MEASUREMENT OF THE ACOUSTIC PERFORMANCE OF ROAD SURFACES

Version: Final Report

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Executive summary

Tyre/road noise is the dominant source of noise from high-speed traffic and, therefore, considerable benefits could be achieved by greater use of surfaces that produce lower levels of tyre noise. However, more information is needed on the methods available for assessing the noise from different road surfaces. This report provides a critical overview of the two main measurement methods and their interrelationships.

Currently, the most widely used test method is the Statistical Pass-by (SPB) technique. This method involves establishing the average noise levels from individual vehicle types at a standard distance and passing speed. The results obtained allow the noise effects of different surfaces to be compared in a form that can be directly related to roadside traffic noise levels. An International Standard SPB method has been developed and this has now been adopted in many countries as the preferred method for assessing the acoustic properties of road surfaces.

There are, however, some disadvantages with the SPB method. The main problem is associated with the acoustical requirements of the test site which can limit the ability to measure at arbitrary locations. A further disadvantage is that the results of measurements taken with the SPB method are not solely dependent on road surface characteristics but also depend upon the characteristics of the vehicles in the traffic stream. SPB measurements taken in the future may, therefore, be affected by changes in vehicle and tyre design, thereby making it difficult to compare such measurements with historical SPB data.

To overcome some of these difficulties, a supplementary method, known as the Close-proximity (CPX) measurement method is currently under development as an ISO standard. This method requires the measurement of tyre/surface noise using receptors located in close proximity to a standard tyre. This type of measurement attempts to isolate the noise specifically from the tyre/surface and therefore overcomes some of the potential difficulties encountered with the SPB method. It also offers the advantage that, with suitable equipment, measurements can be taken at traffic speeds allowing long sections of road to be examined. Its main disadvantage is that the results obtained cannot be simply related to roadside traffic noise levels and that it is fundamentally a more complex type of measurement, requiring the use of specially developed trailer systems or vehicles.

The report includes the results of an analysis that examines the degree of correlation of noise levels taken using the CPX method with corresponding noise levels taken using the SPB method. It is anticipated that the ability to estimate SPB noise levels from CPX data would be of particular value in relating the acoustic characteristics of road surfaces with roadside traffic noise levels and, hence, community noise impact. The greater efficiency of the CPX method would potentially allow large sections of the network to be assessed in this manner.

The objective of examining the correlation between the two types of measurements was achieved by carrying out a series of measurements on different road surfaces using both measurement methods. The statistical correlation between the data was then examined. Seventeen different sites located on thirteen different road sections were included in the measurement programme. The range of surface types included porous asphalt (PA), stone mastic asphalt (SMA), hot rolled asphalt (HRA), exposed aggregate concrete (EAC) and brushed concrete (BC).

It was found that for the non-absorbent road surfaces studied, there was generally a high degree of correlation between SPB noise levels and standard measures of CPX levels which was independent of whether the measurements were taken at 80 km/h or 110km/h. Furthermore, there was no significant change in the degree of correlation achieved when the full set of CPX reference tyres was used (i.e. tyres A, B, C and D) or the reduced set (i.e. tyres A and D only). Typically the amount of variance in the SPB levels explained by the measures of CPX levels examined was about 90% with a standard error of prediction less than 1.0 dB(A).

Currently there are four different test tyres (labelled A, B, C, D) with different tread pattern characteristics that are used to represent the range of tyres in use on different vehicle types. Normally measurements are taken using each tyre and an average obtained which is weighted to represent an average mix of vehicle/tyres in the traffic stream.
When the porous surfaces were included in the analysis the degree of correlation was significantly poorer and the variance explained reduced to about 75%. This was attributed to the inability of the CPX method to detect the influence of the absorption properties of the road surface on noise propagation. The SPB measurements are taken at 7.5m from centre of the test surface and are therefore capable of measuring these effects.

By repeating the analysis using CPX noise levels recorded at non-standard microphone positions located close to the rear and front of the contact patch of the tyre (i.e. microphone positions M6 and M7) it was found that a high degree of correlation was again achieved even when the porous surfaces were included. In this case the variance in SPB levels explained was about 90% and the standard error of prediction was less than 1.0 dB(A). The general improvement in the correlation for all surfaces can be explained by the fact that sound levels recorded at positions to the rear and in front of the contact patch will be influenced by the absorption properties of the road surface due to the so called “horn effect”. This refers to the amplification of the sound due to multiple reflections occurring between the road surface and the tyre tread either side of the contact patch.

