Initial study and development of transverse profile analysis – TTS on local roads

by K Nesnas, S McRobbie and MA Wright

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INITIAL STUDY AND DEVELOPMENT OF TRANSVERSE PROFILE ANALYSIS – TTS ON LOCAL ROADS

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by K Nesnas, S McRobbie and MA Wright (TRL Limited)

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Executive summary

Project Title: Initial study and development of transverse profile analysis – TTS on local roads
Project Officer: Mr E Bunting, Traffic Management Division, DfT
Project Manager: Dr A Wright, Transport Research Laboratory

Objectives of Project
In order to aid the DfT in its goal of introducing automated condition monitoring surveys of local roads in 2005/06 it is necessary to investigate the ways in which transverse profile measurements are made in TRACS Type Survey (TTS), and to determine how appropriate these methods will be on local roads.

- The first objective of this project was to identify the range of dimensions likely to be encountered on the main classes and types of local roads and estimate how frequently they occur on the local road network.
- The second objective of this project was to propose and demonstrate changes in the configuration of the sensors and the processing and analysis of the transverse profile information, to improve the relevance and quality of transverse profile data gathered on all types and classes of local roads.

Project Outputs
The project was required to consider the following outputs:

- Identify the range of dimensions likely to be encountered on the various parts of the non-principal local road network, from experience or by a small sample survey, and characterise these by road class.
- Consider the implications for measuring transverse profile, in terms of both the width to be surveyed and the number and spacing of sensors.
- Consider the implications for characterising transverse profile, in terms of the relevance and appropriateness of the data processing and analysis techniques
- Propose how transverse profile should be measured, analysed and reported to give an indication of road maintenance condition, taking account of the implications of the proposals for the different types and classes of road. The capabilities of the proposed method were to be demonstrated on a sample of local roads.

The requirement for the final output of the project was a brief but comprehensive report covering all aspects of the research, and specifically including: those transverse profile measurement systems, and techniques which are sufficiently well developed and robust enough to be specified for inclusion in TTS surveys of non-principal local roads in 2005/06; the transverse profile measurement systems and techniques which should be researched and developed further in order to enhance the surveys in 2007/08; an assessment of what was required to permit the new techniques and resulting data to be integrated in UKPMS; an assessment of the risks associated with including specific transverse profile measurement and/or analysis techniques at each stage of the survey development.

The report was also to include an outline for the technical specification and quality assurance procedures required for the inclusion of a transverse profile measurement system, data processing and analysis techniques in the specification for 2005/06.
Summary

A review of road widths on the local road network has found that widths range from single track roads with passing places, up to two-lane dual carriageways. Although the road widths typically increase with higher classification this trend is not followed rigidly, with some C or unclassified roads being wider than some B roads. Consideration of current TTS survey vehicles shows that these are typically 2.5m - 3m wide, and it is suggested that current systems should not be expected to survey routes where roads narrower than 5m are likely to be encountered. On such roads the accuracy, particularly of rutting measurements will be reduced. Additionally, oncoming traffic meeting the survey vehicle would cause survey complications. It is concluded that no major hardware modifications should be necessary to allow the majority of the B and C class non-PRN to be surveyed. However, surveys of unclassified roads may be less successful.

Research has been carried out to develop methods to improve current assessments of transverse profile data. This has resulted in the generation of algorithms that improve the measurement of rutting and provide a measure of transverse profile unevenness. The method developed, and recommended for assessing the transverse profile of the pavement, uses a “cleaning algorithm” to find the edge of the pavement and remove features arising from the outer edge of the road (the verge/kerb) that would affect rut and unevenness measurements. Statistical parameters are then calculated to determine the transverse unevenness of the pavement. The results are encouraging. The method reports high levels of unevenness where existing methods report rutting. In addition, it is able to identify areas where transverse profile problems or defects exist, which are not ruts. A description of method is given in Appendix A of this report.

It is felt that the method should be relatively straightforward to implement in TTS systems, as algorithms derived parameters from current measurements. Testing of the implementation by TTS contractors should also be straightforward as, for any given input data, the results of all systems should be identical.

As the new method has undergone only limited testing it is not recommended that it be included in the calculation of BVPI values for 2005/06. However, it is suggested that the method be included in the specification for 2005/06 surveys for testing and to establish its use as part of the assessment toolkit. The new measure will therefore run in parallel with rutting. UKPMS will require modification to accommodate the new measures.

Although the method developed in this work utilises transverse profile measurements provided by typical TTS vehicles. It is suggested that, for future work, other more advanced methods of obtaining transverse profile measurements could be considered. These systems are typically based on scanning laser techniques which can provide transverse profile measurements at transverse spacings of a few mm. Data from such scanning lasers could be used to calculate transverse profile defects either using the existing method, the method proposed as a result of this research, or in an as yet unspecified way, depending on how the research progresses and on the needs of the engineers and other data users.

It is also suggested that further research be carried out into the more detailed evaluation of the methods developed in this work and the consideration of other post-processing techniques including the use of Power Spectral Density. This research may pave the way towards a systematic analysis of the evolution of a particular deterioration and could aid in the routine maintenance of the network.
1 Introduction

The DfT intends to introduce TRACS Type Surveys (TTS) on the Principal Road Network (PRN) and the non-Principal Road Network (non-PRN). The first stage of these surveys began with the introduction of TTS on the PRN in April 2004. This is to be followed by the expansion of the TTS to include the non-PRN in April 2005.

Earlier research by McRobbie and Wright (2004) has shown that engineers carrying out local road maintenance require information on the transverse shape of local roads. Traditionally this information has been measured and expressed in terms of the depths of rutting present on the pavement, and consultations with selected experts in the field of local road maintenance showed that there is still a desire for this type of information.

Transverse profile is measured on the Trunk Road network under the TRACS contract. This specifies that the measuring equipment has a minimum of 20 non-contact sensors over a 3.2m width. This has been found to be suitable and adequate for Trunk Road purposes, and more recently survey vehicles meeting similar specifications have commenced surveys of the PRN. However, the dimensions of the non-PRN are different to those encountered on the Trunk Road network and the PRN. The TRACS Type Surveys for Local Roads Scoping Study (Ekins and Hawker, 2003) recommended that initial research be carried out into the possible range and distribution of road widths which would be likely to be encountered on the non-PRN, and also to undertake an initial research task to assess how best to measure and assess the transverse profile of local roads in the automated surveys scheduled to begin in 2005.

This report presents the results of this initial research, which had the following objectives:

- To identify the range of dimensions likely to be encountered on the main classes and types of local roads and investigate the way in which transverse profile assessments are performed in current TTS surveys.
- Develop a methodology to improve current methods of characterising the unevenness of transversal profiles of non-principal roads in order to obtain reliable measurements with current systems in 2005/06.
- To introduce an interim specification for transverse profile assessments made during TTS surveys on non-principal roads in 2005/06

2 The assessment of local roads with current TTS vehicles

Current TTS vehicles have been developed and designed for the purpose of surveying trunk and principal roads. It is important to consider their dimensions and capabilities in a local road context.

2.1 TTS Survey Vehicles

The consideration of TTS survey vehicles included those vehicles which are operating on roads and already performing routine surveys, and also some of those instruments and vehicles which have been used to survey roads, but are not yet routinely used. These devices may be available for routine surveys in the future.

The existing TTS machines have various sensor configurations for assessing the transverse profile of a pavement, as shown in Table 1. It can be seen that the minimum number of sensors is 18, and the sensor spacing varies from 100mm to 188mm. Given the range of road types to be surveyed under TTS (see below), we can recognise the importance of investigating the effect of these different sensor configurations on the ability of each survey machine to perform the measurements satisfactorily.
<table>
<thead>
<tr>
<th>Machine</th>
<th>Vehicle width</th>
<th>Survey width</th>
<th>Sensor type</th>
<th>Number of sensors</th>
<th>Location on vehicle</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>HARRIS</td>
<td>2.1-2.9m (depending on bar extension)</td>
<td>Up to 3.6m</td>
<td>Laser</td>
<td>25</td>
<td>Front mounted rut bar</td>
<td>Effective sensor spacing of 150mm</td>
</tr>
<tr>
<td>RAV1 / RAV2</td>
<td>2.5m</td>
<td>3.2m</td>
<td>Laser</td>
<td>20</td>
<td>Front mounted rut bar</td>
<td>Sensor spacing of 168mm</td>
</tr>
<tr>
<td>RAV3</td>
<td>2.5m</td>
<td>3.2m</td>
<td>Laser</td>
<td>20</td>
<td>Rut bar mounted in vehicle body, between axles</td>
<td>Rut bar move from front of vehicle to between the axles increases manoeuvrability on narrow roads.</td>
</tr>
<tr>
<td>BABTIE</td>
<td>2.5m</td>
<td>3.2m</td>
<td>Laser</td>
<td>18</td>
<td>Front mounted rut bar</td>
<td>Sensor spacing 188mm</td>
</tr>
<tr>
<td>ARAN (1)</td>
<td>2-3.6m (depending on extension of rut bar)</td>
<td>Up to 3.6m</td>
<td>Ultrasonic</td>
<td>37</td>
<td>Ultrasonic sensors mounted on bar at front of vehicle</td>
<td>Sensor spacing 100mm</td>
</tr>
<tr>
<td>ARAN (2)</td>
<td>2m</td>
<td>4m</td>
<td>Laser</td>
<td>2 scanners</td>
<td>Rear</td>
<td>INO System (See text below)</td>
</tr>
</tbody>
</table>

Table 1: Existing transverse profile / rut measurement sensor configurations utilised on commercial systems available for TTS

As can be seen in Table 1, most systems use discrete non contact measurement devices to record the transverse profile. However, an exception to this rule is the INO system, which uses a combined laser and imaging system in which the laser is used to illuminate the pavement surface in the field of view of the imaging system. The imaging system records the shape of each laser scan on the surface of the pavement and uses this to determine the shape of the pavement surface. The INO system uses two separate laser/imaging pods, and covers a nominal width of 4m, with 1280 points per profile. The INO system can produce a maximum of 25 such profiles per second.

