Using profile variance to identify sites that promote poor truck ride quality

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The material contained in this report is the output of research and should not be construed in any way as policy adopted by the NZ Transport Agency but may be used in the formulation of future policy.

ADDITIONAL NOTE

The NZ Transport Agency (NZTA) was formally established on 1 August 2008, combining the functions and expertise of Land Transport NZ and Transit New Zealand.

The new organisation will provide an integrated approach to transport planning, funding and delivery.

This research report was prepared prior to the establishment of the NZTA and may refer to Land Transport NZ and Transit.

Acknowledgements

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Abbreviations and acronyms

GIS	Geographical information system
GPS	Global positioning system
IRI	International Roughness Index
NAASRA	National Association of Australia State Road Authorities
RAMM	Road asset maintenance management
RP	Route position
TRACS	Traffic Speed Condition Surveys (United Kingdom)
Transit NZ	Transit New Zealand
TRI	Truck ride indicator

Contents

Executive summary

This study was undertaken to develop a more reliable methodology, based on road profile variance, for identifying and prioritising for treatment, road sections that promote poor ride quality for heavy commercial vehicles. Profile variance is a measure of the difference between the actual road profile and its moving average over selected moving average lengths.

The research was based around a comparison of measured on-road truck response data on parts of the state highway network with calculated road profile variance data and available roughness and geometry data from Transit NZ’s road asset maintenance management (RAMM) database.

In November 2004, an instrumented articulated truck was used to survey selected sections of the state highway network in the lower North Island. The aim was to provide baseline truck response data from accelerometers and gyroscopes, and records of driver concerns about safety and ride quality, so that these could be compared with Transit NZ’s existing criteria for selection of potential truck ride improvement sites.

Existing roughness and geometry data for the road sections surveyed with the instrumented truck was extracted from the RAMM database. Road profile variance data for the same road sections was processed from the raw road profile data collected as part of the annual state highway network survey. It was processed to provide 10 m and 100 m values of profile variance for short (3 m), medium (10 m) and long (30 m) wavelengths.

Using global positioning system (GPS) data from the instrumented truck and GPS data provided for Transit NZ’s state highway route position markers, the truck response data, the RAMM roughness and geometry data, and the road profile variance data were spatially matched to provide combined datasets for each of the surveyed road sections.

The profile variance data was compared with the measured truck response data to investigate relationships between them and to establish threshold criteria for short, medium and long wavelength content. The RAMM roughness and geometry data were used to modify these relationships in situations where the longer wavelength profile variance data is affected by geometry factors, ie gradient, curvature and crossfall.

The selection and prioritisation process for sites that promote poor truck ride quality is described below and is followed by recommendations for further work:

Calculate:

- longitudinal wheelpath profile variance for 30 m, 10 m and 30 m wavelengths

Retain:

- road sections with profile variance exceeding 10 mm^2 for 3 m wavelengths, 56 mm^2 for 10 m wavelengths and 300 mm^2 for 30 m wavelengths.

Discard:

- RAMM designated 'urban' road sections
- road sections exceeding any of the wavelength threshold criteria and which are less than 30–40 m long
- road section with horizontal curvature less than 200 m
- road sections with consistent crossfalls larger than +/-10%
- road sections with consistent gradients greater than +/-10%
- road sections with travel speeds less than 65 km/h (18m/s).

Flag:

- road sections exceeding any of the wavelength threshold criteria and which are 50–100 m long, as maintenance responsibilities.

Retaining remaining sections – prioritise in terms of:

- continuous lengths of over 50 m that exceed the 10 m or 30 m thresholds
- clusters where the 10 m or 30 m thresholds are exceeded in either or both wheelpaths. Clusters can be non-continuous or overlapping lengths. Separation should not exceed 20–30 m
- threshold exceedance across all three wavelengths
- levels of Transit NZ truck ride indicator (TRI), which is based on average and inter-wheelpath National Association of Australia State Road Authorities (NAASRA) roughness.

Note:

- profile variance values, particularly for 30 m wavelengths, can be significantly affected by road geometry. Extremely high values in 'tortuous' terrain over the following levels should be treated with caution:
  - profile variance exceeding 30 mm^2 for 3 m wavelengths
  - profile variance exceeding 400 mm^2 for 10 m wavelengths
  - profile variance exceeding 5000 mm^2 for 30 m wavelengths.

Recommendations:

- The potential sites selected in 2008 for truck ride improvement works according to Transit NZ's current selection criteria (TRI), which are predominantly based on differences in lane NAASRA roughness, should be assessed according to the criteria established here for profile variance. The trucking industry should be also approached to identify whether any of the potential sites represent safety issues.
- Development of a truck speed model should be considered. Apart from differences in suspension characteristics and vehicle loading, speed is the primary vehicle based determinant of response to road surface undulations.

- Variations in the profile variance with time should be investigated, as at the time of publication of this report there should be three years of profile variance data available. Significant changes with time can be indicative of potential problems, eg high and increasing levels of 3 m wavelength variance can indicate serious wheelpath cracking or other faulting.
- The effects of treatment of truck ride sites should be investigated by looking at the profile variance data in the year following treatment. As a database of treated sites is built up, different treatments could be rated according to their effects on reducing profile variance levels.
- Investigation of the enhanced profile variance for 3 m and 10 m wavelengths should be considered to assess whether it removes or significantly reduces the effects of road geometry on the calculation of profile variance.

Abstract

The relationships between measured truck response data and road profile variance values derived from raw road profiles for short, long and medium wavelengths were examined. Profile variance is a measure of the difference between the actual road profile and its moving average over selected moving average lengths. The effects of geometry and roughness were also investigated, particularly the effects of geometry, curvature and crossfall on the calculation of the profile variance data. Relationships derived from this study were used to generate a methodology for interpreting profile variance data in New Zealand conditions and to establish threshold levels for wavelength content, so that potential sites for truck ride improvement works can be selected and prioritised.

1. Introduction

This research project was concerned with developing a more reliable and robust methodology for identifying, and prioritising for treatment, road sections that exhibit poor ride quality for heavy commercial vehicles. The methodology was based on wavelength analysis of the road profiles.

It is expected that this research will be relevant to management of the state highway network by Transit NZ and their local network managers. It arose from a need to be able to reliably and efficiently select road sections for remediation, to assess whether a treatment is successful, and to select the most appropriate treatment for each particular section.

1.1 Background

When roads are constructed or maintained, the general intention is to make them as smooth as possible. However, this is not always achieved, because while roughness may be managed, profile is not normally targeted. There will often be differences between the desired smooth road surface and what is built. The resulting undulations in the surface profile or 'road roughness' can be described by their amplitude, or by their wavelength, if related to vehicle speed. Typically, for pavement wavelengths of around 0.3 m or less, the effects of any undulations in the road profile are absorbed by a vehicle's tyres. At most normal road travel speeds wavelengths of 50 m or more do not have any significant effect on vehicle response. It is therefore generally accepted that the important range of wavelengths lies between around 0.5 and 50 m.

These road surface undulations are regarded as one of the most important characteristics of road surfaces, particularly for trucks. They can have a significant effect on how well roads function for all types of vehicles. There are potential significant effects on fuel consumption, tyre and vehicle wear, damage to goods, pavement deterioration, noise, and ride quality. However, undulations of different wavelengths tend to affect vehicles in different ways. Cars and other shorter wheelbase vehicles tend to be affected by shorter wavelengths while long wheelbase trucks tend to be affected by a range of wavelengths, including the longer ones.

The effects of undulations in the road surface can be transferred, or magnified, through a truck's tyres and suspension, to impact on the truck driver. This can result in a very rough or uncomfortable ride, with serious consequences in terms of discomfort, fatigue, vehicle wear and tear, and potential damage to freight. In New Zealand a significant proportion of the freight is carried by heavy commercial vehicles, and the drivers of these vehicles travel long distances for long periods, often travelling the same route on a regular basis. Consequently, they know the sections of road that cause them concern, and reports on such sections are fed back through trucking industry organisations to Transit NZ.

1.2 Need for research

In response to industry needs Transit NZ developed an initiative to tackle the issue of truck ride quality by targeting spending on specific sections of the state highway network. It has spent around $11 million over the past four to five years, which means that selection and prioritisation of potential sites for remediation is very important to make best use of the available funding. However, in the past this has been based on roughness and geometry data contained in Transit NZ's RAMM database, and the level of commercial vehicle traffic. This does not provide any information on the wavelength characteristics of the surface, particularly the long wavelengths that impact more severely on heavy commercial vehicles.

To provide a more reliable and efficient way of selecting and prioritising sites for smoothing, Transit NZ has two practical options (1) instrument a truck and measure the ride quality of the entire network, or (2) process the road profile data that it already collects as part of the annual network survey in such a way as to provide information on the wavelength content. The latter option is the most viable as it does not depend on the response of one particular vehicle that may not be characteristic of the truck fleet, and it also makes more efficient use of data that is being collected anyway on a regular basis.

The profile variance method allows the wavelength content to be determined. It quantifies the level of variation of the road profile from a moving average of the profile over different lengths corresponding to different wavelengths. It is routinely used in the United Kingdom, where wavelengths of 3 m 10 m and 30 m are used (UK Roads Board 2003). High levels of 3 m variance typically arise from short wavelength features such as seal changes, bridge abutments, faulting, potholes and poor reinstatements. Extremely high levels of 3 m variance may be linked with the presence of severe wheelpath cracking. The 10 m variance is often influenced by short undulations, possibly arising from different rates of pavement settlement, or localised subsidence of reinstatements and subsurface utilities. High levels of 30 m variance will have more influence on the user's perception of ride quality, particularly that of truck drivers.

In New Zealand, as elsewhere, the major issue with using the 30m variance is that it covers such a length of the pavement that it can be influenced by the road geometry, either by gradient, crossfall or curvature. Accordingly, we need to understand how to use it in such situations before it can be employed to establish threshold levels for poor ride quality, and rank those road sections that exceed these thresholds.

1.3 Objectives

The objectives of the research programme were to:

- generate a combined database comprising of spatially matched (a) measured truck response data, (b) profile variance data, and (c) geometry and roughness data, for selected sections of the state highway network

- process the measured truck ride response data and RAMM roughness and geometry data to provide data based on a 100 m averaging length
- investigate the relationships between the measured truck response and profile variance data, with consideration of the modifying effects of geometry
- develop a methodology for selecting and prioritising truck ride sites using profile variance as a foundation
- assess threshold values of profile variance under New Zealand conditions.

The primary goal was to provide a more reliable means of selecting and prioritising for treatment, road sections that promote poor ride quality for heavy commercial vehicles.

1.4 Scope of the report

This report presents the results of a study comparing measured truck response data with road profile variance data and roughness and geometry data. Chapter 2 discusses road profile variance, including definitions and the threshold values used in the United Kingdom. Chapter 3 describes the measured truck response data and the process of spatially matching this with the profile variance data and the RAMM roughness and geometry data. Examples are also presented. In Chapter 4, the analysis of the data is discussed, including relationships between the measured truck response data, the profile variance data, and the geometry and roughness data. The proposed methodology for selecting and prioritising truck ride improvement sites is developed in Chapter 5. Finally, conclusions and recommendations drawn from the research are given in Chapter 6.

2. Road profile variance

2.1 Background and definition

Longitudinal road profile data is recorded during Transit NZ's annual survey of the state highway network. This is processed to provide a large number of variables that are currently included in Transit NZ's RAMM database. However, to obtain information on the wavelength content of the profile it is necessary to carry out further processing of the road profile data. In particular, to evaluate the effects of unevenness in the road profile on the ride quality of vehicles we need to examine the variation associated with the range of wavelengths in the road profile that can interact with the suspension of the vehicle. One convenient way to do this is to consider the differences between the profile and its moving average over selected moving average lengths.

In the United Kingdom three averaging lengths are used, ie 3 m, 10 m and 30 m. Accordingly, the road profile data is processed to compare the actual profile and the moving average of the profile over these three lengths. The results are presented in terms of the square of the difference between the moving average of the profile and the measured profile. They are reported as the 3 m, 10 m and 30 m longitudinal profile variance and expressed as averages over 10 m lengths. The concept of profile variance is shown graphically in Figure 2.1 and the methodology for calculating profile variance is given in Appendix A.

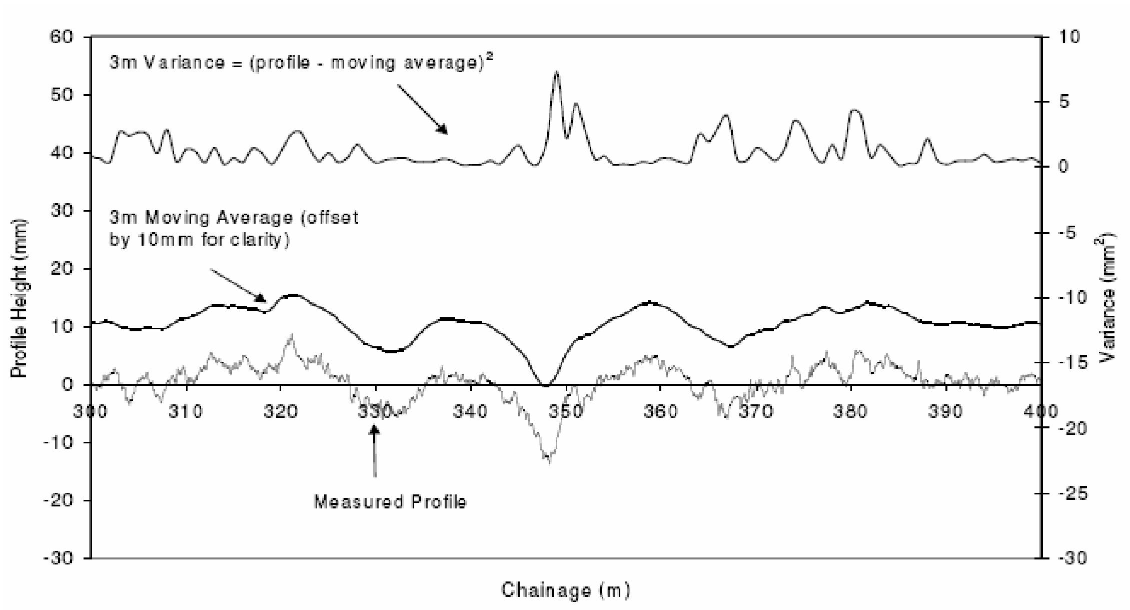


Figure 2.1. The measured profile and profile variance.

2.2 Threshold values

In the United Kingdom there are four condition categories defined by threshold criteria that apply to the data measured by the highway survey vehicles (TRACS-type surveys). These categories, which are based on characteristic values associated with 100 m lengths, are:

- sound – no visible deterioration
- some deterioration – low level of concern (no action unless long lengths are affected)
- moderate deterioration – warning level of concern (investigate)
- severe deterioration – intervention level of concern (action required).

We are interested in determining whether the threshold criteria between categories 3 and 4 used in the United Kingdom are applicable in New Zealand, or if not, what criteria are appropriate. The threshold longitudinal profile variance values for urban dual carriageway and rural single carriageway roads are listed in Table 2.1. It is important to also note here that according to the UK Roads Board (2003) advice note, consideration of profile variance should generally be limited to relatively straight, predominantly high-speed roads and that variations in geometry can affect the calculation of profile variance.

Table 2.1. Profile variance threshold values for 100 m lengths – United Kingdom (UK Roads Board 2003).

(urban dual carriageway and rural single carriageway roads)

Wavelength (m)	Profile variance (mm^2)
3	10
10	56
30	300

A new UK Roads Board (2005) interim advice note received after provision of the profile variance data by WDM Ltd indicated that for the assessment of ride quality the **moving average longitudinal profile variance** was to be replaced by the **enhanced longitudinal profile variance**. This was intended to reduce or remove the contribution of the underlying road geometry to the variance calculations. The new methodology used in the United Kingdom uses sophisticated filters to reduce the occurrences of falsely high levels of variance that can be associated with significant changes in geometry. These filters could not be applied to the data already provided. Accordingly, the profile variance thresholds listed in Table 2.1 are appropriate here.

3. Description and spatial matching of data

3.1 Measured truck response data

In November 2004 an instrumented articulated truck was driven over a number of selected road sections in the lower half of the North Island to provide baseline truck response data and corresponding records of driver concerns about ride quality and safety (Jamieson 2005). This was to provide data to compare with truck response criteria summarised in Jamieson and Cenek (2001) and with Transit NZ's existing truck ride criteria. The truck, which was partially loaded, is shown in Figure 3.1.

Figure 3.1 The instrumented truck used for the survey.

The truck was instrumented with three orthogonal gyroscopes to measure pitch roll and yaw, as shown in Figure 3.2, and three accelerometers to measure longitudinal, lateral and vertical accelerations. It was also instrumented to measure vehicle speed and GPS positional data. An event marker was used to record route position (RP) markers, and sections considered by the driver as raising ride quality or safety concerns. Data was recorded using a PC-based data acquisition system.

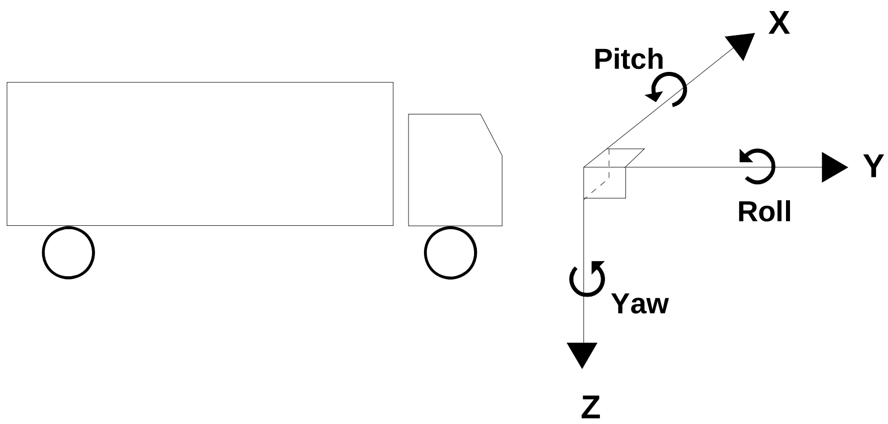


Figure 3.2 Coordinate system for truck ride instrumentation.

Testing was carried out on selected test sections in the lower North Island, as shown in Appendix B. These were chosen to cover a wide variety of roughness conditions, but also included sections previously identified as being of concern to the trucking industry, and sections identified as potential truck ride improvement sites under Transit NZ's current criteria. The vehicle was driven over the selected road sections at speeds consistent with road, traffic and weather conditions. The driver was also asked to flag sections of road that raised concerns about ride quality or safety.

The recorded data was processed to provide rate of rotation (pitch, roll and yaw), accelerations (x, y and z), speed, distance and GPS coordinates. Block and moving averages were also calculated based on an averaging distance of 100 m. Standard deviations of the gyroscope and accelerometer data were calculated. For each 100 m average, the vector sum of the pitch and roll standard deviations was calculated. This is referred to as the 'discomfort factor', or **df**, and is described in Jamieson and Cenek (2001). This earlier research also developed a threshold criteria for poor ride quality in terms of the calculated **df** of ≥4.25 deg/s. Accordingly, the truck ride survey of the lower North Island provided a database of measured truck response data referenced to both the state highway route position markers and GPS co-ordinates.

3.2 Profile variance, RAMM roughness and geometry data

Values of the 3 m, 10 m and 30 m profile variance data for each wheel path for the road sections surveyed by the instrumented truck were calculated by WDM Ltd, the company that carries out the annual survey of the state highway network. These were referenced to Transit NZ route position makers and reference stations. Values for 10 m and 100 m lengths were provided.

Roughness (International Roughness Index ((IRI)) and National Association of Australian State Roading Authorities (NAASRA)) and geometry (gradient, curvature and crossfall) data for the corresponding road sections were also extracted from the RAMM database. Transit NZ provided geographical information system (GIS) data for all its New Zealand reference stations.

3.3 Spatial matching – truck response, profile variance and RAMM data

Transit NZ's reference station GIS data and the GIS data for the event marked locations of the reference stations from the measured truck data was compared to identify appropriate start and end points of each road section that had been surveyed. Figure 3.3 shows a plot of the truck measured GIS data for one of the surveyed road sections, together with the Transit NZ reference stations. Typically, the start and end locations of the reference stations varied by around 10 m or less.

