# Harmonising Automated Rut Depth Measurements - Stage 2

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- Transit New Zealand who provided a sample of transverse profile data from their calibration sections for analysis.

# Contents

# Executive summary

Rut depths are permanent deformations of the pavement structure, and an important indicator of the structural integrity of the pavement as well as having an impact on road user safety. Therefore, most road controlling agencies regularly monitor the levels of rut depths on their pavements.

**Automated rut depth systems**

Four different instruments are used for automated measurement of rut depths:

- Montgomery Watson Harza (MWH) 30-Sensor Ultrasonic System,
- WDM 16-Sensor Laser System,
- Pavement Management Services (PMS) 15-Sensor Laser System,
- Australian Road Research Board (ARRB) 13-Sensor Laser System.

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

**Harmonising rut depths (HRD)**

This computer simulation study, carried out between July 2002 and June 2004, 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),
- smoothing the reference profiles using polynomial or spine 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.

$$KerbERROR = 14.39\ SENSORS^{-0.5770} R^2 = 0.94$$

$$CentreERROR = 11.40\ SENSORS^{-0.3831} R^2 = 0.90$$

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

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

An assessment of the mean rut depth showed that with fewer than approximately 15 sensors, there can be a significant underestimation 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),
- 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 that range from 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 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. A strong linear relationship was identified 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.

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

| Kerb side | Centre lane side | Profilometer |
|---|---|---|
| RD = 1.54 + 0.97 MEAS | RD = 2.22 + 0.88 MEAS | MWH 30-sensor[1] |
| RD = 2.44 + 0.98 MEAS | RD = 3.05 + 0.80 MEAS | WDM 16-sensor |
| RD = 2.09 + 0.96 MEAS | RD = 3.56 + 0.64 MEAS | PMS 15-sensor |
| RD = 2.39 + 0.96 MEAS | RD = 3.20 + 0.77 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

Note 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.

### 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 more closely they sample, the less will be 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 sensors on the 16 and 15-sensor units may need to be repositioned to take additional readings towards the kerb, because of 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 related to different lateral placement can be greater than the change in rut depth related to pavement deterioration.

### Optimal design

The profilometers used to measure rut depth may not always measure the high and low points accurately because of their fixed design and varying critical points. The simulation analysis (between optimal design and equal spacing design) showed that the measurement error could be up to 15% depending on the design of the profilometer. The measurement accuracy can be increased significantly by rearranging the sensors in a

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[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.

profilometer. The increase in accuracy is mainly with the kerb measurements while the accuracy of the centre measurements essentially remains the same. The gain in accuracy is more significant when the number of sensors is in the range of 10 to 16. As the number of sensors increase the gain from any rearrangement diminishes. The measurements can be corrected before undertaking a trend analysis.

### Measurement precision

The HRD (harmonisation of rut depth) software does not consider the precision of the measurements. For example, the ROMDAS (Road Measurement Data Acquisition System) ultrasonic system has a reported standard error of approximately 0.3 mm, with a 95% confidence interval of 0.70mm It would be expected that lasers would have errors of less than 0.1 mm. Since the errors could accumulate, the simulation analysis was undertaken in this project to estimate the measurement error.

The measurement error is not negligible and also not symmetric. Generally the error is positive (tends to overestimate the rut depth than underestimate). The error is more dependent on the number of sensors than the amount of rut depth. The measurement error can be estimated by:

$$\text{KerbE} = 0.013 + 0.0023 * N$$

$$\text{CentreE} = 0.0145 + 0.0024 * N$$

$$\text{Lane Average E} = 0.0137 + 0.0023 * N$$

where E = measurement error
N = number of sensors

### 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 progressive sampling is systematic and increases with the speed of the profilometer (vehicle) and decreases with the amount of rut depth. The progressive sampling error of ultrasonic profilometers can be estimated by (without the effect of rut depth):

$$E_k = 0.027 * V, \ (R^2 = 0.97); \text{ and}$$

$$E_c = 0.041 * V, \ (R^2 = 0.97)$$

where $E_k$ = Error of kerb rut depth (mm)
$E_c$ = Error of centre rut depth (mm)
V = Survey speed (km/h)

In most cases the error is less than 3 mm.

# Abstract

A computer simulation study carried out between July 2002 and June 2004 investigated harmonising rut depth measurements from different profilometers. Software was written which allowed for a standard reference transverse profile to be analysed by different sensor numbers and spacings. This was used to investigate the effect of the number of sensors on predicted rut depth. Accuracy of rut depth was proportional to the number of sensors. This sampling effect results in underestimation of 2-4 mm for the profilometers used in New Zealand. Some configurations appear to have inadequate coverage towards the kerb, so may miss important data if the first sensor measures outside the pavement area. Variation in rut depth which arises from lateral placement can be greater than the change caused by pavement deterioration, which may explain problems found when trying to use profilometer rut depth data for monitoring pavement deterioration trends. Rearrangement of sensors in profilometers could significantly increase accuracy. The error in measurements tends to overestimate rut depths. Measurement error is dependent on the number of sensors used to measure rather than the extent of rut depth. The error caused by progressive sampling of the ultrasonic sensors is systematic and positive, and increases with the speed of the profilometer.

# 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 controlling agencies (RCAs) 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 involve 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 measurements 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 spacing of locations across the pavement. The data are also analysed using algorithms which, although they generally reference back to a 2 m straight-edge (see Section 2.3.3), 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 stages:

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

Following the success of Stage I, Transfund New Zealand approved Stage II of the project. The objectives of Stage II were to:

- undertake additional field surveys to confirm the validity of the Stage I results,
- determine the optimal spacing of the sensors,
- quantify the lateral placement variation,
- determine the impact of measurement precision on the rut depth accuracy,
- estimate the progressive sampling error for ultrasonic sensors,
- develop standard procedures and functions for correlating different profilometers,
- enhance the Harmonisation of Rut Depth Measurements (HRD) software to include the outcomes from the analysis undertaken in Stage II.

Stage II was an extension to and expansion of the Stage I results. The conclusions and discussions from Stage I were drawn on where required in this report to support Stage II analysis. This report summarises the findings of Stage II of the research.
All the objectives of this stage were achieved except for the following:

- **Quantifying lateral placement variation** - The researchers tried several techniques to estimate the lateral placement variation which did not yield conclusive answers.
- **Correlating different profilometers** - Other profilometer providers declined to participate in the project. Hence, a detailed analysis for correlating different profilometers was not achieved. However, the preliminary transformation functions finalised in Stage 1 were recommended to convert rut depths from automated systems back to a reference standard.

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 those relating to the number of sensors and their spacing.

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 spacing 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.

# 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 RCAs have annual data collection programmes. Data are collected using one of two methods:

- **Manual Data.** This is a visual assessment of the pavement condition collected in accordance with the RAMM (Road Assessment Maintenance and Management) 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 (National Association of Australian State road Authorities) 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 usually 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 wheelpaths in each direction on a 2-lane road), the maximum possible value for this measure is 200 m.

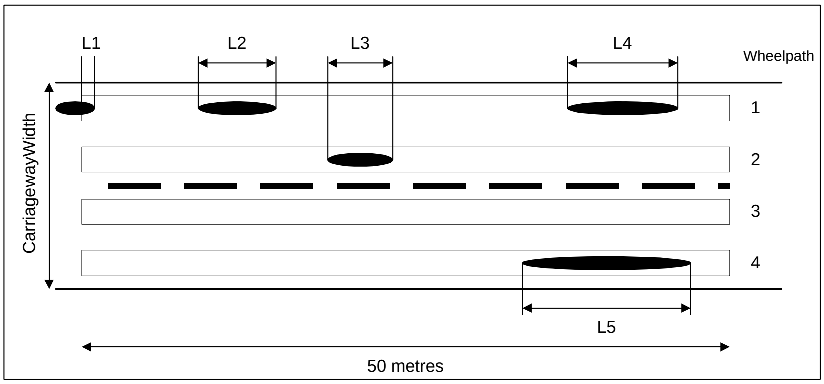


**Figure 2.1 RAMM rut depth rating.**

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 criterion is calculated from the high speed measurements.

With the implementation of the predictive modelling for pavement deterioration (NZdTIMS (New Zealand Deighton's Total Infrastructure Management System) project), the shift of emphasis has been 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. The NZdTIMS project also adopted the use of standard deviation of rutting in pavement deterioration models. These parameters will continue to be used in the NZdTIMS for pavement performance 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. Various terms are used for the equipment depending on the manufacturer but for simplicity they will be referred to in this report as 'profilometers'.

### 2.3.1 Technology

Four technologies are used for estimating rut depths:

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

**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 shows an example of the WDM laser profilometer.

**Figure 2.3 WDM SCRIM (sideways force coefficient routine investigation machine) and survey vehicle.**

- **Scanning lasers**. This is a new technology not currently used in New Zealand. 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 2.3 m above the ground. 950 points are sampled across the transverse profile, every 25 mm along the pavement.

- **Optical systems**. Not used in New Zealand, 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 National Optics Institute (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 New Zealand, the focus of this project was on ultrasonic and point laser systems. The configurations of four different profilometers were considered:

- 30-sensor MWH (Montgomery Watson Harza) ultrasonic system,
- 16-sensor WDM point laser system,
- 15-sensor PMS (Pavement Management Services) point laser system,
- 13-sensor ARRB TR (Australian Road Research Board - Transport Research) 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.

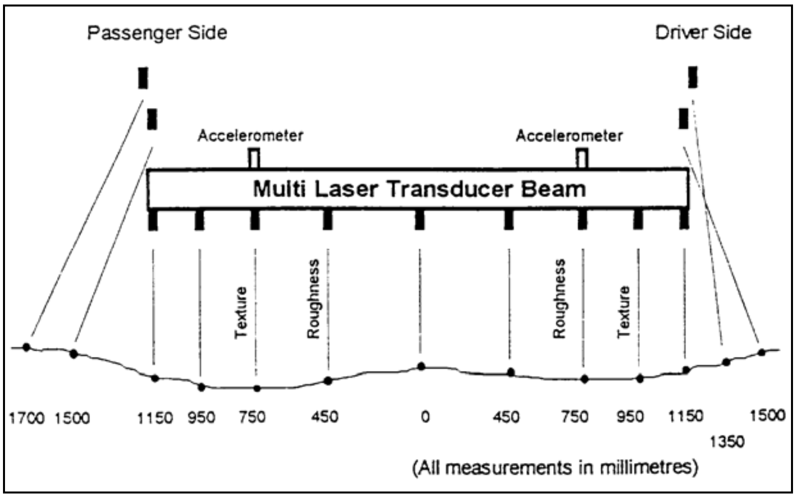


**Figure 2.4 ARRB TR Multilaser Profilometer laser positioning.**

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

### 2.3.3 Analytical process

Three basic algorithms are 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 New Zealand all profilometers report the straight-edge rut depth.

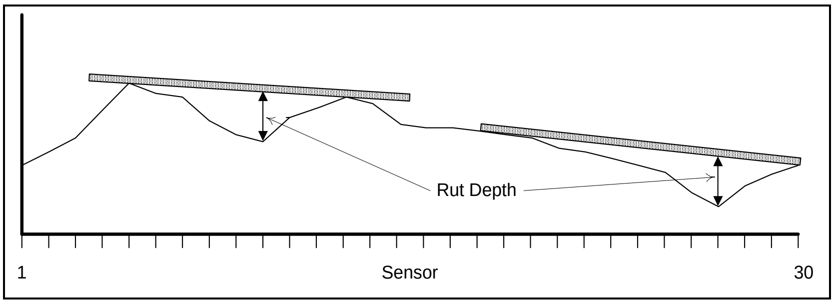


**Figure 2.5 Example of straight-edge simulation.**

- 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 New Zealand the PMS profilometer reports the wire model rut depth in addition to the straight-edge rut depth.