A further system of note that is not currently employed on TTS vehicles, is the Phoenix Scientific Inc. (PSI) Profile Scanning Laser. This device measures the phase change in the laser light emitted from a scanning laser upon returning to the sensor. From this it calculates the distance from the sensor to the road surface and uses this information to create a profile of the road surface. The PSI performs 1000 scans per second, with approximately 1000 data points recorded in each scan, which covers a width of approximately 4m.
2.2 Dimensions of Local Roads

To identify the range of dimensions likely to be encountered on the local road network a consultation was carried out, via questionnaire. The following questions were asked to over 75 Local Authorities:

- What is the distribution and range of road widths on your non principal road network?
- How does this (the distribution of road widths) vary across different road types?

Over 20 responses were received, which gave different degrees of information. Some of the responses were extremely detailed, others gave less quantitative information regarding road widths and distributions. As a result of the response rate, and the comparative lack of detail in many of the replies, it appears that many local authorities have little information regarding the widths of their networks. Therefore it was not possible to derive a comprehensive picture of range of road dimensions which will be encountered on the non-PRN. However, sufficient information was available to enable an estimate to be made of the typical widths, and ranges of widths encountered on local roads. These estimates have been based on those responses which were sufficiently detailed, from experience gained in carrying out practical condition surveys for the purposes of this project, and work carried out by Watson et al (2004) on the automatic identification of edge deterioration on local roads. Table 2 shows the typical widths encountered on various roads on the non-PRN. The column in Table 2 headed “Width range of the majority of (all/Urban/Rural) roads” shows the width range in which most of the roads (excluding the narrowest and widest) of the given type lie, according to the data received.

<table>
<thead>
<tr>
<th>Road classification</th>
<th>Upper and lower widths reported on all roads (m)</th>
<th>Width range of majority of all roads (m)</th>
<th>Width range of majority of Urban roads (m)</th>
<th>Width range of majority of Rural roads (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>3.8 – 15</td>
<td>6 – 10</td>
<td>7 – 9.5</td>
<td>6 – 8</td>
</tr>
<tr>
<td>C</td>
<td>3.5 – 10</td>
<td>6 – 9</td>
<td>7 – 9</td>
<td>6 – 8</td>
</tr>
<tr>
<td>U/C</td>
<td>3 – 11</td>
<td>3.5 – 8.5</td>
<td>4 – 8</td>
<td>4 – 6</td>
</tr>
</tbody>
</table>

Table 2. Variation of reported road widths by category and environment

It is clear from Table 2 that, as would be expected, the unclassified roads are typically the narrowest roads. These are the roads which will pose TTS vehicles the most problems in terms of successfully surveying any given route. Although there are B and C roads which are under 4m wide, most B and C roads have widths lying within the 6-9m width range. Whilst not straightforward, this width range should present less problems for the survey vehicles. It can also be seen in Table 2 that rural roads are typically narrower than urban roads. However, the effective widths of urban roads will be further reduced by on street parking which will effectively reduce the passable width of many of these roads for large periods of time, as well as making any areas underneath the parked cars unsurveyable.

In addition to the quantitative data summarised in Table 2, there was further qualitative evidence that many of the roads which will be encountered are effectively single track roads with passing places, while others were modern dual carriageways of up to 15m in width. However, given the low level of information existing on Local Authority’s databases regarding the road widths it may be difficult for survey contractors to predict the range of widths that will be encountered during their surveys. Indeed, as part of this research work surveys were carried out to collect reference data with the Highways Agency’s HARRIS survey vehicle. These surveys were carried out in Bracknell Forest, Wokingham, Windsor and Maidenhead and Kent. The survey crews were provided with route definitions before
commencing the surveys, covering B, C and Unclassified roads. Whilst some of the B roads encountered during these surveys were easily surveyable and posed no problems to the HARRIS vehicle and crew, other B roads and some of the C and unclassified roads were not able to be surveyed with this system, with the vehicle having to take an alternative route. Such deviations enforced during surveys can lead to increased time and costs.

It can be concluded that, given the current sizes of existing survey vehicles and where safety and practicality is considered, TTS survey vehicles should not be required to survey roads which are less than 3.5m wide. However, if accuracy of the data is also considered, it is unclear whether the data accuracy will be affected on such narrow roads. In particular where the measurement of rutting is concerned the definition of the wheeltracks is unclear on such road widths. It is felt that the data accuracy may be less adversely affected on wider roads, and current TTS survey vehicles should therefore not have problems surveying road widths of 4.5m or wider, assuming that there are no extremely tight bends or corners. However, on roads of this width problems may be caused by meeting oncoming traffic. Hence, to ensure that the vehicle will be able to survey a route without problem and with reasonable accuracy, the road should be a minimum of 5m wide, to avoid problems with meeting oncoming traffic of a comparable size.

The limited nature of the response from the local authorities makes the setting of definite limits impossible, but it seems as if the survey vehicles should be able to survey very nearly all of the B road network without any significant problems or need for hardware adjustment. Experience gained with the HARRIS surveys suggested that the problems on the C roads will be worse than suggested by the data in Table 2, but there are still large proportions of the C roads, which will be surveyable. The data, and experience, suggests that the current generation of survey vehicles will have many problems in surveying the unclassified roads on the non-PRN.

3 Studying the Effect of the characteristics of the transverse profile measurement on rut measurement

This investigation was carried out using existing HARRIS survey data, where it was assumed that HARRIS recorded the profile of the full width of the traffic lane (3.6m), and considered the effects of measurement width and sensor spacing.

Note: The data used here has been subjected to the cleaning algorithm process which is discussed below in Section 4.4. However, the cleaning of the data has not affected the validity of the following investigation, and the results would be equally valid for profiles which have not been cleaned in this way.

3.1 Measurement Width

The measured transverse profile was reduced (in software) in steps from 3.6m to 2.4m, while the central point remained the same, and the effect of this on the offside rut depth predictions and the nearside rut depth predictions was recorded. The results of this are given in Figure 1 and Figure 2 respectively.

The results suggest that an insufficient length of the rut bar to cover the width of the road will yield underestimated values for the rut depth. For the offside rut depth, all the rut magnitudes below the 20mm threshold are reported reliably for a rut bar width between 3.6m and 3m. For this range of the rut bar width, the rut depths above the 20mm threshold are often reported reliably. A rut bar width as small as 2.7m can be used to report offside rut depth but the results should be treated cautiously for deeply rutted sites.

The nearside rut depths are reported reliably if the width of the rut bar is greater than 3.3m. If the widths of the rut bar are between 3.3m and 3m, the rut depth magnitudes above the 20mm
threshold are not reliably reported, for example an actual rut depth of 46mm can be underestimated by 44%. However, it is interesting to note that the rut depths below a 20mm threshold are still reported reasonably well, within a 20% error.

![Figure 1: Effect of the dimension of the rut bar on the A206 Crossways offside rut depth prediction](image1)

![Figure 2: Effect of the dimension of the rut bar on the A206 Crossways nearside rut depth prediction](image2)

### 3.2 Sensor spacing

The sensor spacing was increased incrementally from 150mm to 450mm, the effect of this on the nearside rut depth prediction and the offside rut depth prediction is observed in Figure 3 and Figure 4 respectively. The results suggest that for this site and spacings up to 300mm, the rut depths within a threshold of 20mm are measured reliably. i.e ruts with depths exceeding 20mm are still reported to exceed 20mm, but the absolute accuracy is reduced.
3.3 Implications for current sensor configurations

The sensor configurations for the current generation of TTS machines are shown in Section 2.1, Table 1. These report that the minimum survey width is 3.2m, and the maximum sensor spacing is 188mm.

This information can be compared with the findings of subsections 3.1 and 3.2, which recommend that the measurements be no narrower than 3m if deep ruts must be accurately recorded. However, this can be reduced slightly (to 2.7m) if the requirement is to identify the presence of deep ruts in general, but with reduced accuracy (note this would not meet the current accuracy requirements for TTS). The above subsections have also suggested that similar conclusions may be drawn when assessing the effect of sensor spacing, in that sensor spacing may not adversely affect the rut measurement accuracy up to a spacing of 300mm, when the requirement is to identify the presence of deep ruts in general, but with reduced accuracy.

It is therefore apparent that none of the machines currently available for performing routine TTS surveys should have any problem in accurately measuring rut depths on local roads as a result of having inappropriate hardware or sensor configurations.
4 Characterisation of transverse profiles

An initial review of survey methods, carried out to aid the implementation of TTS on local roads (McRobbie and Wright, 2004) reported that engineers involved in maintaining local road networks rate rutting as a defect which is essential to monitor accurately. It therefore follows that, when considering methods for improving the assessment of transverse profile, these should include the measurement of rutting. However, concern has been previously expressed regarding the use of rutting on local roads. There are two areas of concern. Firstly the measurement of rutting on the PRN has been found, during acceptance tests of TTS systems, to be subject to error on certain roads and it is felt that this error is likely to increase as the surveys move onto the non-PRN. Secondly it is unclear that rutting is suitable as the key method of interpreting transverse profile, and its relevance to all maintenance decisions, particularly on local roads. This concern can be derived from the fact that deterioration of the transverse profile may occur in such a way that traditional rut assessment is unsuitable to quantify the deterioration and hence such sites may be missed from maintenance planning.