A linear regression analysis between SPB vehicle noise indices for high-speed roads and CPX noise levels for the individual reference tyres again showed that the degree of correlation was dependent on whether the porous surfaces were included in the analysis. When the regression analysis excluded the porous asphalt surfaces the explained variance ranged between 84-91% depending on the reference tyre used. The standard error of prediction improved from about 1.4 dB(A) to about 0.8 dB(A). For light vehicles, reference tyre B performed marginally better in estimating the road side SPB levels whereas for the heavy vehicle category both tyre B and tyre D gave a similar and improved performance over the other two tyres.

Repeating the analysis using averaged sound levels recorded at microphone positions at the rear and in front of the contact patch of the tyre, microphone positions M6 and M7, provided a high degree of correspondence between SPB and CPX levels for each reference tyre. In this case, reference tyre B provided a better overall performance than the other tyres for both light and heavy vehicle categories. A step-wise multiple regression analysis confirmed the result that reference tyre B provides the most statistically significant correlation with SPB noise levels from high speed roads.

Overall the results of the analysis of the correlation between CPX and SPB noise levels indicate that it is possible to achieve reliable estimates of SPB noise levels from appropriate measures of CPX noise levels. It is also indicated that it might be possible to simplify the procedure such that measurements are only taken on one reference tyre (tyre B appears to be a suitable candidate) and at a single passing speed without significantly reducing the accuracy of estimating the roadside values of SPB noise levels.

It would appear that the problems of taking CPX measurements on porous road surfaces can be largely overcome by using close-proximity microphone positions located at the optional positions perpendicular to and in line with the tyre rather than at the currently recommended mandatory 45 degree positions as described in the draft standard.

In order to confirm these observations and to establish more comprehensive relationships between SPB and CPX noise levels it is recommended to extend the range of surfaces to include thin surfaces and surface dressings. Since the work thus far is limited to high speed roads, the further study should also examine the relationships between CPX and SPB noise levels for medium and lower speed roads.
1 Introduction

The dominant source of noise from traffic on high-speed roads arises from the interaction between tyres and road surfaces. However the acoustic performance of different types of modern road surfacing materials can vary considerably.

As part of "Transport 2010 - the 10 year plan" (Department for Transport, Local Government and the Regions, 2000) the Government has set the Highways Agency the target of installing quieter surfaces on more than 60% of the road network. It is estimated that achieving this aim will lead to reductions in traffic noise that will benefit up to 3 million people living within 600 m of trunk roads in the UK.

There is a need for a method of classifying the acoustic performance of quieter road surfaces objectively. The Highways Authorities Products Approval Scheme (HAPAS) tests for the certification of Thin Surfacing Systems and includes a noise test which provides a basis for this, but there is still a need to better understand and harmonize test methods particularly those of materials developed and tested elsewhere in Europe (British Board of Agrément, 1998).

The two most important test methods for measuring tyre/road noise are the statistical pass-by (SPB) test procedure and the Close Proximity (CPX) test procedure. The statistical pass-by procedure has been adopted by the International Standards Organisation (ISO) as the preferred method for assessing the influence of road surfaces on traffic noise (International Standards Organisation, 1997). However, there are a number of limitations that restrict the use of this procedure in practice. The more recently developed CPX method is currently less widely used than the SPB method. However, it offers some important advantages over the SPB method and is currently being ratified by ISO as a complementary test procedure for the assessment of road surface noise.

The main aim of this study was to compare the results obtained by the SPB and CPX test methods and then to examine whether SPB noise levels could be predicted from measurements of CPX noise levels. Measurements of both SPB and CPX noise levels have therefore been taken on a range of surfaces and statistical analyses carried out to determine the degree of correlation between the two types of measurements. This report describes this study and the results obtained. It also contains a critical review of these two test methods highlighting their respective strengths and weaknesses.
2 Statistical Pass-By Method

2.1 Introduction

The pass-by method is probably the most frequently used procedure for assessing the influence of road surfaces on vehicle noise emissions. It is relatively simple procedure, and the results produced can be related to overall levels of traffic noise occurring at the roadside.

There are a number of variants of the pass-by method although, for the purposes of assessing tyre/road noise, the most widely accepted is the statistical pass-by, or SPB, method. Essentially, pass-by methods consist of measuring the noise generated by a vehicle or vehicles travelling past a stationary microphone. The SPB technique allows the noise characteristics of different road surfaces to be compared. The method was originally developed at TRL in the 1970s (Franklin, Harland and Nelson, 1979) and has been adopted as the preferred method for comparing noise emission levels from vehicles travelling on different road surfaces (International Standards Organisation, 1997a). The method described in ISO 11819-1, the standard relating to SPB measurements, has also been adopted as the basis of the noise testing component of HAPAS, the Highways Authorities Product Approval Scheme (British Board of Agrément, 1998). The SPB method is also widely used in other countries. For example, the German Ministry of Transport specifies a version of the method in GEStrO.92 (Bundesministerium für Verkehr, 1992) in the German Standard relating to this technique. The ISO procedure has also been adopted by the European Standards Organisation, CEN.