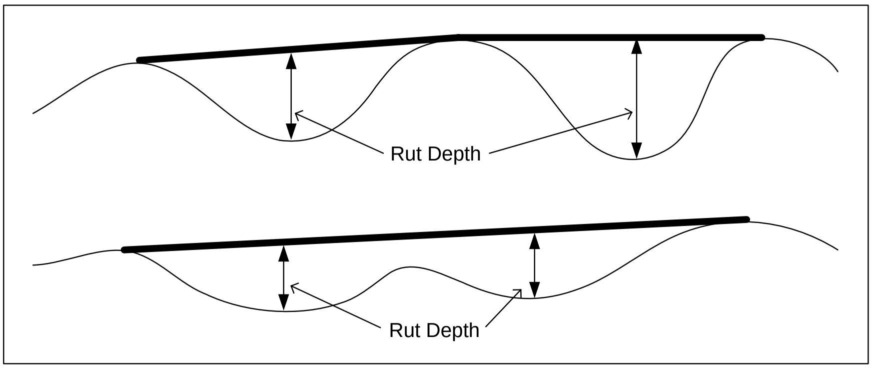


**Figure 2.6 Example of wire model.**

- **Pseudo-ruts** are defined are as the difference (in mm) between a high point and a 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 New Zealand.

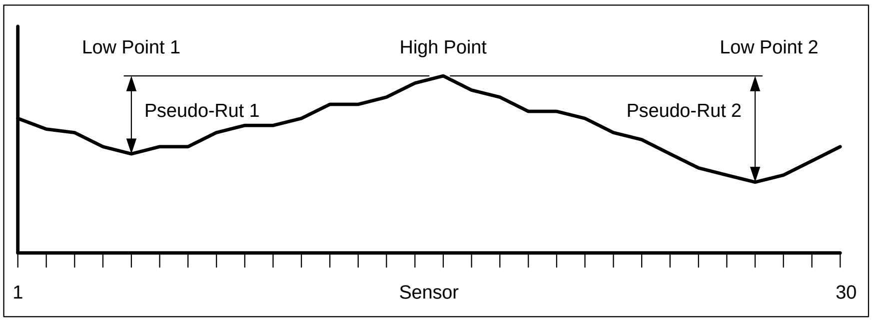


**Figure 2.7 Definition of pseudo-ruts.**

## 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.

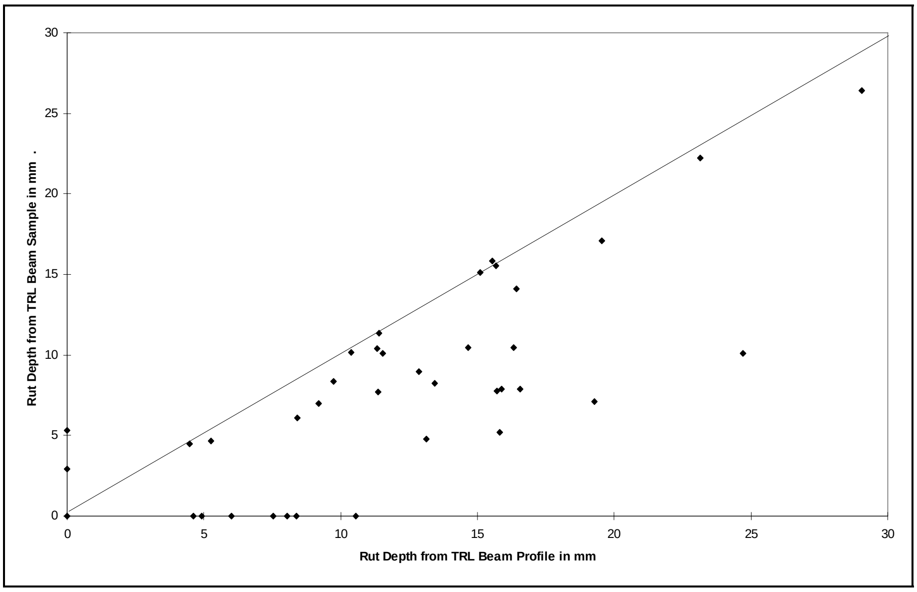


**Figure 2.8 Effect of sampling on rut depth from continuous samples.**

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.

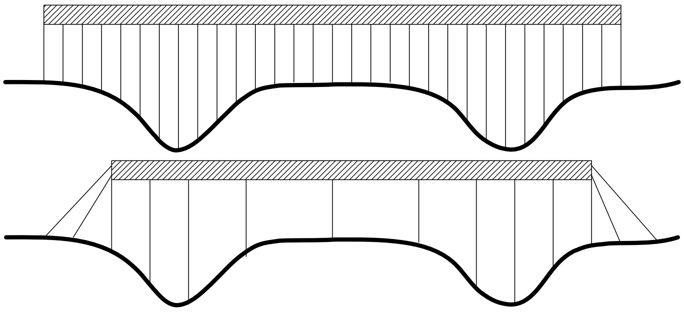
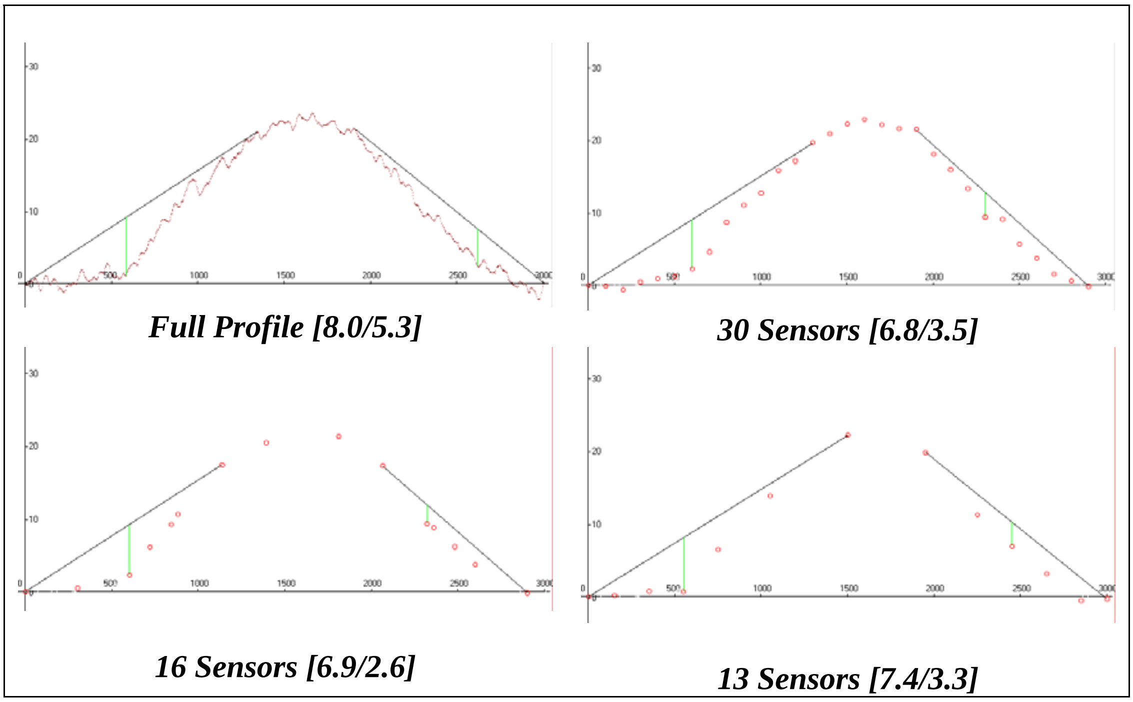


**Figure 2.9 Example of the effect of sensor spacings on transverse profile.**

The sampling effect is important with a single instrument and highlights the need for harmonisation when several different instruments are in use. This need is illustrated in Figure 2.10 which shows the results from three different instruments, each with its 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].



*Full Profile [8.0/5.3]*

*30 Sensors [6.8/3.5]*

*16 Sensors [6.9/2.6]*

*13 Sensors [7.4/3.3]*

**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

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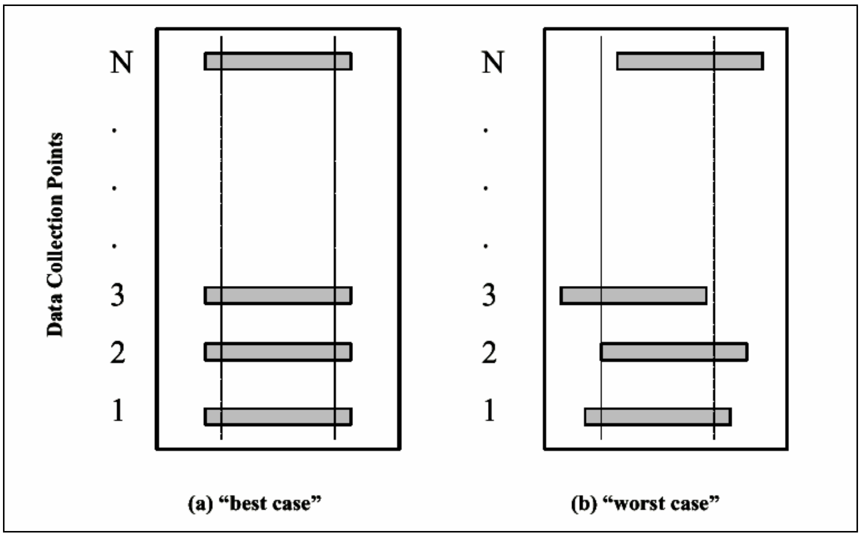
[1] Throughout this report when reporting rut depth results the format will be [kerb, centre]. For example, [6.6/4.4] refers to a 6.6 mm rut depth at the kerb and a 4.4 mm rut depth in the centre of the road.

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 (e.g. +/- 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 wheelpath between successive surveys. While this is typically not a problem during equipment calibration, where the vehicles are operated in a very controlled manner over clearly marked wheelpaths, it becomes an issue during operational surveys.

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 7, this lateral placement variation has a significant impact on the rut depths resulting from any profilometer survey.



(a) “best case”

(b) “worst case”

Figure 2.11 Lateral placement scenarios. (Simpson 2001).

## 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 (opposite).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.

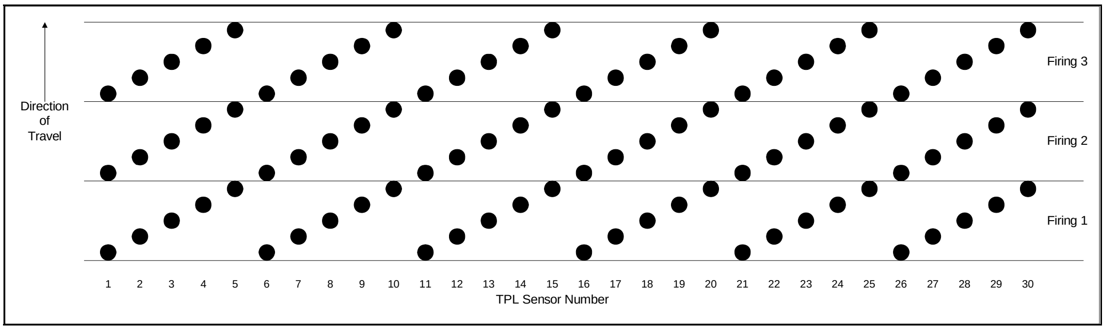


Figure 2.13 30-sensor ultrasonic progressive sample profile.