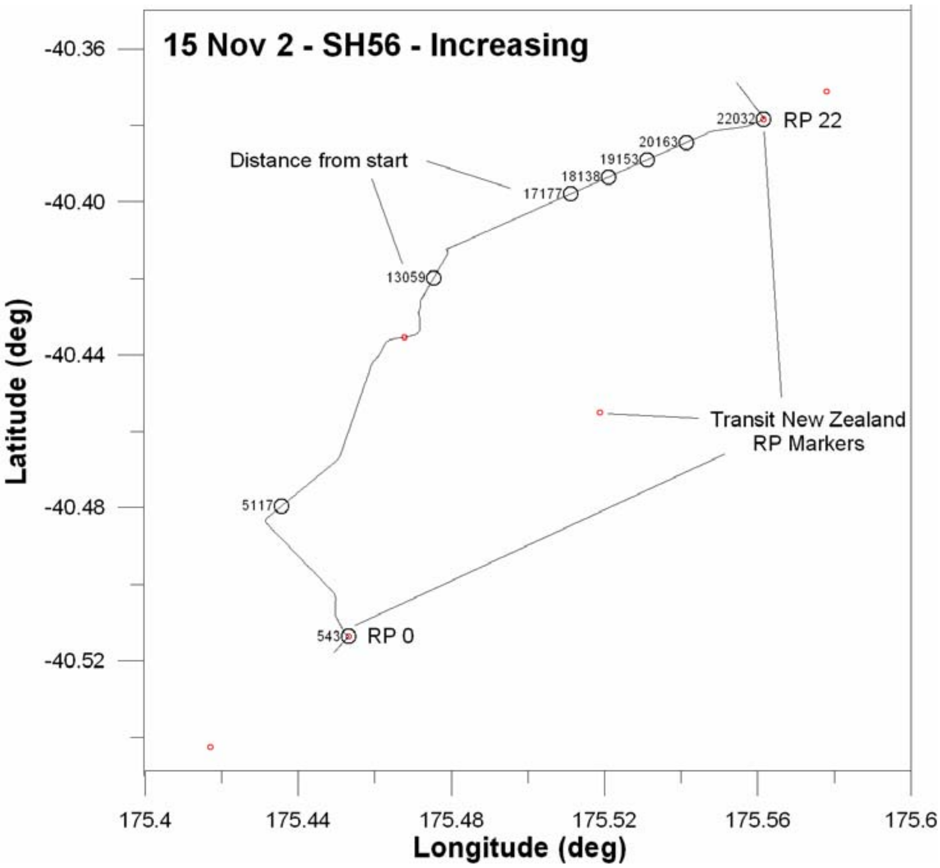


Figure 3.3 Comparison of measured and Transit NZ reference stations.

Having confirmed the start and end points for each location in terms of the measured and reference GIS data, and having also compared the measured distance of each section with the distances specified by RAMM, software routines were written to 'rubberband' the RAMM roughness and geometry data, the profile variance data and the measured truck response data. As a check on the accuracy of the 'rubberbanding', plots were made for each road section of (a) the average measured truck yaw data against 1/curvature and (b) the measured truck distance data against the rubberbanded RAMM distance data. Figures 3.4 and 3.5 show examples from the same surveyed test section for which the GIS data is shown in Figure 3.3.

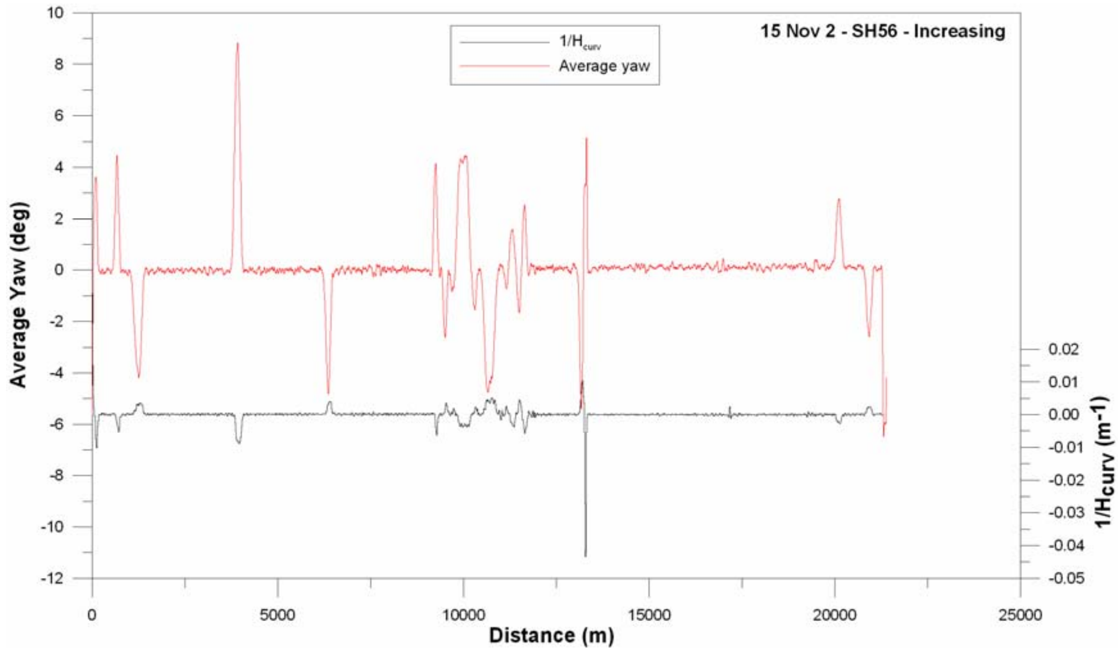


Figure 3.4 Comparison of truck yaw data and RAMM curvature data.

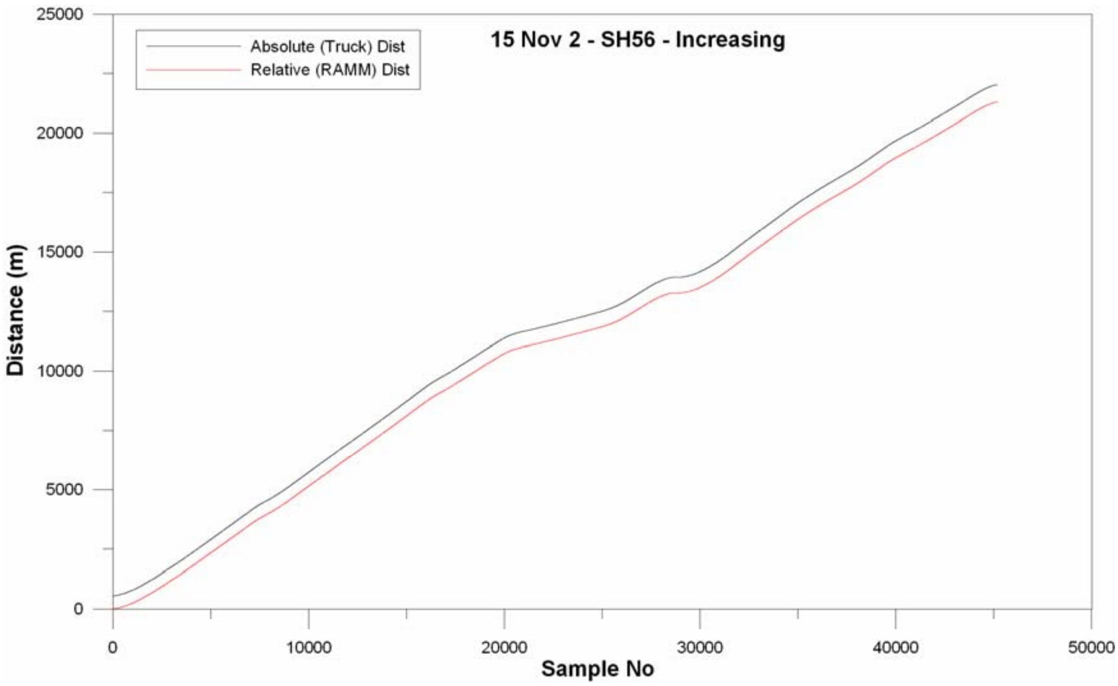


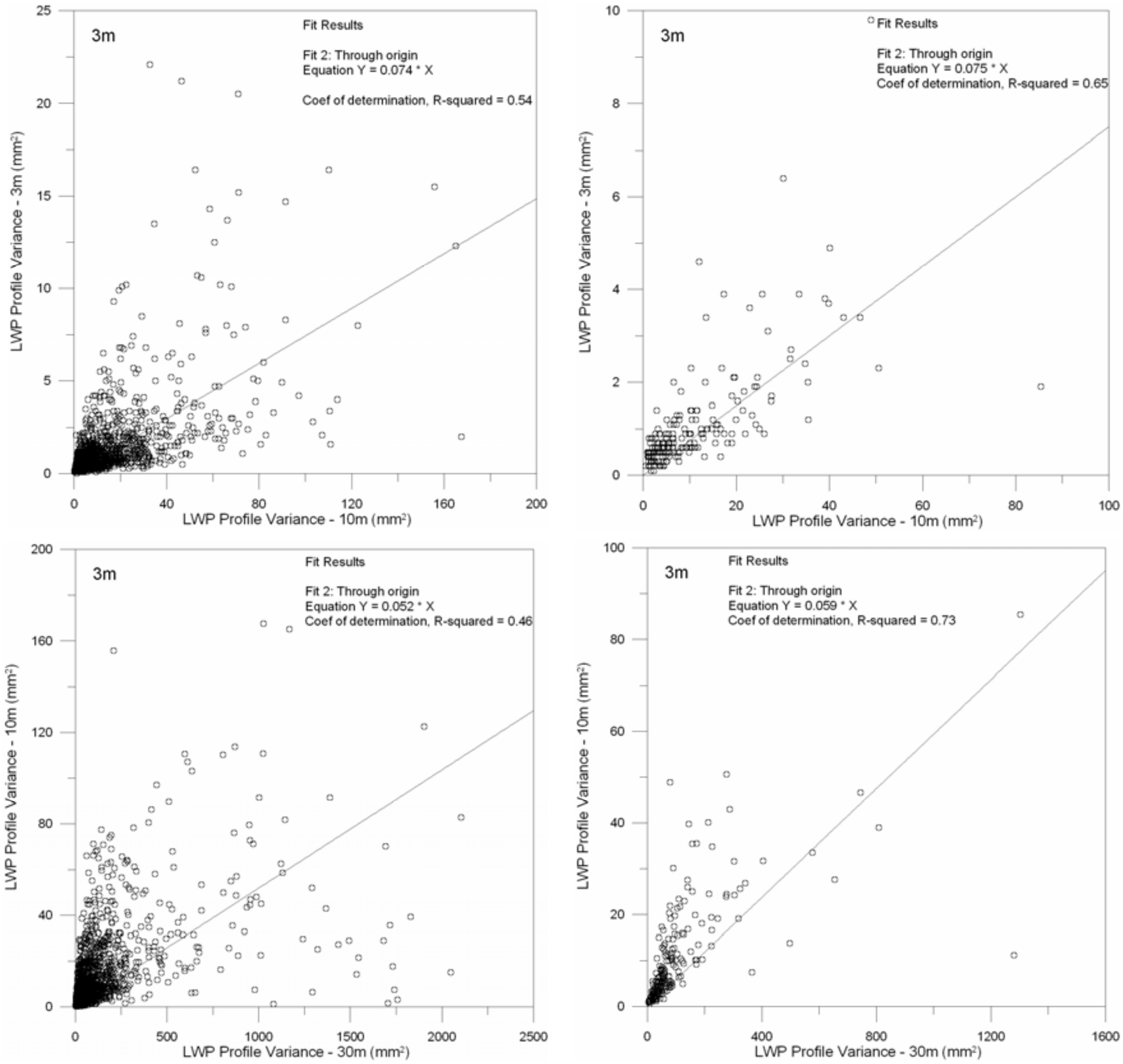
Figure 3.5. Comparison of rubberbanded measured and RAMM distance data
(offset represents difference between start of survey and RP marker)

Note that the measured distance shown in Figure 3.5 starts at 543 m, as shown in Figure 3.3, because sampling was started prior to the route position marker. The RAMM data starts from zero at the route position maker. Figures 3.3, 3.4 and 3.5 show that the measured truck data has been spatially well matched with the profile variance and roughness and geometry data. Variations are expected to be of the order of 10–20 m at times through the test sections.

4. Data analysis

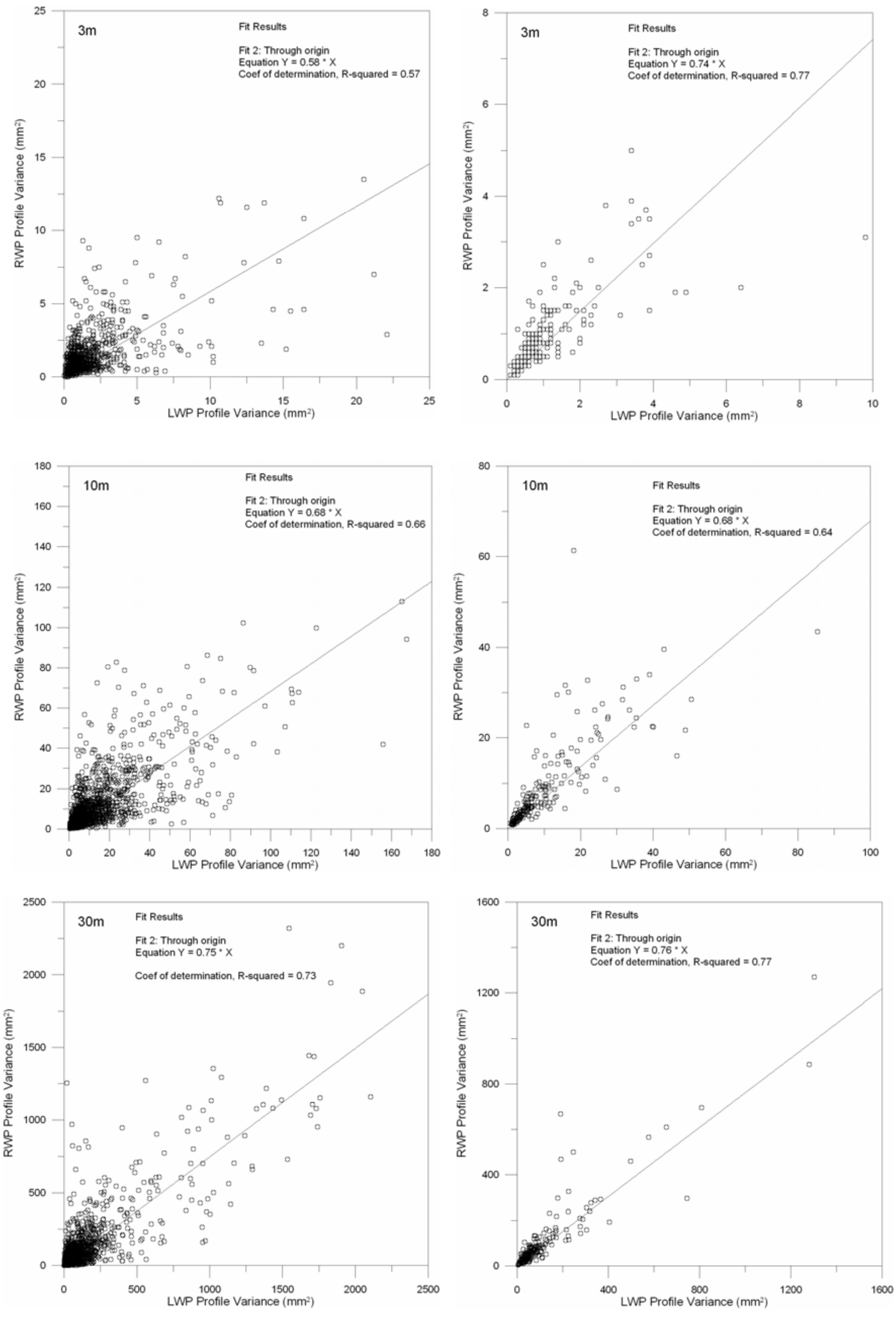
4.1 Distribution of profile variance data and comparison with United Kingdom criteria

Before discussing the comparative analysis of the truck ride response and profile variance data it was considered useful to assess the profile variance data, firstly by comparing the 3 m, 10 m and 30 m variance data for a typical road section, secondly by comparing the left and right wheelpath data for the same typical road section, and thirdly by assessing the distribution of road profile variance data against the threshold criteria from the United Kingdom. Accordingly, Figure 4.1 compares the 3 m and 10 m profile variance, and the 10 m and 30 m profile variance for a typical road section. Figure 4.2 compares the left and right wheelpath 3 m, 10 m and 30 m profile variance for both the 10 m and 100 m lengths.



(a) 10m lengths (b) 100 m lengths

Figure 4.1 Comparison of 3 m, 10 m and 30 m profile variance.



(a) 10 m lengths (b) 100 m lengths

Figure 4.2 Comparison of left wheelpath and right wheelpath profile variance.

Figures 4.1 and 4.2 show that there is considerable scatter in all three of the wavelength classes for both 10 m and 100 m lengths, and that high values of one wavelength do not necessarily mean that values for either one or both of the other two wavelengths will also be high.

Figures 4.3 and 4.4 show frequency distributions of the 3 m, 10 m and 30 m left wheelpath profile variance data for two of the surveyed road sections. One of these is the same road section as illustrated in Figures 3.3, 3.4 and 3.5. This section did not produce any 100 m average discomfort factor (**df**) values above the 4.25 deg/s threshold for poor truck ride (Jamieson and Cenek 2001). The second road section produced the highest 100 m average discomfort factor (**df**) value measured during the survey, this being 6.2 deg/s. Also included on these histogram plots are the corresponding threshold criteria used in the United Kingdom.

Looking across the entire profile variance database for the surveyed road sections the ranges of profile variance values for the three wavelengths were as follows:

3 m wavelength	0 mm^2 to 120 mm^2
10 m wavelength	0 mm^2 to 7000 mm^2
30 m wavelength	0 mm^2 to 250,000 mm^2

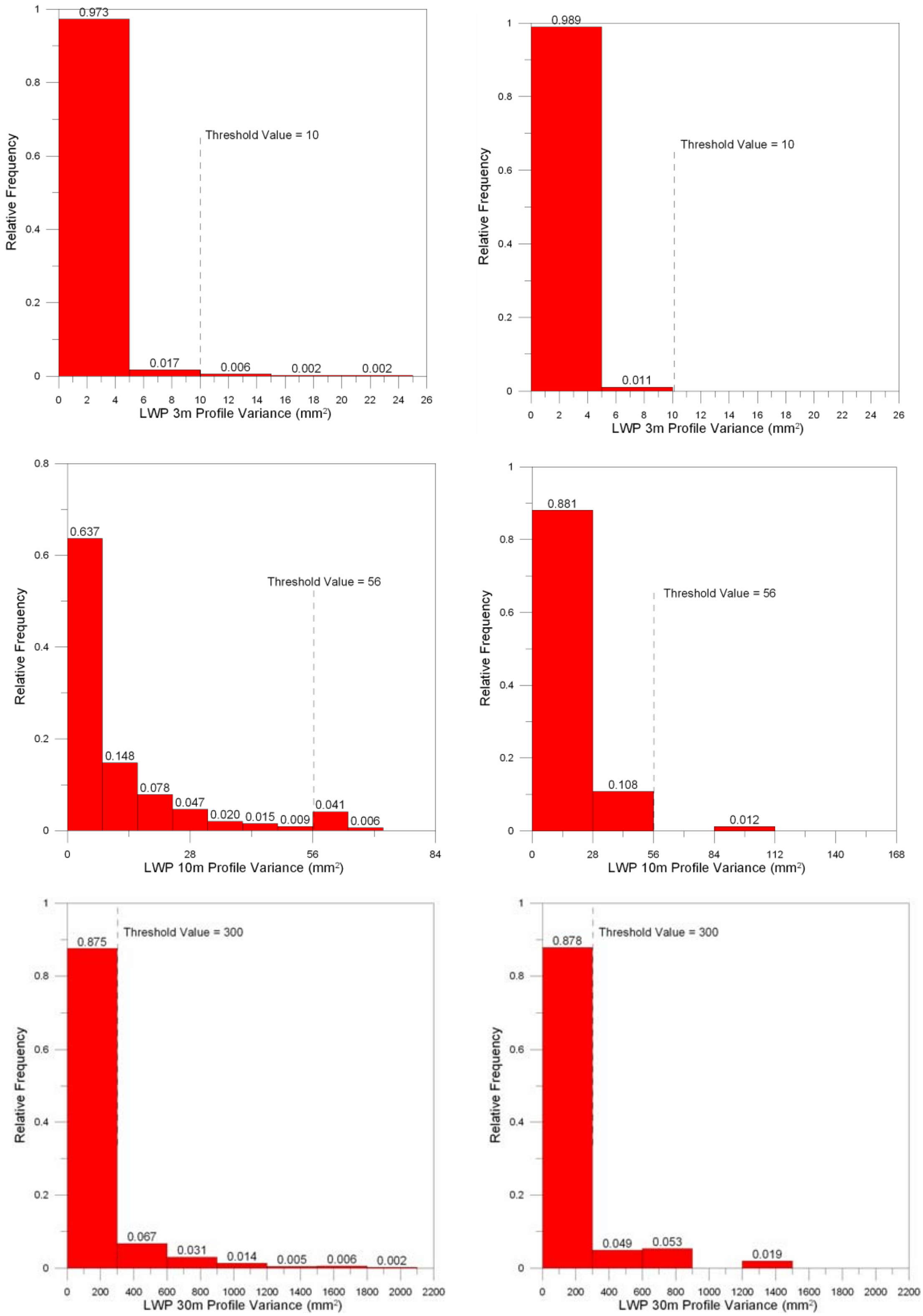
The highest values in each range are markedly higher than the United Kingdom threshold criteria for consideration of maintenance, ranging from around 10 times the criteria for 3 m wavelengths to around 1000 times for 30 m wavelengths. These extremely large values indicate that the effects of geometry on the calculation of profile variance can be very significant, and that any evaluation or assessment of the profile variance data needs to takes this into account.