During an SPB measurement, the maximum noise levels and speeds of individual vehicles selected from the traffic stream are measured. Figure 2.1 shows measurement setup. The traffic population is usually categorized into at least two groups, typically 'light' vehicles and 'heavy' vehicles, and for each data set a regression of noise against the logarithm of vehicle speed is calculated. The major benefits of the method are that it gives both repeatable and reproducible results and, provided a sufficient number of vehicles are measured in each of the vehicle groups, the results can be used to estimate the level of noise emanating from the traffic stream. By taking a statistical sample of live traffic, the influence of the road surface on vehicle and traffic noise levels can be determined without needing to use special test vehicles and tyres.

![Figure 2.1: Typical layout for conducting SPB measurements](image-url)
The main disadvantage of the SPB method is that the acoustical requirements of the test site can restrict the ability to measure at arbitrary locations. A further disadvantage is that the results of measurements taken with the SPB method are not solely dependent on road surface characteristics but also depends upon the characteristics of the vehicles in the traffic stream. SPB measurements taken in the future may be affected by changes in vehicle and tyre design, thereby making it difficult to compare such measurements with historical SPB data.

Another widely used variant of the pass-by procedure is known as the controlled pass-by (CPB) method. The CPB method is normally used for comparing the noise from different tyres on standard testing surfaces and is only rarely used in the UK for testing road surfaces. However some countries, notably Germany and France, have used the CPB method extensively (Beaumont and Soulage, 1990). The German Ministry of Transport has specified this test for GEStrO.92as an alternative to the SPB method. These test methods are discussed further in Section 2.3.

### 2.2 Limitations of the SPB procedure

Whilst the SPB method provides a basis for the standardisation of tyre/road surface noise measurements, there are some important factors that need to be considered in order to obtain reliable and repeatable results. Perhaps, the most significant problem that affects the reproducibility of all pass-by measurements is that test results can be influenced by variations in temperature and wind conditions. This is further complicated by the possibility that temperature effects are also influenced by the type of road surface and test tyre. TRL reports on the topic “Factors Affecting SPB Measurements” for the Highways Agency provide a method of interpreting test results obtained under a range of conditions.

As mentioned previously, pass-by methods also require a number of site selection criteria to be met for the results to be valid. An SPB measurement site must be a section of homogeneous, straight, level road, and at least fifty metres in length, with the running surface in good order. There must also be a twenty-five metre radial area around the microphone position free from any reflecting objects such as building facades, noise barriers, road cuttings and embankments. The widespread presence of such features reduces the ability of highway authorities to assess the acoustic performance of road surfacings at arbitrary locations. A further point is that SPB measurements taken at a specific location can only be related to a relatively short section of road surface. This means that any variability in tyre/road noise levels due to variations in the surface texture characteristics of a road surface along its length can only be determined if SPB measurements are carried out at several locations along the length of the road under study. Apart from the practical difficulties already mentioned, this is a time-consuming and expensive solution. These drawbacks mean that the standard pass-by methods cannot be introduced as a performance based method of routinely specifying and checking the acoustical properties of road surfaces.

An earlier study examined the feasibility of using an amended SPB procedure to overcome some of these restrictions. The modified procedure consisted of positioning a microphone five metres from the centre of the test lane (thereby placing it in front of any safety fence), with an acoustically reflective panel positioned directly behind it. Predictions showed that measurements at this position with the reflective backing board would record an overall noise level 8.1 dB(A) higher than the conventional SPB measurement at 7.5 m. This method (known as the “Backing Board” method, or SPB-BB) allows surveyors to introduce a controlled acoustic environment to arbitrary measurement locations, such as where there are retaining walls and fences, and allows measurements to be carried out that can then be adjusted to give standard SPB results (Kollamthodi et al, 2000).

However, although the backing board method can increase the range of sites where SPB measurements can be taken, there is still a requirement to provide an efficient means of measuring the way road surface noise varies along the length of a section of road surfacing. The method that has been developed specifically for this particular application is the close-proximity (CPX) method, which is described in Section 3 of this Report.
2.3 European methods for assessing the acoustic performance of road surfaces

Although the SPB procedure is widely used across Europe, the specific form of the test varies from country to country. This section describes the different test procedures that are in use in seven different European countries.