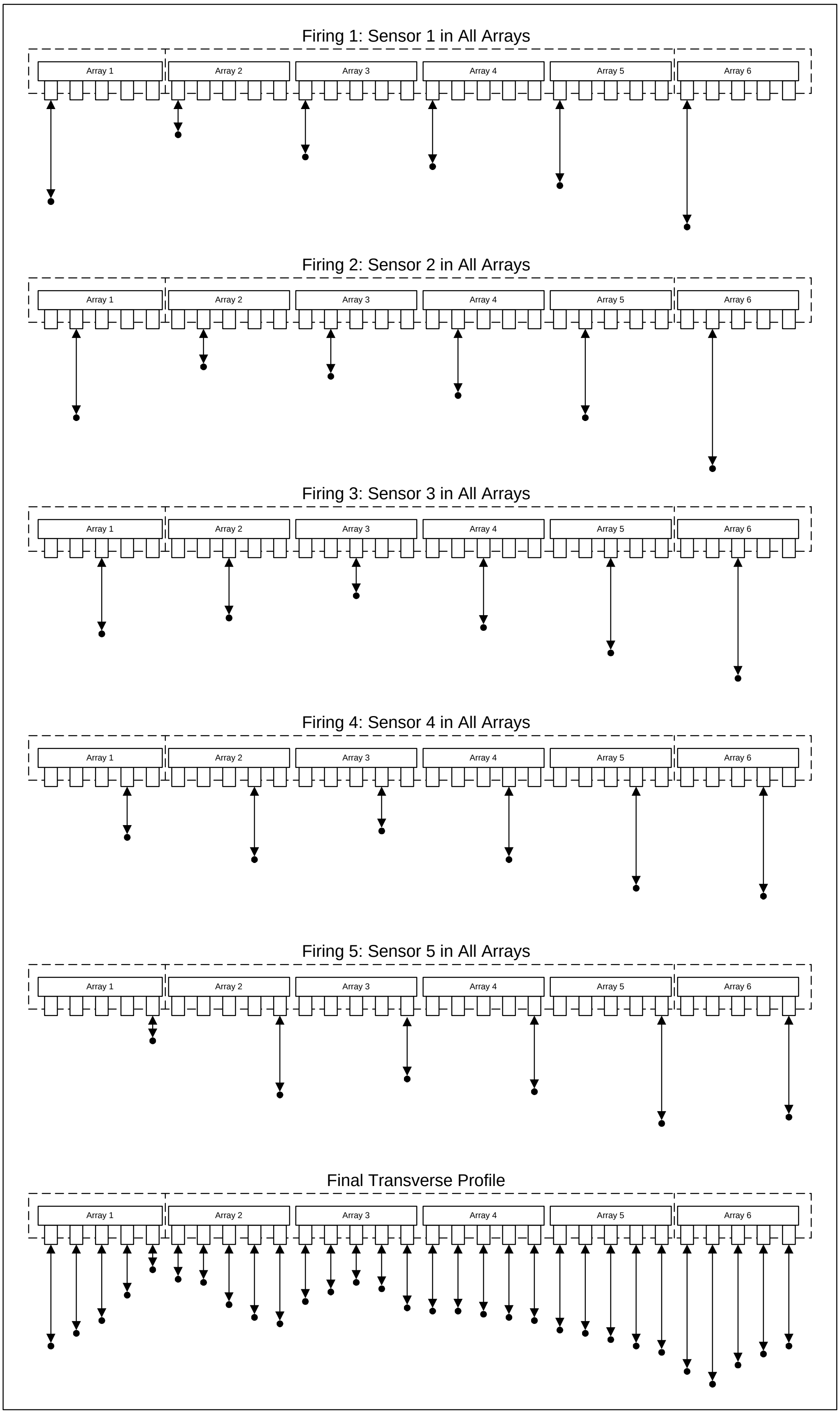


**Figure 2.12 Progressive sampling for 30-sensor ultrasonic system.**

# 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 (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 2 m 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.

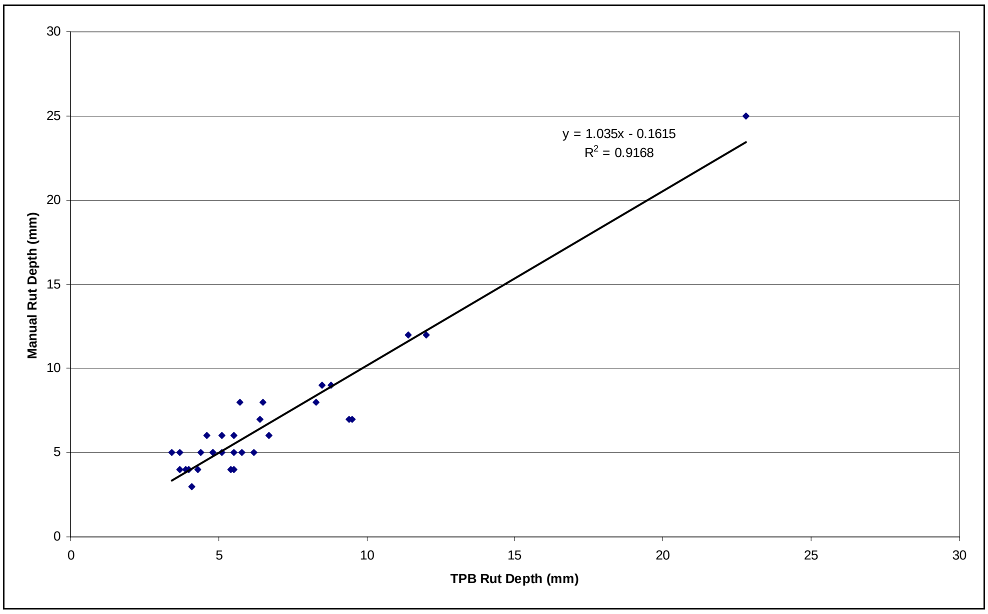


**Figure 3.2 TPB v manual rut depths.**

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 New Zealand. 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,

- GPS co-ordinates.

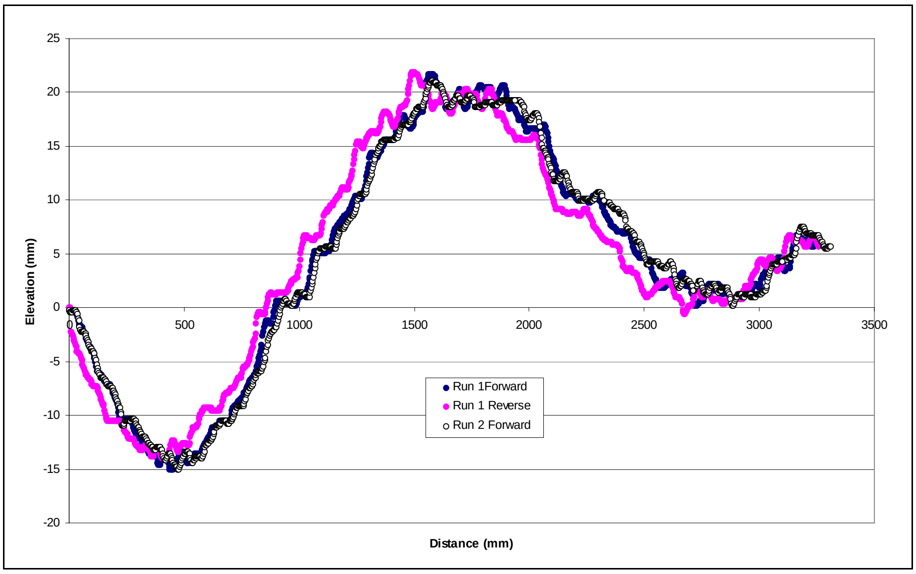


**Figure 3.3 Profile measurements between runs.**

**Figure 3.4 Example of a Transit New Zealand calibration section.**

The TPB was positioned every 10m 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.

# 4. Input data collection

## 4.1 Reference profiles

Stage I of the research recommended using more profiles to validate the results. Transit New Zealand made data available for 361 profiles which included predominant pavement surfaces and profiles existing in the country. These profiles were collected as part of the long-term pavement performance project on the state highway network undertaken by Transit New Zealand. Out of these profiles, a total of 348 observations were used in the analysis after the preliminary screening of the measurements. These profiles were measured with DCL's TPB.

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.

## 4.2 Distribution of profiles

The distribution of the road profiles is discussed by:

- lane width distribution,
- rut depth distribution.

### 4.2.1 Lane width distribution

The lane width of the road profiles considered for the analysis range between 1.9 m and 3.5 m, the average being 3.2 m. The lane width histogram is shown in Figure 4.1.

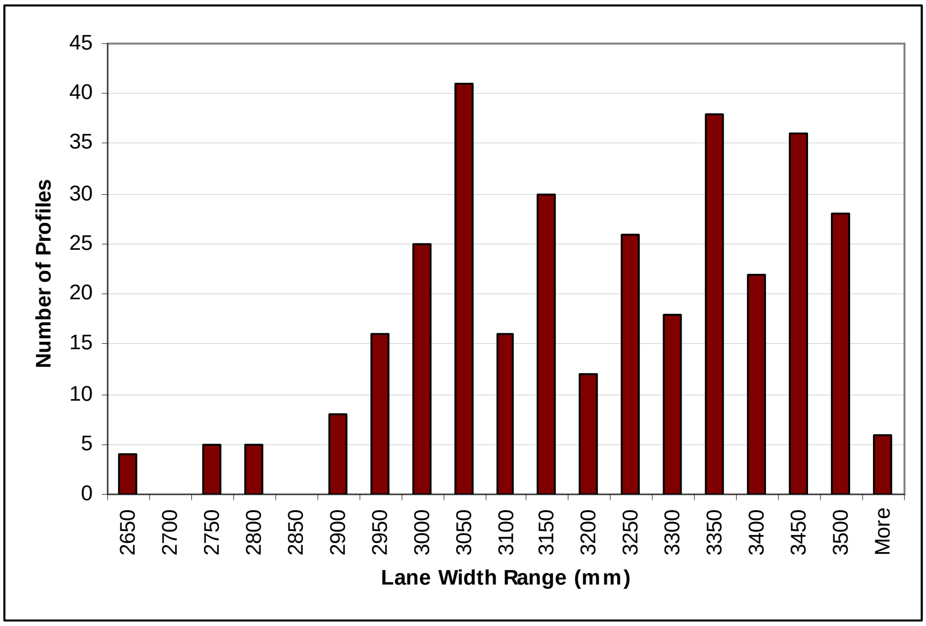


**Figure 4.1 Lane width distribution.**

### 4.2.2 Rut depth distribution

Kerb-side and centre lane-side rut depth histograms are given in Figure 4.2 and Figure 4.3. As shown in the figures, most of the rut depth of the road profiles were less than 20 mm. Kerb-side rut depths were recorded up to 50 mm while the maximum rut depth for centre lane-side was in the order of 40 mm. Kerb-side rut depths were in general higher than the centre lane-side ruts.

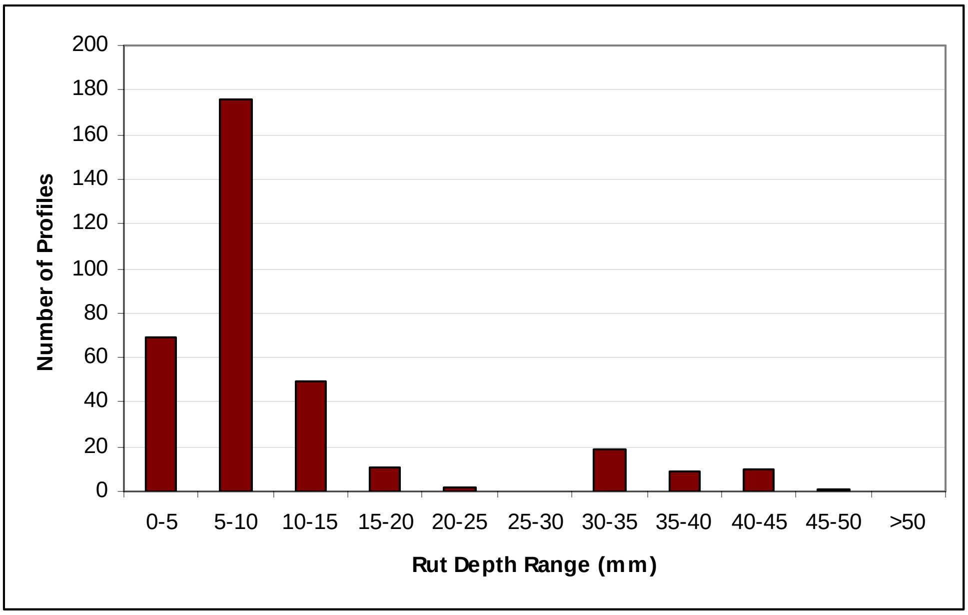


**Figure 4.2 Kerb-side rut depth distribution.**

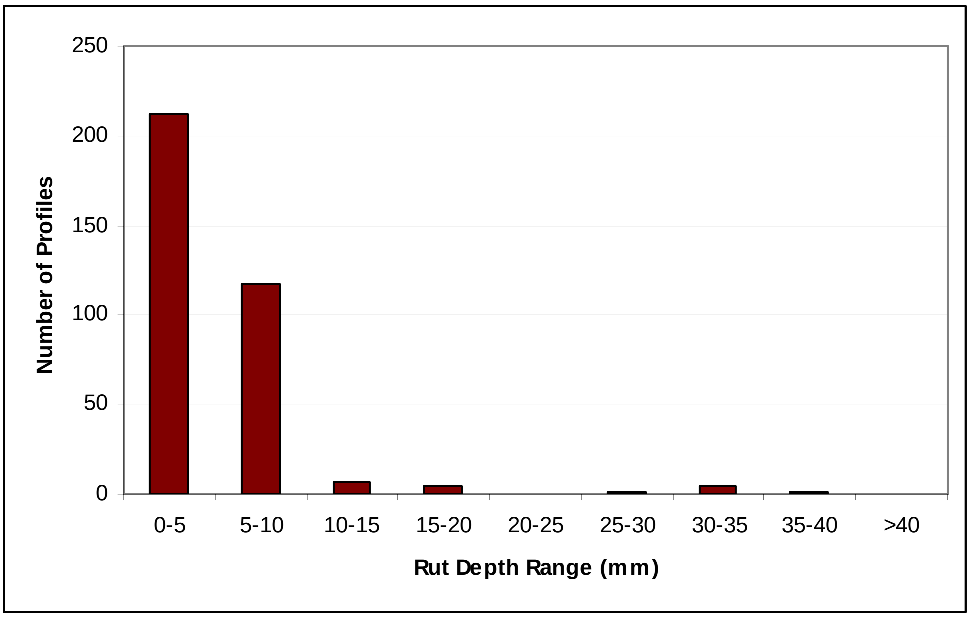


**Figure 4.3 Centre lane-side rut depth distribution.**

## 4.3 Additional surveys

Other analyses such as 'progressive sampling' etc. required special surveys which were not budgeted for in the proposal. The simulation analysis initially proposed was not possible with the available data. Hence, some additional surveys were undertaken to complete the analysis successfully. The additional surveys were undertaken on DCL's control section on Rodney District Council's road network (Old Railway Road section) with the TPB and ultrasonic transverse profile logger (TPL).