Comparing the two road sections in Figures 4.3 and 4.4 shows that:

- for the 3 m LWP profile variance, typically less than 1% of the length of these two road sections exceeds the United Kingdom threshold value of 12 mm^2 for 10 m lengths and there are no 100 m lengths that exceed the threshold
- for the 10 m LWP profile variance, around 5%–15% of the length of these two road sections exceeds the United Kingdom threshold value of 56 mm^2 when 10 m lengths are considered, and around 1%–12% for 100 m lengths
- for 30 m LWP profile variance, around 13–37% of the length of these two road sections exceeds the United Kingdom threshold value of 300 mm^2 when 10 m lengths are considered. This range is similar, at 13%–44% for 100 m lengths.

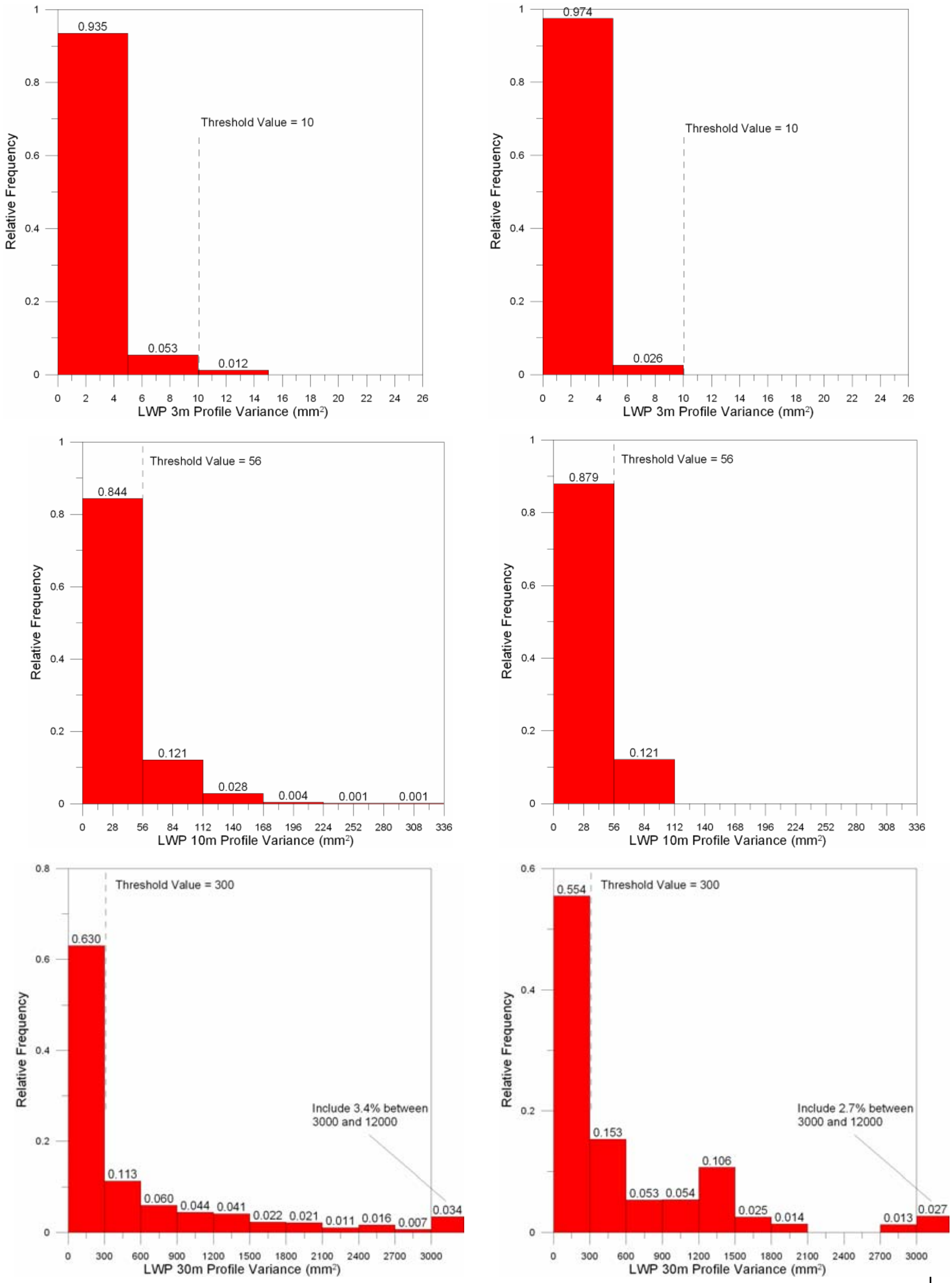
This illustrates one of the issues that any methodology for selecting and prioritising sites according to profile variance needs to overcome, which relates to there being road sections where the profile variance levels exceed the United Kingdom threshold criteria for either 10 m or 100 m lengths, but the measured truck response data do not necessarily indicate poor truck ride according to the discomfort factor criteria established by Jamieson and Cenek (2001).

There may be several reasons for this. Firstly, the criteria used in the United Kingdom may not be appropriate for New Zealand conditions, or they may need to be modified to take account of the potential effects of gradient, crossfall and curvature on profile variance. In addition, comparison of the profile variance data and the measured truck response data is complicated by the effects that traffic and geometry has on the speed at which the response data has been collected.



(a) 10 m lengths (b) 100 m lengths

Figure 4.3 Frequency distribution of profile variance – SH 56 increasing direction.



(a) 10 m values (b) 100 m values

Figure 4.4. Frequency distribution of profile variance – SH 1 increasing direction.

4.2 Comparison of truck response and profile variance data

Plots were prepared for each of the surveyed road sections to compare the measured truck response data, including the discomfort factor, pitch and vehicle speed data, with the profile variance and geometry data. Rather than presenting all of these plots, the same two road sections presented in Figures 4.3 and 4.4 are shown in Figures 4.5 through 4.8, for both 10 m road lengths and 100 m road lengths. Note that in these figures the profile variance data shown is only that which exceeds the threshold criteria for the different wavelengths.

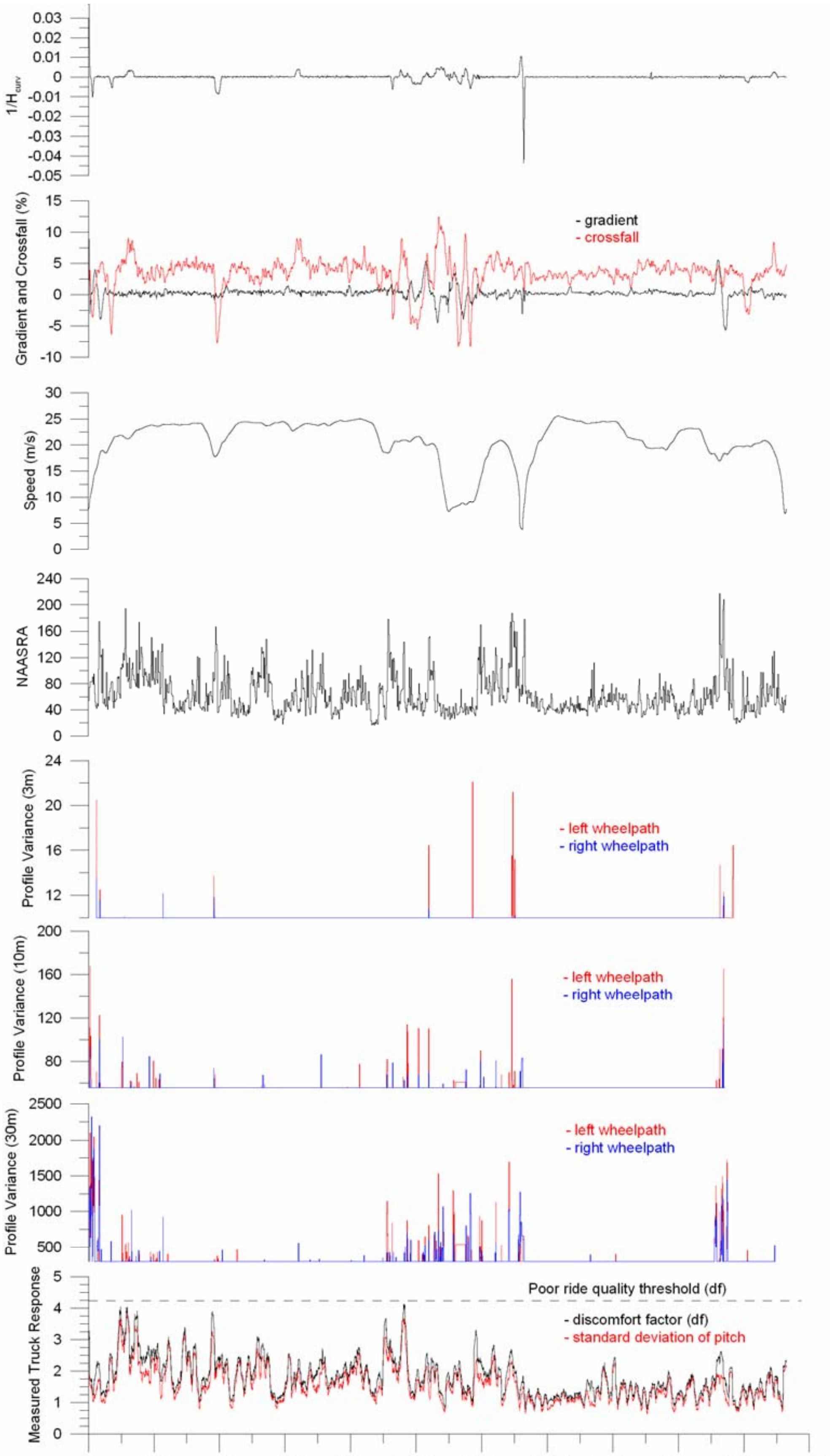


Figure 4.5 Truck response, geometry, profile variance (10 m) – SH 56 increasing direction.

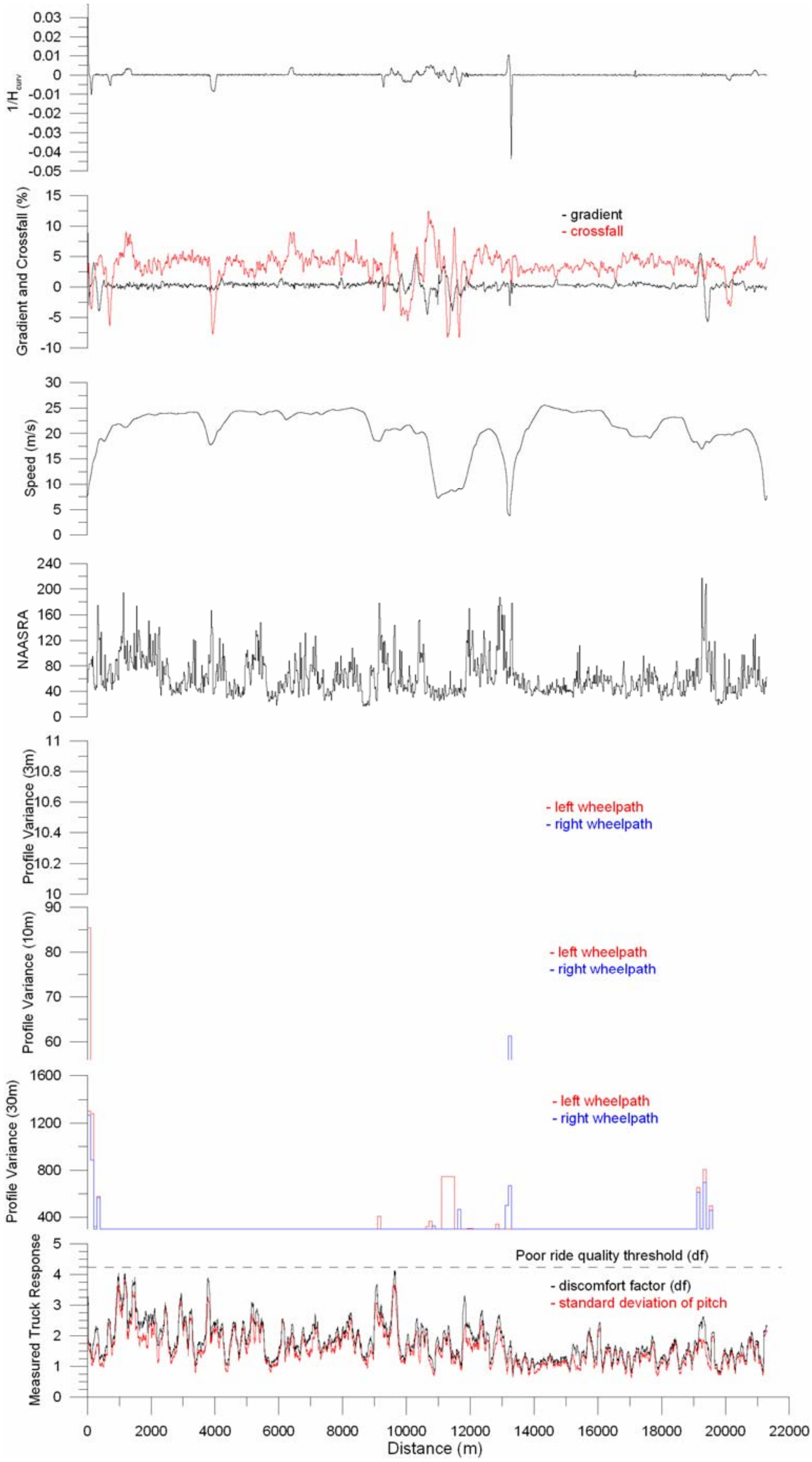


Figure 4.6. Truck response, geometry, profile variance (100 m) – SH 56 increasing direction.

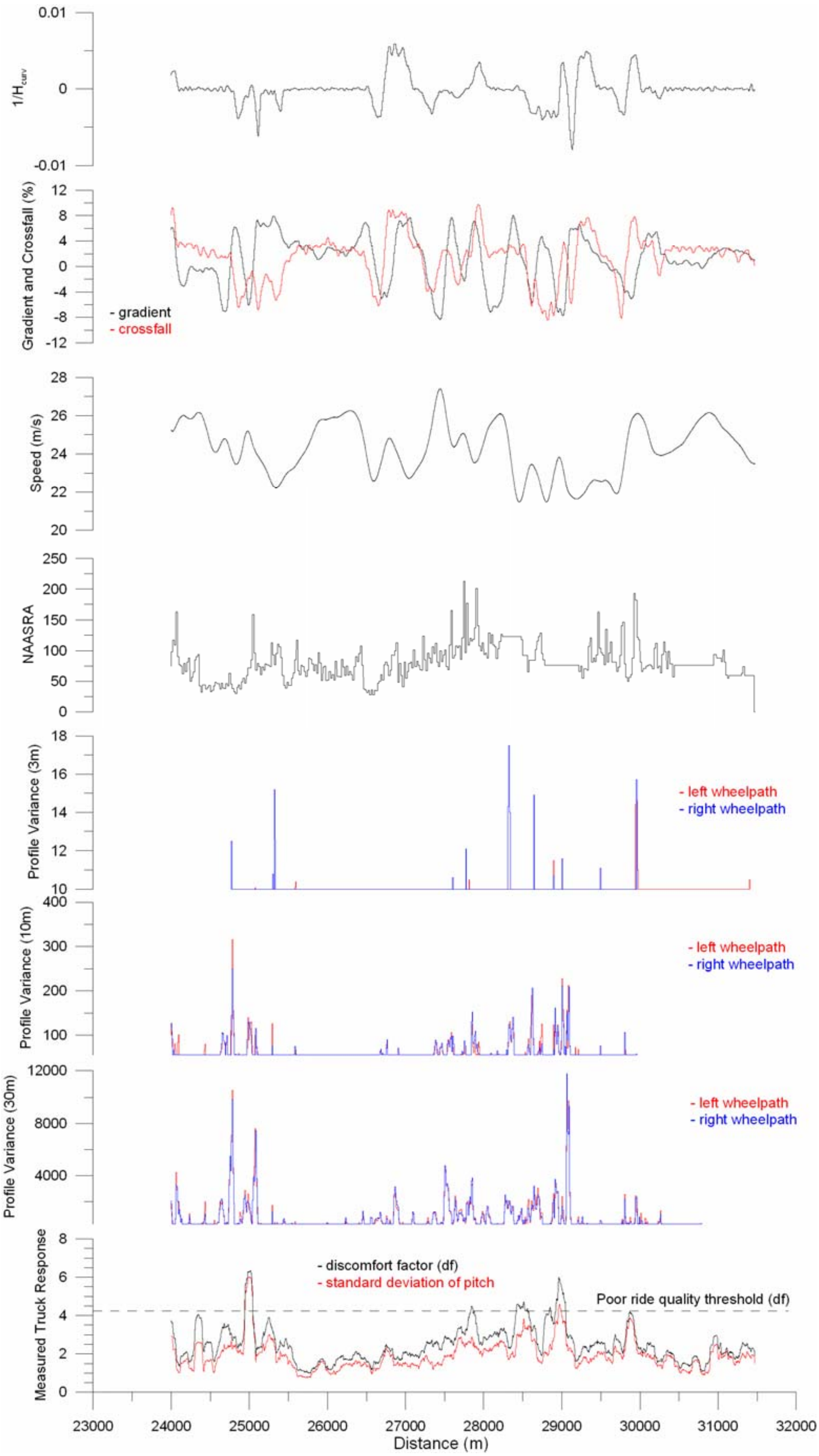


Figure 4.7. Truck response, geometry, profile variance (10 m) – SH 1 increasing direction.

