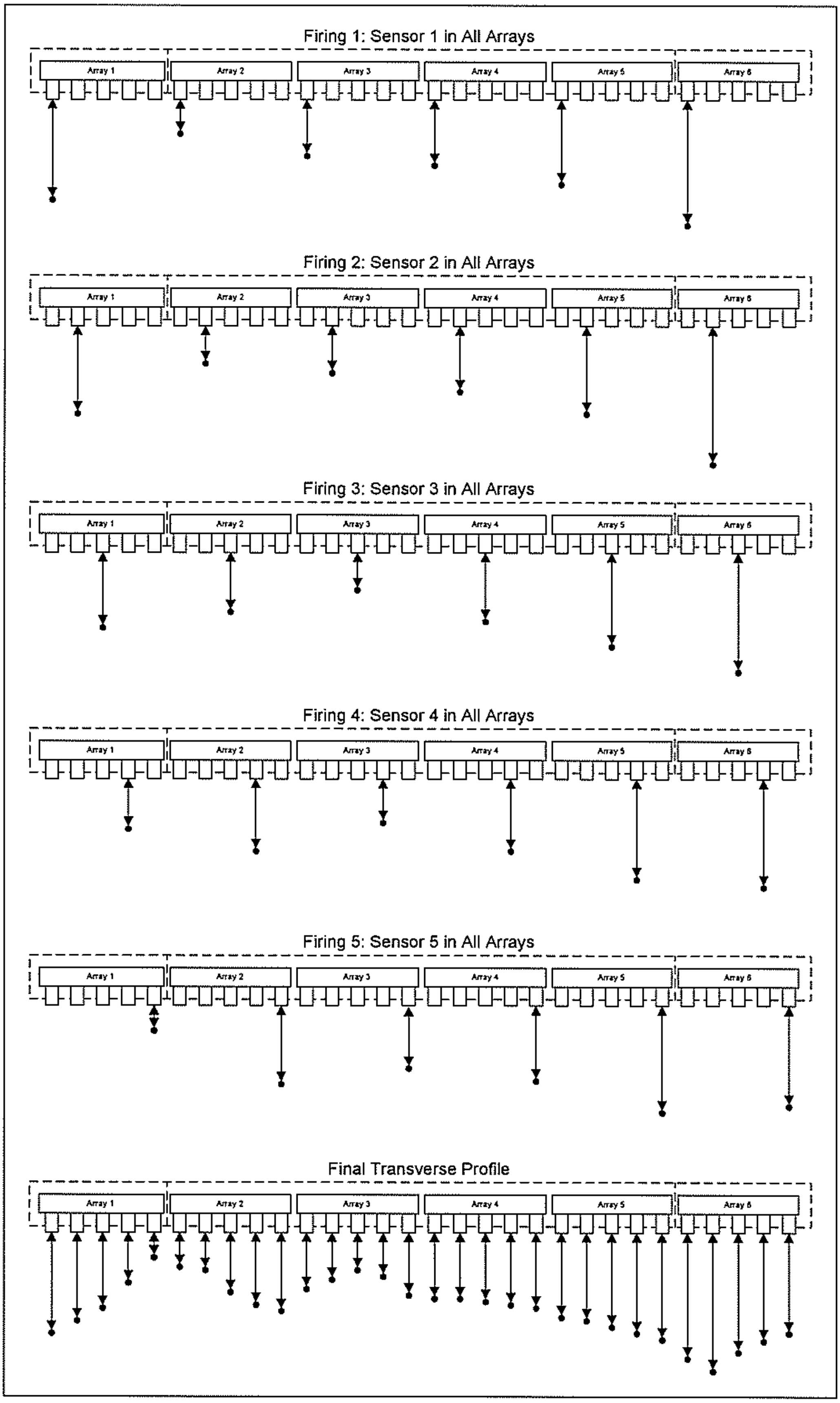


Figure 2.12: Progressive Sampling For 30 Sensor Ultrasonic System

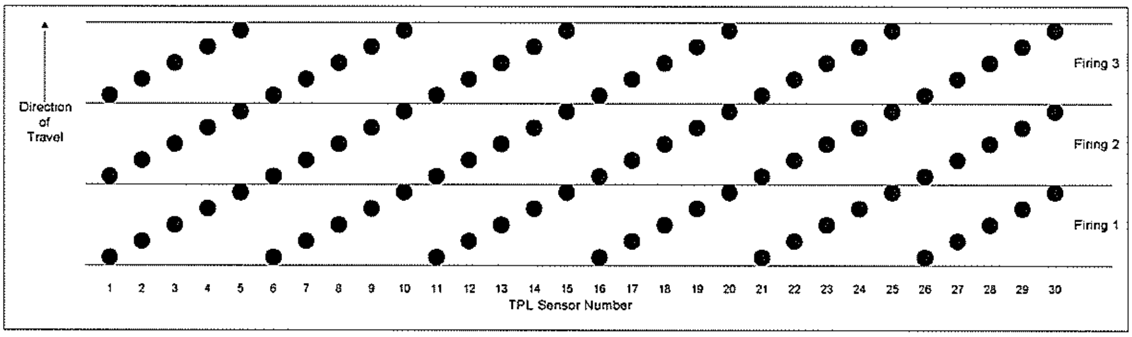


Figure 2.13: 30-Sensor Ultrasonic Progressive Sample Profile

3. Transverse Reference Profiles

3.1 Introduction

A 'reference profile' is a standard against which measurements can be evaluated. For roughness measurements, reference profiles have been established for some time, with profiles measured using the Face Dipstick® or the ARRB TR Walking Profiler being those against which other techniques are compared. However, the same is not true for transverse profiles, where there is no standard.

3.2 DCL Transverse Profile Beam

Data Collection Ltd. (DCL) developed a 'Transverse Profile Beam' (TPB) for the purpose of establishing reference transverse profiles. This is a precision instrument which consists of a 3.6 m wide beam together with a motorised carriage (see Figure 3.1). The carriage moves a wheel across the pavement and vertical and horizontal transducers monitor the position of the wheel and its elevation. With a vertical resolution of 0.2 mm and a horizontal resolution of 3 mm (HTC, 2001a), the TPB provides very precise measurements of the transverse profile.

Figure 3.1: DCL Transverse Profile Beam

As described by HTC (2001a), during validation of the TPB measurements were made at 30 different locations in the left wheelpath using both the TPB and the 2m straight-edge. Figure 3.2 shows the comparison of these two measurements. The differences were in the range of –2.3 to +2.5 mm.

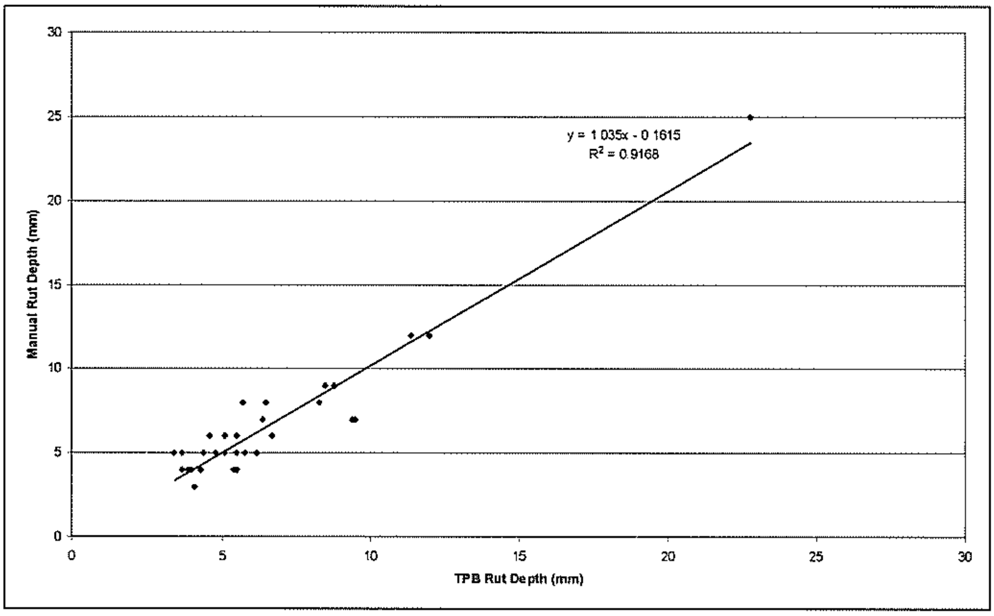


Figure 3.2 TPB vs Manual Rut Depths

The slight difference between the measured manual rut depth and the TPB calculated rut depth was ascribed to two factors:

- **Precision**. The TPB measurements were to the nearest 0.1 mm whereas the straight-edge and wedge measurements were to the nearest 1.0 mm
- **Measurements**. There is a difference between the contact area of the measurement wheel and the wedge used with the straight-edge. One observed effect was that the wheel on the TPB could straddle the chips while the wedge could fit between the chips when the chip size is sufficiently large.

Figure 3.3 shows the profile measurements between two forward and one reverse run (HTC, 2001a). The 50 mm offset between the forward and reverse runs has no impact on the rut depths. The correlation between the forward runs was 0.98.

3.3 Transit Calibration Surveys

In 2001 HTC Infrastructure Management Ltd. (HTC) in association with DCL were awarded a contract to collect data for Transit New Zealand on a series of calibration sections around NZ. These data were to be used by Transit New Zealand to monitor pavement deterioration rates. Figure 3.4 is an example of the site layout with lane markings and safety cones at one of the sections.

The data collected at each site consisted of:

- roughness using an ARRB TR Walking Profiler;
- transverse profile using the DCL Transverse Profile Beam;
- visual condition inspection;
- video logging;
- digital photographs; and
- GPS co-ordinates.

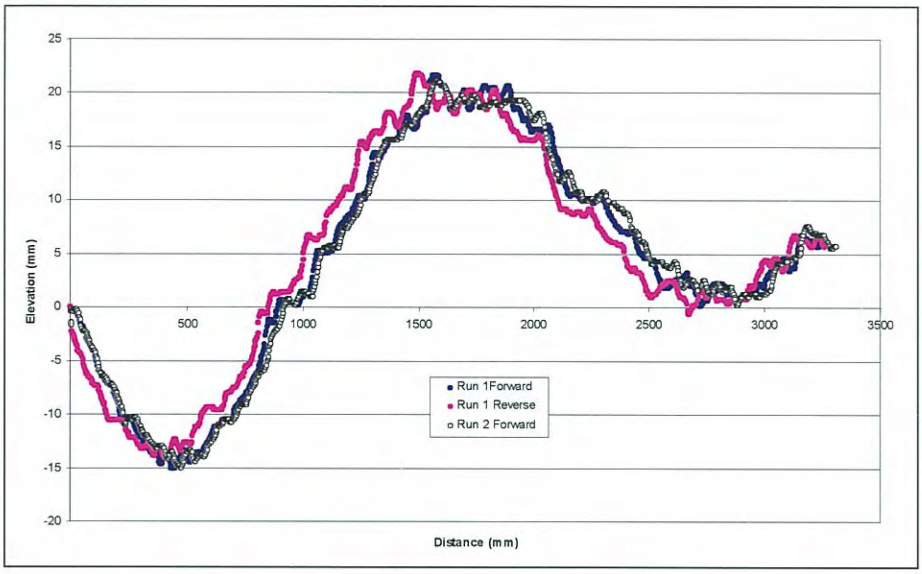


Figure 3.3 Profile Measurements Between Runs

Figure 3.4 Example of Transit New Zealand Calibration Section

The TPB was positioned every 10 m along the pavement and at least two profiles were measured at each position. If the rut depths calculated from these profiles were not within a +/- 2.5 mm tolerance, additional runs were made until the tolerance was achieved. In most instances the tolerance was achieved with only two runs.

3.4 Reference Profiles Used in Analysis

Transit New Zealand kindly made available data from one of the calibration sites for use in this project. The data consisted of profiles measured at 31 locations at Site 53d. There were a total of 65 profiles, with a minimum of two profiles at each location. Figure 3.5 shows photographs from either end of the calibration section.