The work carried out in this study has therefore been aimed at developing the following:

- Stage 1: Methods that shall aid in the level of confidence obtained in the measurement of rutting,
- Stage 2: Methods that, as an alternative to traditional rut measurements, quantify rutting in a way that can be considered consistent with existing techniques, but also give information on those sites with transverse profile defects that are not necessarily associated with rutting.

The work has also had to address the practicalities of introducing the technique for surveys on the non-PRN in 2005. In order to meet this timescale it was necessary that the method require a minimal amount of alteration to existing hardware, as any changes are not simple or cost-effective to implement in short timescales.

4.1 Development Data Source

The development of methods to characterise the transverse profiles required the collection of transversal profiles on sites covering various road classes. The sites for which transverse profiles were obtained are summarised in Table 3, which includes also the road name of the site, the environment, location and length of the road. The sites were selected on the basis that they satisfy one or more of the following criteria:

- Availability of good reference data.
- Presence of a wide variety of edge features.
- Covering a broad range of level of unevenness.

Class A roads were included in this study as they include sites for which good quality reference TTS data is available. The reference transverse profile data was obtained using the Highways Agency’s HARRIS survey vehicle, with manual checking applied to validate the “Cleaning”/Rut algorithm.

For the identification of non-rutting defects, the methodology followed was firstly to show the consistency of the new measure with the rutting measurement. Where no consistency was observed, for example where there was response in the rutting but not in the new measure, this was investigated by plotting the 3 dimensional view of the road at the location where the inconsistency occurred.
<table>
<thead>
<tr>
<th>Site</th>
<th>Road</th>
<th>Environment</th>
<th>Location</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A206</td>
<td>Urban</td>
<td>Crossways, Dartford, Kent</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>A206</td>
<td>Urban</td>
<td>University Way, Dartford, Kent</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>A228</td>
<td>Urban/Rural</td>
<td>Kings Hill, Maidstone, Kent</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>A249</td>
<td>Rural</td>
<td>Detling Hill, Maidstone, Kent</td>
<td>3.0</td>
</tr>
<tr>
<td>5</td>
<td>B3018</td>
<td>Urban</td>
<td>Waltham Road (1), Twyford</td>
<td>1.2</td>
</tr>
<tr>
<td>6</td>
<td>B3018</td>
<td>Urban</td>
<td>Waltham Road (2), Twyford</td>
<td>2.4</td>
</tr>
<tr>
<td>7</td>
<td>B3034</td>
<td>Urban</td>
<td>Forest Road, Binfield</td>
<td>3.1</td>
</tr>
<tr>
<td>8</td>
<td>C8706</td>
<td>Urban</td>
<td>Hungerford Lane, Binfield</td>
<td>2.2</td>
</tr>
<tr>
<td>9</td>
<td>C8707</td>
<td>Urban</td>
<td>Newell Green, Binfield</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 3: Data used in study

4.2 Stage 1: Improving Rut Measurements

Concerns over the measurement of rutting on the non-PRN arise because of the effects of the road widths on the interpretation of the transverse profile data. Rut depths are typically obtained from transverse profile measurements via the application of an algorithm to the transverse profile data that simulates the measurement taken by a manual inspector with a two-metre straight edge and wedge. The algorithms rely on good-quality transverse profile data with the minimum amount of spurious information that arises from features such as raised kerbs, white lines and verges. On the non-PRN such features are likely to be present in a large number of the transverse profile measurements. The effect of such features is the over-measurement of rut depths by the algorithm as a result of poor placement of the simulated straight edge. Examples of such features are given below in Table 4, in Section 4.4.

The aim of the first stage of the transverse profile analysis is therefore to detect the edge of the road indicating a verge, kerb, or any other feature which does not belong to the transversal profile of the trafficked road. We consider this to be a tool that cleans the transverse profile data before the calculation of the rut depth. However, it is noted that, as the verge data appearing at the edge of the transverse profiles is generally unwanted for most analyses of transverse data, the cleaning tool would be applicable regardless of the subsequent analysis.

Several methods were considered for cleaning the transverse profile data, with the following approach being adopted:

1. The noise in each transverse profile is removed by applying a moving average in the transverse direction. If a scanning laser is used to acquire the profile data then the transverse profiles are smoothed to remove noise from the profiles and to simulate a profile measured using lasers on a rut bar as in current TTS surveys.
2. Each transverse profile is re-sampled using a cubic spline algorithm. This results in all transverse profiles being re-sampled to have the same transverse spacing of transverse profile points and therefore caters for different profile configurations.

3. An average transverse profile (as seen in Figure 5) is calculated by calculating the average (mean) transverse profile based on all transverse profiles contained in the averaging length. The averaged transverse profile is designated “the best profile”. As the averaging length is pre-defined, the number of transverse profiles to average depends on the spacing between consecutive transverse profiles.

4. The best profile is assumed to describe the best achievable measured shape for that averaging length. This best profile is then used for the identification and removal of unwanted parts of the profile, such as kerb and verges by a cross correlation technique. It is noted that care has to be taken to avoid the removal of deep ruts which can be easily mistaken to be the descending step of a kerb. This is done by introducing a control parameter, defined as the ratio (R) between the maximum second derivative in the nearside of the road and the maximum second derivative in the offside of the road. The second derivative is used to smooth the calculated average profile in order to obtain the best profile. The second derivative calculated for resampled transverse profiles at 25mm spacing is used to locate the start of a feature which should not be a part of the transverse section of the road. Unwanted features present themselves by abrupt changes in the second derivative of the transverse profile; more explanation of this is given in Appendix A.

![Figure 5: Concept of averaging length and averaged transversal profile](image)

5. Having established which (if any) parts of the best profile were obtained over the kerb or verge, each individual transverse profile within the averaging length is correlated with the best profile. This correlation is performed by comparing the best profile with each individual transverse profile and by shifting the best profile with respect to the transverse profile to determine the shift of each transverse profile required to obtain the maximum correlation. This is described in more detail in section (4.3).

6. The shift value corresponding to the maximum correlation defines how many sampling steps from the position of the first sensor on the transversal profile is...
required to remove. This shift value multiplied by the resampling interval defines the edge position along the transversal profile, this distance is used to compute the number of invalid sensors i.e. the number of sensors which have recorded the unwanted feature.

4.3 Cross correlation theory

The cross correlation theory is used to determine how much an individual profile should be shifted by in order to align with the best profile. The cross correlation theorem states that it is possible to produce a correlation curve $R$ between two profiles as the product of their respective Fourier transforms. The correlation curve is a function of the lag between the two profiles and is given as:

$$ R(d) = F_1 F_2^* $$

where $d$ is the lag value indicating how many samples it is needed to shift the best profile with respect to an individual transverse profile. The highest correlation value corresponds to an optimum shift $d_{\text{max}}$. Figure 6 illustrates the principle behind the cleaning algorithm based on the cross correlation of the best profile with an individual transverse profile. For each shift of the best profile with respect to the raw profile a correlation value is calculated. A maximum correlation value will correspond to a maximum shift $d_{\text{max}}$ for which the best alignment of the best profile and the individual transverse profile is obtained. A more detailed description of the algorithms used in this process is given in Appendix A.

![Figure 6: Principle of the cleaning algorithm](image-url)
4.4 Applying Cleaning

Table 4 presents examples of features contained within measured transverse profiles that can adversely influence the analysis of transversal profiles (detailed views of these profiles are also given in Appendix B). These examples include transverse profiles recorded over the verge and over kerbs. When such transverse profiles are analysed for rut depths without firstly cleaning to remove these edge features, the resultant rut depths are typically inaccurate due to poor placement of the straight edge in the simulation algorithms.

Table 4 also shows the results of the application of the cleaning algorithm. It can be seen that the algorithm has reliably identified the edge feature and, as shown by the red lines, suggested a position for the edge of the profile that may then be used for subsequent analysis of the profile (e.g. the calculation of the rut depth).

The cleaning algorithm should analyse all transversal profiles of a road section before performing a rut analysis or a statistical analysis. Another useful use of the cleaning algorithm is to determine the edge of the road, see Figure 7 where the edge is calculated as a series of successive red circles along the road. This position of the edge is a very important parameter for calculating the edge step. The cleaning algorithm is used as an edge detector for the project concerning the detection of edge deterioration on local roads (Watson et al., 2004).