# 5. Implications of sampling on rut depths

## 5.1 Introduction

As described in Chapter 2, 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.

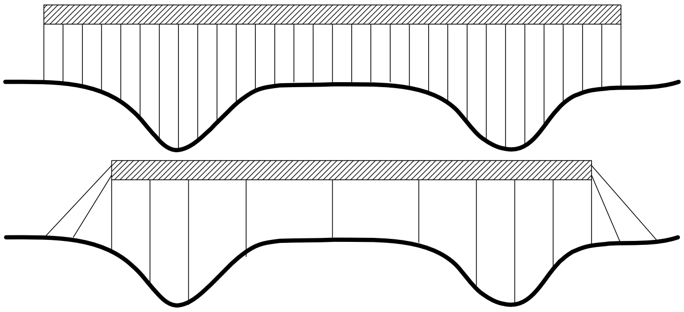


**Figure 5.1 Example of the effect of sensor spacings on transverse profile.**

Please refer to Stage I of the report (Bennett & Wang 2003) for detailed discussion of the investigation into the effect of the number of sensors on rut depth.

## 5.2 Analysis results

In both kerb-side and centre lane-side cases the error decreased with an increasing number of sensors, and the following regressions were fitted to the data:

$$\text{KerbERROR} = 14.39\ \text{SENSORS}^{-0.5770} \quad R^2 = 0.94$$

$$\text{CentreERROR} = 11.40\ \text{SENSORS}^{-0.3831} \quad R^2 = 0.90$$

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

The difference between kerb and centre error is primarily caused by the fact that kerb and centre road profiles are not symmetric and the methods to measure them are not exactly the same. Consider the following example for more explanation.

In many cases, the kerb high point B (shown in Figure 5.2) is at the middle of the profile. In some extreme cases (or in no case), B and C may be very close (or coincide). It is possible for the measured centre rut depth to be greater than the real rut depth. In these cases, we have more sensors to measure the kerb-side rut depth than the centre lane-side rut resulting in more uncertainty in the centre rut depth measurement, and hence kerb and centre road profiles are not always symmetric (and in most cases they are not symmetric).

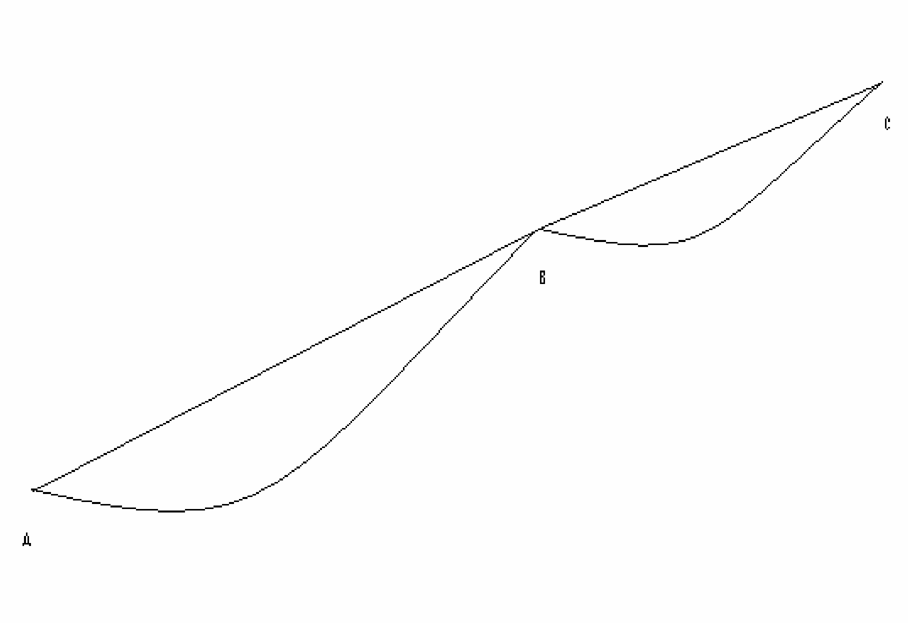


**Figure 5.2 Relationship of high points showing asymmetry.**

## 5.3 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),
- its ability to locate the high and low points in the profile measured.

The positioning of the vehicle is discussed in detail in Chapter 7. 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, and 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 New Zealand is presented in Chapter 6 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. Few ROMDAS readings were below 3 mm, whereas many manual readings were below 3 mm. This was assumed to be caused by 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 probably caused by discrete sampling rather than texture.

The data from profilometers should therefore be adjusted to reflect their systematic underestimation of 2 to 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 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 New Zealand. Two important points to note with the 30 and 16 sensor profilometers are:

- 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 2m straight-edge rut depth in mm |
| | MEAS | is the 2m rut depth in mm for the profilometer configuration using the Strategic Highway Research Program (SHRP) analysis algorithm. More information on SHRP can be sourced from the Federal Highway Administration or on their web site: *(http://www.fhwa.dot.gov/winter/roadsvr/shrp.htm).* |

Note: The actual rut depths predicted by the profilometers may be different from 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, and to 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 datasets so there were three equations for each profilometer. These equations are presented in Table 6.1 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 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.

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[1] As described in Bennett & 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.

**Table 6.1 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. E. | a0 | a1 | $R^2$ | S. E. | a0 | a1 | $R^2$ | S. E. | a0 | a1 | $R^2$ | S. E. |
| 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) | | |
| | Lane (Avg) | 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) | | |
| | Lane (Avg) | 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) | | |
| | Lane (Avg) | 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) | | |
| | Lane (Avg) | 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) | | | | | | |
| | Lane (Avg) | 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) | | | | | | |

* 't' statistic are in parentheses

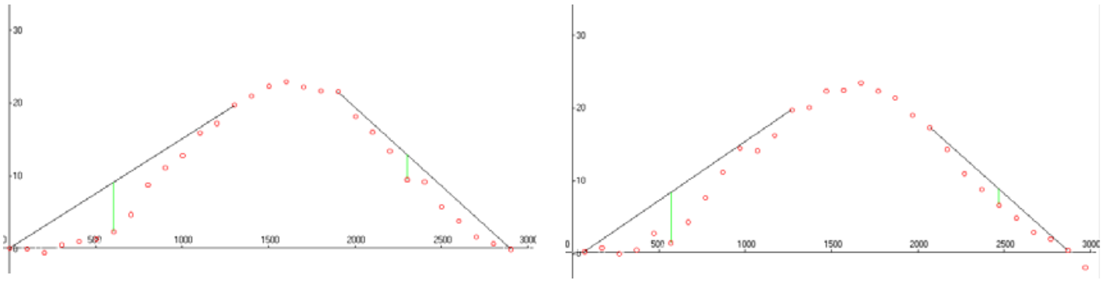
# 7. Implications of lateral placement on rut depths

## 7.1 Introduction

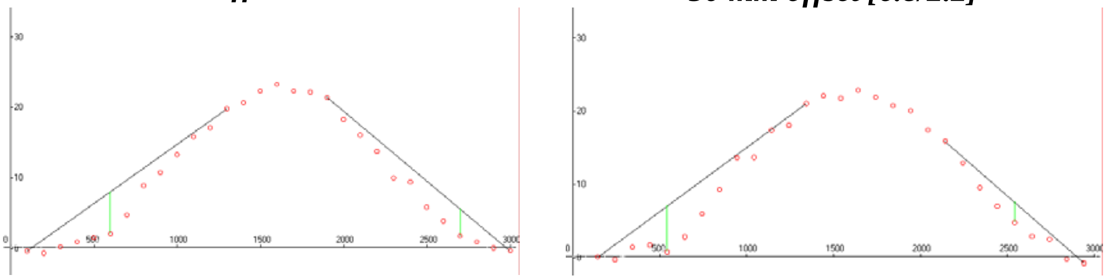
When conducting a survey the lateral placement of the survey vehicle will have a significant impact on the validity of the measurements, particularly when trying to monitor rut depths between years. The impact will depend upon the shape of the profile, the amount of lateral variation as the vehicle drives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

## 7.2 Implications of lateral placement on rut depths

Figure 7.1 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 7.1 Example of impact of lateral placement on rut depths.**

Please refer to Stage I report (Bennett & Wang 2003) for more details.

## 7.3 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 7.2 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. 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.

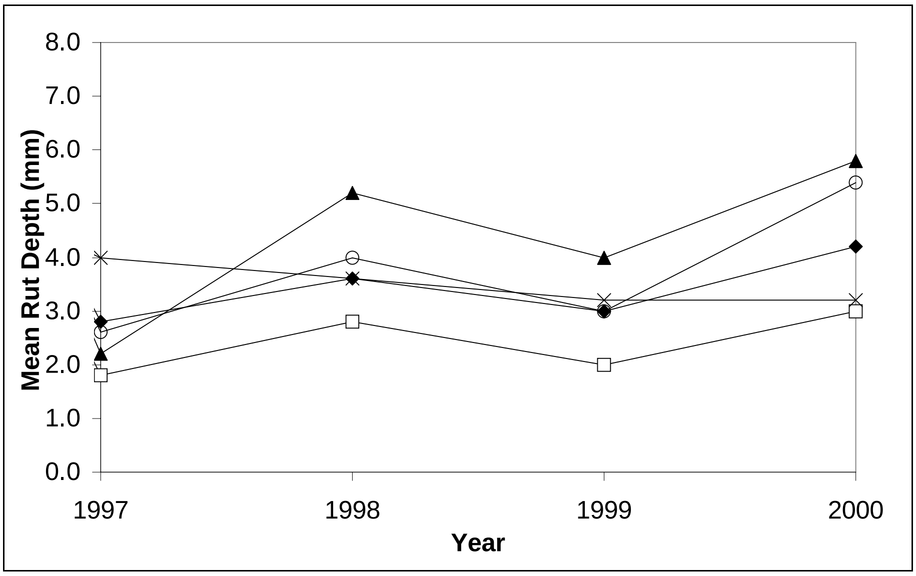


**Figure 7.2 Example of state highway rut depth trend.**

However, lateral placement has no effect on the estimation of the standard deviation of the rut depths.