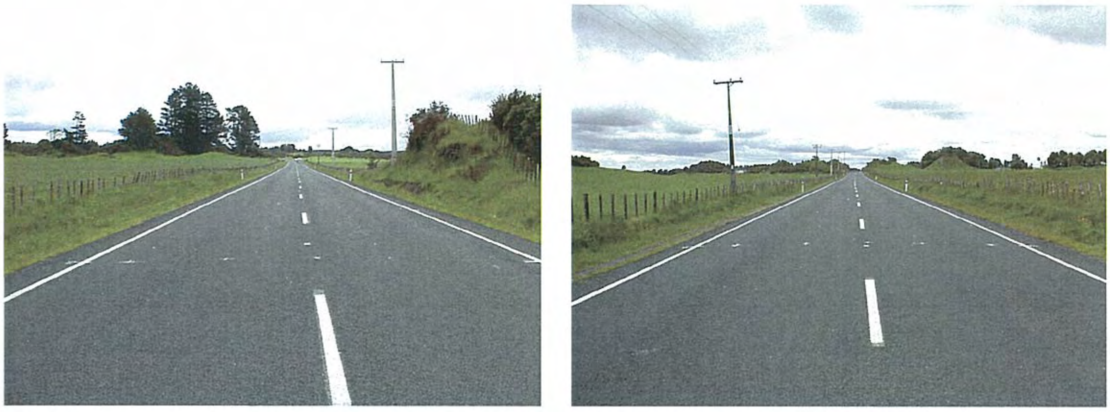


Figure 3.5: Photos of Calibration Section Used For Analysis

Under the arrangement with Transit New Zealand for the provision of the data, only the final results of the analysis are provided in this report.

4. Harmonisation of Rut Depth Software

4.1 Introduction

In order to provide a standard basis for comparing the transverse profiles a software application was written which simulated the measurement of profilometers on a reference transverse profile. Called the 'Harmonisation of Rut Depth Software', or HRD, an evaluation version of the application can be downloaded from www.ROMDAS.com.

This chapter describes the principles and operation of the HRD.

4.2 Principles of Operation

4.2.1 Introduction

The HRD simulates a vehicle travelling along a road sampling the transverse profile using any number of sensors. For each reference transverse profile, the elevations are obtained for the particular configuration of the sensors. These elevations are then analysed to determine the rut depth. As the baseline against which all profilometer measurements are compared, the rut depth is calculated for the reference profile.

The factors which needed to be considered in the analysis were:

- rut depth calculation algorithms and implementation;
- profilometer sensor configuration;
- lateral placement; and
- reference profile smoothing.

The HRD software does not consider the ponding potential caused by rutting.

The features of the HRD software are addressed in the following sections.

4.2.2 Rut Depth Calculation Algorithms

As discussed in Section 2.3, the algorithms used for calculating rut depths from profilometers are the straight-edge, wire and pseudo-rut models.

Straight-Edge Algorithm

The straight-edge rut depth algorithm was based on the SHRP algorithm in Hadley and Myers (1991). The analysis starts at Sensor 1 which is the reading closest to the kerb. It progresses until the rutting in one wheelpath is established. It is then repeated for the second wheelpath starting at the right-most sensor and moving inwards towards the kerb.

To illustrate the analysis process consider Figure 4.1-A which shows a set of hypothetical transverse profile elevations. The algorithm places the end of the straight-edge at a starting point. For each start point, the slopes are calculated between it and all successive points which would fall within the span of the straight-edge. Figure 4.1-B illustrates this using Sensor 3 as the start point. The maximum of these slopes is identified (Sensor 5 in Figure 4.1-B).

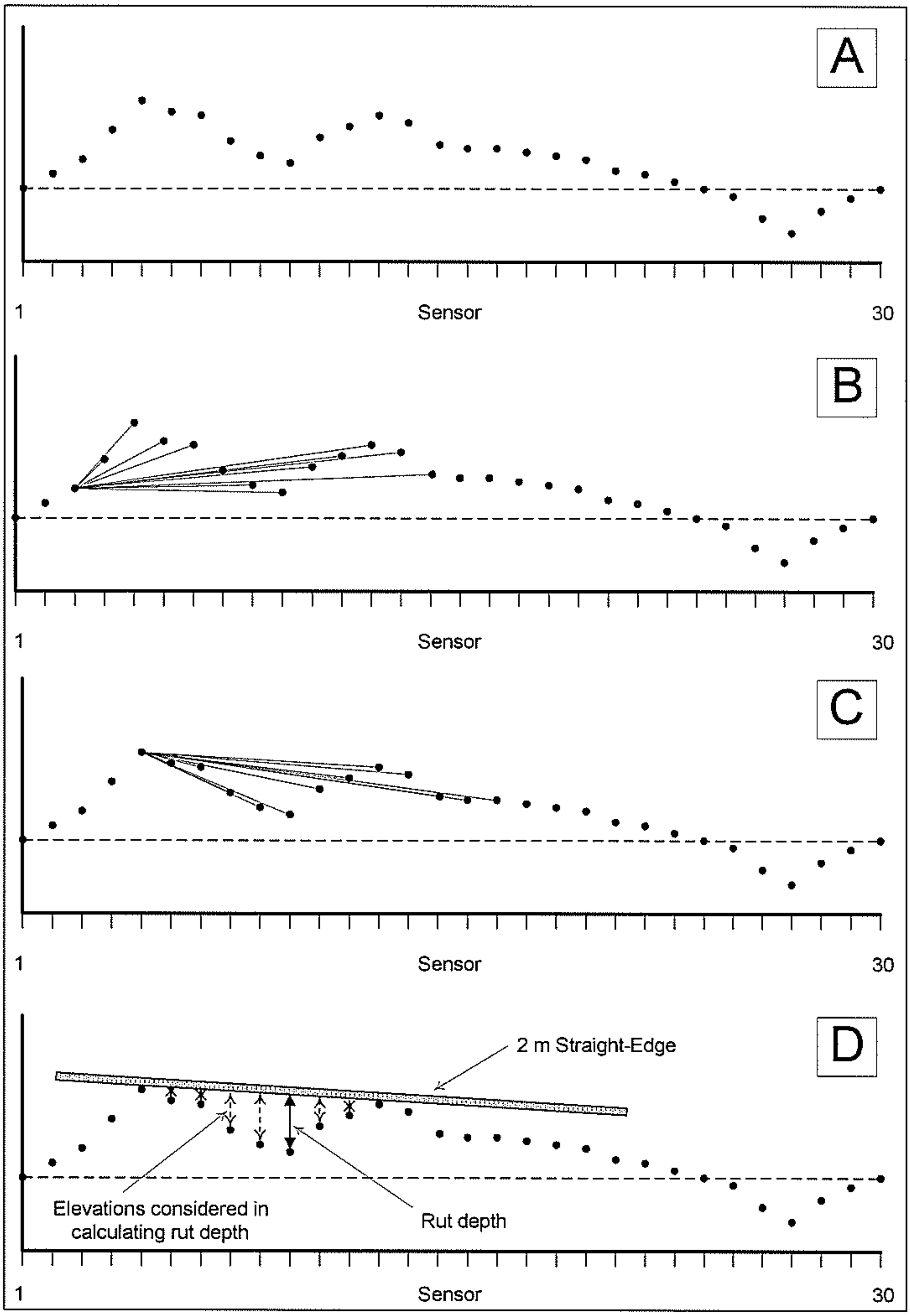


Figure 4.1 Example of Calculating Rut Depth

Two criteria are used to establish whether or not this is a viable placement point for calculating a rut depth. If either of these criteria are met, the current starting point will not produce a rut depth and the analysis moves on to the next starting point. These criteria are:

- if the maximum slope is less than the slope between the start point and the preceding sensor; or
- if the maximum point arises for the point adjacent to the starting point.

Once a viable placement point has been established, the vertical distance of all intermediate placement points are established. In Figure 4.1-C the start point is Sensor 5 and the maximum slope point is Sensor 13. Here, the maximum slope is that closest to the horizontal plane since all elevations are below that of Sensor 5. Figure 4.1-D shows the various possible rut depths for these two points.

For that starting point, the rut depth is the maximum of the vertical distances of all intermediate points. It should be noted that in calculating the rut depth the change in horizontal span due to tilting is assumed not to be significant.

For each possible starting point a maximum rut depth is derived. The largest of these values is taken as the rut depth for the wheelpath in question.

Wire Model Algorithm

The wire model algorithm connected the high points on the profile and established the rut depth under these points.

Pseudo-Rut Algorithm

As described in Section 2.3, pseudo-ruts are calculated as the difference in elevation between the high and low points in the profile. In developing the pseudo-rut algorithm it was found that the results were very sensitive to the slope of the reference profile and that unless the data were 'normalised', so that the reference profile slope was eliminated, the statistic was not appropriate.

To illustrate this, consider Figure 4.2 which compares the pseudo-rut estimates with and without slope correction. The rut depth estimates are [25/16] vs [43/7] for the two cases. Given the basis for the pseudo-rut statistic, the analysis was done using normalised profiles. These were created by adjusting the elevation readings, hereinafter referred to as 'normalisation', so that the end elevation had the same value as the initial elevation—usually 0.

It should be noted that the nature of the straight-edge and wire model rut depth calculations do not necessitate normalisation.

The HRD software can display either the normalised (default) or standard profile.

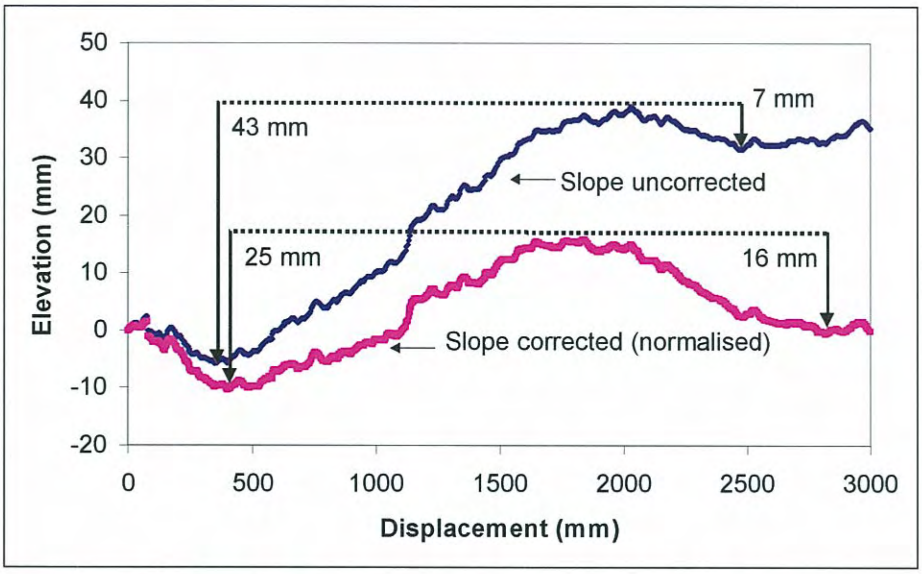


Figure 4.2 Implications of Slope Normalisation on Pseudo-Ruts

4.2.3 Implications of Datum on Rut Measurements

One issue which has not been addressed in the literature is the datum to use for measuring the rut depths under the straight-edge or wire model. As shown in Figure 4.3, there are two options: perpendicular to the datum of the elevation measurements or perpendicular to the straight-edge (or wire).

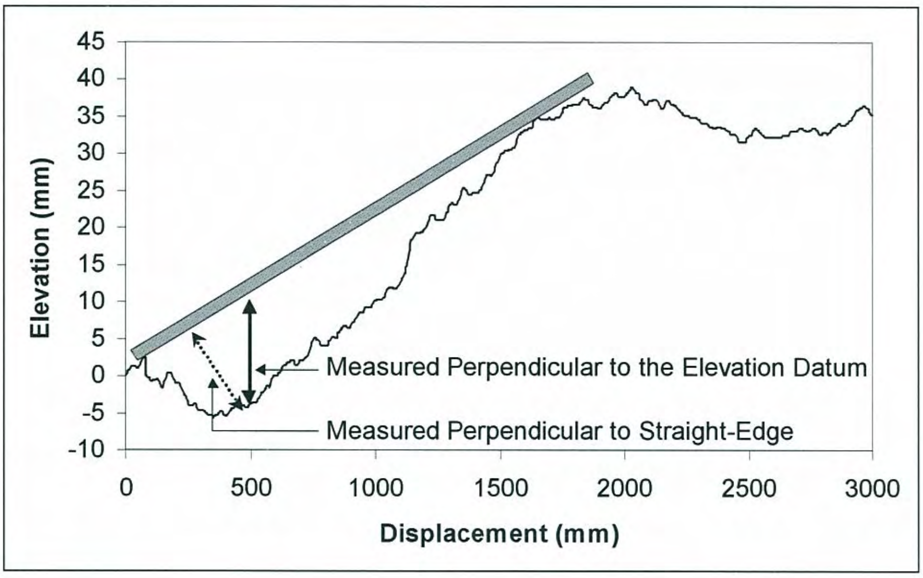


Figure 4.3 Implications of Straight-Edge Datum

The SHRP straight-edge algorithm takes the measurements as perpendicular to the datum so that is what was used in all analyses presented here.