<table>
<thead>
<tr>
<th>EXAMPLE OF TRANSVERSAL PROFILES</th>
<th>FEATURE</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Example Image" /></td>
<td>Kerb</td>
<td>In this example the cleaning algorithm has positioned the red line at the bottom of kerb. The feature to the left of the red line is removed, as it is considered not a part of the road.</td>
</tr>
<tr>
<td><img src="image2" alt="Example Image" /></td>
<td>Verge</td>
<td>The edge of the road steps down to a verge. The verge is removed at the position indicated by the red line.</td>
</tr>
<tr>
<td><img src="image3" alt="Example Image" /></td>
<td>Kerb</td>
<td>This is an example of a more complete feature representing a kerb. In this example the flat top of the kerb was picked by the first sensor</td>
</tr>
</tbody>
</table>
### Table 4: Examples of transversal profiles and road edge prediction

<table>
<thead>
<tr>
<th>EXAMPLE OF TRANSVERSAL PROFILES</th>
<th>FEATURE</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Kerb / defect" /></td>
<td>Kerb /  defect</td>
<td>In this example the cleaning algorithm picked up a deterioration at the edge which is the sinking feature of the road and a part of the kerb (the rising step)</td>
</tr>
<tr>
<td><img src="image" alt="Rut" /></td>
<td>Rut</td>
<td>This is an example of a rut feature at the nearside. The cleaning algorithm was successful in locating the start of a the rutting on the road</td>
</tr>
</tbody>
</table>

**Figure 7: Cleaning algorithm predicting the edge of the road**
4.5 **Prediction of rutting on TTS sites following cleaning**

As noted above, the initial aim for the cleaning of the transverse profile data was to improve the assessment of rutting on local roads. Therefore standard rutting analysis methods, based on the simulated 2m straight edge, have been applied, both with and without the application of the cleaning algorithm (which detects the edge of the road and removes unwanted features which may affect the rut calculations).

Transverse profile data from the HARRIS and RAV1 survey vehicles, has been used to test the algorithm. This data is described in Table 1. The sites used for this assessment are described in Section 4.1. The analyses have been carried out using an averaging length of 1m, with individual transversal profiles being collected at spacing of 0.1m. The threshold for the ratio R was equal to 5.

The reference data for this analysis was obtained from manual analyses of the transversal profile collected using HARRIS. For the manual analysis profile sensors were eliminated from the rut calculation where they were collected off the road edge (based on a visual inspection of the transversal profile), in order to obtain the best set of sensors to use for estimating the actual rut depths.

The HARRIS transverse profile data was then processed using the cleaning algorithm and the rutting calculated. Figure 8 and Figure 9 illustrate the effect of the cleaning algorithm on sample transverse profiles, where it can be seen that the algorithm has successfully removed an unwanted edge feature. Figure 10 and Figure 11 compare the nearside and offside HARRIS rut depths obtained on A206 (Crossways) with the reference data. Figure 12 and Figure 13 show the results obtained when this process was repeated using RAV1 transverse profile data (but still using the rutting obtained from HARRIS for the reference data). It can be seen that rut depths calculated after the application of the cleaning algorithm compare well with the reference data. Note that further examples are given in the Appendices (Appendix D shows A206 Crossways, Appendix E shows A206 University Way, Appendix F shows A228 Kings Hill, and Appendix G shows A249 Detling Hill), and examples using RAV1 data are given in Appendix H. In all cases the automatic prediction compared well with the reference data. Furthermore the repeatability of the results was found to be good.
Figure 8: Calculation of rutting before using the cleaning algorithm – with a kerb on the nearside

Figure 9: Calculation of rutting after using the cleaning algorithm – removal of kerb
Figure 10: Run 1, Crossways, nearside rut depth obtained using HARRIS data

Figure 11: Run 1, Crossways, offside rut depth obtained using HARRIS data
Figure 12: A206, Crossways, nearside rut depth obtained using RAV1 data

Figure 13: A206, Crossways, offside rut depth obtained using RAV1 data
4.6 Summary

The rut prediction methods developed have been tested on the data listed in Table 3, sites 1 to 8. The method includes the use of a data cleaning algorithm to remove datapoints from the verge or kerb in any subsequent rut or profile calculations. It can be seen in Figure 10, Figure 11, Figure 12 and Figure 13 that the method is able to predict the rut depths in a way which is consistent with existing methods. However, the new method does not merely replicate the existing results, but the cleaning algorithm reduces the effect of kerbs, verges, road markings or the edge of the road.

In addition to this the method is able to very accurately determine the position of the edge of the road. This method of determining the edge position has been applied in the development of a technique for detecting edge deterioration on local roads (Watson et al., 2004) which has been undertaken as a parallel research project.

5 Stage 2: Alternative Analysis Methods – Statistical Parameters

Stage 2 of this work aimed to characterise the transverse profile by other parameters rather than the rut depth. This will enable the identification of locations which are affected by transverse profile defects which are not rutting, and which are therefore not detected at present when only rut depth is used to assess the transverse profile of the pavement.

After consideration of the shapes of typical transverse profiles, and the possible analysis techniques, it was concluded that the derivation of statistical parameters that characterised each transverse profile would be the approach most likely to succeed. However, it was not clear which statistical parameters would be the most appropriate to characterise the transverse profile. Therefore the approach adopted was one of experimentation. Hence several parameters were calculated for test profiles and the results analysed to identify the most appropriate parameter.

The parameters considered were the: mean, absolute deviation, standard deviation, variance, skew and kurtosis of the measured transverse profile. Furthermore in addition to the calculation of these from the transverse profile, these parameters were calculated for the first and second derivatives of the measured transverse profile in order to emphasise more local variations in the transverse profile. The calculation of these parameters is summarised in section 5.1.

The success of each parameter in describing the condition of the pavement was then assessed against the current measure of rutting for each test site in order to determine the most appropriate parameter, as described in section 5.2.

5.1 Definition and Calculation of the Parameters

To calculate the statistical parameters from the transverse profile data the transverse profile was firstly cleaned using the algorithms described previously. This stage is important to minimise the effect of unwanted edge points on the assessment. The offset and slope was then removed from the transverse profile and each statistical parameter was then calculated. For this work the transverse profiles were measured at 100mm intervals, which results in the statistical parameters being provided every 100mm.

This process was repeated for the first and second derivatives of the transverse profile. To calculate the statistical parameters from the derivatives of the transverse profile data the offset and slope was firstly removed from the cleaned transverse profile, then the first or second derivative transverse profile was calculated, and then each statistical parameter was calculated
using the first or second derivative profile. As before, this process generated a statistical
parameter every 100mm.

A formal definition of the methods employed for slope and offset removal, calculation of the
derivatives and the statistical parameters is given in Appendix A

5.2 Assessment of the Parameters

Following the calculation of the statistical parameters from the profile, the first derivative of
the profile and the second derivative of the profile, the pattern of variation of the statistical
parameters along the site chainage was studied and compared to rutting patterns on the site. A
simple correlation procedure was followed to compute a correlation value for each case. Note
that the rutting was taken to be the mean of the nearside rut and the offside rut depths. It was
assumed the best statistical parameter would have the highest correlation value with the rut
depth in order to meet the initial requirement (Section 3) that alternative measures to rutting
should be reasonably correlated with the rut depth, as this is still considered a measure of
interest.

A further requirement for the statistical parameter was that for a given road class (here we are
concerned with A, B and C roads), the statistical parameter should have a common sensitivity,
which was defined as the ratio of the maximum value of rut depths to the maximum value of
the statistical parameter.

The following sections demonstrate the methodology used to identify the most appropriate
statistical parameter on the three road classes: A, B and C. In the following subsection we
show the process thoroughly for A class roads on a wide variety of sites using data obtained
with HARRIS and RAV1. For class B roads and C roads the process is shown in a separate
subsection.

5.2.1 A Class road

The statistical parameters and rut depths were computed for the A road sites described in
section 4.5, from transverse profile data provided at a spacing of 0.1m. For analysis the
parameters and rut depths were then averaged over lengths of 10m. The results of the
correlation are given in Table 5 and Table 6 for the HARRIS data and the RAV1 data
respectively. As observed from the tables, high correlation between the statistical parameter
and the rut depths, from greater than 0.5 up to 0.94, was obtained for all the sites for the
absolute deviation, the standard deviation and the variance. Although the absolute deviation
of the profile height gave a reasonably consistent high correlation, the absolute deviation of
the first derivative gave the highest correlation value in all cases.

The statistical analysis appears to demonstrate that the absolute deviation of the first
derivative is a suitable parameter to characterise the unevenness of the transversal profile that
arises from rutting. As a demonstration of the predictive capability of this measure Figure 14
shows the distributions of rutting present on a number of the test sites. These sites were
included in the statistical analysis, which gave rise to the high correlation values discussed
above. This shows that the absolute deviation of the first derivative is able to characterise a
wide range of road unevenness.

Figure 15 and Figure 16 also demonstrate that the correlation between the rut depth and the
absolute deviation of the first derivative is very good. The results shown in the Figures were
obtained for Site 1: A206 (Crossways) and Site 2: A249 (Detling Hill). Both figures show the
ability of the first derivative to characterise the complicated changes in the transverse
unevenness of the road. Note also the ability of the new measure to predict the transition from
high unevenness values to low unevenness values. Results for other sites are presented in
Appendix I and Appendix J, which show the results of the absolute deviation of the profile height and the first derivative respectively.