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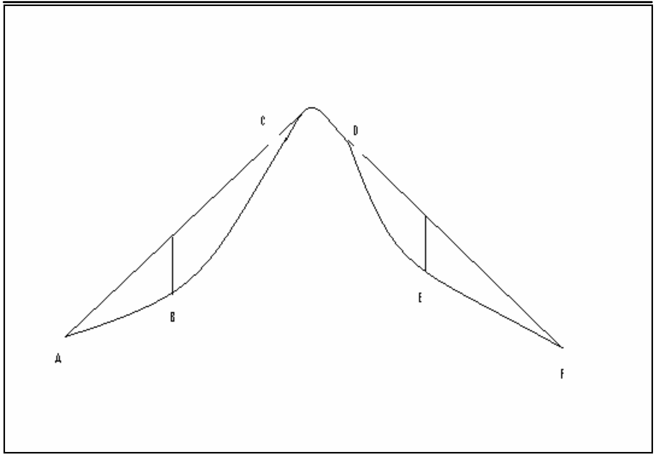
[1] The data were supplied by Transit New Zealand for a research project into the quality of road survey data (Bennett 2001), although their analysis was not included in the report. The original data were sampled at 20 m intervals. By averaging to 100 m this reduced the impact of differences in lateral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

# 8. Optimal design of profilometer

The design of the profilometer has a significant effect on the accuracy and reliability of the final results. This chapter provides a methodology to determine the optimal design of the profilometer.

## 8.1 Optimal design

Theoretically there could be infinite points on a road profile. However, the most important points are the first kerb high point, the kerb low point, the second kerb high point, the first centre high point, the centre low point, the second centre low point (hereinafter referred to as K1, K2, K3, C1, C2, C3, or points 1 to 6). For any given profile six sensors are enough to measure the correct profile of the road provided the design of the profilometer can be modified before measurement. This is practically unrealistic. However, sensors can be kept as close to the key points (as above) as possible on an average. Any design that accomplishes this criterion would be a very good design, rather than an optimal design.



*A = K1 = First Kerb High Point*
*B = K2 =Kerb Low Point*
*C= K3 = Second Kerb High Piont*
*D =C1 = First Center High Point*
*E = C2 = Center Low Point*
*F =C3 = Second Center High Point*

**Figure 8.1 Location of key points on a road profile.**

## 8.2 Analysis technique

### 8.2.1 Definitions

The sensor design consisting of ‘n’ number of sensors ($S_1$, $S_{2,}$ ,..$S_n$) is a vector in that $S_1 < S_2 < \ldots < S_n$.

Let probability distribution of key points be $f_i(x)$ defined as:

$$f_i(x) = \lim_{q->0} \frac{m}{N}$$

Where: N = number of profiles
m = number of key points
x = distance to point zero.

This probability distribution function can be analysed using the distribution of the measured profiles.

### 8.2.2 Distribution of profiles

The distribution of the measured profiles for six key points (K1, K2, K3, C1, C2 and C3) is given in Figure 8.2.

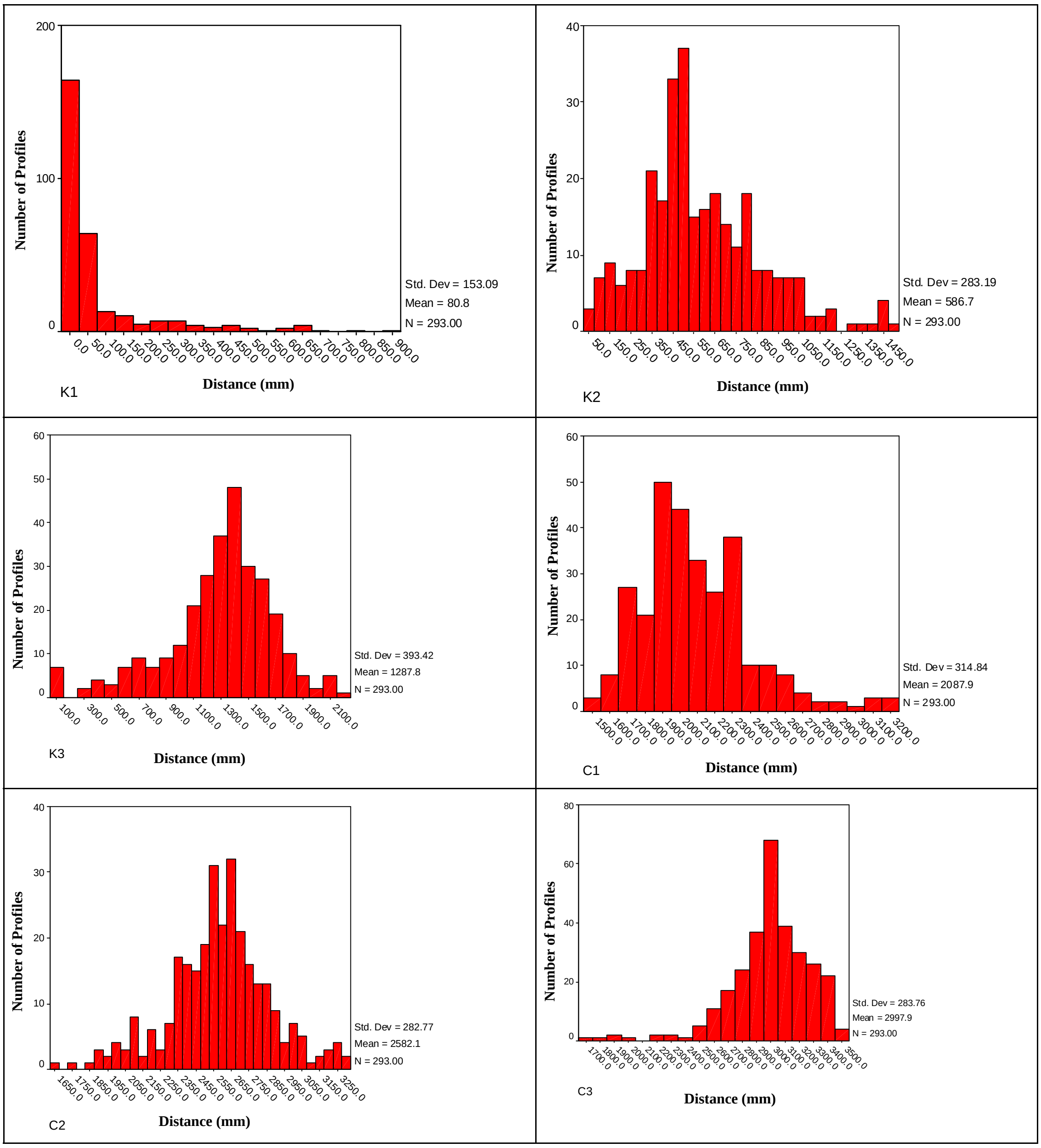


**Figure 8.2 Distribution of measured profiles.**

The probability distribution functions for these key points are calculated as:

$$f_1(x) = 0.0125 * \exp(-81 * x)$$

$$f_2(x) = \frac{1}{\sqrt{2\pi} * 283} \exp(-\frac{(x-587)^2}{2 * 283^2})$$

$$f_3(x) = \frac{1}{\sqrt{2\pi}*393}\exp(-\frac{(x-1288)^2}{2*393^2})$$

$$f_4(x) = \frac{1}{\sqrt{2\pi}*315}\exp(-\frac{(x-2088)^2}{2*315^2})$$

$$f_5(x) = \frac{1}{\sqrt{2\pi}*283}\exp(-\frac{(x-2582)^2}{2*283^2})$$

$$f_6(x) = \frac{1}{\sqrt{2\pi}*284}\exp(-\frac{(x-2998)^2}{2*284^2})$$

### 8.2.3 The loss or measurement error

The six key points may not always be measured accurately resulting in some difference between the true and measured depths. The loss is defined as the difference between the true rut depth and the measured rut depth by a given profilometer.

Then we define the loss function, $L_i=g_i(x)$ where *i* denotes the key point, *x* is the difference between the true key position and the sensor position, L is the loss. So $g_i(x)$ defines a relationship between the mis-locating of the key point and the effect this has on the measurement of rut depth (error).

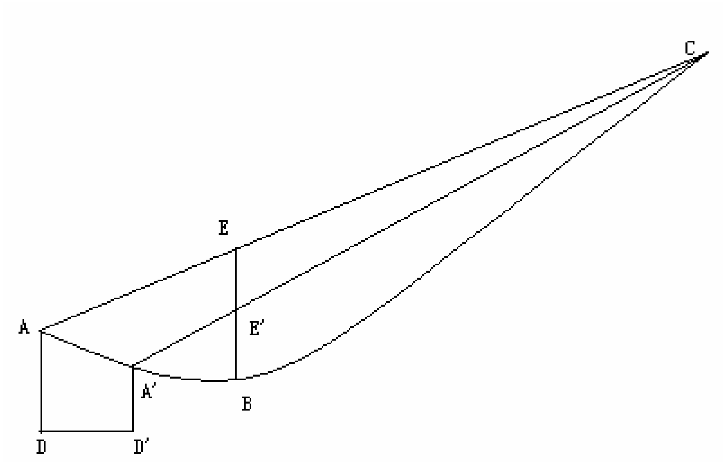


**Figure 8.3 Loss function. Consider this case: the key points B and C are located accurately, but not A. The loss under this scenario would be EE'. Then the loss function $g_i(x)$ defines a function between DD' and EE'.**

It is obvious that the loss would be different for different key points. The average loss estimated from the simulation of the data used in this project, is given below.

$G_1(x) = 0.01 * |x| \quad (\text{if } x<0)$
$\quad = 0.018055 * |x| \; (\text{if } x>0)$

$g_2(x) = 0.005701 * |x| \; (\text{if } x<0)$
$\quad = 0.00708 * |x| \quad (\text{if } x>0)$

$g_3(x) = 0.01282 * |x| \; (\text{if } x<0)$
$\quad = 0.01476 * |x| \; (\text{if } x>0)$

$g_4(x) = 0.02404 * |x| \; (\text{if } x<0)$
$\quad = 0.02161 * |x| \; (\text{if } x>0)$

$g_5(x) = 0.019156 * |x| \; (\text{if } x<0)$
$\quad = 0.02737 * |x| \quad (\text{if } x>0)$

$g_6(x) = 0.01956 * |x| \; (\text{if } x<0)$
$\quad = 0.01 * |x| \quad (\text{if } x>0)$

The loss function for a given sensor and key point can be estimated by:

$$L_i(S,q) = \min(g_i(s_i - q))$$

The whole loss function for the design is

$$L(S,q) = \sum_{i=1}^{6} L_i(S,q)$$

where S = sensor
q = key point

### 8.2.4 Optimisation

The total loss from a particular design is defined as the sum of the losses at the six key points. The loss at the first key point when there is no lateral placement (first sensor located at zero point) can be estimated by:

$$E(L) = \sum_{i=1}^{6} \int_0^{3000} f_i(x) L(x,S) dx$$

In reality, the lateral positioning is a random variable that is generally beyond control. Hence, assume it is normally distributed with zero mean and a standard deviation of 50 mm. Then the probability distribution function is:

$$g(y) = \frac{1}{\sqrt{2\pi} * 50} \exp(-\frac{y^2}{50^2})$$

and the expected loss with the lateral placement is:

$$E(L) = \sum_{i=1}^{6} \int_{0}^{3000} \int_{-\infty}^{\infty} f_i(x) L_i(x, y, S) g(y) dy dx$$

### 8.2.5 Optimal design

Considering the above object functions for a 3m profilometer the optimal design (sensors spacing) for different sensors are given in Table 8.1.