The implications of the two approaches is considered in Chapter 6.

4.2.4 Profilometer Sensor Configuration

Each profilometer has its own unique configuration of sensors. The analysis here considered four configurations:

- **ROMDAS Ultrasonics**. The ROMDAS ultrasonic profilometer has sensors spaced at 100 mm intervals across a 3 m measurement area.
- **WDM Profilometer**. The WDM profilometer has 16 point lasers spaced at irregular intervals across a 3.2 m measurement area. The manufacturer declined to provide the current spacings as it was considered commercially sensitive, so a configuration was assumed based on DCL's understanding of the system
- **PMS Profilometer**. The PMS profilometer has 15 point lasers spaced at irregular intervals. The system is supplied by Greenwood Engineering from Denmark and the configuration of the sensors was supplied by PMS.
- **ARRB TR Profilometer.** The ARRB profilometer has 13 point lasers at irregular spacings. The standard configuration was supplied by ARRB TR, although this may be modified for some customers.

4.2.5 Lateral Placement

As discussed in Section 2.5, the lateral placement (or position) of the vehicle impacts on the location of the sensors and, thus, the rut depth that is calculated for a given profile.

This was considered in the analysis by treating the lateral placement as a random variable drawn from a Normal distribution (see Figure 4.4). Using a Monte-Carlo simulation, for a given standard deviation of lateral placement the position of the vehicle was simulated as it traversed a profile.

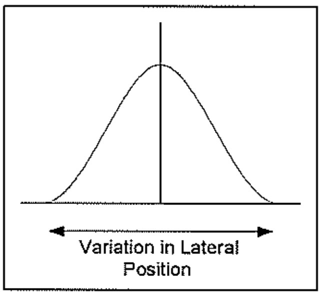
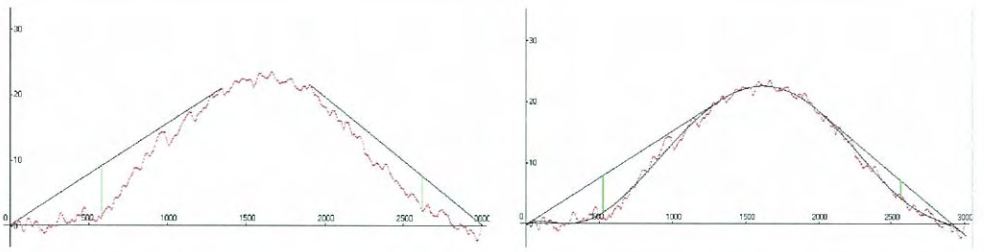


Figure 4.4 Treatment of Lateral Placement

It should be noted that in some instances the lateral placement simulation resulted in some sensors being outside of the 3.0 m width of the reference profile. However, this also happens during field surveys and was not specifically corrected for in the analysis. Thus, for example, there were instances when only 15 of the 16 sensors of the WDM profilometer were measuring on the pavement.

4.2.6 Reference Profile Smoothing

The TPB reference profiles are sampled at very small intervals and so to minimise the effect of texture the profiles can be smoothed using a polynomial equation. Figure 4.5 is an example of a regular versus a smoothed profile, and the resulting rut depths. When profile smoothing is enabled a polynomial equation is fitted to the data and used to generate an analysis profile at 1 mm intervals. In the analyses presented here the profile smoothing option was *not* used.



Regular Profile [8.2/5.2] *Smoothed Profile [6.0/2.9]*

Figure 4.5 Example of Smoothed Reference Profile

4.3 HRD Interface

Figure 4.6 shows the HRD interface screen. The components of the screen are as follows.

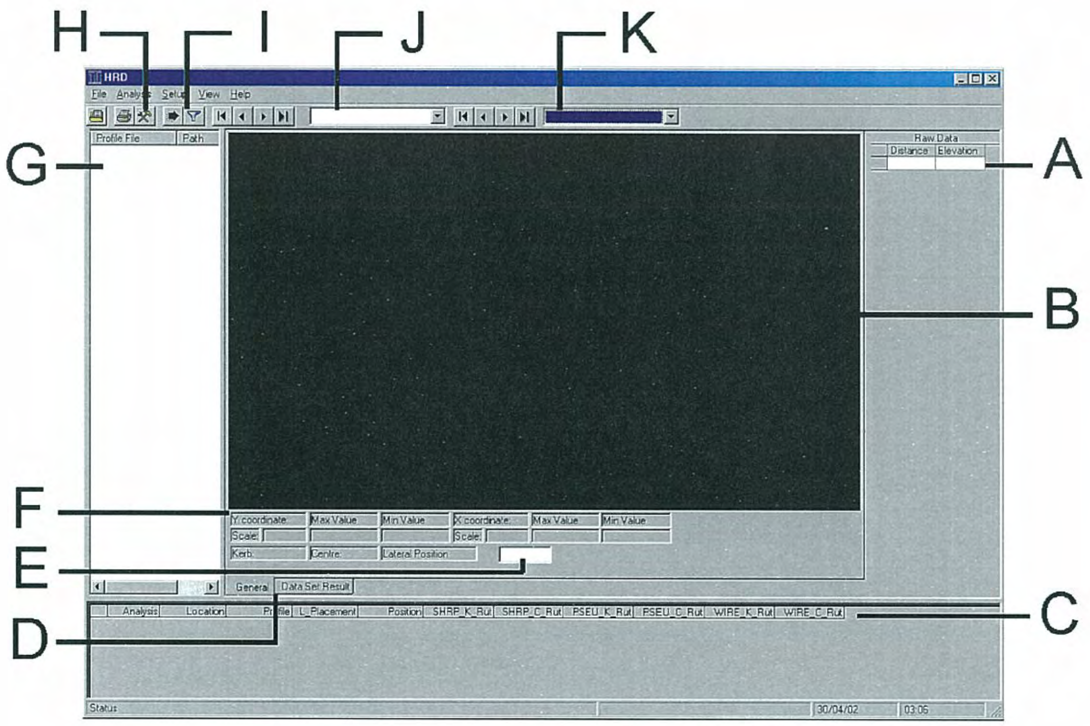


Figure 4.6 HRD Interface Screen

- **A.** **Raw Data:** The reference profile data are displayed in this box as the horizontal distance (mm) and the elevation (mm).
- **B.** **Data Plot:** A graph of the reference profile and rut depth data.
- **C.** **Simulation Results:** The results from the analyses:
  - **Analysis:** Analysis number;
  - **Location:** Profile location number;
  - **Profile:** Profile number from the location;

- **L_Placement:** Lateral placement simulation number;
- **Position:** The lateral location (mm) from the 0 position;
- **SHRP_K_Rut:** Kerb rut depth (mm) using SHRP straight-edge
- **SHRP_C_Rut:** Centre rut depth (mm) using SHRP straight-edge
- **PSEU_K_Rut:** Kerb rut depth (mm) using Pseudo-ruts
- **PSEU_C_Rut:** Centre rut depth (mm) using Pseudo-ruts
- **Wire_K_Rut:** Kerb rut depth (mm) using Wire model
- **Wire_C_Rut:** Centre rut depth (mm) using Wire model

D. **Plot Options:** There are two types of data plots available, one for the individual profile and one showing the average results for all profiles in the data set.

E. **Lateral Position:** The lateral position for the simulation. By changing this value the position can be manually defined.

F. **Summary Data:** Summary data on the co-ordinates used in the analysis and the results of the analysis.

G. **File List:** A list of the reference profiles loaded for analysis and review.

H. **Setup:** Access to the software setup screen.

I. **Calculations:** Calculate the results for all profiles or a single placement.

J. **Location:** The reference profile location number.

K. **Profile Number:** The profile number for the location (typically there are two profiles for each location).

4.4 Setup

4.4.1 General Settings

The general settings are shown in Figure 4.7.

- **Profile Smoothing**: As described in Section 4.2.6, this dictates whether the raw reference profile data are used in the analysis or a smoothed profile. The user can define the type of smoothing to use.
- **Normalise Profile**. This is used for display purposes and will show the end elevation of the plot the same as the start elevation.

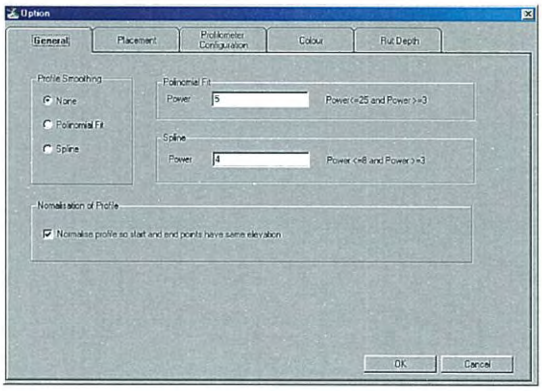


Figure 4.7 General Settings

4.4.2 Lateral Placement Settings

The lateral placement settings are shown in Figure 4.8. These dictate the positioning of the profilometer.

- **Random Variation**: As described in Section 4.2.5, the vehicle is assumed to have a Normal distribution of lateral placement defined by its standard deviation. Setting this value to 0 will eliminate any lateral placement variations.
- **Wheelpath Positioning**. There are two options for considering the positioning of the wheels:
  - Average low point. This analyses each reference profile and places the wheel in the average of all the low points. It represents a 'best case' scenario for actually driving along the road.
  - Left low point. This assumes that the wheel is placed over the left low point for each profile. This is an ideal situation, but would be unachievable in driving the road

  With wheelpath positioning the user can limit the placement so that the wheel is in a sensible location.
- **Zero Point Positioning**. The default method, this assumes that the first sensor is placed over the 0 start point of the reference profile.

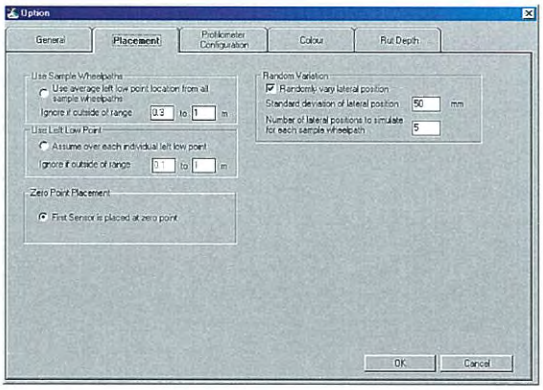


Figure 4.8 Placement Settings

4.4.3 Profilometer Configuration

The profilometer spacing settings are shown in Figure 4.9.

- **Configuration**: The user can define any number of configurations, each representing a different profilometer design.
- **Number of Sensors**. The number of sensors in the profilometer.
- **Sensor Spacing**. The spacing between sensors, starting at the kerb sensor. The number of entries will correspond to the number of sensors.

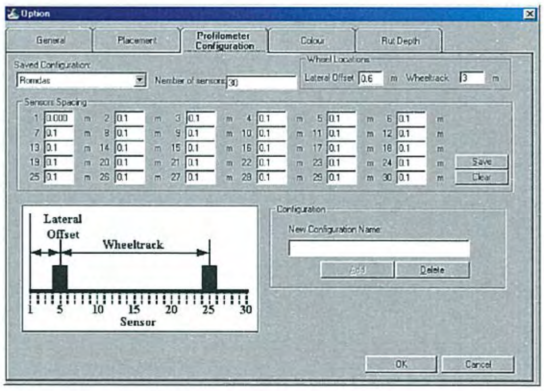


Figure 4.9 Determine Elevations

- **Lateral Offset and Wheeltrack**. These data are used when the lateral placement is calculated based on the wheel positioning (see Section 4.2.5). They dictate exactly where each sensor will be located based on the wheel position.

4.4.4 Colours

Figure 4.10 shows the colour settings that are used in the graphical display. Double clicking on one of the colour bars opens a palette where the user can select the colour to display.

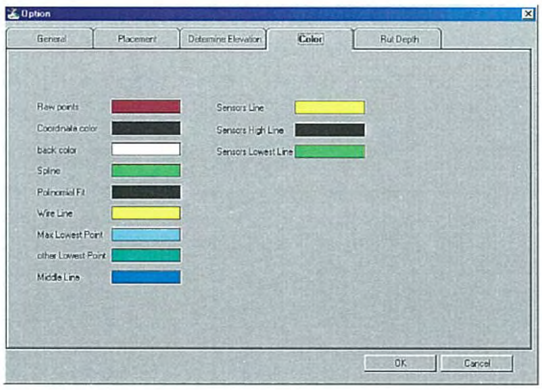


Figure 4.10 Colour Settings

4.4.5 Rut Depths

The rut depth calculation settings are shown in Figure 4.11.