![Graphs showing distribution of rut depths from HARRIS data](image-url)

**Figure 14** Distribution of rut depths from HARRIS data
### Table 5: Cross correlation of HARRIS data with average rut depth

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Correlation values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height</td>
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<tr>
<td>Mean</td>
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</tr>
<tr>
<td>Absolute deviation</td>
<td>0.94</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.95</td>
</tr>
<tr>
<td>Variation</td>
<td>0.95</td>
</tr>
<tr>
<td>Skew</td>
<td>&lt;0</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>&lt;0</td>
</tr>
</tbody>
</table>

### Site 1
- Mean: <0
- Absolute deviation: 0.78
- Standard deviation: 0.83
- Variation: 0.83
- Skew: <0
- Kurtosis: <0

### Site 2
- Mean: <0
- Absolute deviation: 0.83
- Standard deviation: 0.82
- Variation: 0.77
- Skew: <0
- Kurtosis: <0

### Site 3
- Mean: <0
- Absolute deviation: 0.70
- Standard deviation: 0.70
- Variation: 0.68
- Skew: <0
- Kurtosis: <0

### Site 4
- Mean: 0.40
- Absolute deviation: 0.70
- Standard deviation: 0.70
- Variation: 0.68
- Skew: <0
- Kurtosis: <0
<table>
<thead>
<tr>
<th>Site 1</th>
<th>Statistic/Parameter</th>
<th>Site 2</th>
<th>Statistic/Parameter</th>
<th>Site 3</th>
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<th>Site 4</th>
<th>Statistic/Parameter</th>
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</thead>
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<tr>
<td></td>
<td>Mean</td>
<td></td>
<td>Mean</td>
<td></td>
<td>Mean</td>
<td></td>
<td>Mean</td>
</tr>
<tr>
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<td></td>
<td>&lt;0</td>
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<td>&lt;0</td>
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<tr>
<td></td>
<td>Absolute deviation</td>
<td>0.97</td>
<td>Absolute deviation</td>
<td>0.71</td>
<td>Absolute deviation</td>
<td>0.82</td>
<td>Absolute deviation</td>
</tr>
<tr>
<td></td>
<td>0.97</td>
<td></td>
<td>0.95</td>
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<td>0.94</td>
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<td>0.90</td>
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<tr>
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<td>0.97</td>
<td>Standard deviation</td>
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<td>Standard deviation</td>
<td>0.86</td>
<td>Standard deviation</td>
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<tr>
<td></td>
<td>0.96</td>
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<td>0.84</td>
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<td>0.84</td>
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<td>Variation</td>
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<td></td>
<td>0.93</td>
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<td></td>
<td>0.84</td>
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<td>Skew</td>
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<td>&lt;0</td>
<td></td>
<td>&lt;0</td>
</tr>
<tr>
<td></td>
<td>Variation</td>
<td>0.97</td>
<td>Variation</td>
<td>0.77</td>
<td>Variation</td>
<td>0.79</td>
<td>Variation</td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td></td>
<td>0.54</td>
<td></td>
<td>0.67</td>
<td></td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Skew</td>
<td>&lt;0</td>
<td>Skew</td>
<td>&lt;0</td>
<td>Skew</td>
<td>&lt;0</td>
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</tr>
<tr>
<td></td>
<td>&lt;0</td>
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<td></td>
<td>&lt;0</td>
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<td>&lt;0</td>
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<tr>
<td></td>
<td>Kurtosis</td>
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<td>&lt;0</td>
<td>Kurtosis</td>
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<td>Kurtosis</td>
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<td>&lt;0</td>
<td></td>
<td>&lt;0</td>
<td></td>
<td>&lt;0</td>
</tr>
</tbody>
</table>

Table 6: Cross correlation of RAV1 data with average rut depth
An investigation of the sensitivity of the absolute deviation of the first derivative of the transverse profile, defined as the ratio of the maximum rut depth to the maximum of the absolute deviation value, was then carried out. The sensitivity results for all the A road sites are given in Table 7. It can be seen from Table 7 that the sensitivity of the absolute deviation of the first derivative across the sites can be assumed constant for practical purposes. The average sensitivity for HARRIS data is 0.00146 for the first derivative. For RAV1 data, the average sensitivity is 0.00149 for the first derivative. It is therefore noted that even across systems the average sensitivity remains constant (i.e. it makes little difference whether the initial measurements were made using the HARRIS or the RAV1 survey vehicle).

<table>
<thead>
<tr>
<th>‘A road’ Sites (see TABLE 3)</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>HARRIS Data</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.00139</td>
</tr>
<tr>
<td>2</td>
<td>0.00132</td>
</tr>
<tr>
<td>3</td>
<td>0.00150</td>
</tr>
<tr>
<td>4</td>
<td>0.00164</td>
</tr>
<tr>
<td>RAV1 Data</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.00152</td>
</tr>
<tr>
<td>2</td>
<td>0.00156</td>
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<tr>
<td>3</td>
<td>0.00137</td>
</tr>
<tr>
<td>4</td>
<td>0.00152</td>
</tr>
</tbody>
</table>

Table 7: Sensitivity of the absolute deviation of the 1st derivative across sites
Figure 15: Correlation between the average rut depth (Red) and the absolute deviation of the first derivative (Yellow), A206 Crossways

Figure 16: Correlation between the average rut depth (Red) and the absolute deviation of the first derivative (Yellow), A249 Detling Hill
5.2.2 **Class B and C roads**

The absolute deviation of the first derivative, the square of the absolute deviation of the first derivative, the standard deviation of the first derivative and the variance of the first derivative were investigated in order to investigate their use to characterise transversal profile for class B and C roads. The same methodology was followed as above, in which the measure was compared to the rut depths on several sites.

Figure 17 and Figure 18 show examples of the correlation obtained for Site 5: B3018, (Waltham Road) and Site 7: B3034 (Forest Road) respectively; overall the trends of the two curves correspond well. The results of the cross correlation are given in Table 8 for the absolute deviation, the square of the absolute deviation, the standard deviation and the variance. It is observed that the absolute deviation of the 1st derivative, and the square of the absolute deviation of the 1st derivative correlated well with the average rut depth for class B roads.

<table>
<thead>
<tr>
<th>SITE (See Table 3)</th>
<th>Absolute deviation of first derivative</th>
<th>Square of absolute deviation of first derivative</th>
<th>Standard Deviation of first derivative</th>
<th>Variance of first derivative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class B</td>
<td></td>
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</tr>
<tr>
<td>5</td>
<td>0.74</td>
<td>0.71</td>
<td>0.55</td>
<td>0.52</td>
</tr>
<tr>
<td>6</td>
<td>0.71</td>
<td>0.72</td>
<td>0.41</td>
<td>0.36</td>
</tr>
<tr>
<td>7</td>
<td>0.57</td>
<td>0.54</td>
<td>0.37</td>
<td>0.31</td>
</tr>
<tr>
<td>Class C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.27</td>
<td>0.24</td>
<td>0.38</td>
<td>0.37</td>
</tr>
<tr>
<td>9</td>
<td>0.45</td>
<td>0.38</td>
<td>0.51</td>
<td>0.47</td>
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</tbody>
</table>

**Table 8: Cross correlation of HARRIS data with average rut depth**

Table 8 shows that the correlation of the absolute deviation of the first derivative with the average rut depth was not as good on C roads as for B roads. It is possible that, on C roads, the rutting may have dissimilar intensities on each side of the road, which could affect the measure. Furthermore other forms of deterioration based on local unevenness, for example material loss, may also influence the measure. It was found that a higher correlation value was obtained when the absolute deviation was computed for half the transversal profile, and the absolute deviation was correlated to the nearside rut depth in the first half, and the offside rut depth in the second half. The results of applying this approach are shown in Figure 19 and Figure 20, with the correlation values given in Table 9.

<table>
<thead>
<tr>
<th>SITE (See Table 3)</th>
<th>Correlation values</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Nearside</td>
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<tr>
<td>Class C</td>
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<tr>
<td>8</td>
<td>0.40</td>
</tr>
<tr>
<td>9</td>
<td>0.45</td>
</tr>
</tbody>
</table>

**Table 9: Half width cross correlation of absolute deviation with rut depth**

The sensitivity of the absolute deviation of the first derivative on the B and C road sites are given in Table 10. It is observed that the sensitivity values do not vary significantly, although it differs somewhat from that obtained on the A road sites. An average value of 0.0030 is computed for Class B and C roads.
Figure 17: Correlation of absolute deviation of first derivative (Red) with average rut depth (Yellow), Class B Site 5

Figure 18: Correlation of absolute deviation of first derivative (Red) with average rut depth (Yellow), Class B Site 7. (Figure 25 shows 3-D surface profile of location highlighted with black ellipse, Figure 24 shows 3-D surface profile of location highlighted with orange ellipse)
<table>
<thead>
<tr>
<th>SITE (See Table 3)</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class B</td>
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</tr>
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<tr>
<td>7</td>
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<tr>
<td>Class C</td>
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<td>8</td>
<td>0.0030</td>
</tr>
<tr>
<td>9</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

Table 10: Sensitivity of the absolute deviation across sites

5.2.3 Detection of non-rutting unevenness

The following section focuses on the use of the absolute deviation of the first derivative to predict non-rutting defects. To achieve this, non-rutting defects were investigated on Site 9 and Site 6 (Table 3). The locations where the investigation has been carried out are shown in Figure 19 and Figure 20, for chainages 80m (red ellipse), 590m (orange ellipse), and 640m (brown ellipse). At these locations the rut depths (based on a two meter straight edge) are reported to be very low, and sometimes zero in either the nearside or the offside wheel path. In contrast the method based on the absolute deviation of the first derivative predicted a high unevenness of the transversal profile compared to the predictions of the old method.

Three dimensional profile views of the roads corresponding to the locations given in Figure 19 and Figure 20, are depicted in Figure 21 through Figure 23.

Figure 21 shows that the first half of the road (nearside) is depressed compare to the second half of the road (offside), this explains why the magnitude of the absolute deviation reported at 80m into the site is higher that the magnitude of the rutting. It is also observed that both the nearside and the offside part of the road presents unevenness that the rutting was not able to capture, see for example the pothole at chainage 83m in the nearside and the nodulation of the road in the offside.