**Table 8.1 Optimal design of sensors.**

| Number of Sensors | Sensor Spacing in mm |
|---|---|
| 8 | 0, 170, 750, 1335, 1810, 2230, 2605, 3000 |
| 9 | 0, 170, 775, 1290, 1680, 2095, 2435, 2745, 3000 |
| 10 | 0, 140, 620, 1035, 1430, 1810, 2160, 2460, 2750, 3000 |
| 11 | 0, 130, 500, 845, 1175, 1490, 1840, 2210, 2500, 2770, 3000 |
| 12 | 0, 140, 500, 810, 1140, 1435, 1730, 2000, 2285, 2525, 2815, 3000 |
| 13 | 0, 120, 425, 695, 965, 1245, 1525, 1825, 2120, 2375, 2605, 2840, 3000 |
| 14 | 0, 125, 410, 665, 885, 1120, 1355, 1575, 1805, 2065, 2330, 25690, 2795, 3000 |
| 15 | 0, 105, 305, 580, 830, 1095, 1325, 1545, 1780, 2005, 2205, 2400, 2600, 2820, 3000 |
| 16 | 0, 95, 240, 520, 735, 935, 1155, 1380, 1600, 1820, 2010, 2205, 2400, 2600, 2820, 3000 |
| 17 | 0, 100, 310, 550, 730, 940, 1145, 1330, 1530, 1730, 1935, 2115, 2305, 2500, 2690, 2875, 3000 |
| 18 | 0, 100, 300, 535, 725, 910, 1065, 1225, 1375, 1540, 1725, 1910, 2105, 2300, 2500, 2690, 2880, 3000 |
| 19 | 0, 100, 255, 470, 665, 815, 985, 1160, 1325, 1480, 1645, 1810, 1975, 2140, 2315, 2500, 2690, 2880, 3000 |
| 20 | 0, 95, 250, 475, 638, 780, 940, 1105, 1265, 1425, 1585, 1755, 1895, 2060, 2215, 2380, 2540, 2710, 2880, 3000 |

### 8.2.6 Comparison between optimal design and equal spacing design.

The simulation results of the average rut depth measured by a profilometer with equal spacing and a profilometer with optimised design are given in Figures 8.3, 8.4 and 8.5. As shown in the figures, the gain in the accuracy varies from 0.25 mm to 0.67 mm (between 5% and 15%). This proves that the measurement accuracy can be increased significantly by rearranging the sensors in a profilometer. However, the increase in accuracy is mainly with the kerb measurements while the accuracy of the centre measurements essentially remains the same. The gain in accuracy is more significant when the number of sensors is in the range of 10 to 16. As the number of sensors increases the gain from any rearrangement diminishes.

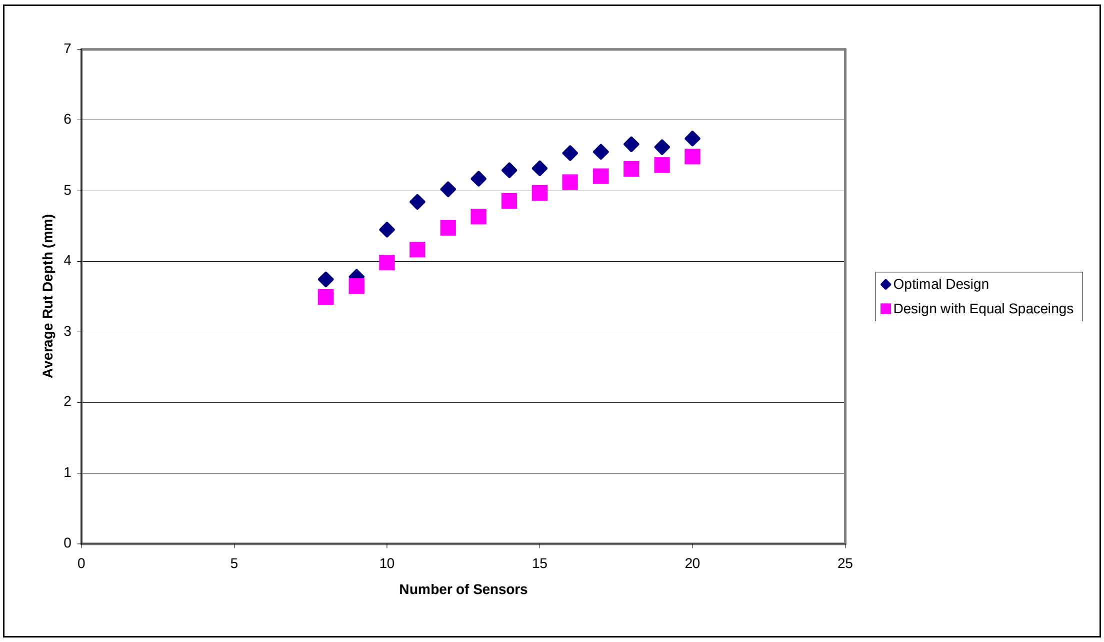


**Figure 8.3** Comparison of kerb rut depth of optimised design and design with equal spacing.

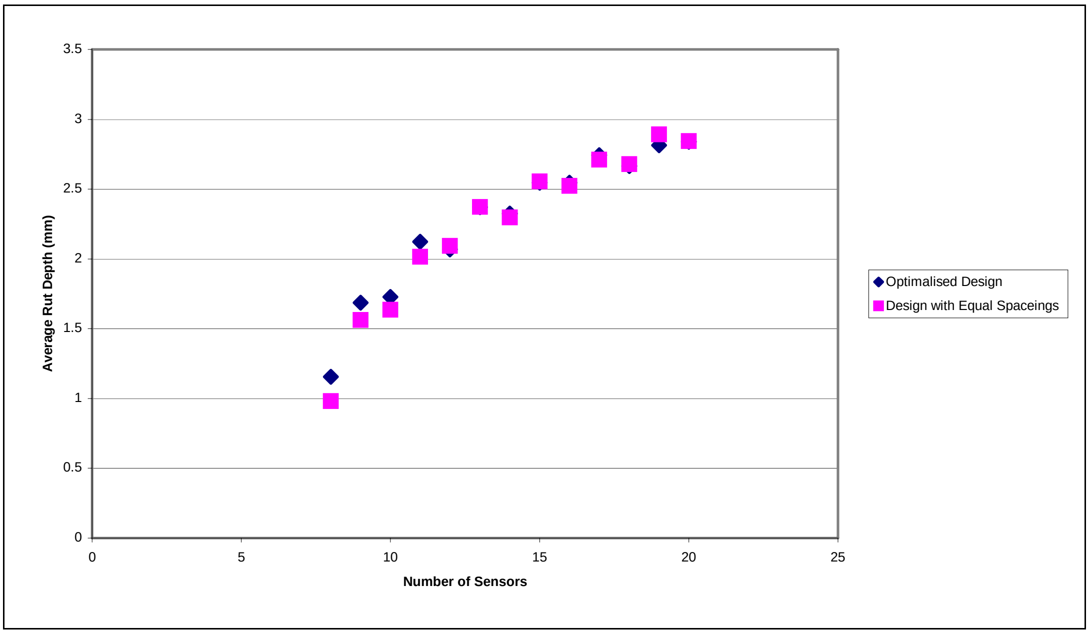


**Figure 8.4** Comparison of centre rut depth of optimised design and design with equal spacing. Note that vertical scales differs from Figure 8.3.

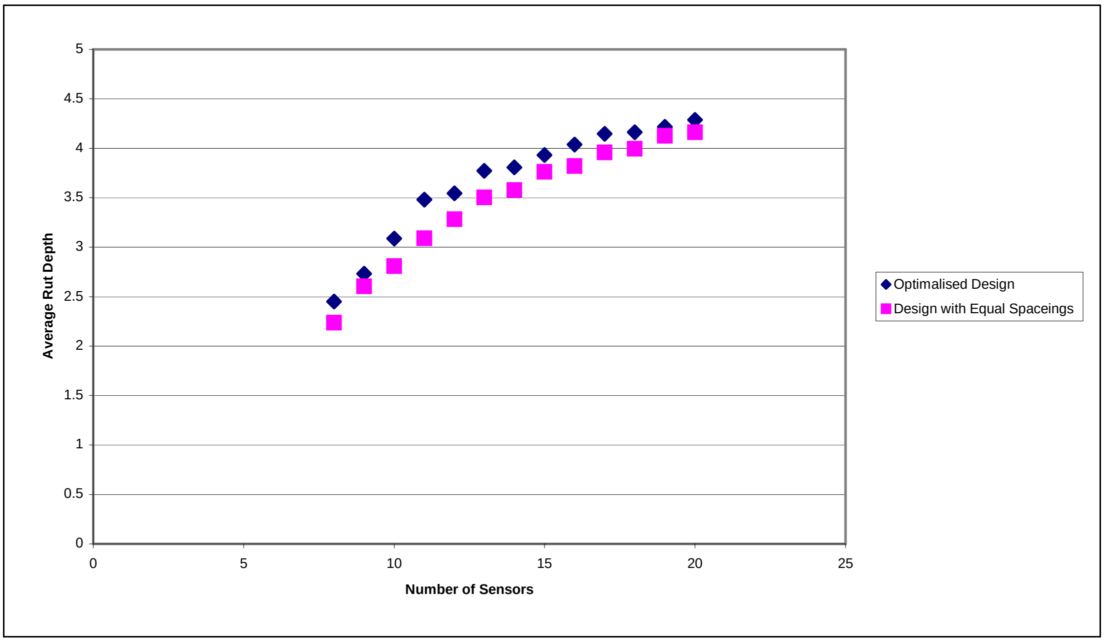


**Figure 8.5 Comparison of rut depth of optimised design and design with equal spacing.**

## 8.3 Implication of findings

The analysis showed that measurement accuracy can be increased up to 15% by rearranging the sensors. The analysis also indicated that the second sensor should be placed near the zero point to offset the effect of lateral positioning. The maximum gain in measurement accuracy was achieved when the number of sensors varied between 10 and 16.

The following factors should be considered in measuring and reporting the rut depth trends:

- All the six key points on a road profile may not always be possible to locate accurately; hence, the true rut depths are not always measured and reported.
- Use of the different profilometers yield a range of rut depths.
- The lateral placement of the survey vehicle could potentially create a 500 mm error which should not be ignored (even using the same profilometer).

Considering that different profilometers with varying designs (number of sensors and their spacing) are used in New Zealand, the true rut depths may not always be possible to report. Variation in historical rut depths (without a definite trend) is a common issue in the trend analysis in New Zealand. This can be minimised by using the transfer functions recommended in this report before undertaking a trend analysis.

# 9. Effects of sensor measurement error on rut depths

## 9.1 Introduction

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). Lasers would be expected to 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.

## 9.2 Distribution of error

The above analysis assumes that the sensor accurately measures the distance (rut depth). In reality, measurement error is not negligible. Furthermore, the effect of measurement error on the final result is not symmetric. Measurement error will be more likely to overestimate the rut depth than underestimate it. At first glance, because measurement error is assumed to be symmetric, its effect on measurement should be symmetric. The simulation analysis of a perfect profilometer and a profilometer with error of standard deviation 0.3 mm for 30 sensors is given in Figure 9.1. The analysis shows that the error is asymmetric and in most cases it is overestimated.

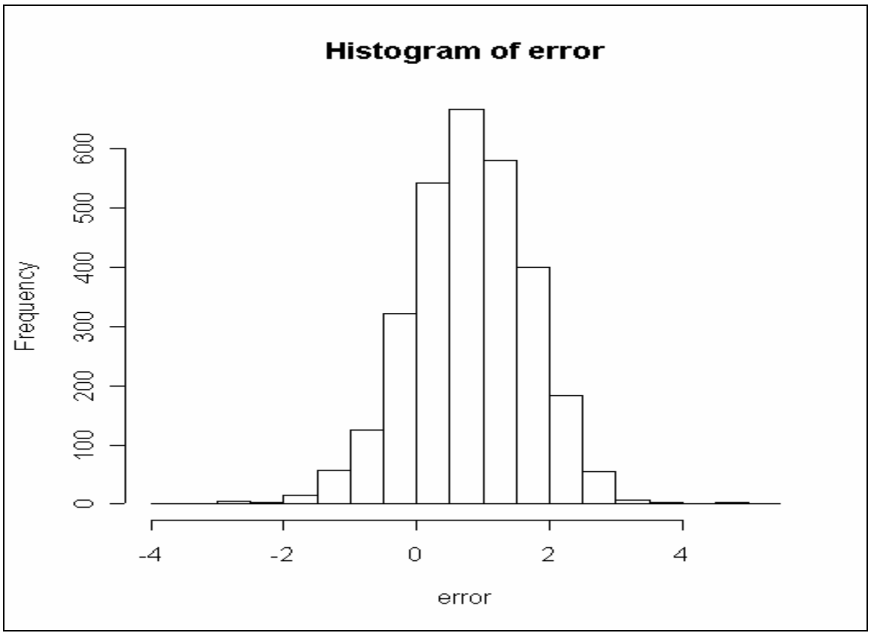


**Figure 9.1 Distribution of measurement with and without measurement error.**

## 9.3 Systematic bias

The rut profile is illustrated in Figure 9.2. Point A is the low point; points B and C are close to it. The effect of measurement error on point A is symmetric while on point B and C it is not. When the elevation of point B is overestimated there would be no effect on the measured rut depth. But when the elevation of B is underestimated, B' will become the new low point and there would be over-measurement of rut depth. There would be under-measurement only when point A is under-measured and neither point B nor C is overestimated. The probability of this happening is certainly less than 0.5, hence in the majority of cases, the rut depth will be overestimated and there is systematic positive bias.