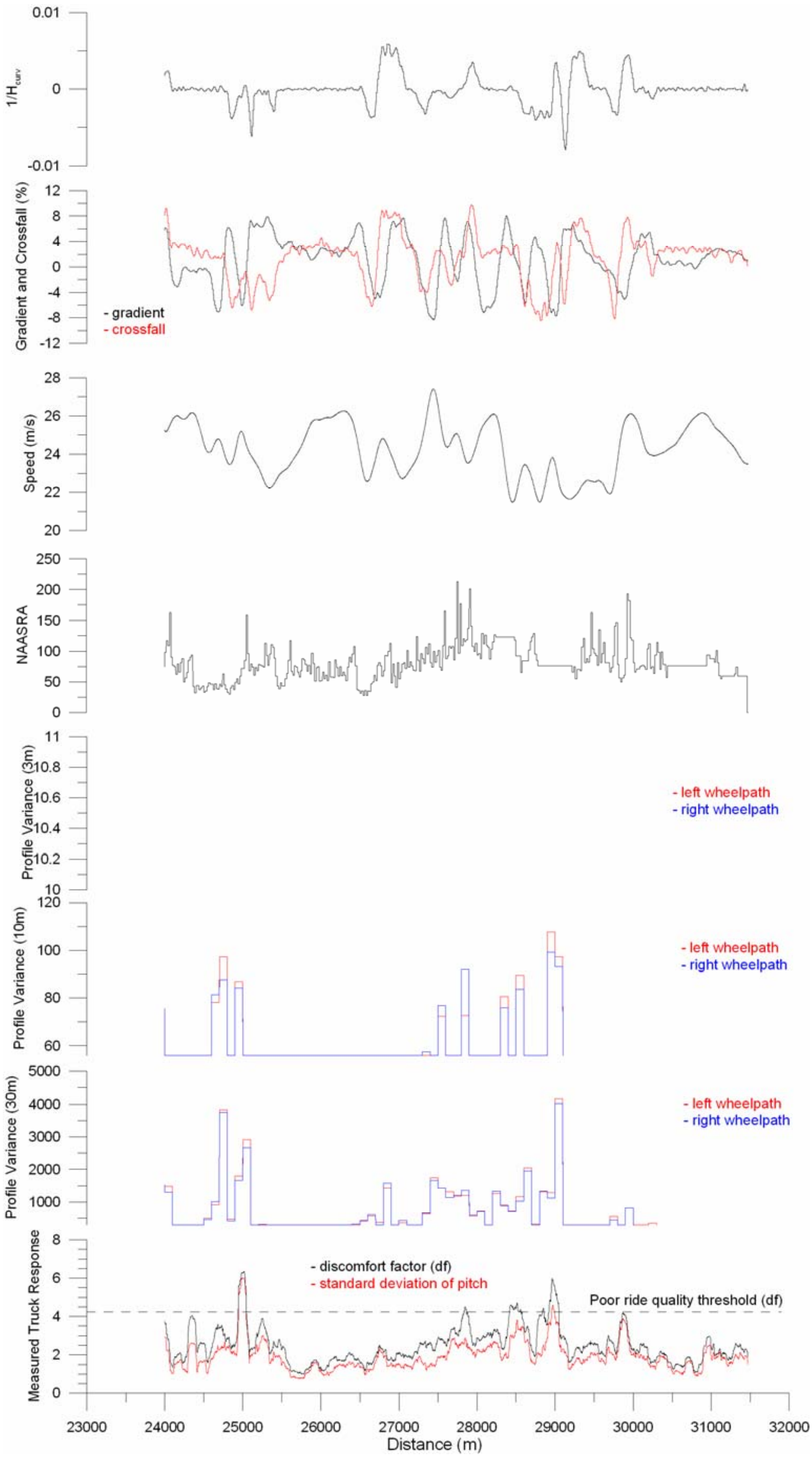


Figure 4.8. Truck response, geometry, profile variance (100 m) – SH 1 increasing direction.

Again it can be seen from Figures 4.5 to 4.8 that both of these road sections have profile variance values that exceed the United Kingdom threshold criteria for poor truck ride, if we look at either the 10 m or 100 m lengths. However, of the two, only the SH1 section shows measured truck responses over the established threshold. These figures do show that, generally speaking, the peaks in the measured truck response correspond to peaks in the profile variance data. The same trends occur in the remainder of the data for the surveyed road sections. These factors suggest that if criteria in terms of profile variance are to be used, they will need to be modified or filtered, either in magnitude, or according to changes in geometry (gradient, curvature and crossfall) and vehicle speed.

Examination of the entire database of surveyed road sections led to the following additional observations:

3 m profile variance

- Continuous road sections where the 3 m profile variance exceeded the 10 mm^2 United Kingdom threshold typically did not exceed 20 m in length, ie only one or two 10 m sections.
- There were few if any 100 m lengths over the 3 m variance threshold.
- There were very few road sections where the 3 m variance for the 10 m lengths exceeded the threshold value that did not have 10 m or 30 m variance values in one of the wheelpaths that exceeded the corresponding thresholds.
- Where the 3 m profile variance exceeded the threshold, but neither the 10 m nor the 30 m profile variance values exceeded the corresponding thresholds, there was no major evidence of significant lengths exhibiting poor truck ride according to the measured response data.
- There does not appear to be any significant evidence to suggest that the 10 mm^2 criteria is unreasonable for either 10 m or 100 m averaging lengths, in terms of the level of vehicle response that high levels produce, and the proportion of the roading network that exceeds this criteria.

10 m profile variance

- Continuous road sections where the 10 m profile variance exceeded the 56 mm^2 UK threshold typically ranged in length from 10 m to around 100 m in length, ie from one to around ten 10 m sections.
- There were very few 10 m or 100 m long road sections where the 10 m variance exceeded the threshold value that did not have 3 m or 30 m variance values in one of the wheelpaths that exceeded the corresponding thresholds.
- Where the 10 m profile variance exceeded the threshold, but neither the 3 m nor the 30 m profile variance values exceeded the corresponding thresholds, there was some evidence of poor truck ride according to the measured response data, although the lengths involved were relatively short. Figure 4.9 shows one example from the road section displayed in Figure 4.7. Here the 10 m averaged discomfort factor values exceeds the 4.25 deg/s threshold for poor truck ride, but the 100 m averaged data

does not. There did not appear to be any locations where high 10 m profile variance alone was sufficient to produce poor truck ride when the 100 m averaged discomfort factor data was considered.

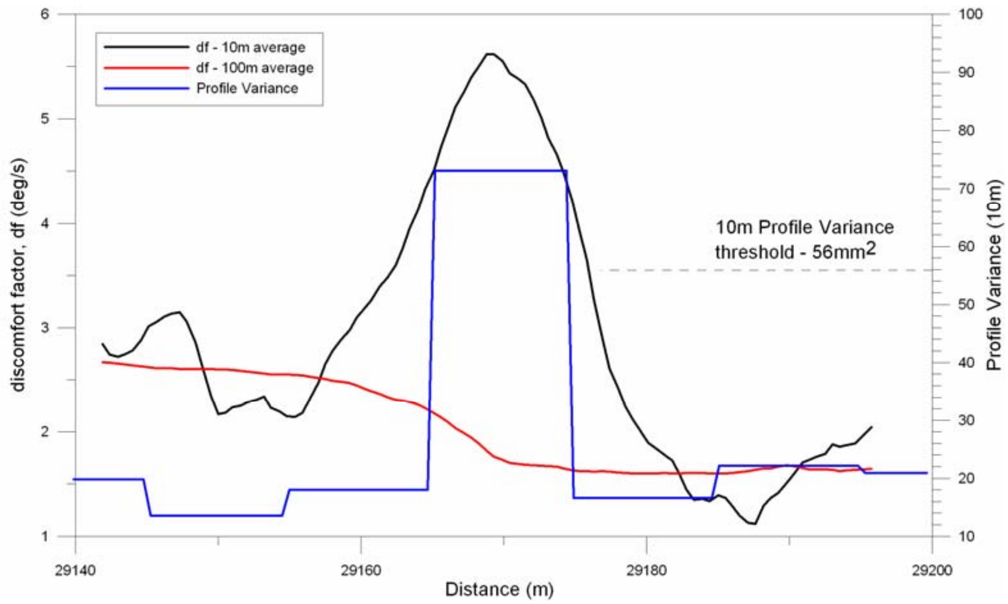


Figure 4.9 Localised 10 m variance and measured truck response.

30 m profile variance

- Continuous road sections where the 30 m profile variance exceeded the 300 mm^2 United Kingdom threshold typically ranged in length from 10 m to around 200 m in length, ie from one to around twenty 10 m sections. There are also clusters of road sections where the profile variance exceeded the threshold value and these could be much longer. Figure 4.10 shows one example from the road section displayed in Figure 4.7. Also shown in this figure is the corresponding 100 m averaged discomfort factor data. It can be seen that much of a 500 m section has 30 m profile variance that exceeds the threshold level for poor truck ride.
- There were few road sections where the 30 m variance exceeded the threshold value that did not have 10 m profile variance values, and often 3 m profile variance values, in one of the wheelpaths, that exceeded the corresponding thresholds. It can also be seen from Figure 4.2 that, more often than not, high values in one wheelpath means high values in the other wheelpath for either 10 m or 100 m lengths.
- Most, if not all, of the sections where the measured response discomfort factor data exceeded the threshold value for poor truck ride also had 30 m profile variance values that exceeded the threshold of 300 mm^2, and often also 10 m profile variance values that exceeded the threshold of 56 mm^2. However, as can be seen from Figure 4.10 there are also sections where profile variance values exceed the thresholds but do not show poor truck ride.

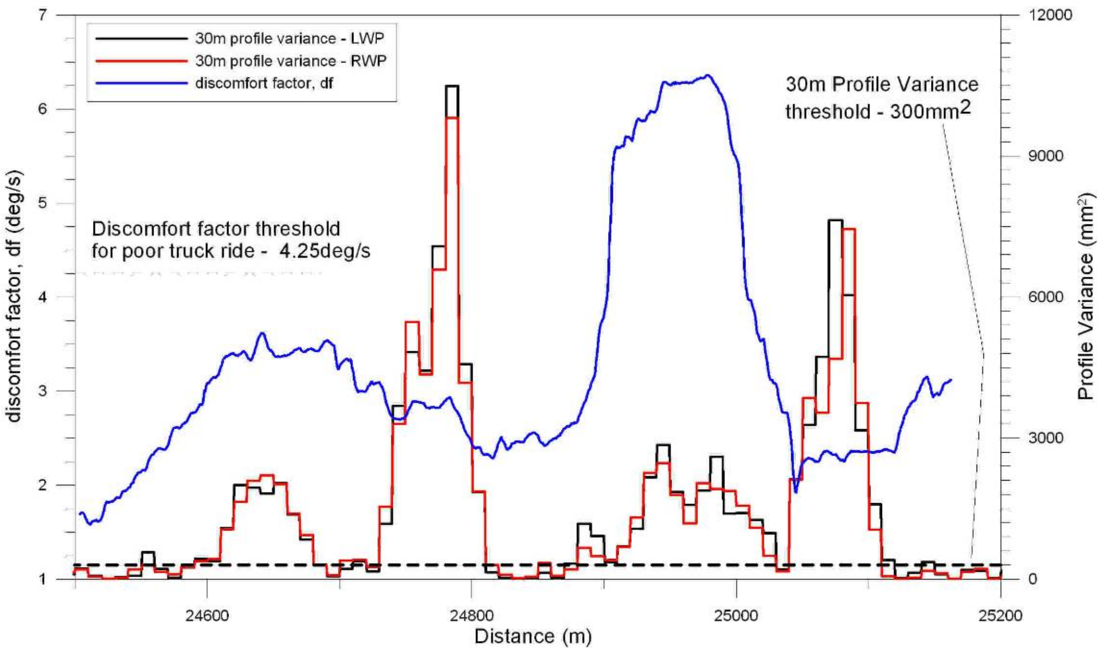


Figure 4.10. Localised 10 m variance and measured truck response.

4.3 Assessment of modifying factors

We have seen that high values of profile variance, particularly the 10 m and 30 m wavelength data, generally correspond to locations exhibiting poor truck ride quality in the measured on-road data. However, there are many sections with high profile variance that do not show poor truck ride. If profile variance is to be used successfully to select and prioritise road section for remediation we need to modify or filter the profile variance according to geometry factors and/or vehicle speed. We have indicated previously that in the United Kingdom consideration of profile variance is limited to relatively straight predominantly high-speed roads (UK Roads Board 2003) and that variations in geometry can affect the calculation of profile variance. Accordingly, we now consider the effects of curvature, crossfall and gradient on the 30 m profile variance and the measured truck response, and also the effect of vehicle speed. We have not considered looking at the 10 m profile variance because (1) only the 30 m data spans more than the 10 m or 20 m lengths that are used to characterise the geometry and roughness data and (2) more often than not there is a mutual occurrence of high levels of 30 m and 10 m variance.

4.3.1 Effect of road curvature

The potential effects of lane curvature on the 30 m profile variance values are entwined with those of the lane crossfall, given that typically as the radius of curvature on corners decreases, the crossfall increases to prevent vehicles sliding off the road. However, we will first look at these individually before looking at any combined effects. Figure 4.11 shows a comparison of the 30 m profile variance and 1/curvature for a number of road sections that are typical of those surveyed with the instrumented truck. Note that here the values for 100 m lengths are shown. Figure 4.12 shows a comparison of the 100 m averaged discomfort factor data and 1/curvature for the same road sections.

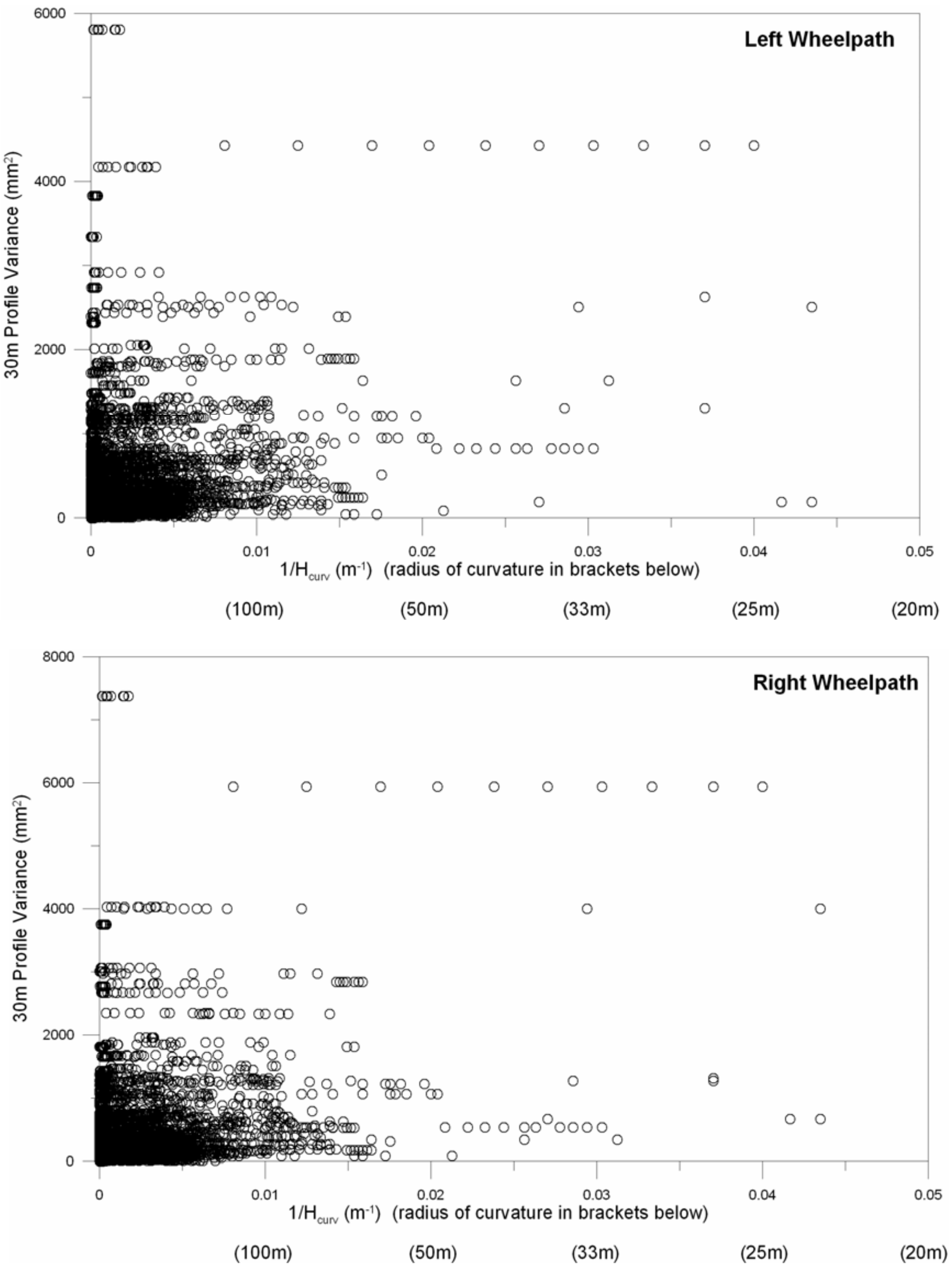


Figure 4.11 Comparison of 30 m profile variance and 1/curvature.

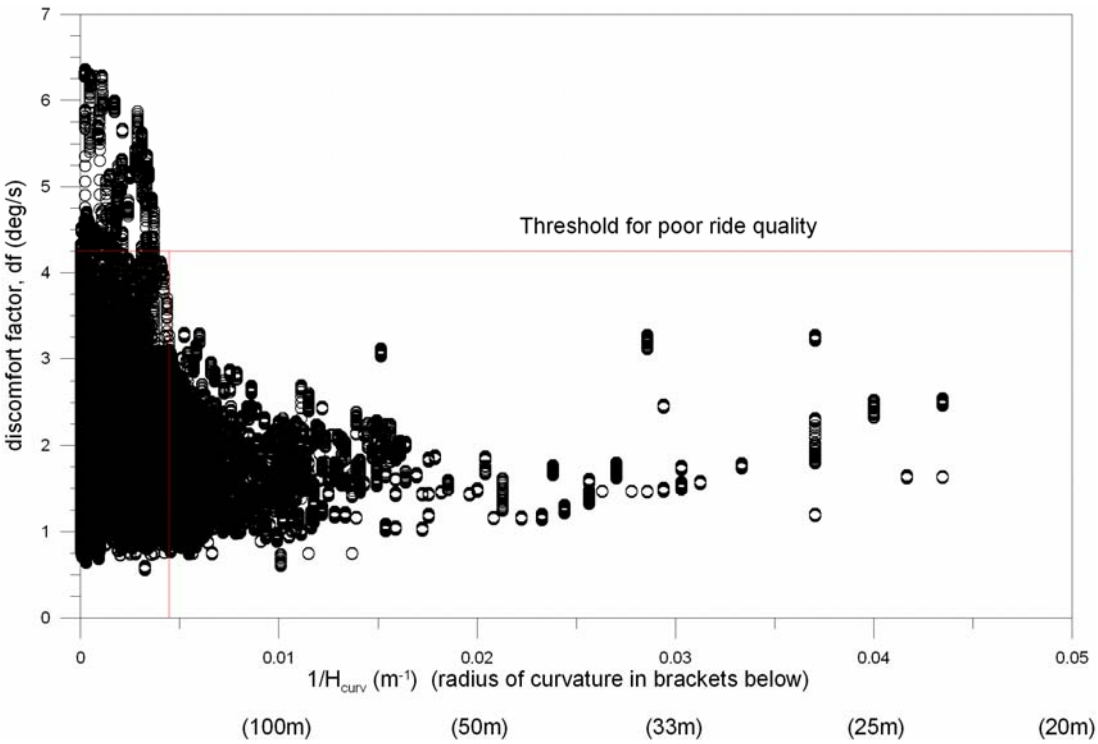


Figure 4.12 Comparison of measured discomfort factor and 1/curvature.

Figure 4.11 shows that there is no distinct relationship between the curvature and profile variance, although the majority of the higher profile variance values (greater than 2000) occur for curves with a radius of curvature of less than 500 m.

Figure 4.12 does indicate a distinct relationship with curvature, with all of the sites shown exhibiting poor ride quality only for curvature of around 200 m or higher. That is, ride quality would not generally appear to be a problem on tighter corners. This is more likely to be because of the reduction in vehicle speed that is often required on winding roads or in hilly terrain. Accordingly, curvature will form one of the criteria for the selection of potential sites for treatment in the absence of any suitable general truck speed model.

4.3.2 Effect of crossfall

The potential effects of crossfall on the values of profile variance that are derived from the actual measured profiles are likely to be similar to those of gradient, in that changes in either can appear as changes in profile, especially over longer averaging lengths such as 30 m. For example, Figure 4.13 shows, in an idealised way, how a change in crossfall or gradient could significantly affect the profile variance calculation in either or both wheelpaths.

To assess the likely effects of crossfall on the profile variance we have plotted the 30 m profile variance values against crossfall for the same road sections as used for curvature, in the previous section. These are shown in Figure 4.14 for the left and right wheelpaths for 100 m lengths.