At a location of 590m, no rutting is reported in the nearside whereas the new method predicts that there is some degree of unevenness which may be unevenness from rutting or other forms of unevenness, Figure 22 shows that in fact the road presents some nearside rutting that the rutting measure was not able to predict, see for example the depression at location 587m and the undulations which are clearly observed in the nearside.

At a location of 640m, both the new method and the rutting measurement predict that there is unevenness, which is more likely to be due to rutting. In the offside, the new method predicts a higher degree of unevenness. Inspection of the road in Figure 23 shows that the road is rutted in the nearside. Also it is observed that there is some degree of rutting that the rut method was not able to pick up.

Two other locations in Site 7 are investigated and shown in Figure 18 for chainages 1550 (black ellipse) and 1600 (orange ellipse). At 1550m the levels reported by the two methods are similar, however at 1600m the current rut algorithms predict high rutting compared to the values reported by the new method. Inspection of Figure 24 shows that the road is indeed rutted at 1600m, but if we consider Figure 25 it is apparent that the level of rutting at 1550m has broadly the same level. Hence it is felt that the level of rutting predicted by the rut algorithm is not reliable at 1600m (in the sense that the rut levels varied suddenly over a short
distance) whereas the new method predicts consistently more or less the same level of rutting at both locations 1550m and 1600m.
Figure 19: Correlation of absolute deviation (Yellow) with nearside rut depth (Red), Class C Site 9. (Figure 21, Figure 22 and Figure 23 show the 3-D surface profiles of location highlighted with the red, orange and brown ellipses respectively)

Figure 20: Correlation of absolute deviation (Yellow) with offside rut depth (Red), Class C Site 9. (Figure 21, Figure 22 and Figure 23 show the 3-D surface profiles of location highlighted with the red, orange and brown ellipses respectively)
Figure 21: Road view at location 80m, Site 9 (red ellipse in Figure 19 and Figure 20)

Figure 22: Road view at location 590m, site 9 (orange ellipse in Figure 19 and Figure 20)
Figure 23: Road view at location 640m, site 9 (brown ellipse in Figure 19 and Figure 20)

Figure 24: Road view at location 1600m at site 7 (orange ellipse in Figure 18)
5.3 Summary

Statistical parameters of the profile height, the first derivative and the second derivative were computed for class A, B and C roads. The cross correlation of these parameters (i.e. the absolute deviation, the standard deviation and the variance) gave correlation values above 0.5, with correlation values between 0.84 and 0.97 being obtained for the absolute deviation first derivative on class A and between 0.57 and 0.74 on class B roads. For C class roads the correlations of the parameters with the average rut depth were not as good as for class A and B roads. However, it was possible to obtain a better correlation by computing the statistical parameters separately for two halves of the transverse profile and correlating these half profile parameters to the nearside rut depth in the first half and the offside rut depth in the second half respectively.

The study has shown that the absolute deviation of the first derivative gave the highest correlation with the rut depth for A, B and C roads. However, unlike the way the rut depth is currently calculated, the absolute deviation of the first derivative is calculated using all the points of the transversal profile. This means that:

- The effect of vehicle alignment on the road will have less effect on the absolute deviation than on existing methods of calculating rut depths.
- The rut depths, as presently calculated with a 2m straight edge, can be estimated easily and reliably.
- Any additional unevenness of the transversal profile, other than the rut depth, can also be quantified easily and reliably. This means that it will be possible to detect non-rutting transverse profile defects.
- The unevenness of the road can be characterised for any shape and any dimension of the road, assuming sufficient data points defining the transversal profile have been measured.
The sensitivity of the absolute deviation of the first derivative (slope) across the sites considered in this study did not vary significantly. Therefore the results of the method can be expected to be equally valid on all roads, and are not especially site specific. An average sensitivity value of 0.0015 was calculated for class A roads and an average value of 0.0030 was calculated for class B and Class C roads.

The study in Section 5.2.3 showed that the new method, based on the absolute deviation of the first derivative, is able to consistently predict transverse road unevenness. The conclusion was reached that the method is better and more reliable than existing methods at predicting unevenness of the road due to rutting or other forms of unevenness such as potholes.

6 Stage 2: Alternative Analysis Methods – the PSD

An alternative approach to characterising the transverse shape of the pavement was investigated which made use of the Power Spectral Density (PSD) of the Fourier transform of the pavement profile. This methodology was explored as it was felt that, as well as being able to detect rutted pavement sections, it may be a good way of detecting and characterising non-rutting profile defects.

Details of the PSD calculations are given in Appendix B.

It was found that in order to calculate meaningful PSD data it was necessary to have profile data which had been sampled at far more than the currently used 18 – 37 points (Table 1). Such profiles would be available from surveys performed using scanning lasers, such as the PPS or INO systems described in Subsection 2.1, but were not currently routinely available, and were not likely to be available in time for routine use in 2005/06.

6.1 Effect of spectral parameters on the PSD

The parameters which influence the PSD calculations are:

1. The length of the Fourier Transform: this controls the frequency resolution or in terms of the ISO technical specification the constant bandwidth narrow band of the spectrum. It defines the evaluation length of the section of the road to be tested for the presence of anomalies. If the evaluation length is 1 then the frequency resolution is defined as $1/l$.

2. The number of averaged segments used to calculate the PSD.

3. The degree of overlapping between two consecutive segments.

In the following analysis the effect of the spectral parameters is shown by applying the power spectral density approach to transverse profiles obtained using the PPS scanner. Figure 26 depicts the input profile data for the power spectral calculations. The PPS scanner transversal profile shows two peaks representing white lines marking the road.
6.1.1 Length of the Fourier transform

The effect of the length of the Fourier transform on the resolution of the spectral response is shown in Figure 27. The results of the analysis were obtained for different lengths of the Fourier transform. The lengths used for calculating the spectral curves are 64, 128, 256 and 512 profile points. The figure shows that the frequency resolution decreases as the length of the Fourier transform increases. This suggests that the precision with which the PSD is calculated will depend on the length of the Fourier transform.
6.1.2 Number of averaged segments

Figure 28: Effect of the number of averaged segments on the power spectral calculations

The effect of the number of averaged segments on the spectral response is shown in Figure 28. The calculations were performed by using four segments with a Fourier Length of 128 points. Three curves were calculated. The first curve, in green, represents the spectral response without averaging; the second curve, in red, represents the spectral response obtained by averaging two segments; and the third curve represents the spectral response obtained by averaging four segments. The effect of segment averaging is clearly observed in Figure 28, the peak of the PSD curves attenuates with averaging.

6.1.3 Degree of overlapping

Figure 29: Effect of overlapping on the power spectral calculations
To study the effect of overlapping on the PSD calculations a Fourier length of 512 points was split into two segments of 256 points. The calculation were performed for different degrees of overlapping, these are 0%, 25%, 50% and 75%. The results are depicted in Figure 29. With respect to 0% overlapping, the peak reduced slightly for 25% and 50% overlapping compared to the much larger reduction which occurred with 75% overlapping. This suggests that an overlapping of greater than 50% should not be used to be able to pick up the feature detected by the peak.

It is therefore recommended that the PSD approach should be developed as a research tool but it is not recommended for inclusion in the initial roll out of TTS type surveys in 2005/06.
7 Implications of this work for TTS on local roads

The problem of assessing the transverse profile condition of a pavement using the measurements made by existing TTS vehicles has been considered with respect to what may realistically be implemented for the 2005/06 survey period.

Road and vehicle dimensions

It was found that the types of road encountered on the non-PRN ranged from single track roads with passing places, right up to two-lane dual carriageways. As expected the typical road widths were different on the different classes of roads, with B roads tending to be wider than C roads, which were generally wider than the unclassified parts of the network. However, this trend was not rigidly adhered to and there were exceptions, with some C roads, or unclassified roads being wider than some B roads.

Given that current survey vehicles are of the order of 2.5m - 3m wide they should not be expected to survey routes where roads narrower than 3.5m are likely to be encountered. The position of the wheeltracks on such narrow roads is unclear and the ways in which the accuracy of the data will be affected by surveying such roads is not fully understood. It is likely that on the narrower roads the accuracy of rutting measurements will be reduced. Additionally, oncoming traffic meeting the survey vehicle would cause survey complications, and if this is to be avoided then the current generation of survey vehicles should not be expected to survey roads of 5m width or less.

Sensor configurations

Sections 3.1 and 3.2 describe an investigation into the effect which sensor hardware configurations have on the measured rut depths. When comparing the findings of these investigations with the hardware specifications (sensor spacings, survey widths) of existing survey vehicles (Table 1) it was concluded that no major hardware modifications would be necessary to allow the majority of the non-PRN to be surveyed (where the survey vehicle was able to successfully negotiate the road).

Existing rut measurements are made difficult if the survey has included the kerb, verge, or even road markings in the data. They are also complicated if the driving line taken during the survey has moved, either towards or away from the edge of the road. All of the above factors make correctly locating the wheelpaths difficult, and can lead to incorrect measurements of rutting.

Accurate measurements of unevenness associated with rut depth was a key requirement of local authority maintenance engineers in the earlier review exercise (McRobbie and Wright, 2004) and the method developed here could prove sufficient for their purposes.

Identifying transverse profile unevenness

An algorithm was developed to detect unwanted features of the surveyed profiles. Such features can then be removed from any subsequent rut calculations. This process is known as ‘cleaning’ the profiles, and makes use of all the survey data present in each profile.