- **Rut Depth to Display**. Selects which rut depth calculation method to show on the graphical display.
- **Parameter Settings**. Sets parameters controlling the various rut depth calculations.

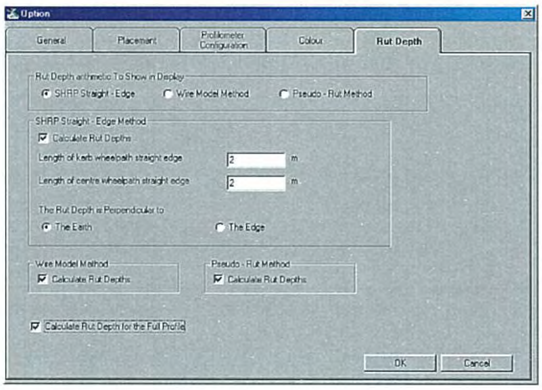


Figure 4.11 Rut Depth Settings

4.5 Performing an Analysis

Once the settings have been established the HRD can be run. The steps are:

- Load a TPB reference profile using **File|Open Reference Profile**
- Highlight the file to analyse in the file list (F in Figure 4.6).
- Select the **Calculate All** button (G in Figure 4.6). The reference profiles will be calculated.

The results will be displayed on the graph. It is possible to select any location or profile run using the control buttons shown below.

4.6 Reviewing the Results

Figure 4.12 is an example of the results of an HRD analysis. The data plot shows the reference profile and the circular points on the profile are the locations of the sensors on the profilometer (in this example the 30-sensor MWH ROMDAS system). These are governed by the lateral placement of the vehicle and the sensor spacings

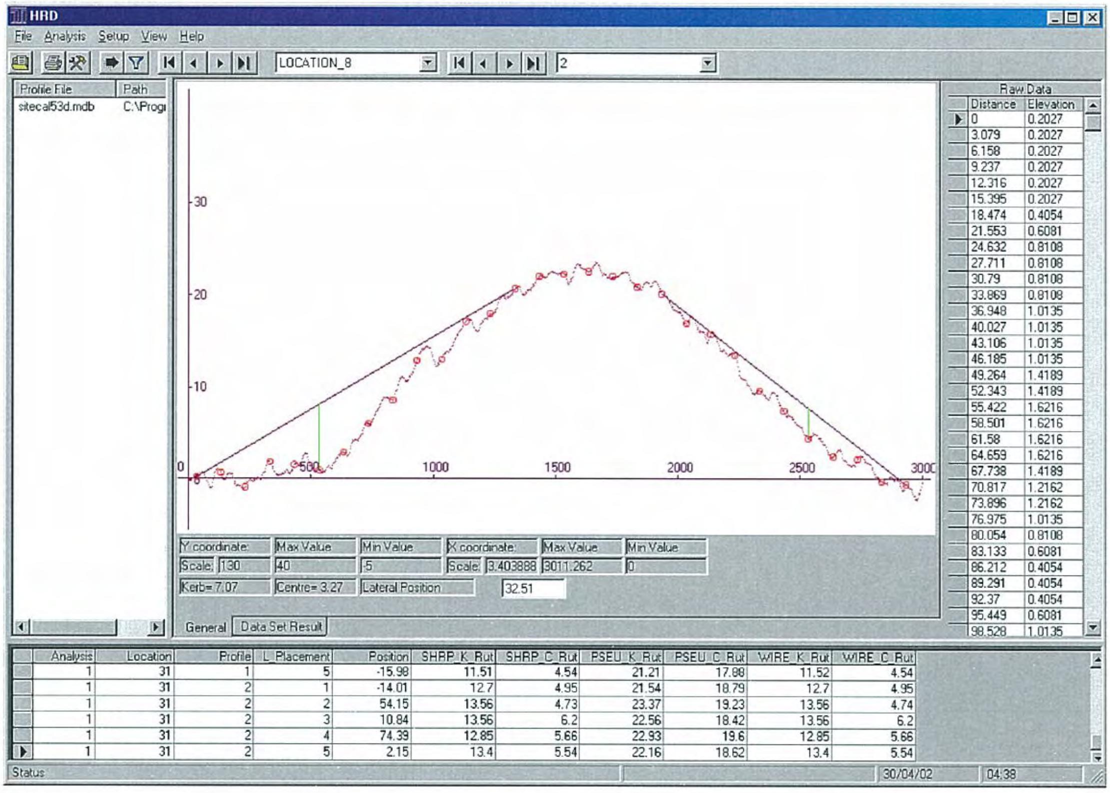


Figure 4.12 Example of HRD Analysis Results

The summary data below the plot give the kerb and centre rut depth values, here 7.07 mm and 3.27 mm respectively. The data plot shows the location of the straight-edge, governed by its high points, along with the low point and the rut depth as represented by the vertical line beneath the straight-edge. The lateral placement for the simulation is given in the box to the right of the rut depth values, here 32.51 mm from the start of the profile.

The simulation results are given at the bottom of the display.

5. Implications of Sampling on Rut Depths

5.1 Introduction

As described in Section 2.4, profilometers sample the transverse profile at discrete points. Since the ability to correctly measure the rut depth depends upon the ability of the profilometer to locate the high and low points of the profile, the number of sensors and their spacing—hereinafter referred to as 'sampling'—will have an impact on the results. This was illustrated in Figure 2.9 (reproduced below as Figure 5.1) which shows a hypothetical example of two different systems measuring the same profile. Each will result in different high and low point elevations and, thus, different estimates of rut depth.

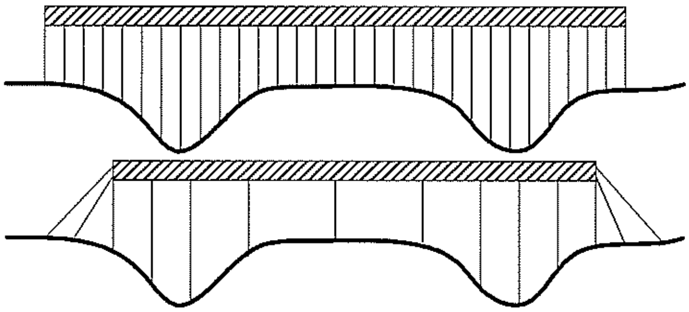


Figure 5.1 Example of Sensor Spacings on Transverse Profile

This chapter describes the result of an investigation into the effect of the number of sensors on the rut depth.

5.2 Analysis Technique

Each reference profile was analysed using the SHRP algorithm with a 2 m straight-edge. This gave the baseline rut depth, hereinafter called the '**true**' rut depth.

A series of different profilometer configurations was adopted, with the number of sensors ranging from 5 to 60, equally spaced over a 3 m measurement area. The analysis was done with a lateral placement standard deviation of 0 to constrain the effects to sampling only.

A regression was made with the results from each number of sensors|location|run simulation against the true rut depth. For comparative purposes three statistics were adopted:

- **Intercept of Regression Line:** This is the **systematic** error;
- **Standard Deviation of Regression:** This represents the **random** error; and
- **Standard Error:** The sum of these two components.

.

5.3 Analysis Results

The results of the analysis are presented in Figure 5.2 for the kerb and centre rut depths. In both cases the error decreased with an increasing number of sensors, and the following regressions were fitted to the data:

Kerb	ERROR = 14.39 $SENSORS^{-0.5770}$	$R^2 = 0.94$
Centre	ERROR = 11.40 $SENSORS^{-0.3831}$	$R^2 = 0.90$

where ERROR is the standard error in mm
SENSORS is the number of sensors

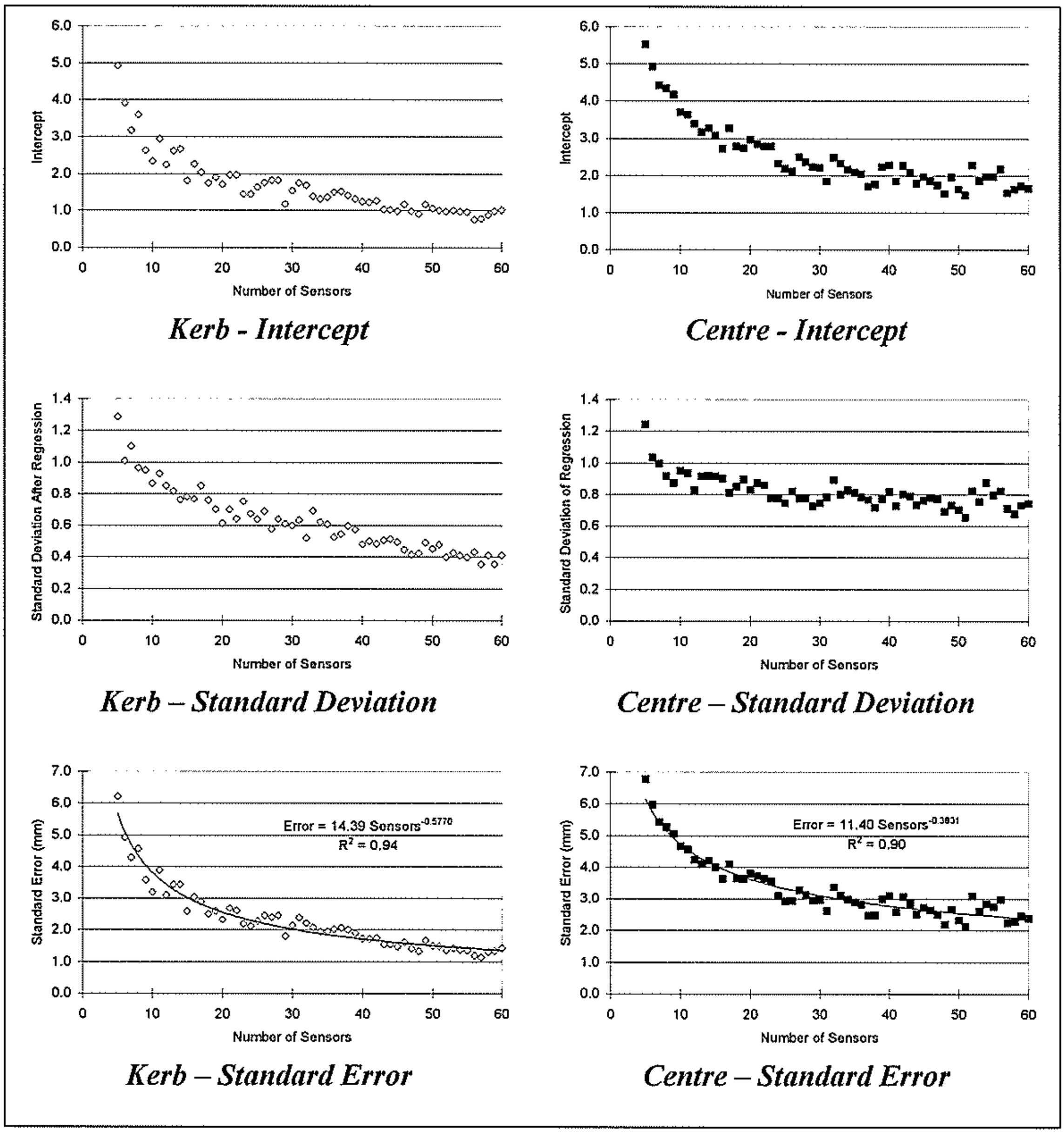


Figure 5.2 Effect of Number of Sensors on Accuracy

The results indicate that there are significant improvements made in accuracy by increasing the number of sensors, but the marginal benefits decline with increasing sensor numbers. From 25 sensors there are much less benefits from adding additional sensors.

Although there is an increase in accuracy with an increasing number of sensors, how does this impact on the mean rut depth of a section? To investigate this, the mean rut depths were calculated for the kerb, centre and both wheelpaths as a function of the number of sensors. The results are shown in Figure 5.3. This shows that with less than approximately 15 sensors, there can be a significant under-estimation of the true rut depth. It is notable that even with 60 sensors the rut depth would still be underestimated by approximately 1 mm.