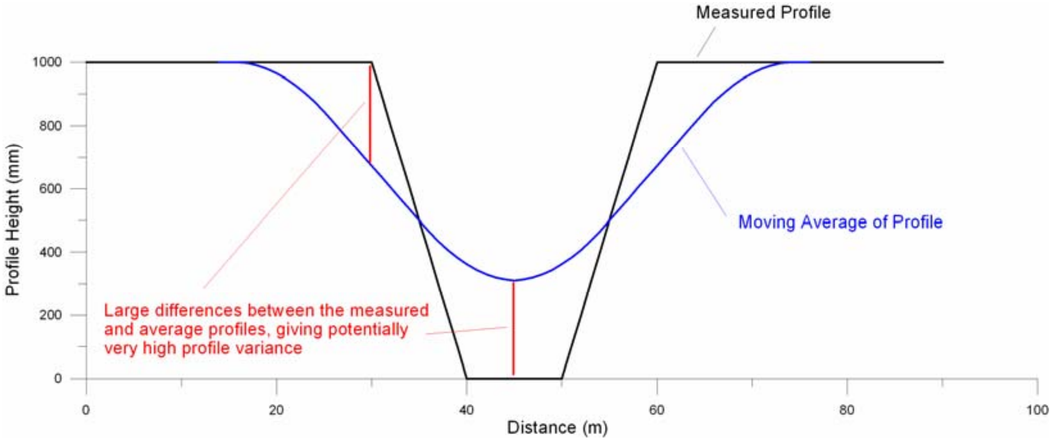


Figure 4.13 Changes in crossfall or gradient – effect on profile variance.

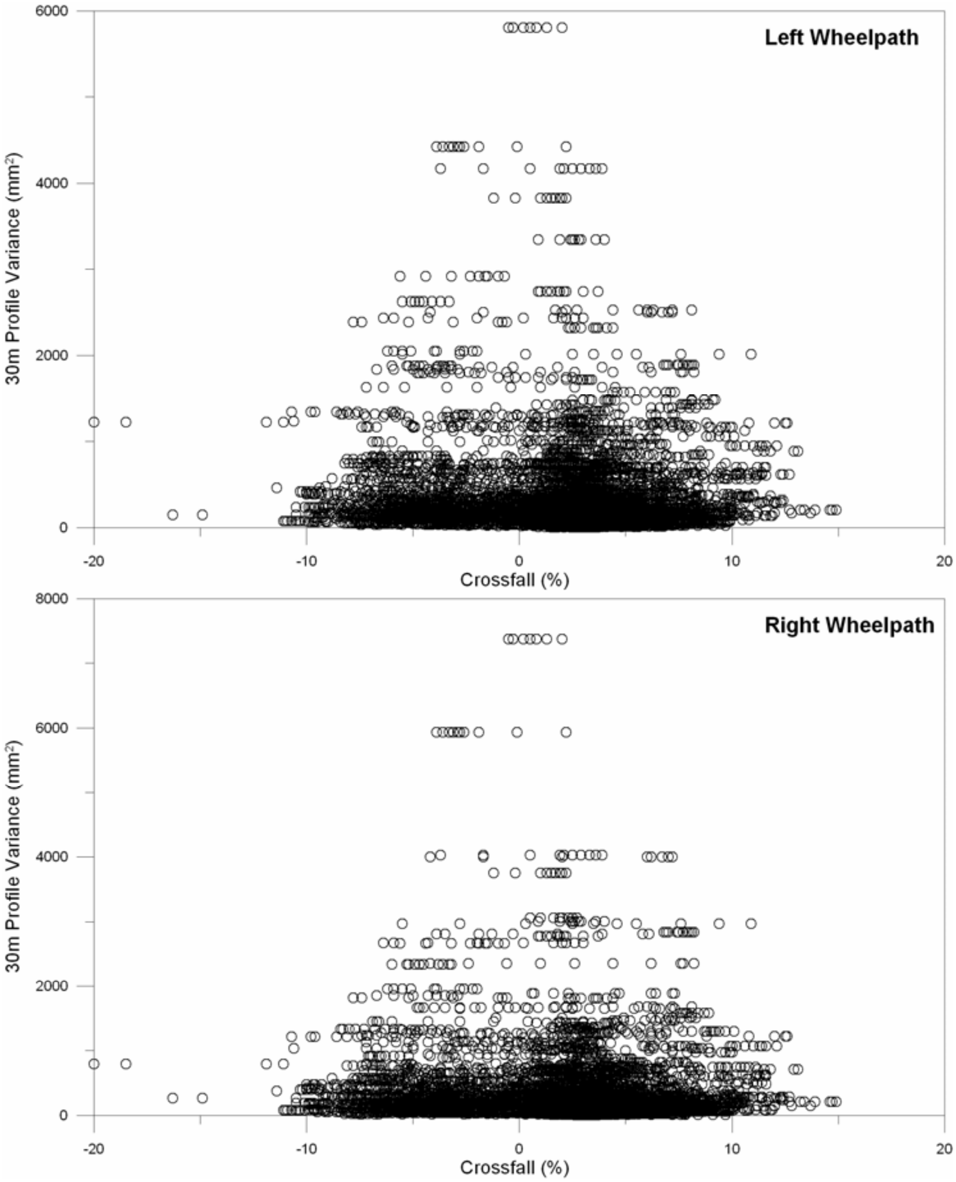


Figure 4.14 Comparison of 30 m profile variance and crossfall.

Figure 4.14 shows that there is little indication that lane crossfall values alone have a significant effect on long wavelength profile. Rather, as indicated in Figure 4.13, it is more likely to be the variation in crossfall that might affect the calculation of 30 m profile variance values. Accordingly, Figure 4.15 shows the variation across three consecutive 10 m crossfall values plotted against the 30 m profile variance values. Here, the profile variance values used are for 10 m lengths.

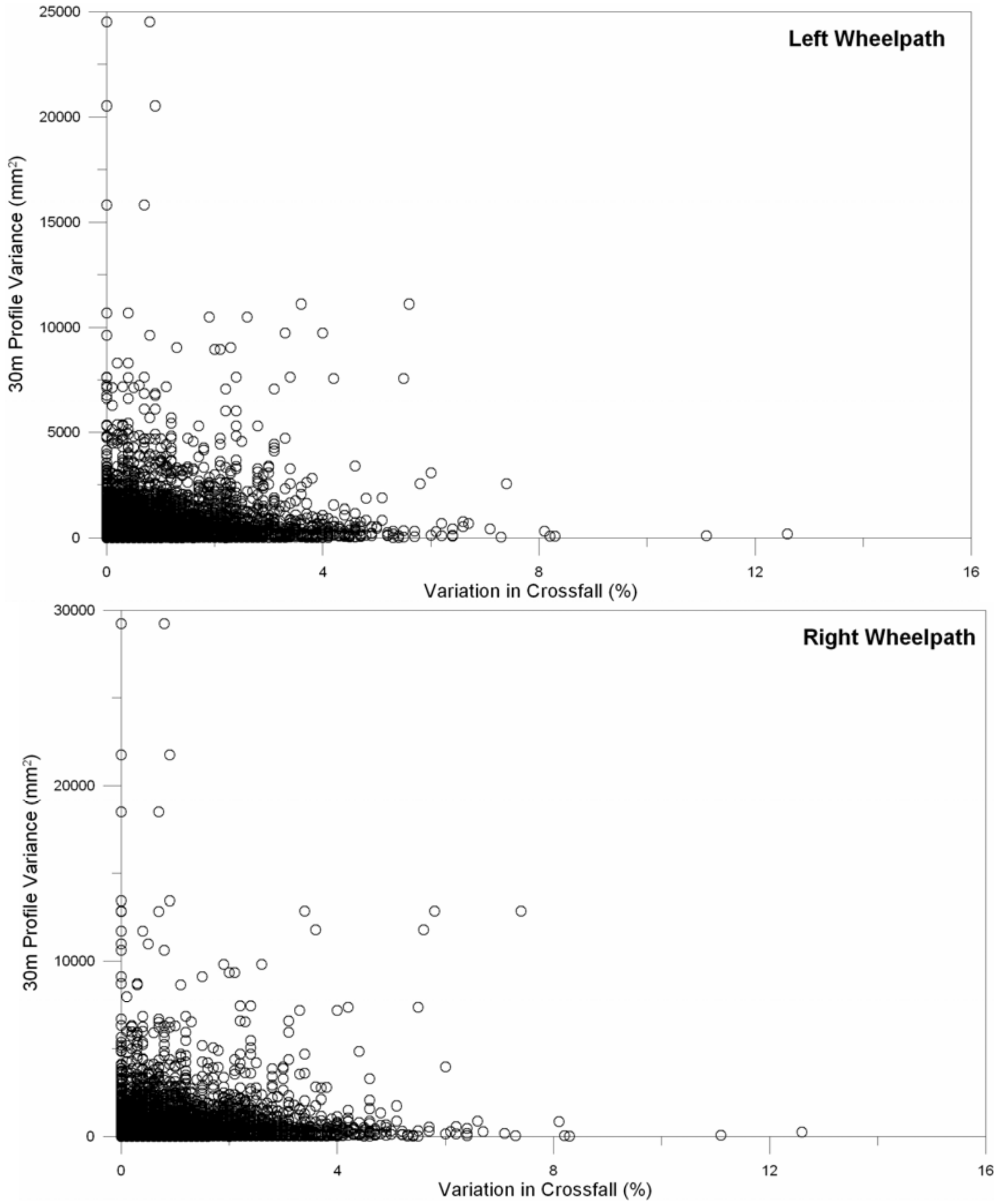


Figure 4.15 Comparison of profile variance and variation in crossfall.

Again, these figures show that there does not appear to be any consistent relationships between profile variance and the variation in crossfall across the ranges shown. There are some high crossfall and/or variation in crossfall sections that have high profile variance, and some that have low profile variance.

Figure 4.16 shows the variation of the 100 m averaged discomfort factor data and crossfall for the same road sections used previously. Looking at this representative plot shows that sections exhibiting poor ride quality were found to occur only for values of crossfall lying between +10% and -10%. This range is consistent with all of the road sections surveyed by the instrumented truck.

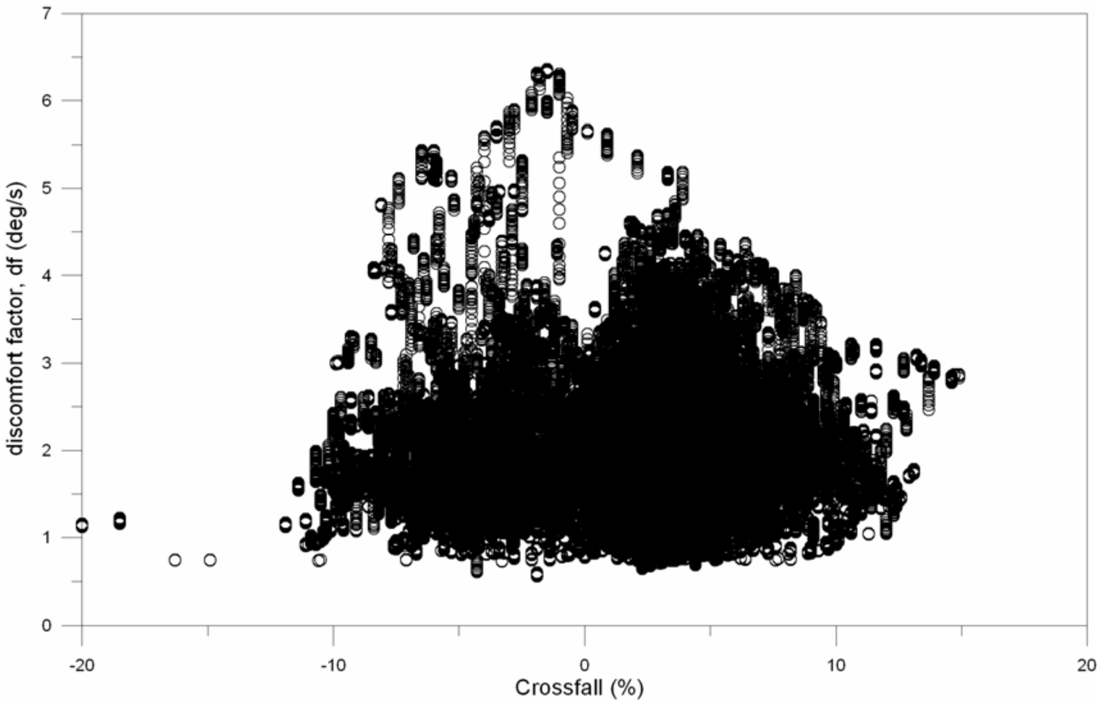


Figure 4.16 Comparison of measured discomfort factor and crossfall.

4.3.3 Effect of gradient

Figure 4.17 shows the variation of the 30 m profile variance with gradient for the same road sections used in the previous sections on curvature and crossfall.

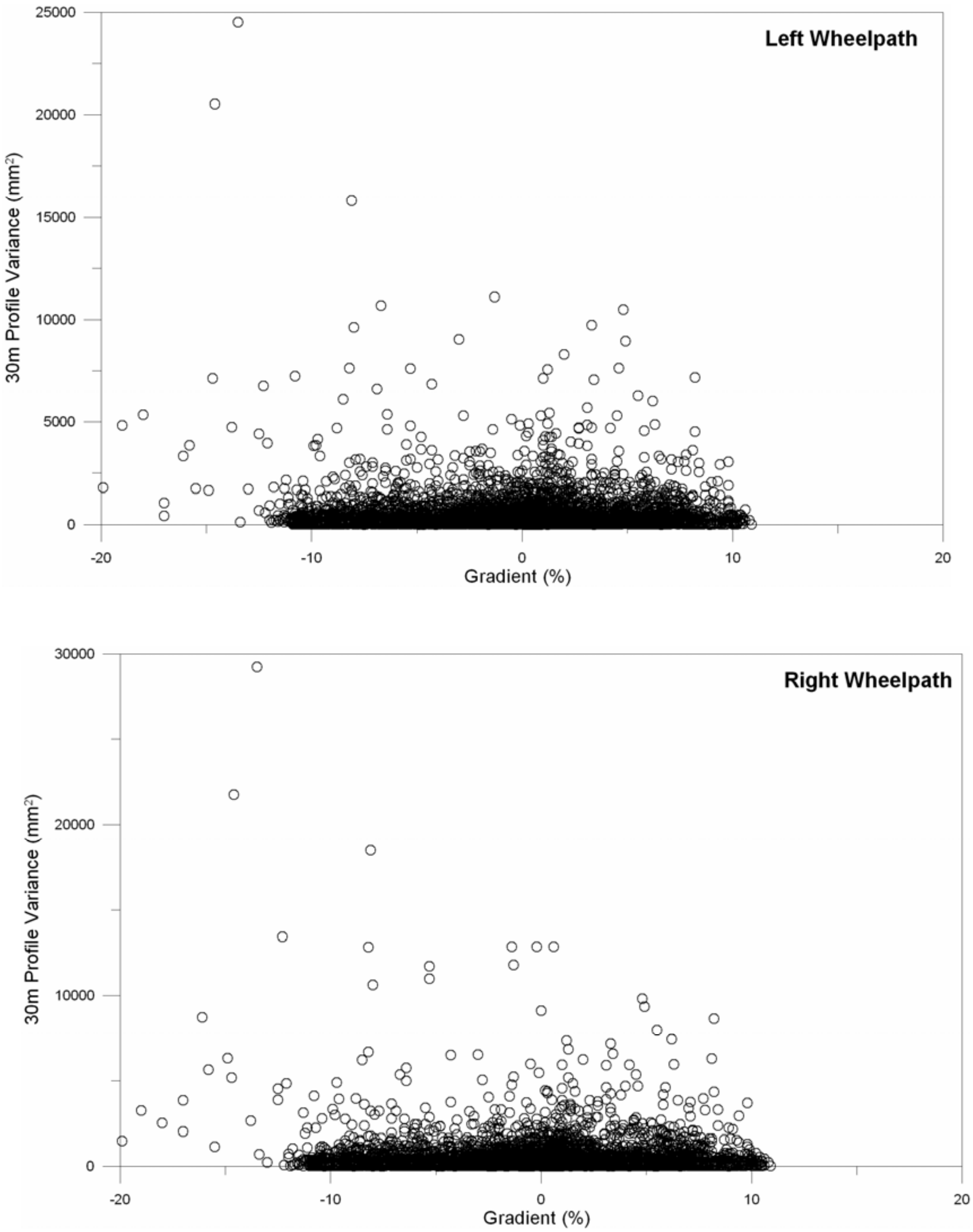


Figure 4.17 Comparison of 30 m profile variance and gradient.

Again there is little evidence of a strong relationship between the 30 m profile variance and gradient. Accordingly, as with the crossfall data, we looked at the variation in gradient across three consecutive 10 m lengths. The results are shown in Figure 4.18.

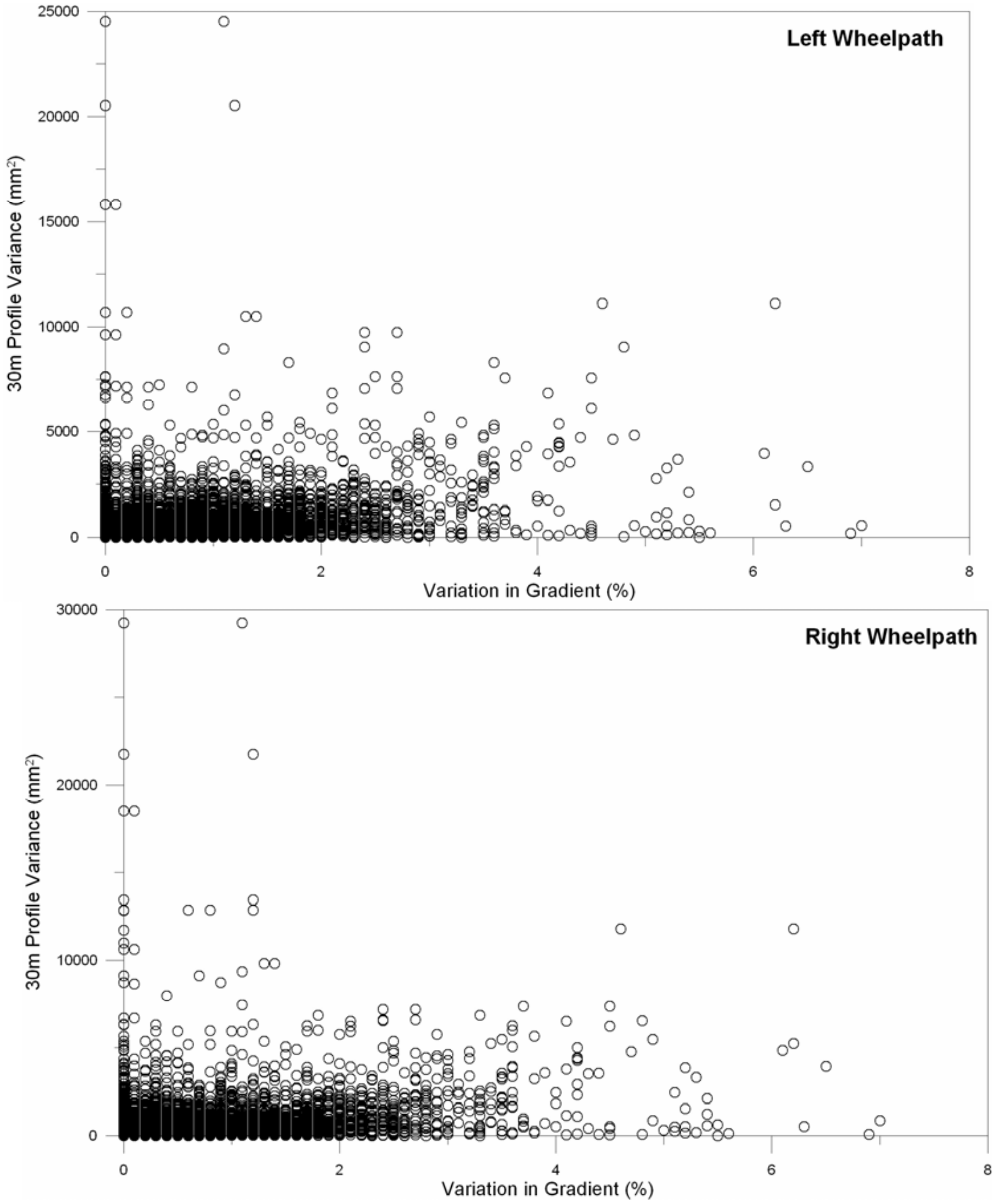


Figure 4.18 Comparison of 30 m profile variance and variation in gradient.

As with the variation in crossfall, there is little evidence of a strong relationship between variation in gradient and the 30 m profile variance. This suggests that either there is no relationship, or it is being disguised by other factors.