The method developed, and recommended for assessing the transverse profile of the pavement, uses the “cleaning algorithm” to find the edge of the pavement and removes feature arising from the outer edge the road (the verge/kerb). It then makes use of statistical parameters to determine the transverse unevenness of the pavement. The results obtained with the new method (shown in Section 4) are encouraging. The algorithm reports high levels of unevenness where existing methods report rutting. In addition to this it is able to identify areas where transverse profile problems or defects exist, which are not ruts. Full technical details of the method are given in Appendix A.

On local roads, particularly the narrower ones, where there are not two clearly defined lanes with obvious wheeltracks in each lane, the measurement of rutting may prove difficult. By using these new techniques and detecting non-rutting defects it may be possible to gain a better understanding of such sites. Another advantage of the method developed during this work was that the profile cleaning can be used to identify the edge of the pavement. This method has therefore already been implemented in parallel research on detecting edge deterioration on local roads (Watson et al., 2004).
Other approaches

Other methods of making transverse profile measurements were also considered during this research. These were the PPS system, provided by PSI, and the INO system as deployed on the ARAN vehicle.

These systems would provide far more detail in each profile, with the PPS producing almost 1000 data points over a 4m width, and the INO measuring 1280 points in each profile, also of 4m width. However, although the transverse resolution of the scanning devices is very good, the current longitudinal resolution of the INO system is low. The INO system operates at 25 scans per second (compared to 1000 scans per second with the PPS) and so, at survey speeds of 80km/h there would be almost 1m (89cm) between scans.

However, both systems are worth researching further. Data from such scanning lasers could be used to calculate transverse profile defects either using the existing method, the method proposed as a result of this research, or in an as yet unspecified method, depending on how the research progresses and on the needs of the engineers and other data users.

Risks

Because the existing fleet of TTS vehicles will not have to significantly change their hardware or data collection approaches the risk of this preventing the successful adoption of the new transverse profile assessment methodology is greatly reduced.

The software used to process the data will need to be altered in order to use the new method. This new software will have to be able to ‘clean’ the profiles to remove extraneous points and determine the position of the edge of the road, and will then need to be able to calculate and use the newly defined statistical parameters. It is likely that this software will be required to run in parallel with the existing rut measurement software. None of this is likely to be hard to achieve, and should hopefully present no significant obstacle to the roll out of the new techniques. However, careful and close liaison with TTS system manufacturers will be required in order to successfully implement the method.

The new method may have some limitations when used to survey certain road conditions. For example the ‘cleaning’ algorithm depends on the assumption that the shape of the transversal profiles does not vary much within the averaging length. Additionally the ‘cleaning’ algorithm requires that at least the first sensor is over the edge of the road. If the road shape changes dramatically over a short length, or the vehicle driving line deviates too much then the cleaning algorithm will fail, or produce unreliable output, and the subsequent rut depths may be also incorrect. For the implementation of the algorithm on the survey vehicles it will therefore be necessary to define clear requirements for instances where the output of the algorithm should be treated with caution.

UKPMS

Due to the limited scope for testing a significant and representative sample of the non-principal road network within the timescale of this research, it is not recommended that the new method be included in the calculation of BVPI values for 2005/06. The methods included in the specification for 2005/06 surveys should be implemented for maintenance engineers to establish how useful the outputs really are on their roads, and a full examination of that year’s data will then enable the performance of the methods to be more readily assessed. The assessment of the data collected during this period may lead to the refinement of the methods, or may confirm that they are suitable for BVPI purposes.

One implication of running the proposed method for a year without using it to calculate the BVPI is that two separate calculations will have to be performed. The first, for use with the BVPI, will be done with the existing rut depth calculations, while the second calculation will be the generalised concept of transverse profile unevenness characterised by the absolute deviation of the first derivative of the average cleaned profiles, as defined in this study. The UKPMS database will have to be able to accommodate both inputs, at least for the period when the transverse profile unevenness is being trialled, and will also have to be flexible enough to deal with any changes to the transverse profile unevenness indicator which come about as a result of the data analysis.
Technical specification and QA procedures

Appendix A gives an outline for the technical specification in order to implement the proposed method in software. In terms of the required hardware the survey vehicles should be able to cover the width of the road (a survey width of between 2.5m and 3.6m), should themselves be of the order of 2.5m to 3m wide to negotiate the roads likely to be surveyed and encountered, and should have an inter-sensor spacing of no greater than 300mm.

Once the survey contractors are in a position where they are able to perform the surveys it will be necessary for them to undergo a QA procedure. This should be relatively straightforward as the output of the method is a derived parameter. That is, for any given input data, the results of all systems should be identical. The only variable therefore is the ability of the sensors to measure the profile of the pavement accurately enough, and this is already covered in existing accreditation tests. It should therefore be straightforward to check that the survey providers have correctly implemented the new transverse profile assessment method during the accreditation testing procedure.

Continued testing and development for 2007/08

1. Evaluate data collected in first year of operation

The recommendations are for the calculation of rut depths to continue as at present, with parallel calculation of the transverse unevenness in the first year. The results from the new method are not to be used for any BVPI calculations, but are to be available to engineers as additional information to assist them. At the end of the first year’s surveys the quality and usefulness of the transverse unevenness measure should be assessed, and, in the light of the results of this assessment the method should be altered as appropriate, and further consideration given to adoption of the method as the recommended assessment method, including use in the BVPI.

2. Consider upgrading TTS transverse profile measurements

To enhance the data available from transverse profile surveys one aim is to accurately model features of the transversal profile which the current systems cannot detect. Such features include, for example, the presence of cracking, the exact geometry of a pothole or the exact location of road repairs. More detailed measurements could be used to identify these features.

3. Power Spectral Density

The PSD, as discussed in Section 6 is a powerful technique which can split a signal into its wave contents; an analogy is of a prism splitting white light into the colours of the rainbow. It is proposed to develop a methodology based on the hypothesis that a particular deterioration in the transversal profile can be identified and filtered using their wavelength signatures. This research may pave the way towards a systematic analysis of the evolution of a particular deterioration and could help to guide the routine maintenance of the network.

4. Development of an integrated transverse profile parameter

A single parameter, based on the absolute deviation of the first derivative of the transversal profile should be developed. This integrated parameter would be calculated as a weighted sum of the contributions of the different deteriorations that are affecting the quality of the transversal profile in terms of comfort and safety. The deterioration will be quantified as a threshold of the absolute deviation of the first derivative. The method should be able to filter the different deteriorations and quantify their occurrence along the road, and would provide a useful alternative to the currently utilised rut depth parameter, as the integrated parameter would also be able to detect the presence of non-rutting defects.
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9 References

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Appendix A. Algorithm Definitions

A.1 Cleaning Algorithm

The following provides a summary description of the cleaning algorithm. Figure 30 depicts the flow chart of the cleaning algorithm.

A.2 Resampling the data

Each transverse profile is resampled in order to create a uniform sampling interval and also to obtain refined sampling intervals for the first and second derivative calculations. The resampling of data is performed using a cubic spline algorithm. This method of resampling is the best as it fixes “rigidly” the points to resample between the splines.

A.3 Average profile

An averaging length is defined (1m has been used in this work). The average transverse profile is calculated from the statistical mean of the transversal profiles within the averaging length. The number of transversal profiles to average is defined by the spacing between the transversal profiles.

A.4 Smoothing of the Average profile

The smoothing of the average profile is performed in order to remove unwanted features such as verges and kerbs. The smoothing uses the first and the second derivative of the profile, to locate the verge or the kerb and then truncate it.

The smoothing algorithm uses the sign of the second derivative at the location where the first derivative vanishes to decide on the curvature of the kerb if it is convex or concave. Then depending on the type of the curvature the algorithm searches for a minimum or a maximum. The minimum will indicate for example the top a kerb feature or a rutting feature, and the maximum will indicate the bottom of the kerb feature or the rutting feature.

The smoothing algorithm distinguishes between the descending step of a kerb and the one of a rut by calculating the ratio (R) between the maximum derivative in the first half of the profiles and the maximum derivative in the second half of the profile. A ratio of R=5 was used for the rut calculations.

A.5 Correlate the average profile and compute the edge

A comparison is carried out between the average profile and each individual profile within the averaging length. This comparison is based on the discrete cross correlation theorem which states that:

“The discrete correlation of two real pair is defined as:

\[ \text{corr}(g, h) \leftrightarrow G^* H \]

where \(G\) and \(H\) are the discrete Fourier transforms of \(g\) and \(h\), and the asterisk denotes complex conjugation”

The implementation of this theorem and its application has been implemented in the eighties and addressed in several numerical text books. A numerical coding of the correlation theorem which uses an elegant subroutine calculating both the direct Fast Fourier Transform (FFT) and its Inverse Fast Fourier Transform (IFFT), is given in the literature (Press et al). To summarise, the correlation theorem is implemented as follows:
• The FFT of the average profile and the individual profile is obtained
• Multiply on resulting transform by the complex conjugate of the other.
• Inverse FFT the product.

The results ($r_k$) will formally be a complex vector of length N. However its imaginary parts are zero since the original set of data are both real numbers. The components of $r_k$ are the values of the correlation at different lags with negative and positive values stored in a wrap around order. The correlation at zero lag is in $r_0$, the correlation at lag 1 is in $r_1$, the correlation at lag -1 is in $N-1$ etc.…

One inconvenience of the FFT is it requires periodic intervals, therefore it is necessary to use zero padding although this method is not always the best solution. The length of padding will depend on the lag we are interested with. If a correlation for lags as large as +/- K is required then it is necessary to append a buffer zone of zeros at the end of both input data sets.