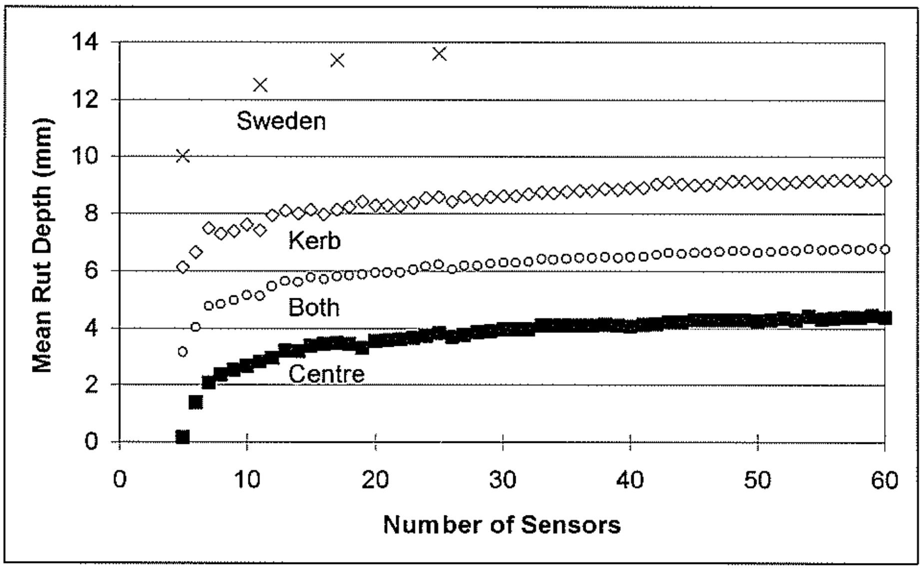


Figure 5.3 Mean Rut Depth vs Number of Sensors

Figure 5.3 also shows four data points from Willet, *et al.* (2000) showing the effect of the number of sensors from data collected in Sweden. Their data have a similar asymptotic effect to that predicted from this analysis, although the slope is greater. This suggests that the impact is also proportional to the magnitude of the rut depths.

5.4 Implications of Findings

The analysis here assumed that the sensors were equally spaced across a 3 m measurement area. However, in reality profilometer manufacturers optimise the placement of their sensors to maximise the value of the data returned. Thus, 5-sensor systems typically have one sensor mounted approximately in the middle of the road, one above each wheel, and the other two at the outside of the wheelpath. The goal is to position the sensors as close to the high and low points as is practicable. In the same way, the 16-sensor WDM, 15-sensor PMS and 13-sensor ARRB laser systems each have different configurations, again positioned by the manufacturers to provide the maximum amount of detail possible.

The accuracy of a profilometer measurement depends upon two operational factors:

- its position on the road (lateral placement); and
- its ability to locate the high and low points in the profile measured.

The positioning of the vehicle is discussed in detail in Chapter 8. In essence, even if the profile is being very accurately measured, if the vehicle is not positioned in such a way that the true high and low points are being sampled, there will be an error. In this analysis there was no variation in lateral placement so the focus was on the ability to locate the high and low points. Not surprisingly, the greater the number of sensors the greater the probability of locating the high and low points, so the lower the error. A continuous sample (such as provided by a scanning laser) would in theory give the same results as the 'true' profile.

The actual sampling bias of the profilometers operated in NZ is presented in Chapter 7 which gives transfer functions for measurements from the different instruments.

The findings suggest that there will be underestimation errors of 2-4 mm with operational profilometers in New Zealand (13 to 30 sensors). Interestingly, HTC (2001b) used data from Chile to compare field measurements of rut depths under a 1.5 m straight-edge with those from a 30-sensor ROMDAS profilometer. It was found that there were few ROMDAS readings below 3 mm, whereas there were a large number of manual readings below 3 mm. This was assumed to be due to a texture effect so the ROMDAS analysis algorithm was modified to correct for this apparent bias. The 3 mm correction factor is supported by the results of the analysis presented above but it was likely due to discrete sampling rather than texture.

The data from profilometers should therefore be adjusted to reflect their systematic underestimation of 2-4 mm. This adjustment is particularly important when the data are being used to trigger maintenance treatments since it could mean the difference between maintenance being performed or postponed.

6. Rut Depth Analysis Algorithms

6.1 Introduction

As described in Section 4.2.2, the HRD software contains three different methods for predicting the rut depth of a reference profile:

- Straight-edge;
- Wire model; and
- Pseudo rut.

This chapter presents an assessment of the different algorithms and other pertinent issues.

6.2 Evaluation of Pseudo-Rut Model Predictions

To evaluate the pseudo-rut model the reference profiles were first analysed using the 2 m straight-edge model to establish the 'true' rut depth. These same data were then analysed with the pseudo-rut model. As described in Section 4.2.2 (see Figure 4.2), the data were normalised to correct for the elevation differences in the measurements. The results are presented in Figure 6.1.

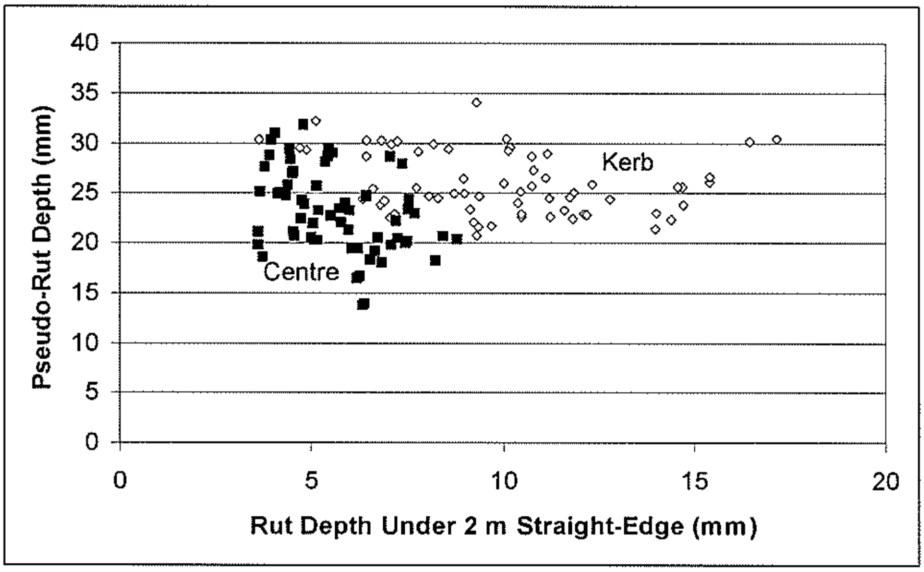


Figure 6.1 Pseudo vs Straight-Edge Rut Depths for True Profile

The analysis shows that even using full-profile data, the pseudo-rut statistic is poorly correlated to the rut depth under a 2 m straight-edge. When used with only a few sensors—in the USA it is commonly applied with only 5 sensors—the differences would be magnified. The use of this statistic is therefore very questionable.

6.3 Comparison of Straight-Edge and Wire Models

As shown, in Figure 6.2, the wire model calculates the rut depth by stretching an imaginary wire between the high points on the profile. The rut depth is the distance from this wire to the low point.

Wire model rut depths are influenced by the profile shape. There are two scenarios that arise when comparing them to the straight-edge rut depths, either:

- the high points are spaced at a distance less than or equal to the length of the straight-edge; or
- the high points are at a distance greater than the straight-edge length.

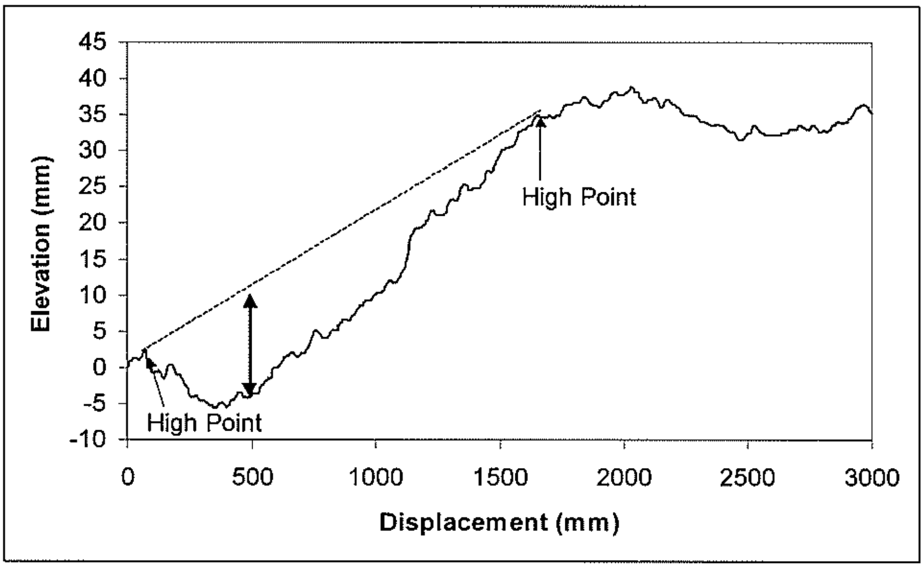


Figure 6.2 Wire Model Over Profile

With the first scenario, the rut depths calculated from the wire and straight-edge models will be identical (see Figure 2.6). This was confirmed through an analysis of the profiles using the HRD software since in all instances the high and low points were less than or equal to 2 m.

However, when the high points are spaced at a distance greater than the straight-edge width, the wire model rut depths will be greater than those from the straight-edge model. The amount of the difference will be entirely dependent on the shape of the profile. It did not prove possible to test this due to the limited range of profile shapes in the database.

6.4 Implications of Straight-Edge Datum On Measurements

As described in Section 4.2.3, there are two ways by which the rut depth could be estimated from a straight-edge or wire model calculation: perpendicular to the elevation datum or perpendicular to the straight-edge (or wire).

As shown in Figure 6.3, the impact of change of datum, from perpendicular to the elevation datum to perpendicular to the straight-edge, can be assessed through geometry. The rut depths z and z' are calculated as:

$$z = y \tan(\alpha)$$

$$z' = y \sin(\alpha)$$

Even when dealing with ruts of 50 mm—which are greater than those found in any of the Transit sections—the angle α will be small so $\tan(\alpha) \approx \sin(\alpha)$. Thus, the difference between z and z' (i.e., $z - z'$) will be very small. This is illustrated in Figure 6.4 which shows $(z - z')$ as a function of the rut depth using the elevation datum. These values were calculated for a 2 m straight-edge assuming that the low point was located 1 m from the high point. This effect was verified using the HRD software. When the elevation profiles were analysed with both scenarios the rut depths were essentially identical which was expected given that the rut depths were less than 20 mm.

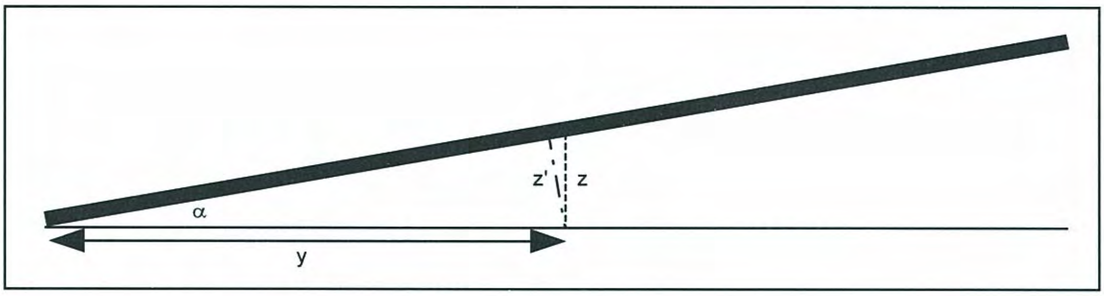


Figure 6.3 Comparison of Datum Geometry

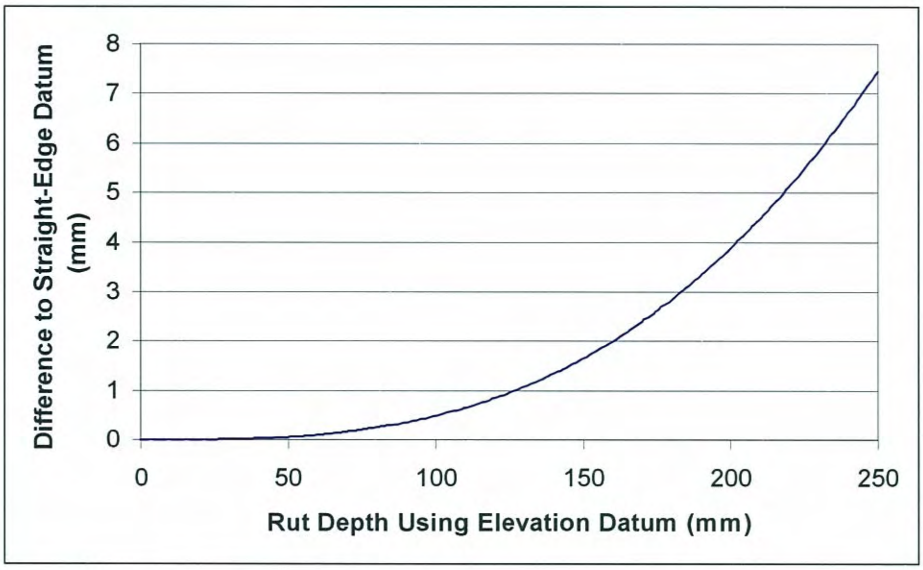


Figure 6.4 Difference Between Datum Level Rut Depths

Given that even with extreme rut depths the effect of taking the datum perpendicular to the straight-edge, compared to the elevation datum, results in a difference in rut depths of only 2.8%, and that below 50 mm the difference was effectively zero, this effect can be ignored for most analyses.