Figure 4.19 shows the variation of the 100 m averaged discomfort factor data and gradient for the same road sections used previously. This representative plot shows that sections exhibiting poor ride quality were found to occur only for values of gradient lying between +10% and -10%. This range is consistent with all of the road sections surveyed by the instrumented truck. Again, as with curvature, the seemingly limiting effects of gradient are more likely to be due to the limiting effects of gradient on the truck speed during the survey.

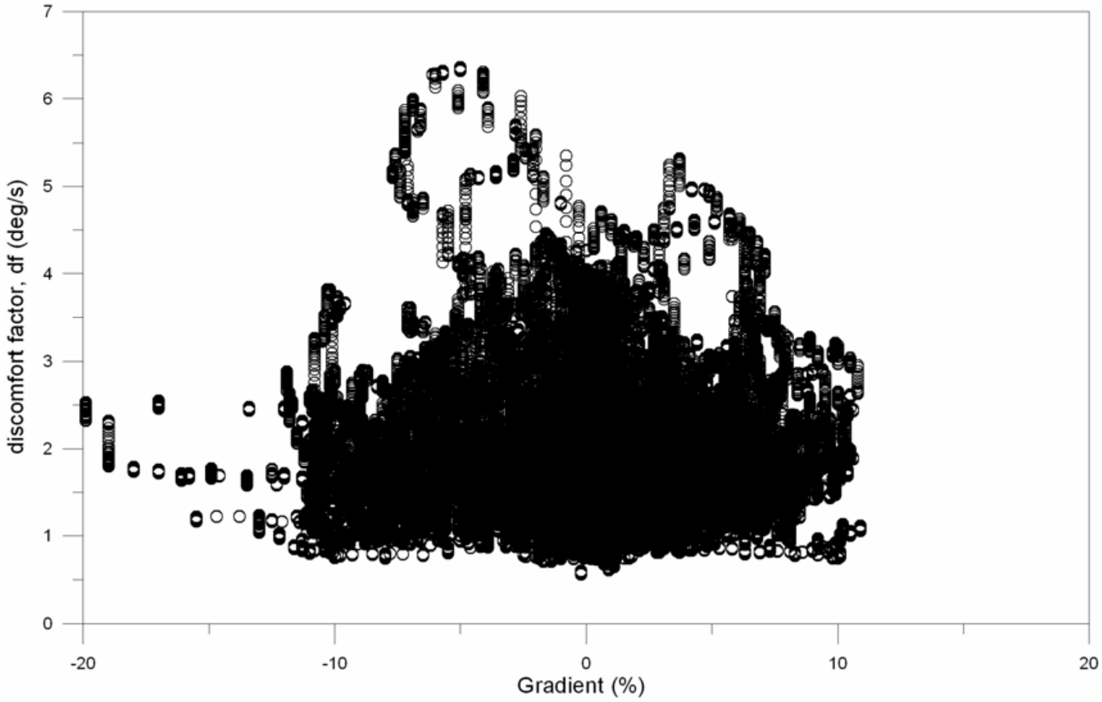


Figure 4.19 Comparison of measured discomfort factor and gradient.

4.3.4 Combined effects of geometry (gradient curvature and crossfall)

It was pointed out in section 2.2 that according to the UK Roads Board Interim Advice Note (2003) consideration of profile variance should generally be limited to relatively straight predominantly high-speed roads, and that variations in geometry can affect the calculation of profile variance. A new UK Roads Board (2005) interim advice note received after provision of the profile variance data by WDM Ltd indicated that for the assessment of ride quality the **moving average longitudinal profile variance** was to be replaced by the **enhanced longitudinal profile variance**. This was intended to reduce or remove the contribution of the underlying road geometry to the variance calculations. The new methodology used in the United Kingdom uses sophisticated filters to reduce the occurrences of falsely high levels of variance that can be associated with significant changes in geometry. These filters could not be applied to the data already provided.

We have seen from the previous sections that looked at the variation of the profile variance with variations in gradient, curvature and crossfall, that there do not appear to be strong or consistent relationships that would allow us to filter the profile variance data on the basis of these parameters. However, we decided to look at the spread of the profile variance data across the entire database to see if a threshold level could be established that would alert us to potential effects of road geometry on the profile variance calculations. Accordingly, Table 4.1 lists the maximum values of 3 m, 10 m and 30 m profile variance in all of the road sections traversed by the instrumented articulated truck, and these have been plotted in Figure 4.20.

Table 4.1 Maximum values of profile variance.

Road section	Profile variance (mm^2) (10 m averaging length)		
	Maximum 3 m	Maximum 10 m	Maximum 30 m
1	24	200	4000
2	24	200	2500
3	24	240	10,000
4	28	400	30,000
5	19	600	16,000
6	90	300	6000
7	35	300	8000
8	24	240	5000
9	28	600	3000
10	28	220	7000
11	28	200	4000
12	40	240	6000
13	28	1000	12,000
14	45	400	20,000
15	17	300	12,000
16	70	600	40,000
17	50	7000	250,000
18	22	160	5000
19	40	200	1600
20	26	160	1500
21	120	500	6000
22	40	900	60,000
23	30	180	4000
24	28	160	2000
25	20	200	2000
26	24	400	10000
27	20	110	2400
28	18	140	2400
29	20	200	5000
30	35	230	4500
31	28	240	8000
32	24	130	2500
33	32	900	20,000
34	22	400	25,000
35	22	160	2500
36	14	170	7000
37	18	300	7000
38	22	200	4000
39	26	260	4000
40	28	500	30,000
41	35	1200	40,000
42	28	350	25,000
43	45	1200	40,000
44	28	450	16,000
45	24	400	12,000
46	26	250	7000

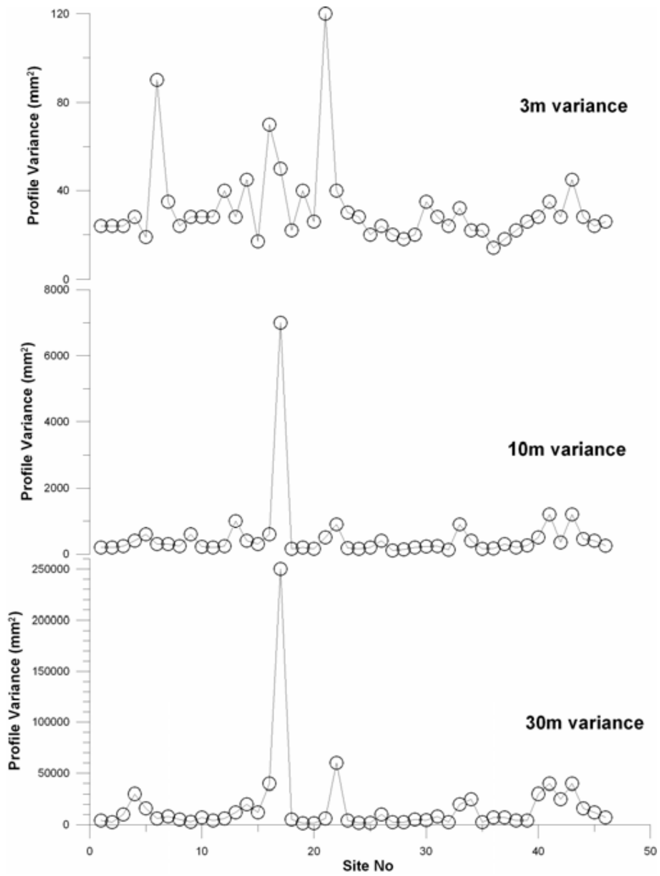


Figure 4.20 Maximum profile variance values (10 m lengths).

Table 4.1 and Figure 4.20 show that there is a considerable spread of profile variance values across all three of the wavelengths. For a 10 m averaging length some of these values, particularly those for the 10 m and 30 m wavelengths, are very high. Generally speaking the bulk of the values fall below (1) 30 mm^2 for 3 m wavelengths, (2) 400 mm^2 for 10 m wavelengths and (3) 5000 mm^2 for 30 m wavelengths. Looking at some of the very high values in more detail shows that a significant proportion do occur on small radius curves (<250 m), and most occur in what might be termed 'tortuous' terrain, where there are significant changes in curvature, gradient and crossfall over relatively short distances. This is consistent with the restriction to relatively straight flat roads described in the UK Roads Board (2003) advice note. This does not necessarily mean that profile variance values over these thresholds should be discarded or ignored for the purposes of considering truck ride quality, rather they should be treated with caution and considered together with other variables.

4.3.5 Effect of vehicle speed

The truck response model developed by Jamieson and Cenek (2001) incorporated geometry factors and the vehicle speed. Intuitively, it can be expected that the greater a vehicle's speed the greater its response to changes in the road profile. Similarly, depending on the magnitude and wavelengths of road profile variations, there will be a speed threshold below which the vehicle response does not produce poor ride quality.

Figure 4.21 shows a plot of the measured truck response against speed for the same road sections used previously to assess the effects of geometry. Minimum threshold speeds that produced poor truck ride, ie a response of over 4.25 deg/s, were determined. These minimum speeds are compared in Figure 4.22 with the maximum value of the discomfort factor that was measured on the particular road section.

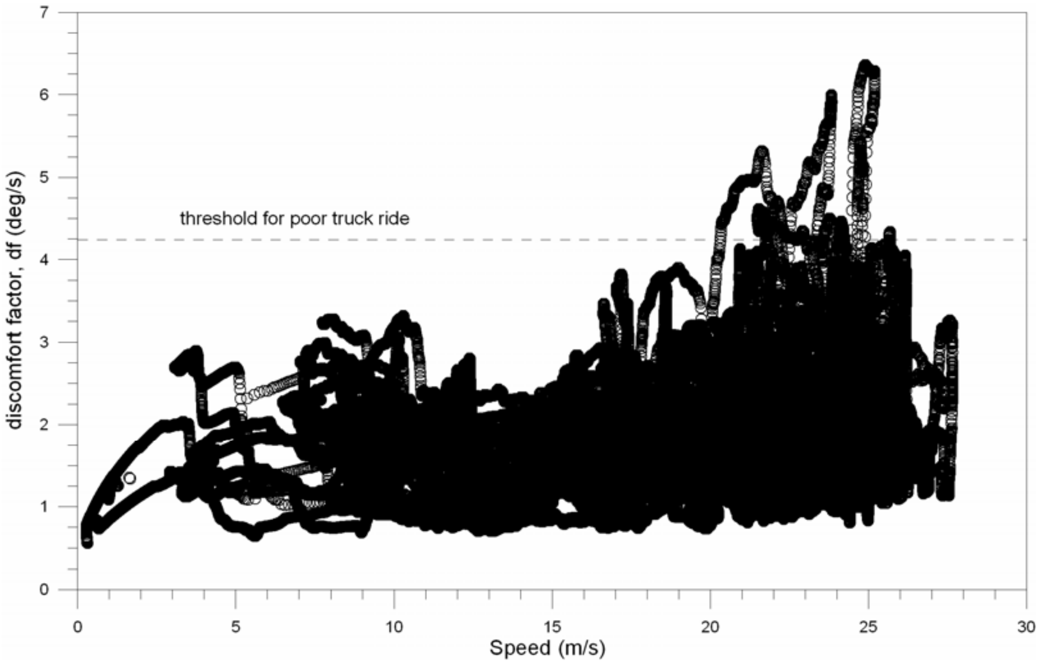


Figure 4.21 Comparison of measured discomfort factor and speed.

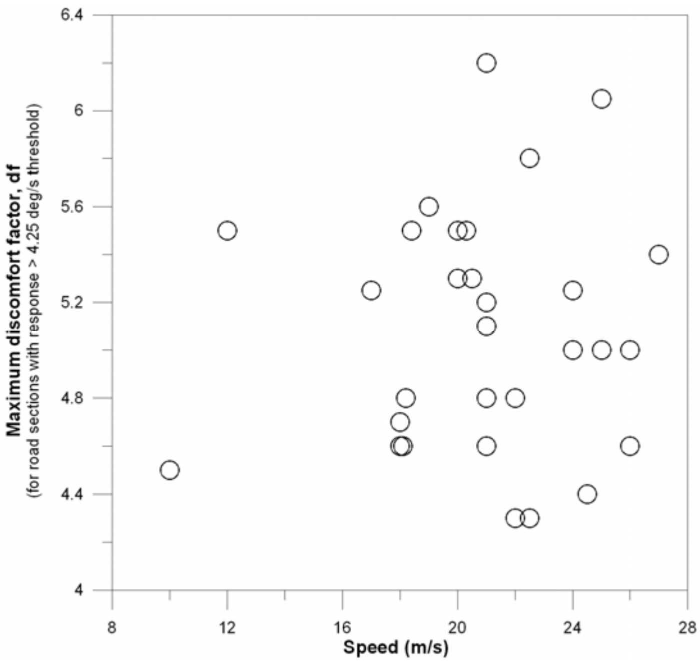


Figure 4.22 Minimum speeds for poor truck ride on surveyed sites.

The first of these two figures shows how significant the effect of speed is on the response of vehicles, and commercial vehicles in particular, to variations in the road profile. The second figure shows that a speed of 18 m/s (~65 km/h) or greater was required to generate poor truck ride on all but three of the road sections surveyed. Speeds of around 10–12 m/s (~40 km/h) were found on the lowest two, although at these locations the speed was changing quite rapidly.

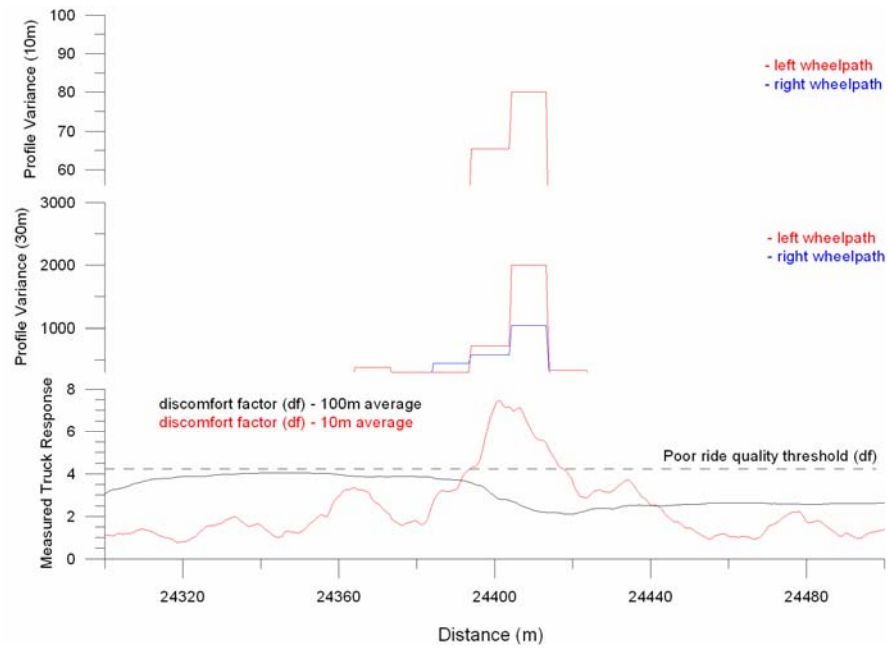
We have seen previously that road sections can have profile variance in any one or all of the three wavelength classes that exceed the established United Kingdom thresholds for poor ride quality. However, not all of these sections will necessarily produce poor ride quality. The major reason is vehicle speed is not high enough, either because of traffic, speed restrictions, or most often, steep grades and winding roads. Accordingly, any methodology that endeavours to select and rank sites for ride quality must be able to take into account vehicle speed. This can be done either through a speed model for commercial vehicles, or using geometry factors (gradient, curvature and crossfall) as filters. As there is currently no suitable speed model for commercial vehicles, the limits that we have developed earlier for gradient, curvature and crossfall represent the only current way of removing at least some of those road sections where low speed means low response.

4.3.6 Effects of variable lengths exceeding profile variance thresholds

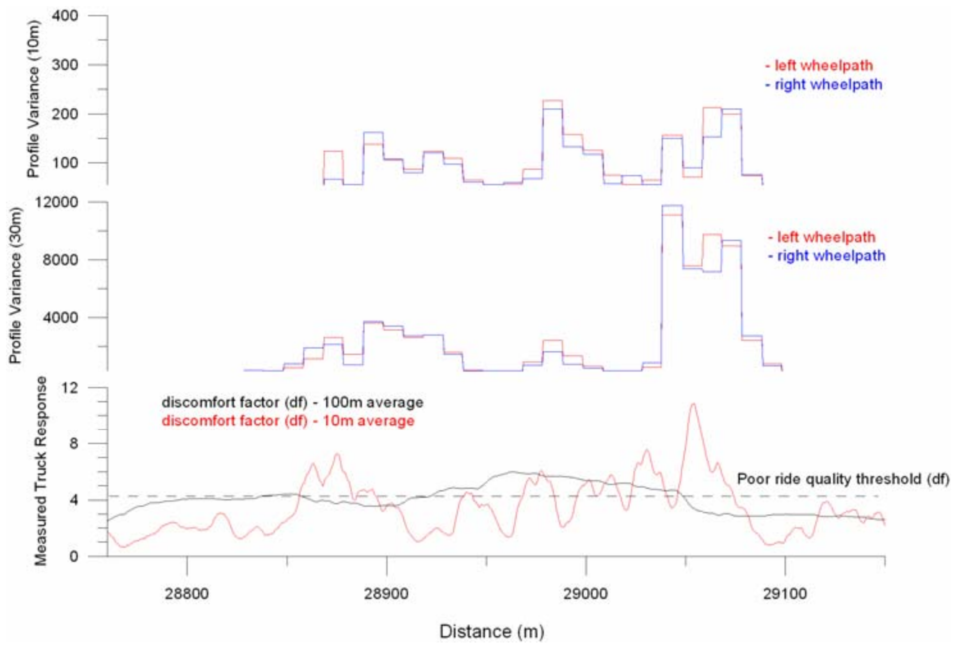
We have noted earlier that the continuous lengths of road sections with 10 m or 30 m profile variance values that exceed the United Kingdom threshold levels for poor truck ride can range up to around 100 m or 200 m respectively. We have also shown that there can be much longer sections where the bulk, but not all, of the profile variance values exceed the thresholds. Intuitively, it is expected that the longer the road sections with high profile variance levels, the more significant the impact on vehicle response, both in terms of time and severity. This effect is shown in Figure 4.23. Here we show two short road sections, one where a short length exceeds the 30 m threshold criteria and a longer one where a cluster of sections exceed the 30 m criteria.

The first plot shows that where profile variance is high for a short distance, we get a ride response that exceeds the threshold for poor ride quality for a 10 m averaging length, but not for a 100 m averaging length. Typically, to get poor ride over a 100 m averaging length, profile variance needs to exceed the 30 m wavelength thresholds for at least 40 m. In contrast, the second plot shows several closely spaced sections over the profile variance thresholds. Here, we get several peaks over the poor ride quality threshold for a 10 m averaging length and also lengths of poor ride quality averaged over 100 m.

These results suggest that in considering profile variance lengths over the 10 m and 30 m criteria of 56 mm^2 and 300 mm^2 respectively, we should select both distinct sections over 40 m long, but more importantly, look for clusters where combinations of 10 m and 30 m wavelength variance exceeds the criteria in either left or right wheelpaths, or both.



(a) Short section



(b) Longer section – cluster of values over threshold

Figure 4.23 Effect of section lengths exceeding profile variance thresholds.

4.3.7 Effects of roughness

The current methodology used in New Zealand by Transit NZ for identifying and prioritising truck ride improvement site is the TRI. This is based on the roughness measures contained in Transit NZ's RAMM database, namely the NAASRA wheelpath roughness and inter-wheelpath roughness. To assess how NAASRA roughness relates to the profile variance data we have plotted the high speed (10 m) NAASRA roughness data for the same road sections as used earlier against the 3 m, 10 m and 30 m profile variance data. This allows us to identify which of the wavelengths best relate to the NAASRA wheelpath roughness. These plots are shown in Figures 4.24 through 4.26.