## 9.4 Relationship between rut depth and systematic bias

When the number of sensors is large more sensors would be near the low point A (Figure 9.2), so the probability that points like B will overestimate is greater. Therefore, the systematic bias towards overestimation is greater. On the other hand, when the rut depth is large, it is more likely the profile is steep, the vertical distance between point A and B is greater, and the probability of overestimating the low point is small. The simulation analysis confirmed this argument.

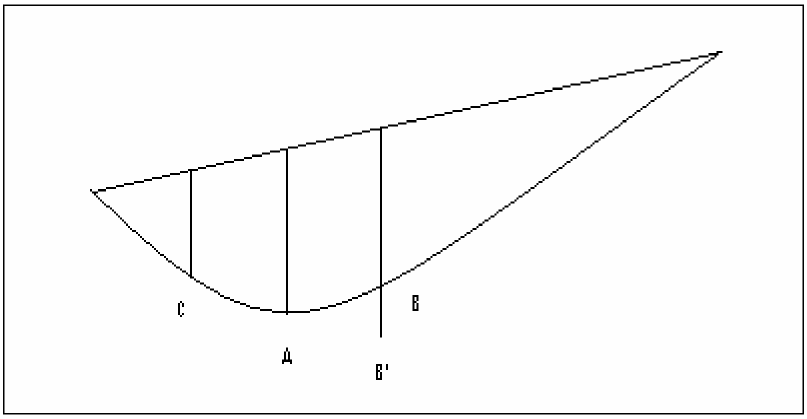


**Figure 9.2 Rut profile.**

The simulation result (error against rut depth) with a 30-sensor profilometer is given in Figure 9.3. The simulation shows that a negative relationship exists between rut depth and the error. The equation parameters (constant and slope) are significantly different from zero. However, the $R^2$ is very small (0.0046) which indicates a very poor correlation between rut depth and measurement error.

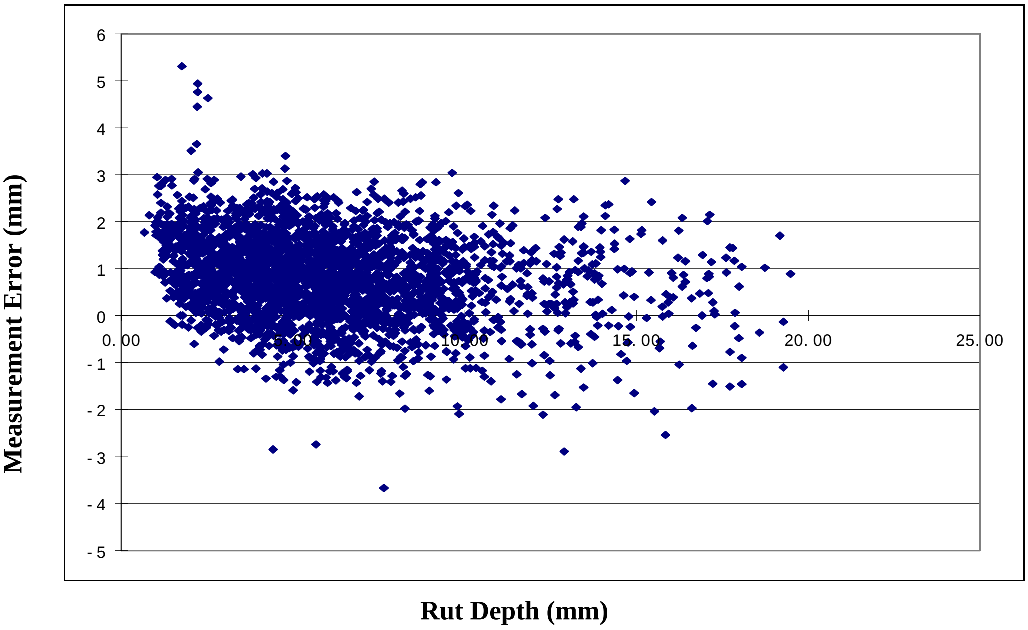


**Figure 9.3** **Relationship between rut depth and the systematic bias.**

## 9.5 Relationship between sensor numbers and systematic bias

Considering the very low relationship between true rut depth and systematic bias, the relationship between number of sensors and systematic bias at different points was investigated. The simulation used equal spacing design. The results (average error against the number of sensors) are given for kerb point, centre point and average of both (kerb and centre) in Figures 9.4, 9.5 and 9.6.

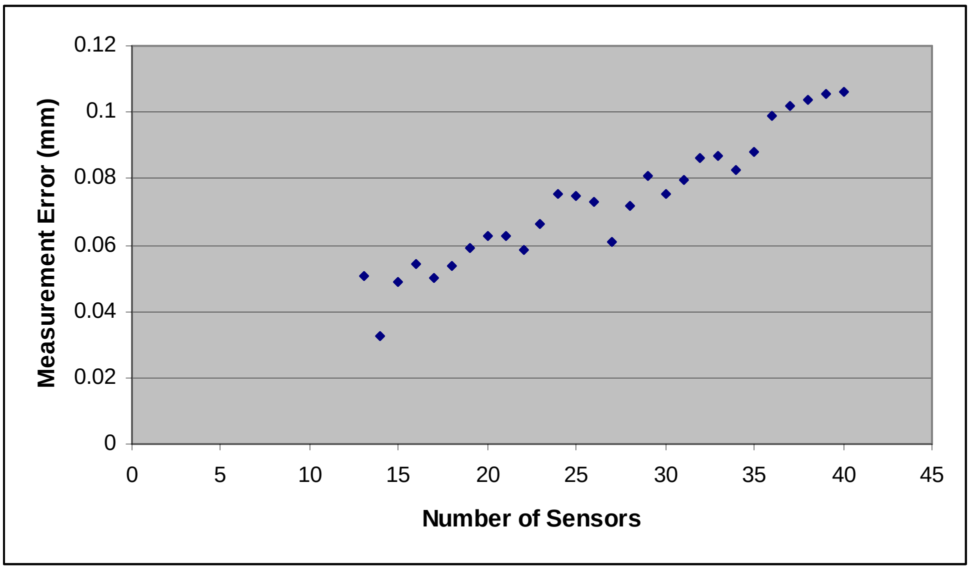


**Figure 9.4** **Relationship between number of sensors and kerb systematic bias.**

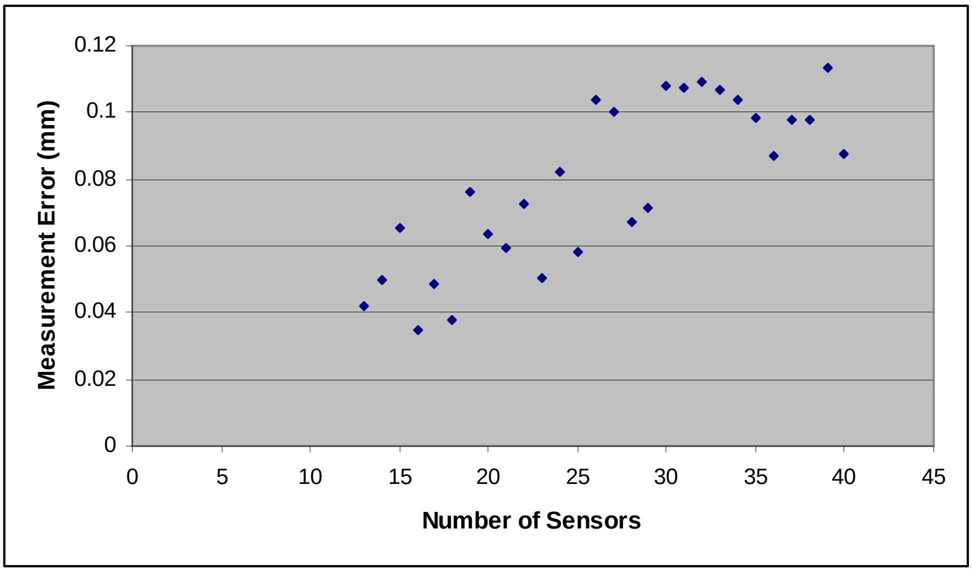


**Figure 9.5 Relationship between number of sensors and centre systematic bias.**

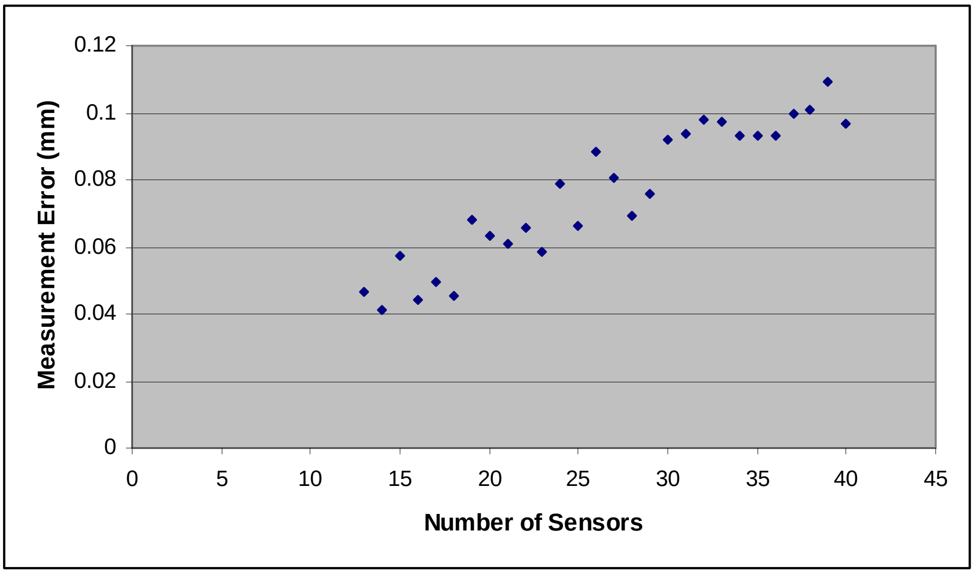


**Figure 9.6 Relationship between number of sensors and average systematic bias.**

The resulting regression equations are given below:

| **Scenario** | **Equation / Error** | **$R^2$** |
|---|---|---|
| Kerb point | E = 0.013 + 0.0023 * N | 0.921 |
| Centre point | E = 0.0145 + 0.0024 * N | 0.648 |
| Both (average) | E = 0.0137 + 0.0023 * N | 0.886 |

The $R^2$ is quite high indicating a strong relationship between the number of sensors and the rut depth.

## 9.6 Implication of analysis

The data collected from the profilometers may not always provide a stable trend. One of the possible reasons for this is the systematic bias in the rut depth measurements. The systematic bias (difference between the true rut depth and measured rut depth) generally tends to overestimate the rut depth. The bias is dependent on two factors:

- Number of sensors – the analysis indicated a strong relationship between the measurement error and number of sensors. The bias increases as the number of sensors increases; hence there is some downside for using a profilometer with a large number of sensors.
- Extent of rut depth – a very weak relationship between measurement error and amount of rut depth as per the analysis undertaken in this study.

It is suggested that the rut depth measurements should be corrected for systematic bias before using the data, particularly in the trend analysis. The HRD software has been enhanced in this stage to offset the systematic bias errors.

# 10. Effects of progressive sampling

## 10.1 Introduction

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.

To avoid sensors interfering with each other, in practice, the sensors of an ultrasonic profilometer are not fired at the same time. For a 30-sensor profilometer, sensors 1, 6, 11, 16, 21, 26 are fired and record the measurement simultaneously. After 25 ms sensor 2, 7, 12, 17, 22, 27 are fired. Since the vehicle has already moved forward during this time, the profilometer is measuring points on different profiles. Therefore, the progressive sampling can potentially introduce extra errors into the measurements.

## 10.2 Methodology

The methodology adopted in this project to analyse the effects of progressive sampling is to treat it as a special case of measurement error. But the variance of the error is different for different sensors. It is assumed that sensors fired at the same time would have the same variance. The variance increases with the time lag between sensors fired from the initial profile created.