7. Rut Depth Transfer Functions

The HRD software was used to generate the predicted rut depth under a 2 m straight-edge using the configurations for each of the four profilometers used in NZ. There are two important points to note with the 30 and 16 sensor profilometers:

- The 30-sensor MWH profilometer is an ultrasonic based system and, as such, it does not take its 30 measurements in a single location but progressively samples over a section of road which may be several metres in length (see Section 2.6). Since data were not available to consider progressive sampling, the results here would only apply if there were no changes to the transverse profile over the progressive sampling interval—something which is not likely in practice.
- The 16-sensor WDM profilometer had an assumed configuration, since the manufacturer considered the configuration to be commercially sensitive information.

The analysis was done assuming that the left-most sensor measured at the start of the reference profile – i.e., without any lateral placement effects. The data showed linear trends for all cases and linear regression functions were fitted of the form:

$$RD = a0 + a1\ MEAS$$

where RD is the predicted 2 m straight-edge rut depth in mm
MEAS is the 2 m rut depth in mm for the profilometer configuration using the SHRP analysis algorithm

NOTE: The actual rut depths predicted by the profilometers may be different to those used here since each manufacturer has its own proprietary algorithm. The results therefore only reflect profilometer configurations.

The analysis was done both with regard to converting from the profilometer to the 'true' rut depth of the reference profile, as well as enabling conversions to be made between individual profilometers. It should be noted that an 'orthogonal' regression[1] was not done, so different equations are given for converting from profilometer 'A' to 'B' and 'B' to 'A'.

The regression was done for the kerb, centre and combined data sets so there were three equations for each profilometer. These equations are presented in Table 7.1 along with their coefficient of determination (R^2) and standard error. All coefficients were significant at 95% confidence, with the 't' statistics presented in parentheses below each coefficient. In some instances the coefficient a0 was given a value of 0. This was done when the coefficient for the regression model was not significant. As

[1] As described in Bennett and Paterson (1999), orthogonal regressions yield one equation which can be used for converting from profilometer 'A' to 'B' and 'B' to 'A'. Since the equation has a poorer overall fit than two individual equations this technique was not adopted.

would be expected, the transfer functions are generally statistically quite robust with R^2 for the combined profiles above 0.88 and standard errors below 1.5 mm, with many below 1.0 mm.

Table 7.1 Rut Depth Transfer Functions

Measurements To Convert To (PRED)	Wheelpath	Regression	Transfer Functions To Convert From (MEAS)															
			MWH 30 Sensor				WDM 16 Sensor				PMS 15 Sensor				ARRB 13 Sensor			
			a0	a1	R^2	S. Error	a0	a1	R^2	S. Error	a0	a1	R^2	S. Error	a0	a1	R^2	S. Error
True Profile	Kerb	Equation	1.54	0.97	0.96	0.36	2.44	0.98	0.93	0.61	2.09	0.96	0.95	0.46	2.39	0.96	0.92	0.78
		't'	(6.91)	(39.74)			(9.15)	(30.16)			(8.71)	(34.98)			(7.83)	(26.42)		
	Centre	Equation	2.22	0.88	0.69	0.56	3.05	0.80	0.63	0.67	3.56	0.64	0.51	0.88	3.20	0.77	0.61	0.70
		't'	(7.26)	(11.99)			(11.06)	(10.39)			(12.46)	(8.27)			(11.83)	(10.06)		
	Both	Equation	1.97	0.93	0.95	0.47	2.56	0.97	0.93	0.65	2.69	0.89	0.92	0.75	2.70	0.92	0.92	0.75
		't'	(15.28)	(51.27)			(18.10)	(42.84)			(17.96)	(39.69)			(18.00)	(39.66)		
MWH 30 Sensor	Kerb	Equation					1.07	0.99	0.93	0.62	0.65	0.98	0.97	0.31	1.01	0.97	0.92	0.75
		't'					(3.98)	(30.20)			(3.27)	(43.05)			(3.34)	(27.13)		
	Centre	Equation					1.30	0.82	0.74	0.42	2.22	0.52	0.37	1.01	2.25	0.52	0.31	1.11
		't'					(5.65)	(13.41)			(7.23)	(6.21)			(6.61)	(5.44)		
	Both	Equation					0.73	1.01	0.95	0.56	0.92	0.93	0.92	0.87	0.99	0.95	0.90	1.11
		't'					(5.56)	(48.77)			(5.70)	(38.67)			(5.44)	(33.87)		
WDM 16 Sensor	Kerb	Equation	-0.52	0.95	0.93	0.59					0.00	0.95	0.93	0.49	0.00	0.97	0.91	0.72
		't'	(-1.80)	(30.20)								(93.81)				(78.01)		
	Centre	Equation	0.00	0.84	0.72	0.46					1.87	0.43	0.23	1.36	1.41	0.58	0.35	1.14
		't'		(41.51)							(5.25)	(4.46)			(4.08)	(5.99)		
	Both	Equation	-0.41	0.94	0.95	0.52					0.43	0.88	0.88	1.18	0.39	0.92	0.90	1.03
		't'	(-2.97)	(28.77)							(2.27)	(31.40)			(2.22)	(33.84)		
PMS 15 Sensor	Kerb	Equation	-0.36	0.99	0.97	0.32	0.52	0.99	0.94	0.53					0.00	1.03	0.92	0.58
		't'	(-1.77)	(43.05)			(2.09)	(32.96)								(91.75)		
	Centre	Equation	0.00	0.84	0.36	1.43	1.51	0.56	0.23	1.75					0.72	0.81	0.53	1.07
		't'		(23.47)			(3.40)	(4.46)							(2.17)	(8.55)		
	Both	Equation	-0.45	0.99	0.92	0.92	0.00	1.04	0.88	1.34					0.00	1.02	0.92	0.85
		't'	(-2.25)	(38.67)				(64.67)								(81.56)		
ARRB 13 Sensor	Kerb	Equation	0.00	0.92	0.90	0.74	0.00	1.02	0.90	0.75	0.00	0.97	0.93	0.55				
		't'		(78.56)				(78.01)				(91.75)						
	Centre	Equation	0.85	0.61	0.31	1.29	1.20	0.62	0.35	1.21	1.03	0.66	0.53	0.88				
		't'	(1.82)	(5.44)			(3.26)	(5.99)			(3.60)	(8.55)						
	Both	Equation	-0.37	0.94	0.90	1.10	0.00	1.01	0.89	1.10	0.00	0.96	0.92	0.80				
		't'	(-1.89)	(33.87)				(69.32)				(81.59)						

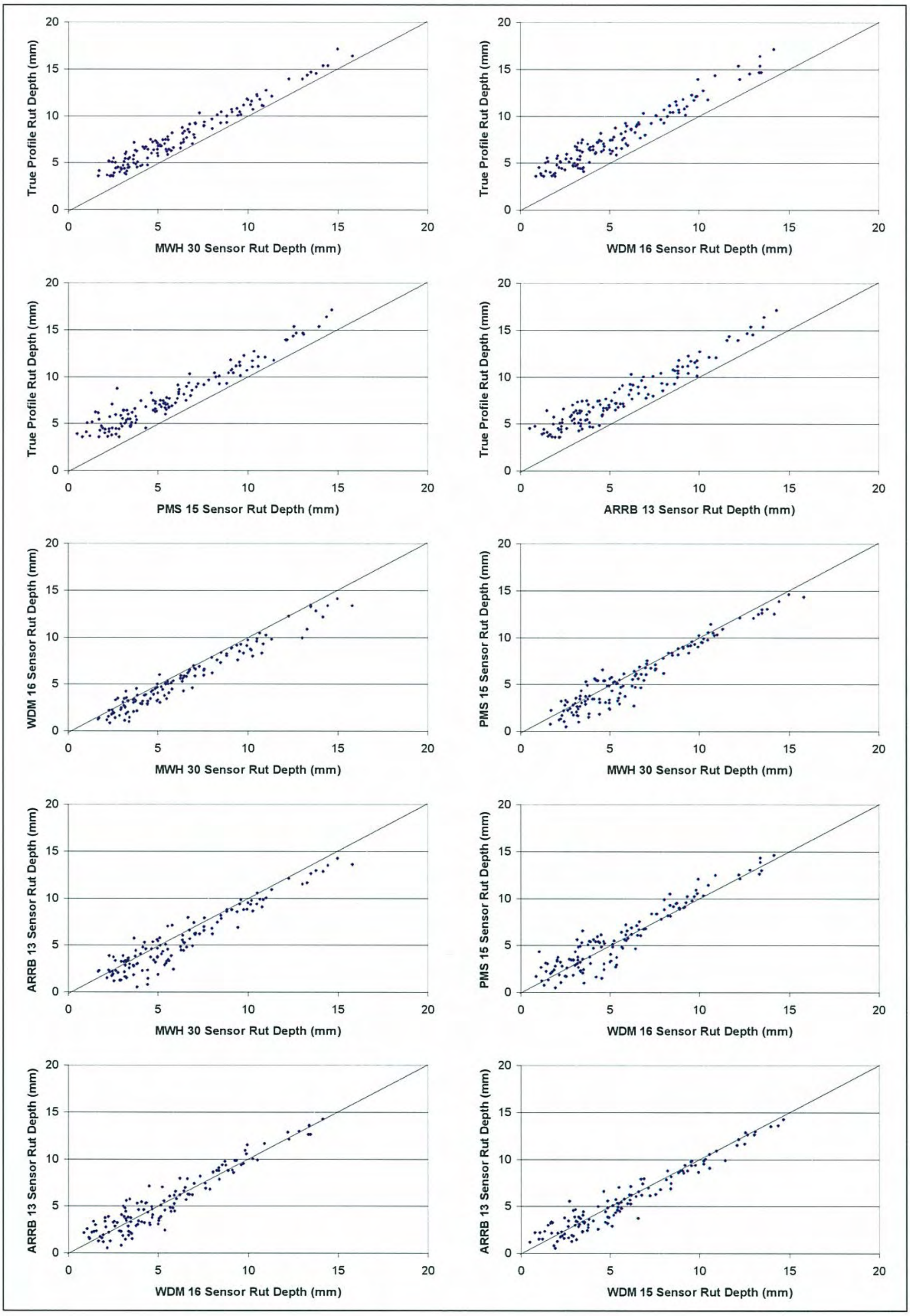


Figure 7.1 Comparison of Rut Depth Measurements

8. Implications of Lateral Placement on Rut Depths

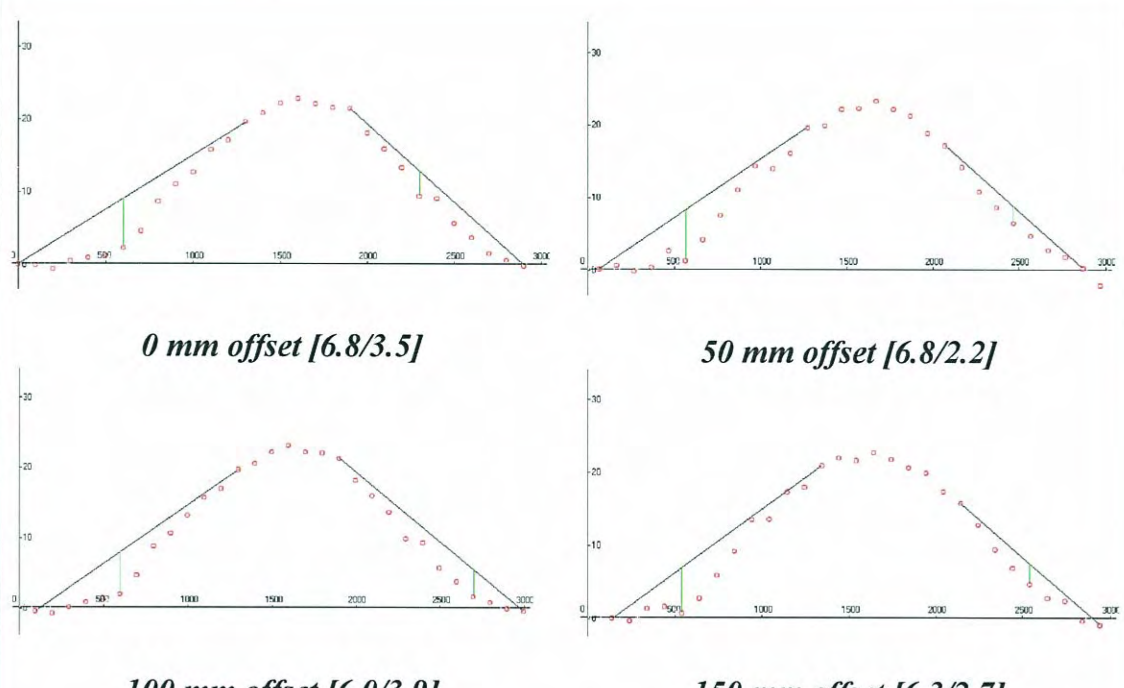
8.1 Introduction

When conducting a survey the lateral placement of the survey vehicle will have a significant impact on the validity of the measurements, particularly when trying to monitor rut depths between years. The impact will depend upon the shape of the profile, the amount of lateral variation as the vehicle drives down the road, and the number of sensors on the vehicle. The more sensors and the closer they sample, the less impact on lateral variations in position.