A.6 Compute the maximum shift and the edge position

The shift value corresponding to the maximum correlation defines how many sampling steps from the position of the first sensor on the transversal profile is required to remove. This shift value multiplied by the resampling interval defines the edge position along the transversal profile, this distance is used to compute the number of invalid sensors i.e. the number of sensors which have recorded the unwanted feature.
Main input parameters:
Matrix of transversal profiles
Averaging length
Sensor spacing

Figure 30: Flow Chart of the cleaning algorithm
Statistical Parameters

The following provides a summary description of the calculation of the statistical parameters.

**Resampling:**
Each of the transverse profiles is resampled using a cubic spline algorithm to create a dataset with uniformly sampled data.

**Slope and Offset Removal:**
The best fitting straight line is calculated through the profile data-points. This straight line is then subtracted from the profile in order to remove the offset and slope present in the data.

**The First and Second Derivative:**
To calculate the first and second derivatives of the transverse profile the profile was firstly re-sampled to a transverse measurement interval of 25mm and the formula $\Delta y/\Delta x$ and $\Delta^2 y/\Delta x^2$ applied for the calculation of the first derivative and the second derivative respectively.

**Mean:**
The first parameter used in the statistical analysis of transversal profiles is the mean value:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$  \hspace{1cm} (A.1)

**Variance:**
The second parameter is the variance, defined as:

$$Var = \frac{1}{(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2$$  \hspace{1cm} (A.2)

**Standard Deviation:**
The third parameter is the standard deviation. This is defined as:

$$\sigma = \sqrt{Var}$$  \hspace{1cm} (A.3)

**Absolute Deviation:**
The fourth parameter is the absolute deviation, which is defined as:

$$abs \_ Dev = \frac{1}{n} \sum_{i=1}^{n} |x_i - \bar{x}|$$  \hspace{1cm} (A.4)
Skewness:
The fifth parameter is the skewness (the degree of asymmetry of a distribution around its mean) and is defined as:

\[ Skew = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{x_i - \bar{x}}{\sigma} \right)^3 \]  
(A.5)

Kurtosis:
The sixth parameter used is the kurtosis (the relative degree of peakedness or flatness of a distribution). This is defined as:

\[ Kurt = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{x_i - \bar{x}}{\sigma} \right)^4 - 3 \]  
(A.6)
Appendix B.  Power Spectral Density method

In the following the different steps used in computing a power spectral density based on the Fourier Transform method is described briefly. The numerical implementation of the Power Spectral Density (PSD) calculations is based on the method described in the 3rd working Draft of ISO TECHNICAL SPECIFICATION (ISO/TS 13473-4). The components of the PSD calculations are depicted in Figure 31 and are described in the following subsections.

B.1 Slope offset and suppression
To obtain a profile curve useful for mathematical calculations it is necessary to remove any slope to ensure the mean level of the profile over the evaluation length is reduced to zero. This is based on subtracting a least-squares fit from the profile.

B.2 Windowing
The digital Fourier transform is based on the assumption that the input signal repeats itself with a period equal to the signal duration. For instance a signal sampled over a distance l is considered to repeat itself at \ldots-2l, -l, 0, l, 2l,\ldots etc. At the end of the signal there might be a jump in the composite signal, this effect is known as leakage. To prevent leakage the method uses a window to reduce the signal to zero at the edges. The preferred window in the standard is the Hanning window which has the shape of a squared cosine and is defined as:

\[ w_i = 1 - \cos \left( \frac{2\pi i}{N} \right) \quad \text{for} \quad i=0,\ldots,N-1 \]  

(B.1)

The window is applied by multiplying the signal with the filter function as:

\[ Z_{i,\text{win}} = \frac{w_i Z_i}{\sqrt{\frac{1}{N} \sum_{i=0}^{N-1} w_i^2}} \quad \text{for} \quad i=0,\ldots,N-1 \]  

(B.2)

B.3 Digital Fourier Transform
The Digital Fourier Transform is defined by:

\[ Z_k = \frac{1}{N} \sum_{i=0}^{N-1} Z_{i,\text{win}} e^{-j2\pi ik/N} \quad \text{for} \quad k=0,\ldots,N-1 \]  

(B.3)

For each sampled point \((i)\) in the spatial domain corresponds a Fourier transform \(k\) in the frequency domain. The results of the Fourier Transform are narrow band values with complex values. The resolution of the Fourier transform will depend on the evaluation length \((l)\) and is equal to:

\[ \Delta f_{\text{spatial}} = \frac{1}{l} \]  

(B.4)
### B.4 Power spectral density calculations

The power spectral density is defined as:

$$Z_{\text{PSD},k} = \frac{2|Z_k|^2}{\Delta f_{\text{spatial}}} \quad \text{for} \quad k=0,\ldots,\left(\frac{1}{2}N-1\right) \quad (B.5)$$

or by its logarithmic transform as:

$$L_{\alpha,k} = 10 \log \left(\frac{2}{\alpha_{\text{ref}}} \frac{|Z_k|^2}{\alpha_{\text{ref}}}\right) \quad \text{for} \quad k=0,\ldots,\left(\frac{1}{2}N-1\right) \quad (B.6)$$

where:

- $\alpha_{\text{ref}}$ is the reference root mean square value
- $L_{\alpha,k}$ is the profile level with frequency band $f_k$ with bandwidth $\Delta f_{\text{spatial}}$ (decibels)

**Figure 31**: A brief flow chart for the power spectral density implementation
Appendix C. Detailed views of cleaned transverse profiles

In the following a series of examples illustrating edge location predictions on full transverse profile using the cleaning algorithm are given. A wide variety of edge features are included in the examples such as kerbs, verges and other defects. The cleaning algorithm delimits the edge features by a vertical red line. Some of the examples illustrate the ability of the algorithm to recognize rutting features.
Figure 32: Examples of full transverse profiles and edge predictions.
Appendix D. Site 1: A206, Crossways

Figure 33: Site1 Run1: Crossways A206

Figure 34: Site1 Run1: Crossways A206
Figure 35: Site 1 Run2: Crossways A206

Figure 36: Site 1 Run2: Crossways A206
Appendix E.  Site 2: A206, University Way

Figure 37: Site 2 Run1: University Way A206

Figure 38: Site 2 Run2: University Way A206
Figure 39: Site 2 Run3: University Way A206

Figure 40: Site 2 Run4: University Way A206
Appendix F. Site 3: A228, Kings Hill

Figure 41: Site 3 Run1: Kings Hill A228

Figure 42: Site 3 Run1: Kings Hill A228
**Figure 43:** Site 3 Run2: Kings Hill A228

**Figure 44:** Site 3 Run2: Kings Hill A228
Figure 45: Site 3 Run3, nearside rut depth

Figure 46: Site 3 Run3, offside rut depth
Appendix G. Site 4: A249, Detling Hill

**Figure 47:** Site 4 Run1, A249 Detling Hill, nearside rut depth

**Figure 48:** Site 4 Run1, A249 Detling Hill, offside rut depth
Figure 49: Site 4 Run2, A249 Detling Hill, nearside rut depth

Figure 50: Site 4 Run2, A249 Detling Hill, offside rut depth
Figure 51: Site 4 Run3, A249 Detling Hill, nearside rut depth

Figure 52: Site 4 Run3, A249 Detling Hill, offside rut depth
Appendix H. Rut Analyses using RAV data

Figure 53: Site 1 nearside rut depth

Figure 54: Site 1 offside rut depth
Figure 55: Site2, nearside and offside rut depths
**Figure 56:** Site3 nearside rut depth

**Figure 57:** Site3 offside rut depth
Figure 58: Site 4 nearside rut depth

Figure 59: Site 4 offside rut depth
Appendix I. Cross correlation of the profile height

In the following the rut depth is represented by the yellow curve and the absolute deviation is represented by the red curve.

Figure 60: Site 1, rut depth – absolute deviation of profile height correlation

Figure 61: Site 2, rut depth – absolute deviation of profile height correlation
Figure 62: Site 3, rut depth – absolute deviation of profile height correlation

Figure 63: Site 4, rut depth – absolute deviation of profile height correlation
Appendix J.  Cross correlation of the first derivative

In the following the rut depth is represented by the yellow curve and the absolute deviation is represented by the red curve.

**Figure 64:** Site 1, rut depth – absolute deviation of 1st derivative correlation

**Figure 65:** Site 2, rut depth – absolute deviation of 1st derivative correlation
Figure 66: Site 3, rut depth – absolute deviation of 1st derivative correlation

Figure 67: Site 4, rut depth – absolute deviation of 1st derivative correlation
Appendix K. Cross Correlation between rut depth and first derivative of the absolute deviation: B & C roads

In the following the rut depth is represented by the yellow curve and the absolute deviation is represented by the red curve.

**Figure 68:** Site 5, rut depth – absolute deviation of 1st derivative correlation

**Figure 69:** Site 6, rut depth – absolute deviation of 1st derivative correlation
Figure 70: Site 7, rut depth – absolute deviation of 1st derivative correlation

Figure 71: Site 8, rut depth – absolute deviation of 1st derivative correlation
Figure 72: Site 9, rut depth – absolute deviation of 1st derivative correlation
Figure 73: Site 5, rut depth – absolute deviation of 1st derivative correlation. Nearside

Figure 74: Site 5, rut depth – absolute deviation of 1st derivative correlation. Offside
Figure 75: Site 9, rut depth – absolute deviation of 1st derivative correlation. Nearside

Figure 76: Site 9, rut depth – absolute deviation of 1st derivative correlation. Offside