## 10.3 Sampling error

The sensors were divided into five groups considering the sensors firing group (as explained above) and assigned a group identifier as 'k'. The 'k' value is zero (k = 0) for sensors 1, 6, 11, 16, 21 and 26. For sensors 2, 7, 12, 17, 22 and 27, the value k=1, and so on.

For sensor i,

$y_i$ denotes the corresponding measurement on the starting profile and

$\hat{y}_i$ denotes the measurement recorded by the profilometer.

When k = 0 (since the profilometer is measuring the starting profile):

$$\hat{y}_i = y_i$$

When k > 0, assume:

$$\hat{y}_i = y_i + a_k + b_{i,k} \quad \text{where } i = 0 \text{ to k}$$

where $a_k$ is the average change of the whole profile compared with the previous one and $b_{i,k}$ is the change of every individual point relative to the average change at sensor *i.* Assume that both $a_i, b_i$ follow AR(1) process[1], that is to say:

$$a_0 = 0, b_0 = 0$$

$$a_k = \beta a_{k-1} + \varepsilon_k$$
$$b_{i,k} = \beta b_{i,k-1} + \nu_{i,k}$$

$$\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$$
$$\nu_i \sim N(0, \sigma_\nu^2)$$

And $\varepsilon_i$ and $\nu_i$ are normally and independently distributed with variance $\sigma_\varepsilon^2$ and $\sigma_\nu^2$. Using the TPB (Transverse Profile Beam) data to estimate β, $o_a^2$ and $o_b^2$, the results are:

$$\beta = -0.42$$

$$o_a = 0.31\,\mathrm{mm}$$

$$o_b = 0.16\,\mathrm{mm}$$

## 10.4 Simulation analysis

The above variance results were used to simulate the effects of progressive sampling. The time difference between firing of two sensor groups is 25ms. Then the distance between firing of different sensors is given by:

D = V*0.025/3.6

Where: D = distance between firing in meters
V = speed of the profilometer in km/h

The simulation result clearly showed that the error caused by progressive sampling is systematic and increases with the speed of the profilometer. Since the progressive sampling can be treated as a special case of measurement error, as discussed earlier in this report, measurement error can cause a systematic positive bias to the measurement. When the speed of the profilometer increases, the distance between the two adjacent profiles increases causing the variance of the measurement error to increase resulting in increased error (bias caused by progressive sampling).

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[1] AR(1) process is jargon from time-series statistics. Process x is an AR(1) process if $x_{t+1} = \beta x_t + \varepsilon_t, -1 < \beta < 1$, where $\varepsilon_t$ is a white-noise process (means there is no trend and pattern in $\varepsilon_t$).

This simulation result is given in Figure 10.1. The relationships between the speed and measurement error caused by progressive sampling are:

$E_k = 0.027 * V, (R^2 = 0.97)$; and,

$E_c = 0.041 * V, (R^2 = 0.97)$

Where:
$E_k$ = Error of kerb rut depth (mm)
$E_c$ = Error of centre rut depth (mm)
V = Survey speed (km/h)

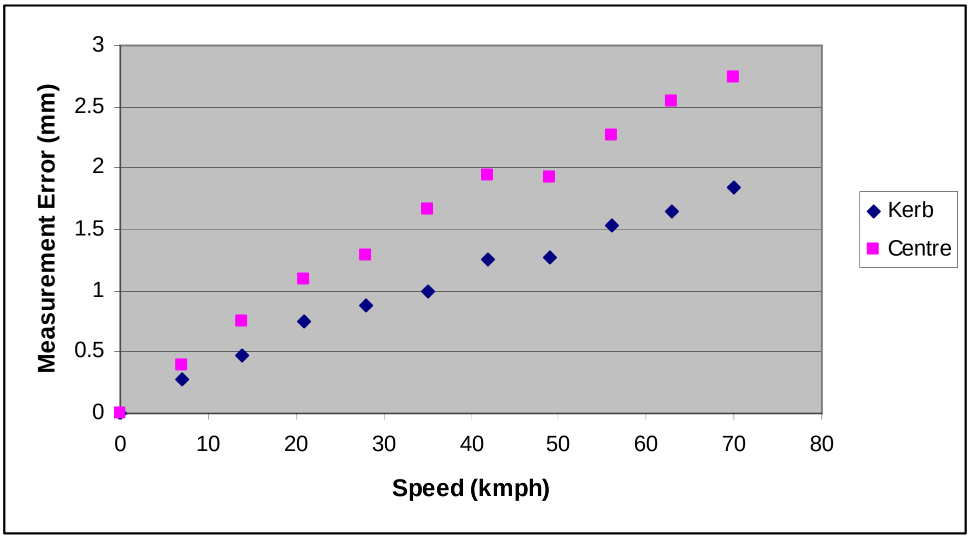

**Figure 10.1 Progressive sampling error.**

## 10.5 Effect of progressive sampling on standard deviation

Progressive sampling has two effects on the standard deviation of rut depths:

- a smoothing of the profiles so the standard deviation should be lower,
- on the other hand, as shown in the report, overestimating rut depths; the standard deviation will be inflated as the estimated rut depth is inflated.

The analysis concluded the following:

- Progressive sampling underestimates the standard deviation of the kerb side rut depths.
- Progressive sampling significantly overestimates the standard deviation of the centre lane side rut depths.

## 10.6 Implication of analysis

The analysis indicated that the progressive sampling will introduce positive errors in the measurement similar to systematic bias. The effect of the progressive sampling is dependent on the speed of the profilometer and directly proportional to the speed.

HTC (2000) reported a systematic bias of 3mm when comparing manual measurements (by 2-m straight-edge) with 30-sensor ultrasonic profilometer measurements. This bias also included the inability to record the correct rut depth by manual measurements. The error was also found to be inversely correlated to the measured rut depth. At low rut depths, the error was large.

Overall, progressive sampling will introduce a positive error and the error is dependent on the speed of the vehicle and rut depth. In most cases, the error is less than 3 mm. The ultrasonic measurements can be corrected before using the data, particularly in trend analysis.

Progressive sampling underestimates the standard deviation of the kerb-side while significantly overestimating the standard deviation of the centre lane-side rut depths. Overall, progressive sampling creates a positive error in the standard deviation.

Please note the discussions and results presented in this report are based on a limited data sample collected for this research. More field surveys are recommended to support the results.

# 11. Conclusions

Stage I of the Harmonisation of Automated Rut Depth Measurements project (Bennett & Wang 2003) has shown that it is possible to harmonise the measurements of different rut depth profilometers while Stage II focused on further understanding of key areas with regard to rut depth measurements.

## 11.1 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.

## 11.2 Sampling

Rut depth profilometers sample the transverse profile at discrete points across the profile. In New Zealand, 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),
- 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 to 4 mm.

## 11.3 Rut depth transfer functions

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

| Kerb side | Centre lane side | Profilometer |
|---|---|---|
| RD = 1.54 + 0.97 MEAS | RD = 2.22 + 0.88 MEAS | MWH 30-sensor[1] |
| RD = 2.44 + 0.98 MEAS | RD = 3.05 + 0.80 MEAS | WDM 16-sensor |
| RD = 2.09 + 0.96 MEAS | RD = 3.56 + 0.64 MEAS | PMS 15-sensor |
| RD = 2.39 + 0.96 MEAS | RD = 3.20 + 0.77 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

note 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.

## 11.4 Impact of lateral placements

During a profilometer survey it is impossible to ensure that the vehicle is in the same wheelpath as that used during the previous year’s survey. The HRD software treats lateral placement as a random variable that is 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 an improvement in the accuracy was recorded for the kerb measurements. This was because of the configuration of the profilometer where the number of measurements near the kerb was insufficient.

When a profilometer travels down a lane, it is possible that the kerb sensor will record outside the pavement. All manufacturers include algorithms which check for this and exclude measurements which violate certain rules that identify them as falling outside 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 very substantial, which can exceed any changes in rut depths between years caused by pavement deterioration. This perhaps explains the difficulties encountered when trying to use profilometer rut depth data for monitoring pavement deterioration trends in that there is insufficient accuracy to isolate pavement deterioration from measurement effects.

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[1] Note 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.

## 11.5 Optimal design

The profilometers used to measure rut depth may not always measure the high and low points accurately because of their fixed design and varying critical points. The simulation analysis (between optimal design and equal spacing design) showed that the measurement error could be up to 15% depending on the design of the profilometer. The measurement accuracy can be increased significantly by rearranging the sensors in a profilometer. The increase in accuracy is mainly with the kerb measurements while the accuracy of the centre measurements essentially remains the same. The gain in accuracy is more significant when the number of sensors is in the range of 10 to 16. As the number of sensors increases, the gain from any rearrangement diminishes. The measurements can be corrected before trend analysis.

## 11.6 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 simulation analysis was undertaken in this project to estimate the measurement error.

The measurement error is not negligible and also not symmetric. Generally the error is positive (tending to overestimate the rut depth rather than underestimate). The error is more dependent on the number of sensors than the amount of rut depth. The measurement error can be estimated by:

Kerbside rutE = 0.013 + 0.0023 * N
Centre-lane side rutE = 0.0145 + 0.0024 * N
Mean lane rutE = 0.0137 + 0.0023 * N

Where: E = measurement error in mm
N = number of sensors.

The HRD software has been enhanced to offset the measurement errors.

## 11.7 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 progressive sampling error is systematic and increases with the speed of the profilometer (vehicle) and decreases with the amount of rut depth. The progressive sampling error of ultrasonic profilometers can be estimated by (without the effect of rut depth):

$$E_k = 0.027 * V; \quad R^2 = 0.97$$

$$E_c = 0.041 * V; \quad R^2 = 0.97$$

Where: $E_k$ = Error of kerb rut depth (mm)

$E_c$ = Error of centre rut depth (mm)

V = Survey speed (km/h)

In most cases the error is less than 3 mm.

# 12. References

Bennett, C.R. 1998. Evaluation of a transverse profile logger. *Proceedings 4th International Conference on Managing Pavements*, Durban. *www.htc.co.nz*

Bennett, C.R. 2001. Evaluating the quality of road survey data. *Transfund Research Report No. 200.*

Bennett, C.R., Paterson, W.D.O. 1999. Guidelines on calibration and adaptation. *HDM-4 Reference Manual Volume 4*. PIARC, Paris.

Bennett, C.R., Wang, H. 2003. Harmonising automated rut depth measurements. *Transfund New Zealand research report No. 242*

Cenek, P.D., Patrick, J.E., McGuire, J.F., Robertson, D.A. 1994. New Zealand experience in comparing manual and automatic pavement condition. *Proceedings 3rd International Conference on Managing Pavements, San Antonio 2:* 265-278.

Data Collection Ltd (DCL). 1996. Accuracy of ROMDAS ultrasonic measurement system. *Technical Memo ST2. Data Collection Ltd*, Auckland *www.ROMDAS.com.*

Hadley, W.O., Myers, M.G. 1991. Rut depth estimates developed from cross profile data. *SHRP Long Term Pavement Performance Program Technical Memo AU-179*, Texas Research and Development Foundation, Austin.

HTC 2000. Validation of ROMDAS transverse profile logger. Internal Paper, HTC Infrastructure Management Limited, Auckland *http://www.romdas.com/romdascd/info/working/f003-1.pdf*)

HTC 2001a. Equipment calibration and validation. *Contract SM3-688/P6/10 Report to Transit New Zealand.* HTC Infrastructure Management Ltd, Auckland.

HTC 2001b. Validation of ROMDAS transverse profile logger. *Internal Report F003/1*. HTC Infrastructure Management Ltd, Auckland *www.ROMDAS.com*

Simpson, A. 2001. Characterization of transverse profiles. *Publication FHWA-RD-01-024*. Federal Highways Administration, McLean, VA. *http://www.tfhrc.gov///pavement/ltpp/pdf/01-024a.pdf*

Transfund 1997. *RAMM road condition rating and roughness manual.* Transfund New Zealand, Wellington.

Willett, M., Magnusson, G., Ferre, B. 2000. Theoretical study of indices. *FEHRL Investigation on Longitudinal and Transverse Evenness of Roads—Concluding Workshop.* Nantes.

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