As described in Section 4.2.5, the HRD software treats lateral placement as a random variable that was Normally distributed. The standard deviation is used to govern the level of variability. This chapter presents the results of an analysis into the implications of lateral placement on rut depths using this technique.

8.2 Implications of Lateral Placement on Rut Depths

Figure 8.1 shows how varying the lateral placement resulted in rut depth measurements in the range of 6.0 – 6.8 mm and 2.2 – 3.9 mm for the kerb and centre on the same profile. Different profiles showed much greater ranges.



0 mm offset [6.8/3.5]

50 mm offset [6.8/2.2]

100 mm offset [6.0/3.9]

150 mm offset [6.3/2.7]

Figure 8.1 Example of Impact of Lateral Placement on Rut Depths

The net effect of these variations is illustrated in Figure 8.2 which shows the rut depths for each of the 65 reference profiles with standard deviations of 10 and 200 mm for the 30-sensor MWH and 13-sensor ARRB TR profilometers. The horizontal axis is the 'true' rut depth (i.e., the rut depth of the reference profile) while the vertical rut depth is the 'sampled' rut depth (i.e., the rut depth based on the profilometer).

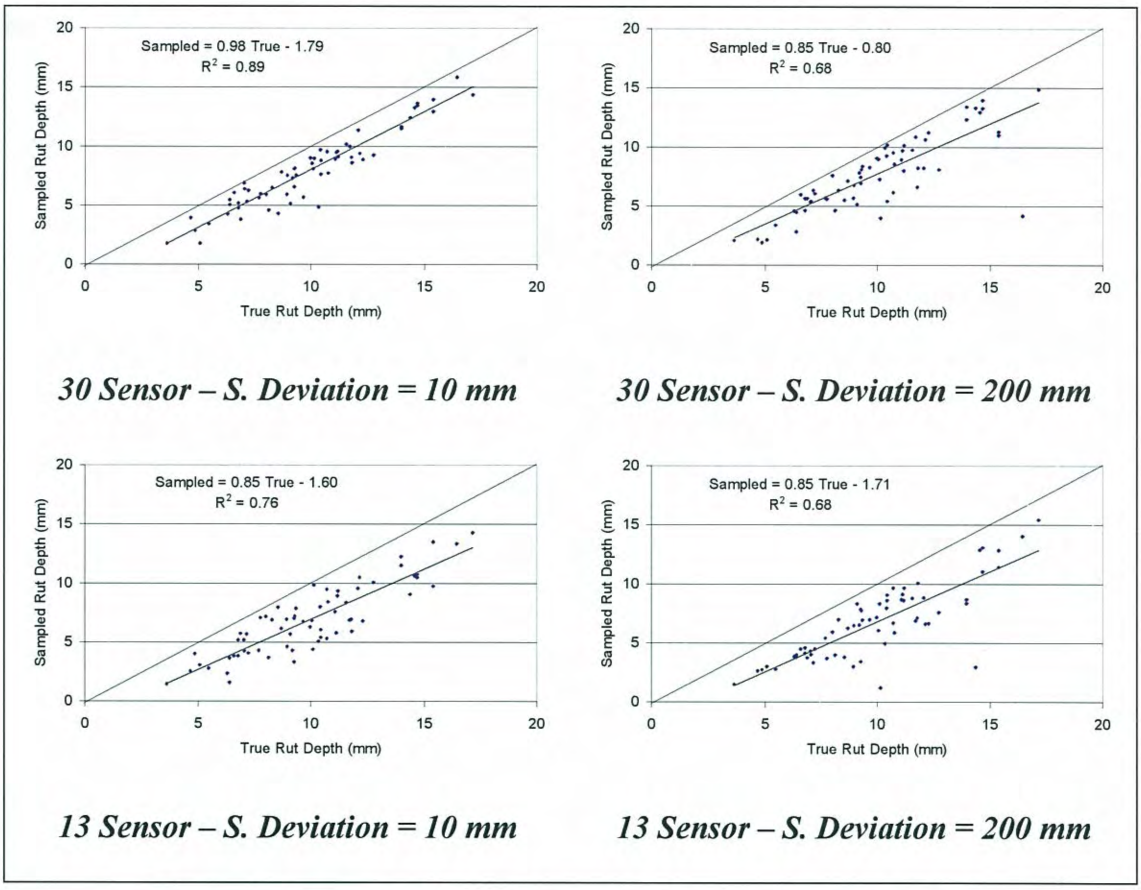


Figure 8.2 Implications of Lateral Placement on Rut Depths

The data in Figure 8.2 show that increasing the amount of lateral variation significantly decreases the accuracy of the predicted rut depth. This is evidenced by the increase in scatter with increasing standard deviation, and the decrease in the coefficient of determination (R^2).

It is interesting to note that the equations for the MWH 30-sensor system were markedly different for the two scenarios tested, whereas there was little change in the equations for the 13-sensor system. This suggests that the dominant effect with the 13-sensor system was the number of sensors, although the decrease in the coefficient of determination indicates that there was also a lateral placement effect.

8.3 Analysis Technique

In order to investigate the impact of lateral placement, each profile was first analysed using the SHRP algorithm with a 2 m straight-edge. This gave the baseline rut depth, hereinafter called the 'true' rut depth.

A regression was made with the results from each location|run|lateral placement simulation against the true rut depth. For comparative purposes three statistics were adopted:

- **Intercept of Regression Line:** This is the **systematic** error;
- **Standard Deviation of Regression:** This represents the **random** error; and
- **Standard Error:** The sum of these two components.

8.4 Results of Analysis

Figure 8.3 shows the results of the analysis for the 30-, 16-, 15- and 13-sensor profilometer configurations for the kerb and centre wheelpaths. There are three figures for each configuration: intercept, standard deviation of regression and standard error.

The smaller the intercept, the closer the predicted rut depth would be to the 'true' rut depth. Thus, this is a measure of the accuracy of the profilometer rut depth prediction. The results show different trends[1] for the four profilometer configurations tested. The 30- and 13-sensor profilometer accuracies improve for the kerb rut depth with increasing lateral placement up to 30-50 mm, after which there is a continual decrease in accuracy with increasing standard deviation. The 16- and 15-sensor profilometers also show an increase in the accuracy of the kerb rut depth with increasing standard deviation, but this only continues to approximately 100 mm after which it stabilises. For all systems, the centre rut depth accuracy continually decreases the greater the variation in the lateral placement. The same trends can be observed in the standard deviations of the regression.

The standard error shows the overall impact of lateral placements on the accuracy. For both the 30- and 13-sensor configurations the accuracy decreases with increasing lateral placement while for the 16- and 15-sensor configurations it shows different trends for the kerb and centre. These results reflect two operational issues that are encountered with profilometers:

- measurements arising outside of the pavement; and
- ability to locate the high and low points.

When a profilometer travels down a lane, there is a possibility that the kerb sensor will record outside of the pavement. All manufacturers include algorithms which check for this and exclude measurements which violate certain rules identifying them as falling outside of the pavement area. The higher the standard deviation of lateral placement, the more likely the system is to have measurements outside the pavement. The impact of this on the results is dependent upon the number of sensors and their placement; with few sensors the impact can be quite large, whereas with many sensors it will be quite small.

[1] The variations in the trends arise because of the use of stochastic simulation.

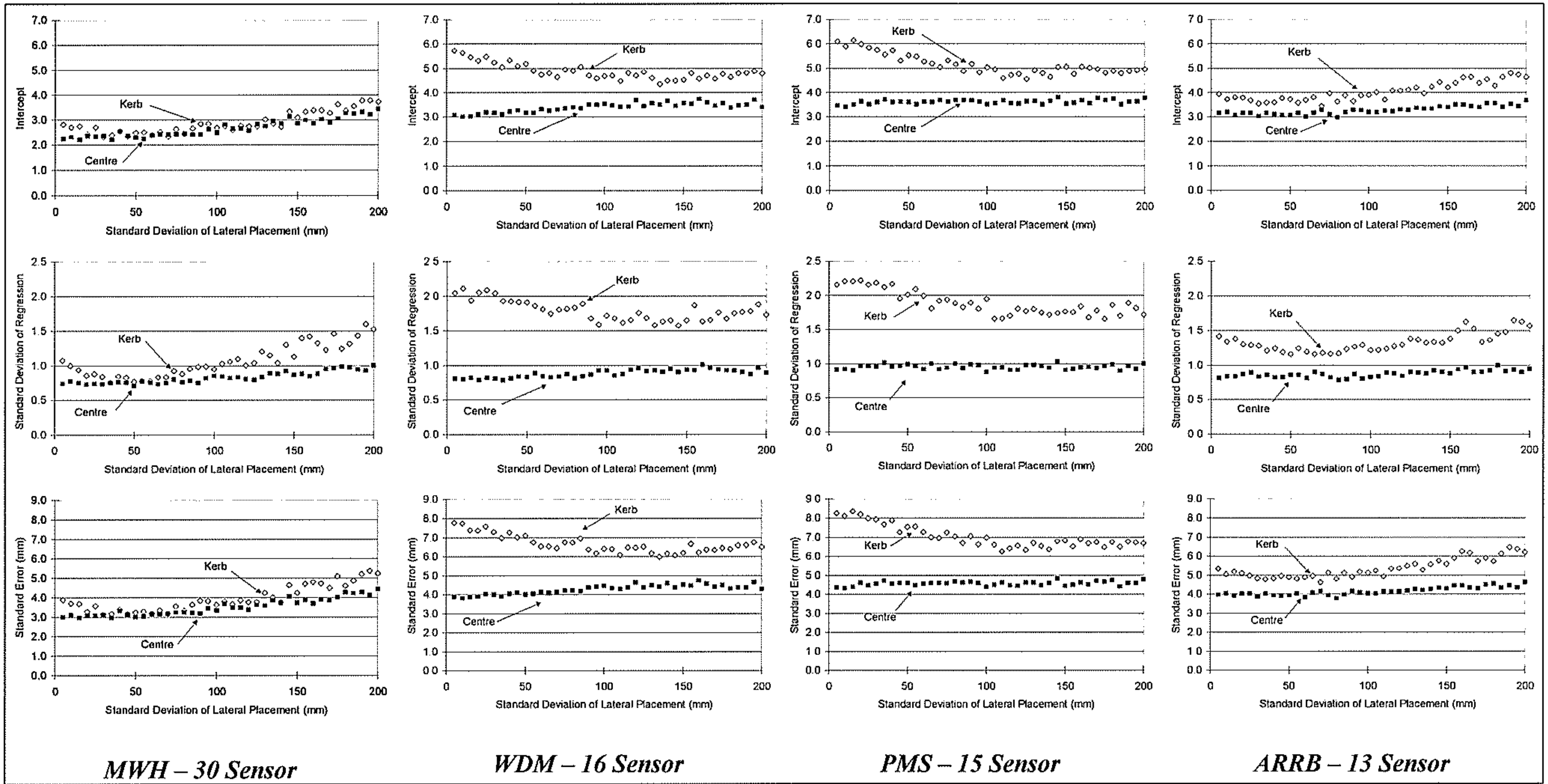


Figure 8.3 Effect of Lateral Placement on Accuracy

As previously stated, the accuracy of any rut depth measurement is based on the ability of the profilometer to sample the high and low points on the pavement which are used to calculate the rut depth. The effects of varying lateral placement are to move the measurements closer or further away from locating these points.