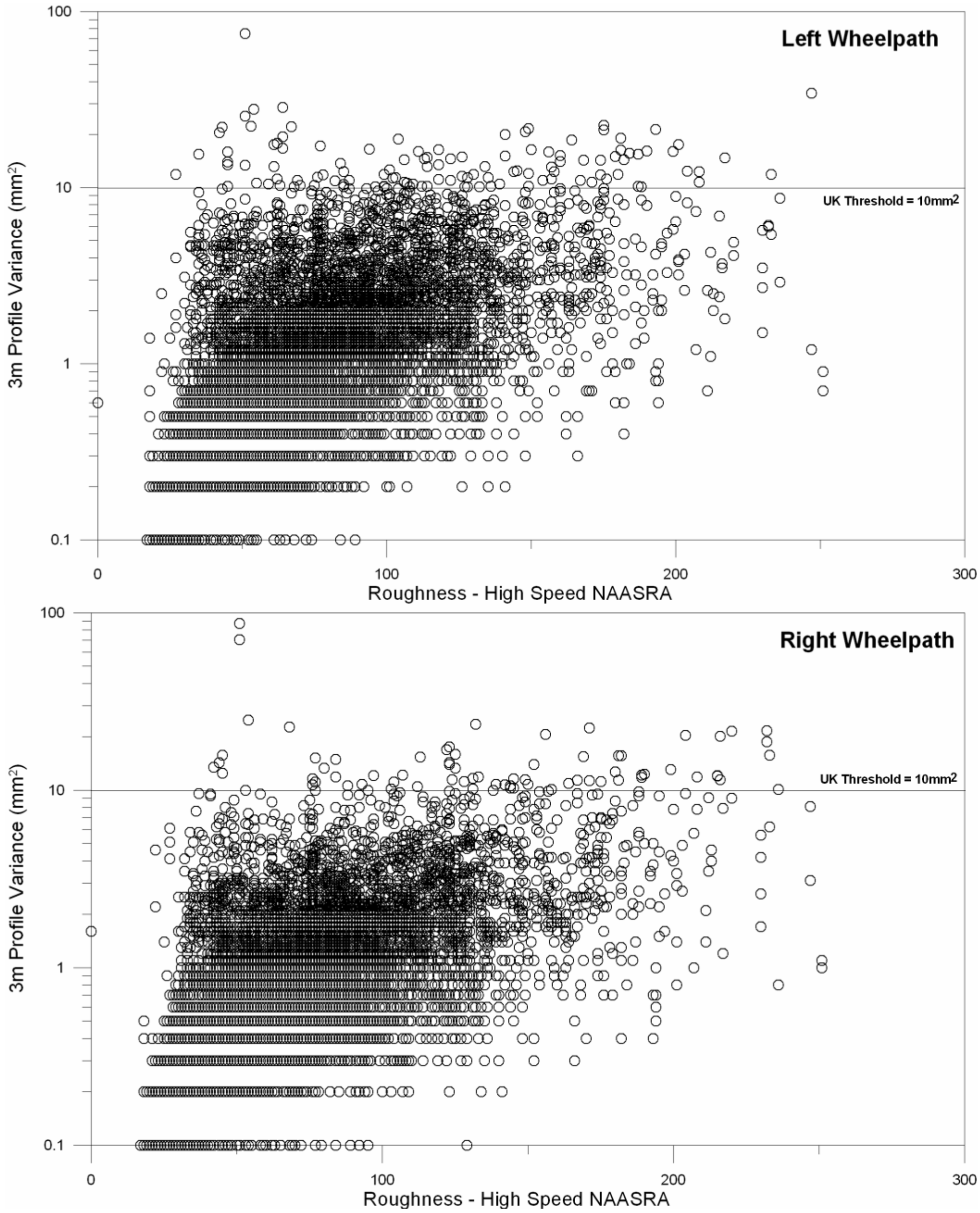


Figure 4.24 Comparison of NAASRA roughness and 3 m profile variance.

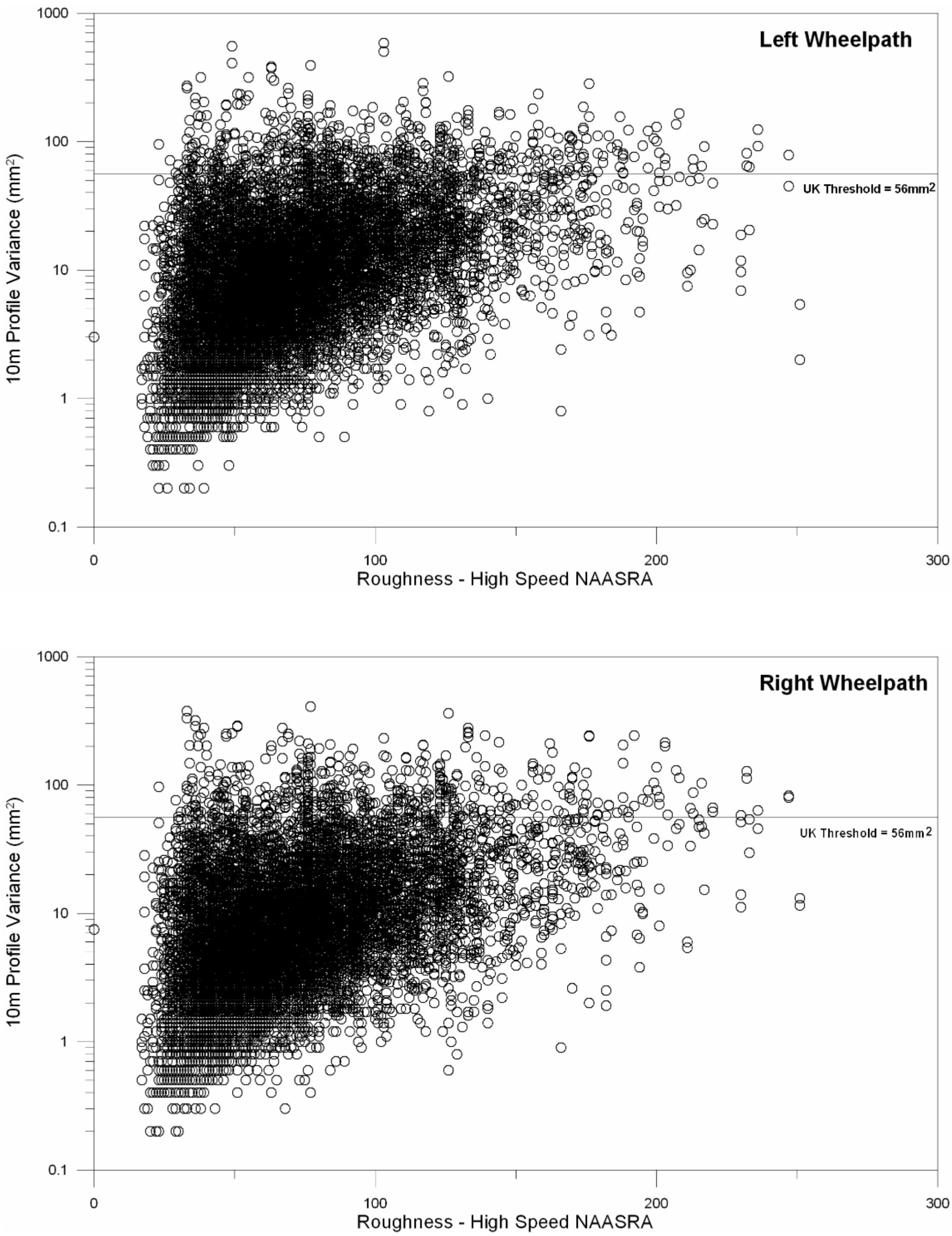


Figure 4.25 Comparison of NAASRA roughness and 10 m profile variance.

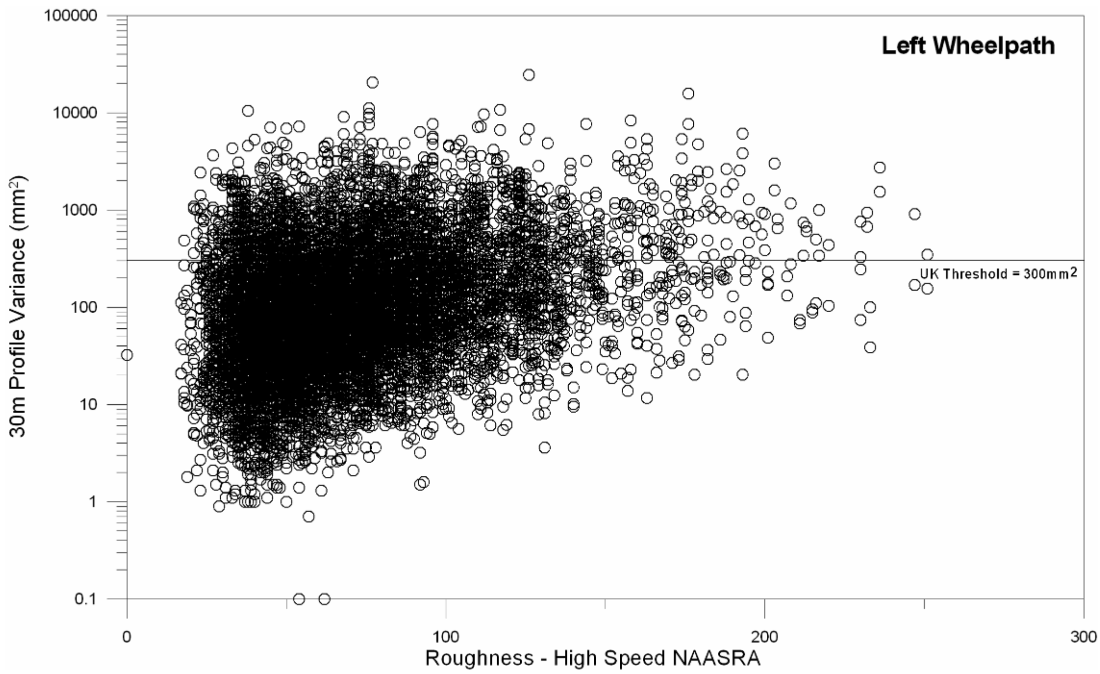


Figure 4.26 Comparison of NAASRA roughness and 30 m profile variance.

With reference to Figures 4.24 to 4.26, there is a trend for higher profile variance values to coincide with higher NAASRA roughness across all three of the wavelengths. However, there is also a considerable spread of profile variance values at moderate to low roughness, across all three wavelengths. This suggests that Transit NZ's TRI, which is based on roughness, may form a secondary means of ranking sites, being indicative of general roughness rather than specific wavelength content. To assess the relationships between the NAASRA roughness and the measured truck response the high-speed (10 m) and low-speed (100 m) NAASRA values have been plotted against the measured discomfort factor data for the same road sections as used previously. These are shown in Figure 4.27.

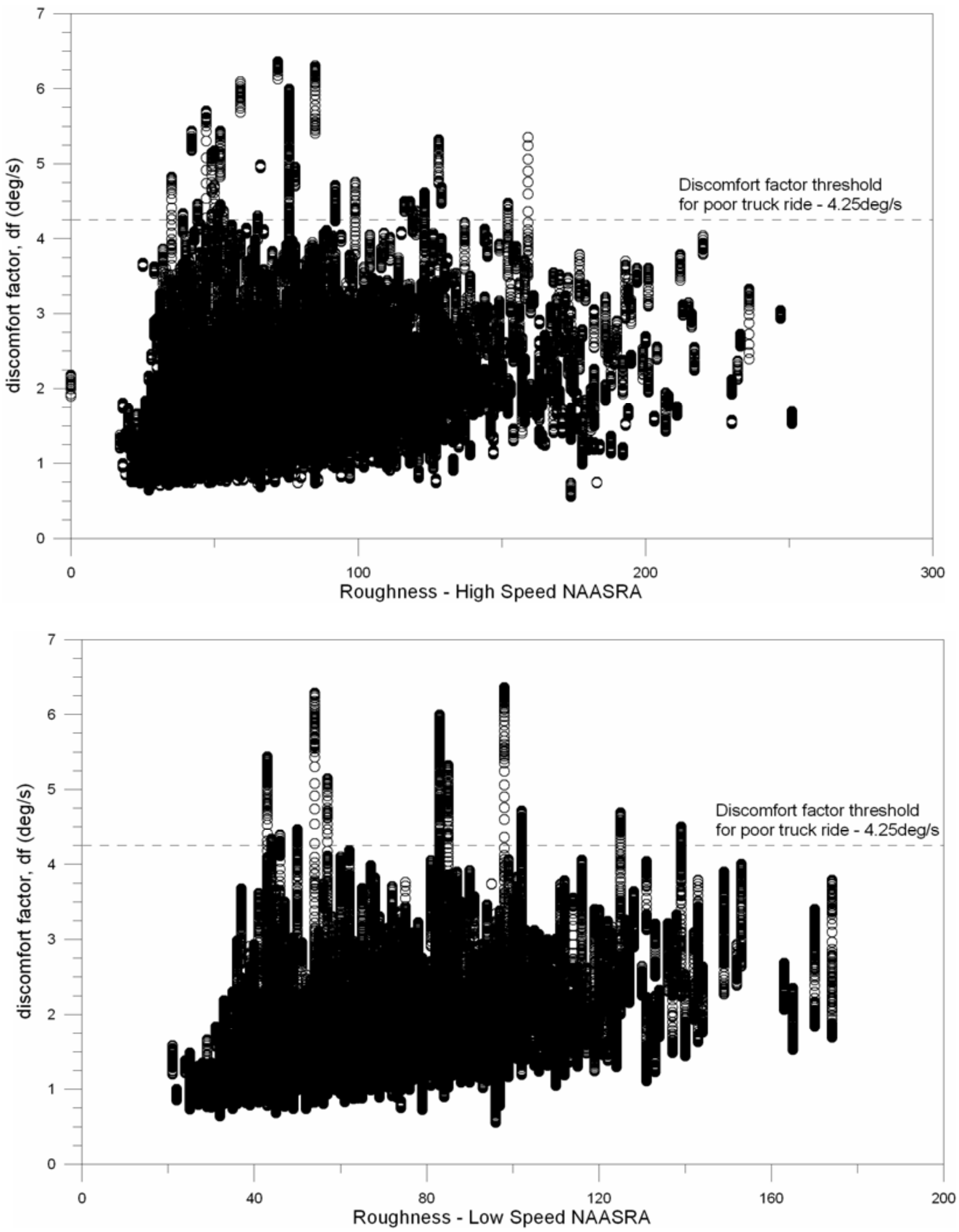


Figure 4.27. Comparison of measured discomfort factor and roughness.

These plots show that generally speaking the NAASRA roughness is not, on its own, a strong indicator of the measured truck response, when the data is taken globally. Here we can see that where the 4.25 deg/s threshold for poor truck ride is exceeded, the roughness varied from slightly over 40 NAASRA to around 140 NAASRA.

However, this is not to say that NAASRA roughness is not useful in identifying and prioritising truck ride sites. Figures 4.28 and 4.29 show road sections where high NAASRA roughness does correspond with high measured truck response. However, it can also be seen that these locations also have high values of 3 m, 10 m and 30 m profile variance.

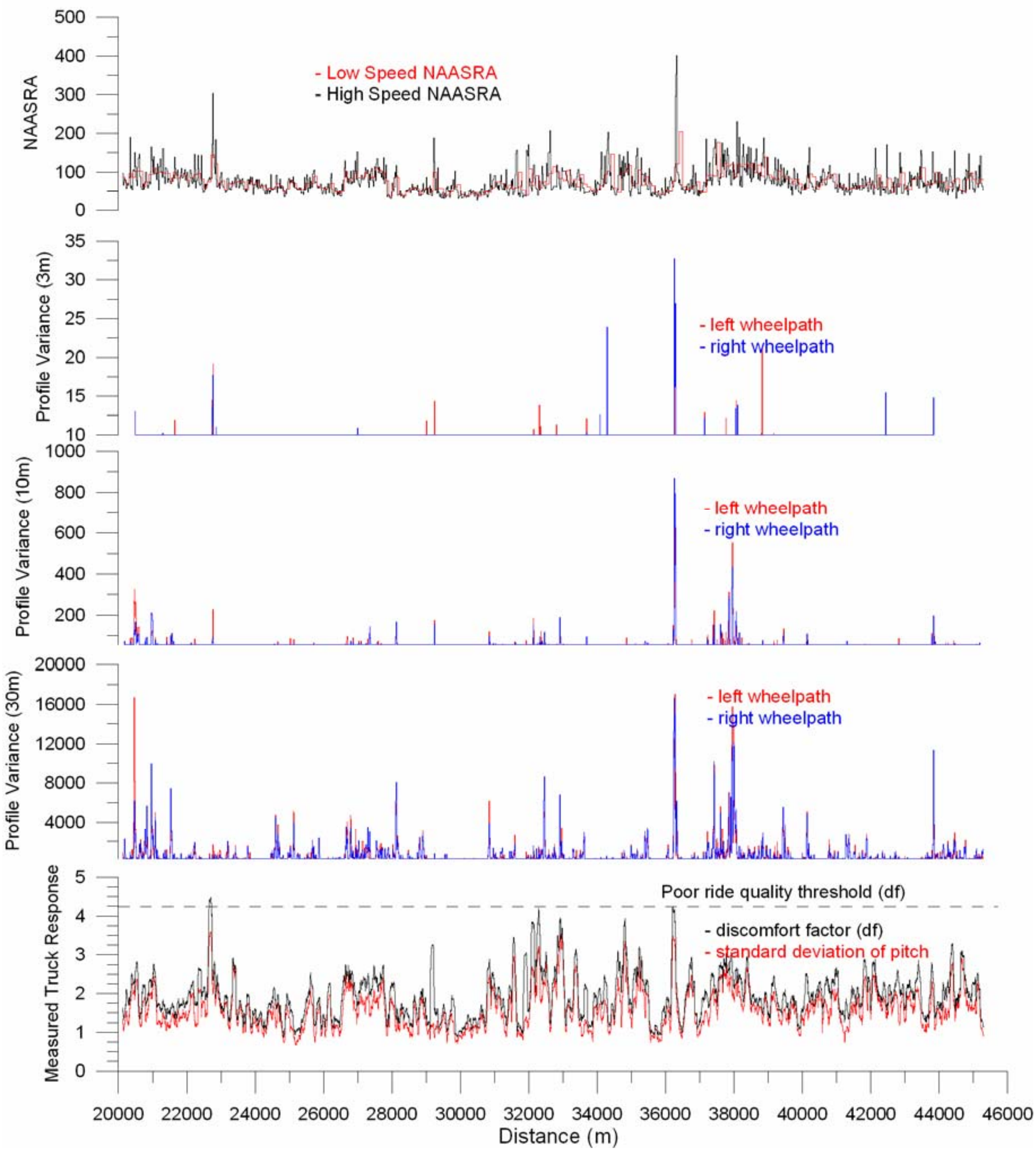


Figure 4.28. High roughness, profile variance and response – example 1.