With small variations in lateral placement there will be few problems with the measurements arising outside of the pavement. Thus, most of the effect is due to locating the high and low points. When the standard deviation of lateral placement reaches approximately the same level as the spacing between the first two sensors, the results will be affected by excluding any sensors measuring outside of the pavement. This effect is evidenced by the 30-sensor system where the maximum accuracy arises at 50 mm, which is half the spacing of the first two sensors. The variation in the curve is symmetrical around 50 mm.

The 16- and 15-sensor kerb measurements show much less accuracy than the 13-sensor measurements. This is ascribed to the spacing between sensors 1 and 2 being too large. For example, with the 16-sensor configuration adopted, a lateral placement of –1 mm would result in no measurements being made from 0 – 299 mm. By comparison, the 13-sensor profilometer had a spacing of 150 mm between the first two sensors so the effects were much less.

It is important to note that the overall lateral variation effect also embodies the effects of the number of sensors and their spacings discussed in Chapter 5. Thus, a component of the error shown in Figure 8.3 would be due to this effect.

8.5 Implications of Findings

The results of this analysis show that lateral variations can have a significant impact on the rut depths. This may be one reason why it is often difficult to isolate trends in rut depths using data collected in regular profilometer surveys. For example, consider Figure 8.4 which shows the 100 m average rut depth for a 500 m section of a State Highway[1]. The annual changes were in the range of –1.2 to + 3.0 mm without any clear trend. These changes fall within the expected standard error for small lateral variations and so cannot be taken as indicative of changes in the 'true' rut depth.

The degree of lateral placement variability does not appear to have been addressed in much detail in the literature. Also Simpson (2001) suggested a standard deviation of 127 mm; this was based on limited data and seems excessive: the 95% confidence intervals would be +/- 250 mm. Thus, there would be up to 500 mm of variation in the position of the vehicle as it travels down the road. From a review of data collected with a 30-sensor profilometer this seems to be excessive. Unfortunately, the available data did not allow for the lateral position variation to be investigated in any detail.

1 The data were supplied by Transit New Zealand for a research project into the quality of road survey data (Bennett, 2001), although their analysis was not included in the report. The original data were sampled at 20 m intervals. By averaging to 100 m this reduced the impact of differences in lateral placement.

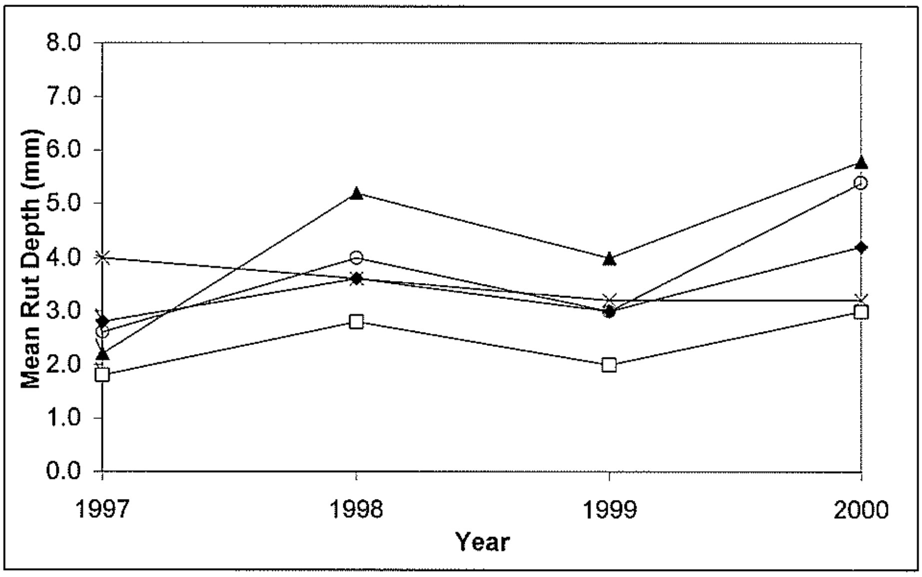


Figure 8.4 Example of State Highway Rut Depth Trend

9. Extending the Results

9.1 Introduction

The objective of this project was to confirm the viability of establishing a methodology for harmonising the rut depth measurements from different profilometers. The simulation software developed has confirmed that such transfer functions can be established, thereby providing practitioners with a 'standard' rut depth. However, there are a number of enhancements which are required in Phase II to complete the project.

9.2 Range of Profiles

The analysis was done using a sample of 31 profiles measured 2-3 times on a 300 m section of a single State highway. These profiles generally had the same shape and the range of rut depths was limited. These similarities precluded an evaluation of the wire model since all high points were within 2 m of each other, thereby yielding the same results as the straight-edge model.

The profiles need to be extended to be representative of a wider range of roads. In particular, the emphasis should be on sampling pavements with high shoving and 'bowl' shaped depressions. This would require measuring additional roads using the TPB and developing the transfer functions so that they cover the full range of road profiles likely to be encountered.

9.3 Evaluating Rut Depth Routines

The 2 m straight-edge analysis routine used in the HRD was developed from one published as part of the SHRP study. This routine is used with the ROMDAS system. The basis of the algorithms used in other profilometers is not known but it is certain that they have their own approach for analysing the profile data to calculate rut depth. It is necessary to analyse the output from these algorithms for the same profiles to ensure that the data are harmonised.

The analysis would consist of feeding into the algorithms the elevations corresponding to how a reference profile would be sampled by the profilometer. The output, in terms of the 2 m straight-edge rut depth, would then be compared to outputs from the algorithms of other suppliers to confirm/enhance the transfer functions developed in Chapter 7.

9.4 Optimal Spacing of Sensors

The analysis has shown that when there are less than 25 sensors the placement of sensors can have a significant impact on the accuracy of the measurements. The optimum spacing for sensors should be investigated so that manufacturers have guidance on how to best configure their profilometers. This would be done by analysing a series of profiles to establish the configuration for a given number of sensors, thus minimising the measurement error for a given level of variation in lateral placement.

9.5 Measurement Precision

The HRD software does not consider the precision of the measurements. For example, the ROMDAS ultrasonic system has a reported standard error of approximately 0.3 mm, with a 95% confidence interval of 0.70 mm (DCL, 1996). It would be expected that lasers would have errors of less than 0.1 mm. Since the errors could accumulate, the analysis should be enhanced by introducing a vertical measurement accuracy component to the HRD software. This would be done in a similar manner to the existing lateral placement approach, where it is modelled as a random variable following a Normal distribution.

9.6 Lateral Placement Variation

An investigation should be made into the degree of lateral placement variation in field surveys. This would provide firm data from which the standard deviation of lateral placement could be derived for use in establishing the transfer functions.

9.7 Progressive Sampling

Ultrasonic systems do not measure at a single position on the road but instead take a series of measurements over an interval (which is a function of the instrument and vehicle speed), establishing a composite transverse profile. The transfer functions presented in this report were unrealistic in that they did not consider this effect. Research would need to be done by taking a series of reference profile measurements at intervals of approximately 200 mm and then investigating the effects of progressive sampling and the resulting rut depths.

10. Conclusions

Phase I of the Harmonisation of Automated Rut Depth Measurements project has shown that it is possible to harmonise the measurements of different rut depth profilometers. During the course of the study, insight was gained into a number of key areas with regard to rut depth measurements.

Harmonisation of Rut Depth Software

The HRD software developed as part of this project provides a powerful tool for investigating rut depths from profilometers. It is possible to test the measurements of any profilometer configuration on a series of standard reference profiles including factors such as variations in lateral placement. The software calculates the rut depth for any configuration using straight-edge, wire and pseudo-rut models.

Sampling

Rut depth profilometers sample the transverse profile at discrete points across the profile. In NZ, the number of samples range from 13 to 30. The accuracy of a profilometer measurement depends upon two operational factors:

- its position on the road (lateral placement); and
- the ability to locate the high and low points in the profile measured.

Even if the profile is being very accurately measured, if the vehicle is not positioned in such a way that the true high and low points are being sampled, there will be an error. Not surprisingly, the greater the number of sensors the greater the probability of locating the high and low points so the lower the error. A continuous sample (such as provided by a scanning laser) would in theory give the same results as the 'true' profile.

On the basis of the simulation software developed for the project, the effect of taking discrete samples across the pavement was estimated to result in underestimation errors of 2-4 mm.

Rut Depth Analysis Algorithms

The project considered three different rut depth algorithms: straight-edge simulation, wire model, and pseudo-rut model.

The straight-edge and wire models will both give the same results if the high points of the pavement are at intervals less than or equal to the length of the straight-edge. When they are not, the wire model will yield a higher rut depth than the straight-edge, although it was not possible to confirm by how much, due to the absence of any reference profiles with such features.

With both the straight-edge and wire models the rut depth can be calculated using a datum which is perpendicular to the straight-edge/wire or perpendicular to the elevation datum. The SHRP straight-edge algorithm uses the elevation datum. For the levels of rutting found on NZ pavements, the difference between these two approaches will be negligible.

With the pseudo-rut model it was found that to enhance the accuracy the profile needs to be normalised so that the end elevation is the same as the start elevation. Even when this is done, the model was found to be an extremely poor predictor of rut depths. Given that the model appears to be used with 3-5 sensor rut depth systems, the resulting data would be of very limited use.

Transfer Functions

The following are transfer functions to convert the measurements of different profilometers to the 'true' rut depth:

RD = 1.54 + 0.97 MEAS	MWH 30 Sensor[1]
RD = 2.44 + 0.98 MEAS	WDM 16 Sensor
RD = 2.09 + 0.96 MEAS	PMS 15 Sensor
RD = 2.39 + 0.96 MEAS	ARRB 13 Sensor

where RD is the 'true' rut depth in mm
MEAS is the rut depth measured by the profilometer in mm using the SHRP 2 m straight-edge simulation

It should be noted that the configuration of the WDM 16-sensor profiler was assumed, since the manufacturer considered the information commercially sensitive and so the above function may not be completely valid.

Impact of Lateral Placements

During a profilometer survey it is impossible to ensure that the vehicle is in the same wheelpath as during the previous year's survey. The HRD software treats lateral placement as a random variable that was Normally distributed. The standard deviation is used to govern the level of variability.

The results showed that in general there was a decrease in accuracy with an increase in lateral placement. An exception to this was with the 16- and 15-sensor profilometers where there was an improvement in the accuracy for the kerb measurements. This was due to the configuration of the profilometer where there was an inadequate number of measurements near the kerb.

When a profilometer travels down a lane, there is a possibility that the kerb sensor will record outside of the pavement. All manufacturers include algorithms which

[1] It should be noted that this transfer function is predicated on all measurements being made at the same position along the road. Since ultrasonic systems use progressive sampling this is not correct and should be viewed as the 'best case' scenario.

check for this and exclude measurements which violate certain rules that identify them as falling outside of the pavement area. The higher the standard deviation of lateral placement, the more likely the system is to have measurements outside the pavement. The impact of this on the results is dependent upon the number of sensors and their placement; with few sensors the impact can be quite large whereas with many sensors it will be quite small.

The errors arising from lateral placement variations can be as large as 8 mm, which can exceed any changes in rut depths between years due to pavement deterioration. This perhaps explains the difficulties encountered when trying to use profilometer rut depth data for monitoring pavement deterioration trends: there is insufficient accuracy to isolate pavement deterioration from measurement effects.

Extending the Results

The results need to be extended to complete the project's objectives, which would entail:

- measuring additional transverse profiles so that the full range of pavement shapes in NZ are considered;
- working with profilometer suppliers to test their algorithms. This would be done by supplying a sample of profile data to them and analysing the resulting rut depths;
- investigating the optimal spacings of sensors so that providers are given guidance on how to configure their systems; and
- considering the impact of measurement precision on the rut depth accuracy and transfer functions.

The HRD software should also be enhanced so that it can form the basis of a stable procedure that can continue to be used for harmonising rut depths. This procedure would render it applicable to future instruments and technologies that may be implemented in NZ for measuring rut depths.

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