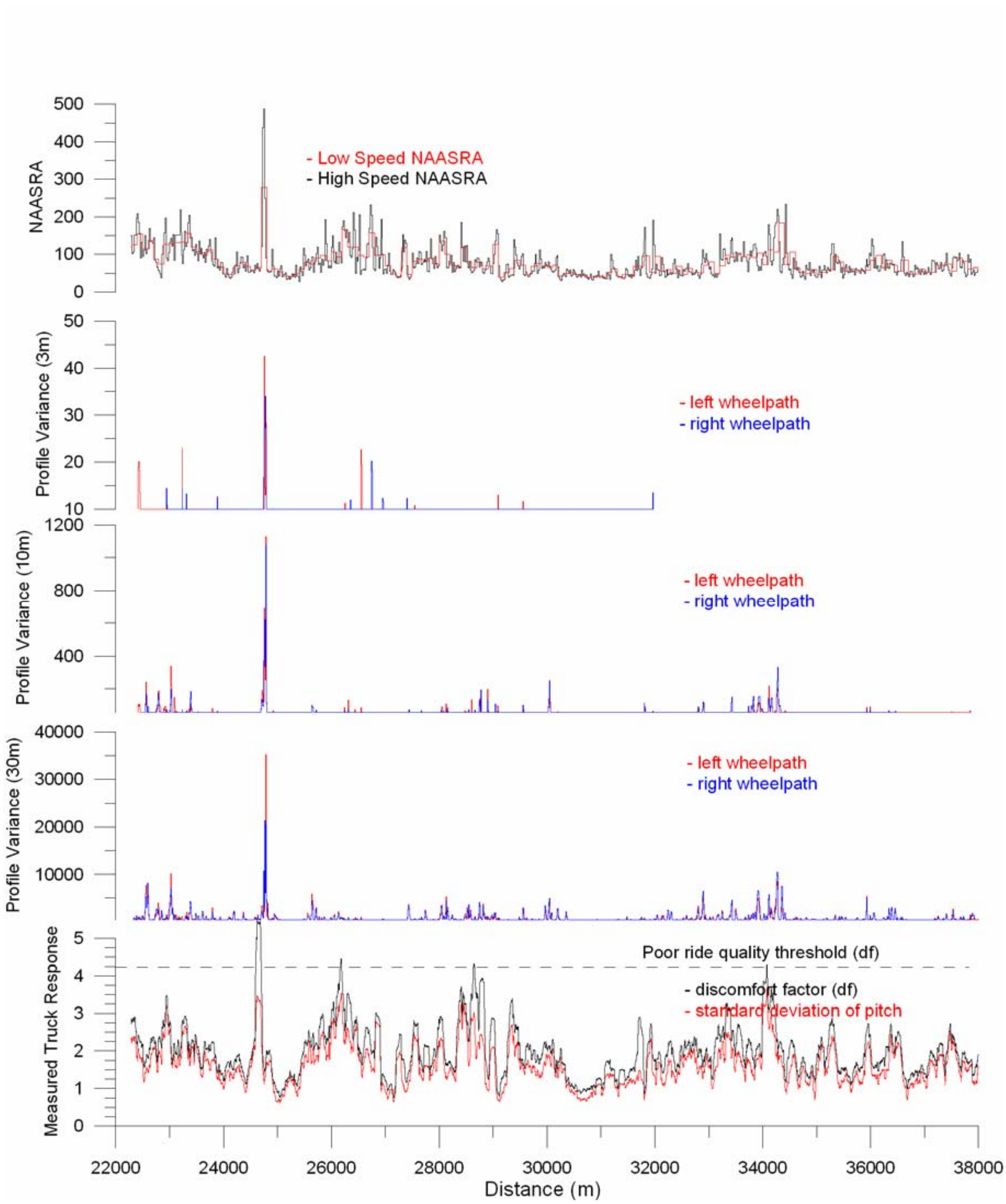


Figure 4.29 High roughness, profile variance and response – example 2.

4.4 Characteristics of areas of concern to the trucking industry

In the road sections surveyed by the instrumented truck, there were nine areas about which the trucking industry had previously expressed as being of concern with respect to ride quality (Jamieson and Cenek 2001). These were surveyed in one or both directions. Of the 14 truck passes over these areas of concern, eight produced measured responses that exceeded the 4.25 deg/s discomfort factor threshold for poor ride quality and another four were close to it. Of these 14 passes, the driver of the instrumented truck identified 13 as having an element of concern about ride safety (requiring increased concentration or vehicle control input), while the other was identified as being a ride quality (reduced comfort and increased irritation) issue. Accordingly, it was decided to examine these areas of concern to assess whether they exhibited (1) high profile variance, (2) high roughness, or (3) variable geometry. Figure 36 shows the data from one of the road sections surveyed that contained one of these trucking industry areas of concern.

Figure 4.30 shows that the example area of concern does have a measured response over the 4.25 deg/s threshold for poor truck ride established by Jamieson and Cenek (2001). It also shows that this area has 3 m, 10 m and 30 m profile variance values in both left and right wheelpaths over the United Kingdom thresholds for poor truck ride, and the level of NAASRA roughness is high.

Figure 4.30 reinforces some of the issues that have been highlighted earlier. There are several locations that have high levels of profile variance, but do not show high levels of measured response. Indeed, the location with the highest values of 3 m, 10 m and 30 m variance, as well as the highest level of roughness, did not exceed the poor ride quality criteria of 4.25 deg/s. The reason for this is the reduction in speed required by the sharp curvature at this location. There are also a number of other locations where there are high values of profile variance in areas where the curvature, gradient and crossfall change over relatively short distances. Here, the truck speed tends to be lower, with consequently lower response.

Generally, all of the areas of concern exhibited high levels of profile variance that exceeded the thresholds for poor ride quality listed in Table 2.1, often across all three of the wavelengths (3 m, 10 m and 30 m). These were not necessarily seen as continuous lengths, but rather as clusters of high variance, as described earlier. Recorded NAASRA roughness values in these areas of concern were also generally, but not always, high, with 10 m lane roughness values often exceeding 200 NAASRA, and 100 m average roughness often exceeding 105 NAASRA. This latter level of roughness is part of Transit NZ’s current criteria for the selection of potential truck ride improvement sites. An attempt was made to distinguish between sites identified by the survey truck driver as being ride safety issues and those identified as being ride quality issues. However, this was not successful, largely because of the geometry based effects on the profile variance.

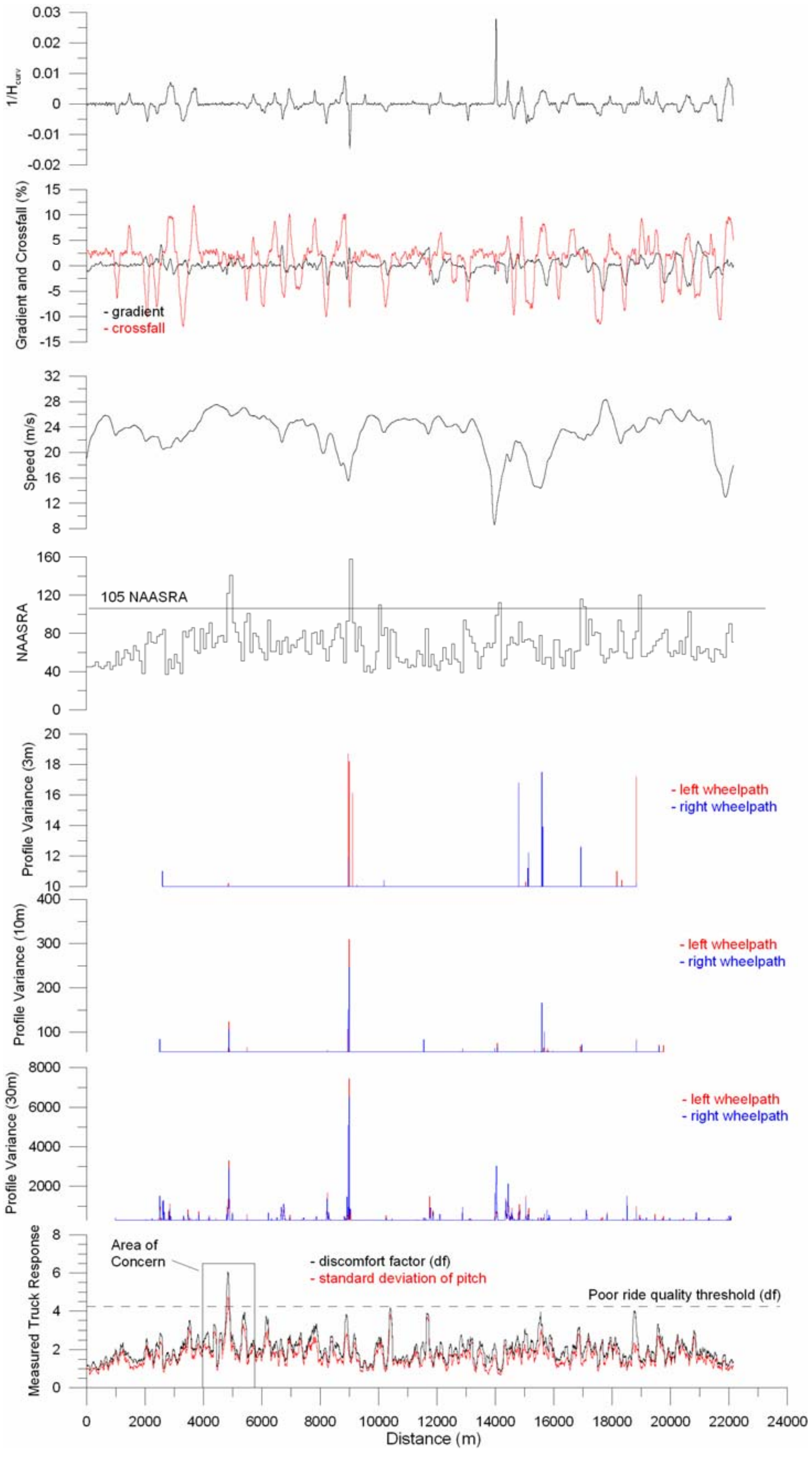


Figure 4.30 Area of concern – measured response data and geometry data.

5. Proposed methodology for selecting and prioritising truck ride sites using profile variance

5.1 Selection methodology

Our proposed methodology is based on the findings described in Section 4. In the current absence of a suitable truck speed model we have used the roughness and geometry parameters as modifying 'filters' to remove road sections that are expected to be lower speed areas. The proposed methodology for selecting sites is as follows:

5.1.1 Threshold profile variance levels

Based on the 10 m averaging length longitudinal profile variance data supplied, the 3 m, 10 m and 30 m wavelength threshold criteria used in the United Kingdom prior to 2005 for indicating consideration of maintenance are appropriate for New Zealand. Road sections with 10 m profile variance values below the criteria of 10 mm^2 for a 3 m wavelength, 56 mm^2 for a 10 m wavelength, and 300 mm^2 for a 30 m wavelength, did not produce measured truck response that exceeded the threshold identified by Jamieson and Cenek (2001) as producing poor ride quality.

Please note that the longitudinal profile variance upon which this study has been based has been superceded in the United Kingdom by the enhanced profile variance. This latter measure incorporates sophisticated filters that attempt to remove the effects that road geometry has on the calculation of profile variance, particularly for 30 m wavelengths. We cannot comment on the thresholds that have been established for the enhanced profile variance. Currently, the longitudinal profile variance is the parameter that is recorded in Transit NZ's RAMM database.

5.1.2 Lengths exceeding thresholds

Short isolated lengths of up to approximately 30–40 m that exceed the threshold criteria in any of the three wavelengths can effectively be ignored. Typically, these are too short to excite a truck's suspension for a significant length of time. We have based this consideration on Transit NZ only being interested in road sections that produce poor truck ride over lengths of more than 100 m.

Any continuous lengths of 50 m or more that exceed either or both the 10 m or 30 m profile variance threshold criteria in either or both wheelpaths should be considered. More importantly, clusters of lengths where the profile variance exceeds either or both the 10 m or 30 m criteria in either or both wheelpaths should be considered. These clusters can be non-continuous or overlapping lengths. Typically, separation of lengths exceeding the criteria in a particular wheelpath or particular wavelength should not exceed 20–30 m.

5.1.3 Vehicle speed

In the absence of a suitable truck speed model we can only filter for low vehicle speed (less than 56 km/h) in a very general way. Firstly, we can exclude all road sections classed as **urban** (speed limits of 70 m/h or less) according to the RAMM database. Secondly, we can filter for geometry parameters that were shown in the measured response data not to produce poor truck ride because of their effect on vehicle speed.

5.1.4 Curvature

Road sections with a radius of curvature of less than 200 m can be excluded. Sharp curves did not produce high measured truck response, primarily because of their effect on moderating vehicle speed and the consequent effect on vehicle response.

5.1.5 Crossfall

Road sections with crossfall higher than +/-10% can be excluded, primarily because they mostly occur in areas with low radii of curvature.

5.1.6 Gradient

Road sections with gradients higher than +/-10% can be excluded, primarily of their effect on moderating vehicle speed and the consequent effect on vehicle response.

5.1.7 Extremely high values of profile variance

The calculation of profile variance, particularly for 30 m wavelengths, can be significantly affected by road geometry. Accordingly, treat the following with caution:

- profile variance exceeding 30 mm^2 for 3 m wavelengths
- profile variance exceeding 400 mm^2 for 10 m wavelengths
- profile variance exceeding 5000 mm^2 for 30 m wavelengths.

5.2 Prioritisation of selected road sections

Having selected road sections on the basis of exceeding the threshold criteria, either in continuous or clustered lengths, the prioritisation in terms of vehicle response is as follows:

5.2.1 Length

The greater the distance for which threshold criteria is exceeded, particularly the 30 m wavelength criteria, the greater the distance that is likely to produce poor truck ride.

5.2.2 High profile variance across multiple wavelengths

Road sections that have profile variance values that exceed the criteria across all three wavelengths (3 m, 10 m and 30 m) generally produce higher response.

5.2.3 Road roughness

The analysis of the longitudinal road profile in terms of specific wavelengths, ie 3 m, 10 m and 30 m, does discard all of the other wavelength information that is generally recorded by survey vehicles. This can range from zero to 50 m or 100 m. Accordingly, sites can be further prioritised according to the levels of 100 m NAASRA roughness.

5.2.4 Vehicle speed

In the absence of a suitable truck speed model, and having filtered sites according to geometry that is expected to reduce vehicle speed to levels unlikely to produce poor ride quality, road sections can be further prioritised if the truck speed can be assessed through other means. These could include speed surveys or assessment of the road geometry.

6. Conclusions and recommendations

The following selection and prioritisation process for road sections that exhibit poor truck ride quality has been developed from an analysis of measured truck response data, longitudinal road profile variance, road geometry and roughness data. Recommendations for additional work are also made.

6.1 Selection and prioritisation process

1. Road sections that have longitudinal profile variance levels below the following threshold criteria do not exhibit poor truck ride behaviour:

3 m wavelengths	–	10 mm^2
10 m wavelengths	–	56 mm^2
30 m wavelengths	–	300 mm^2

   These threshold criteria pertain to the original definition of longitudinal profile variance as utilised in RAMM, not the enhanced profile variance recently introduced in the United Kingdom which employs filtering during the data collection process to reduce the effects of road geometry.
2. Road sections designated as 'urban' according to Transit NZ's RAMM database can be discarded, primarily because vehicle speeds in such areas do not generally generate poor ride quality.
3. Short isolated lengths of up to 30–40 m that exceed the threshold criteria for profile variance in any of the three wavelengths can effectively be ignored as being too short to excite a truck's suspension and produce poor truck ride. This is based on the assumption that 100 m is the minimum length that will be considered for remediation.
4. Continuous lengths of 50 m or more that exceed either or both the 10 m or 30 m threshold criteria for profile variance in either or both wheelpaths should be considered. Lengths of 50–100 m where the profile variance exceeds the thresholds should be considered for treatment as maintenance responsibilities.
5. Clusters where the profile variance exceeds either or both the 10 m or 30 m criteria in either or both wheelpaths should be considered. These clusters can be non-continuous or overlapping lengths. Separation of lengths exceeding the criteria in a particular wheelpath or particular wavelength should not exceed 20–30 m.
6. Road sections with horizontal curvature of 200 m or less can be discarded, primarily because in these conditions the vehicle speed is reduced to levels that do not generate poor truck ride.
7. Road sections with consistent crossfalls larger than +/-10% can be discarded.
8. Road sections with consistent gradients greater than +/-10% can be discarded.

9. Profile variance values, particularly for 30 m wavelengths, can be significantly affected by road geometry. Extremely high values in 'tortuous' terrain, over the following levels, should be treated with caution:

   profile variance exceeding 30 mm2 for 3 m wavelengths
   profile variance exceeding 400 mm2 for 10 m wavelengths
   profile variance exceeding 5000 mm2 for 30 m wavelengths

10. Road sections which are known to be low speed areas (<65 km/h (ie 18 m/s)), either through measurement, or assessment of geometry, can be discarded.
11. Having selected potential sites for remediation, these can be prioritised according to (a) the road lengths that exceed the thresholds, (b) whether the profile variance values exceed the thresholds across all three wavelengths and (c) the levels of NAASRA roughness.

6.2 Recommendations

1. The potential sites selected in 2008 for truck ride improvement works according to Transit NZ's current selection criteria, which are predominantly based on differences in lane roughness, should be assessed according to the criteria established here for profile variance. The trucking industry should also be approached to identify whether any of the potential site sites represent safety issues.
2. Development of a truck speed model should be considered. Apart from differences in suspension characteristics and vehicle loading, speed is the primary vehicle based determinant of response to road surface undulations.
3. Variations in the profile variance with time should be investigated, as at the time of publication, there should be three years of profile variance data available. Significant changes with time can be indicative of potential problems, eg high and increasing levels of 3 m wavelength variance can indicate serious wheelpath cracking.
4. The effects of treatment of truck ride sites should be investigated by looking at the profile variance data in the year following treatment. As a database of treated sites is built up, different treatments could be rated according to their effects on reducing profile variance levels.
5. Investigation of the enhanced profile variance should be considered to assess whether it removes or significantly reduces the effects of road geometry on the calculation of profile variance without affecting its ability to identify road features that compromise truck ride and handling.

7. References

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Appendix A: The calculation of longitudinal profile variance

The calculation of longitudinal profile variance (UK Roads Board) is carried out as follows:

1. The number of profile points corresponding to a moving average length (eg 3 m, 10 m or 30 m) is calculated as:

   $$m = \frac{(\text{moving average length})}{l} \quad \text{rounded to the nearest odd integer}$$

   where l = interval between profile point readings (eg 0.1 m)

   eg for 3 m, 10 m and 30 m moving average lengths, with a reading interval of 0.1 m, the number of points would be 31, 101 and 301 respectively.

2. The number of profile points corresponding to length L over which the longitudinal profile variance is to be averaged (eg 10 m) is calculated as:

   $$J = \frac{L}{l} \quad \text{rounded down to the nearest integer}$$

   where l = interval between profile point readings (eg 0.1 m)

   eg for 10 m averaging lengths, with a reading interval of 0.1 m, the number of points would be 100.

$$\overline{Y}_k = (1/m) \sum_{j=i}^{j=i+m-1} Y_j$$

3. For each point *k* on the survey run, a moving average is calculated as:

   $i = k - (m\text{-}1)/2$ where Y = profile amplitude at point *j*

   k ranges from (m+1)/2 to M-(m-1)/2

   where M is the total number of readings in the run

4. For each point *k* on the survey run, a profile amplitude deviation from its corresponding moving average is calculated as:

$$d_k = Y_k - \overline{Y}_k$$ where Yk = profile amplitude at point k

5. The moving average longitudinal profile variance (LPV) over each length L starting at point i is calculated as:

$$LPV_i = (10^6/J) \sum_{k=i}^{i+J-1} (d_k)^2$$

the 10^6 factor is to convert from m^2 to mm^2.

Appendix B: Truck ride survey (lower North Island) survey route

Figure B1 shows the road sections selected for the truck ride survey conducted in the lower half of the North Island in November 2004 and described in Jamieson and Cenek (2001). Table B1 lists the selected road sections.

Figure B1 Truck ride survey (lower North Island) – selected road sections.

Table B1 Truck ride survey (lower North Island) – selected road sections

No	SH	Area	Start point		End point		Test directions
			RP	Description	RP	Description	
1	1	Wellington	1050	Paremata Roundabout	1023	Paraparaumu Overbridge	Inc & dec
2	56	Manawatu	0	Junction with SH 57	22	Palmerston North	Inc
3	54	Manawatu	40/0	Bridge Abutment - Fielding	0/0	Vinegar Hill	Dec
4	4	Central NI	127/0	Manganui Bridge South Abutment	94/0	Junction with Oio Rd	Inc & dec
5	4	Central NI	70/0	Junction with SH 43	0/0	Junction with SH 3	Inc & dec
6	3	Central NI	76/0	Junction with SH 30 Te Kuiti	88/0	Junction with SH 4	Inc & dec
7	1	Central NI	675/0	Junction with SH 46 Rangipo	708/0	Desert Rd Summit	Inc & dec
8	32	Central NI	0/0	Junction with SH 1 Tokoroa	82/0	Whanganui Stream Bridge	Inc & dec
9	30	Central NI	61/0	Waitomo/Taupo District Boundary	84/0	Whakamaru Junction with SH 32	Inc & dec
10	1	Central NI	569/0	Junction with SH 30	575/0	Atiamuri Rd	Inc & dec
11	1	Central NI	575/0	Atiamuri Rd	606/0	Junction with SH 5	Inc
12	5	Hawkes Bay	150/1 0	RP Marker	249/0	Dillons Hill Culvert	Inc
13	5	Hawkes Bay	190/0	Regional Boundary Marker	190/3	3km from Boundary Marker	Dec
14	2	Hawkes Bay	592/0	Waikare Coast Rd	638/0	Napier Junction with SH 5	Inc & dec
15	2	Gisborne	443/0	Junction with SH 35	533/0	Wairoa Junction with SH 38	Inc & dec
16	2	Gisborne	361/0	Regional Boundary Marker	429/0	Ormond School Whitmore Rd	Inc &dDec