2.3.1 United Kingdom

In the United Kingdom the measurement technique detailed in the ISO Standard 11819-1 “The Statistical Pass-By Method” is used as the basis for the characterization of road surface acoustic performance. The method described in this Standard has been adapted for the assessment of the acoustic performance of thin surfacings. The method forms part of the British Board of Agrément’s HAPAS procedure. The results are used by highway authorities to classify proprietary surfacing systems.

There are a few notable differences between the noise test procedures set out in ISO 11819-1 and in HAPAS. The HAPAS method requires that the surface under test has undergone at least 12 months of normal traffic use since the surface was laid prior to testing. The HAPAS method is also more stringent than the ISO Standard with regard to vehicle selection. For example, the HAPAS Standard does not permit the selection of coaches and buses, vehicles that have different acoustic characteristics to trucks. In addition, Category 1b vehicles in the ISO Standard (e.g. cars towing trailers or caravans, and other light vehicles including minibuses and motor homes) are not selected for measurement.

The HAPAS statistical pass-by method uses three categories of vehicles, $L_1$, $H_1$ and $H_2$, which are defined as follows:

- $L_1$ vehicles - light vehicles including passenger cars and car derived vans, excluding vehicles towing trailers
- $H_1$ vehicles - commercial trucks with 2 axles and greater than 3.5 tonnes in weight
- $H_2$ vehicles - commercial trucks with more than 2 axles and greater than 3.5 tonnes in weight

To determine the influence of a surfacing on overall traffic noise levels a method is used that was originally developed by the Technical Sub-Committee of the Noise Advisory Council for the prediction of traffic noise (Noise Advisory Council, 1978). This prediction method allows traffic noise to be determined from the maximum noise levels of different classes of vehicle. By knowing the typical speeds of each class of vehicle, the maximum noise levels can be converted into Sound Exposure Level (SEL) values. The SEL gives information about the total sound energy of a pass-by event which, with knowledge of the number of vehicles, can be used to calculate the equivalent continuous noise level ($L_{eq}$) for any time period.

A-weighted traffic noise levels, $L_{Aeq}$, can be calculated from pass-by vehicle noise levels using this method with the prediction equation in the following form:

$$ L_{Aeq} = 10 \log_{10} \left( \frac{N}{100} \sum_{n=1}^{m} p_n \cdot 10^{L_{Axn}/10} \right) + C \quad (2.1) $$

where

- $N$ = total traffic flow in given time period.
- $m$ = the number of different vehicle categories.
- $p_n$ = the percentage of vehicles in the traffic stream classified as vehicle category $n$.
- $L_{Axn}$ (SEL) = $L_{Axmax} - 10 \log_{10} \nu$
- $L_{Axmax}$ = the maximum pass-by noise level from a vehicle travelling at speed $\nu$ (km/h) at given reference distance
- $C$ is a constant for a given site layout and specified time period.
By substituting the HAPAS vehicle classes into equation 2.1:

\[
L_{Aeq} = 10 \log_{10} \left( N \left( W_{L1}^{10} \cdot \frac{L_{A1}}{10} + W_{H1}^{10} \cdot \frac{L_{A1}}{10} + W_{H2}^{10} \cdot \frac{L_{A2}}{10} \right) \right) + C \tag{2.2}
\]

where:

\( W \) = the proportion of vehicles in each category. Typical values are defined later in this section.

For a road under test, when a sufficient number of vehicle pass-by measurements have been taken, linear regression analysis can be performed in accordance with ISO Standard 11819-1. For each of the vehicle categories defined above, the Vehicle Sound Level, \( L_{veh} \) is calculated as the ordinate sound level of the regression line at the reference speed for the category of road given in Table 2.1.

To compare the influence of a range of surfaces, it is necessary to assume similar traffic conditions on each surface and then use the SPB noise levels to predict an overall level. In this analysis, assumptions are made for the values of the relative weighting conditions (i.e. the proportion of vehicles in each category, \( W_x \)) associated with each reference speed on a typical UK motorway (see Table 2.1).

**Table 2.1: Reference speeds and weighting factors (\( W_x \)) for the different road speed categories**
(British Board of Agrément, 2000)

<table>
<thead>
<tr>
<th>Vehicle Category</th>
<th>Road Speed Category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Reference Speed (km/h)</td>
</tr>
<tr>
<td>( L_1 ) - Light Vehicles</td>
<td>80</td>
</tr>
<tr>
<td>( H_1 ) – Trucks with Two Axles</td>
<td>70</td>
</tr>
<tr>
<td>( H_2 ) - Trucks with more than Two Axles</td>
<td>70</td>
</tr>
</tbody>
</table>

For the purpose of classifying road surfaces in terms of their traffic noise levels it is useful to be able to compare their noise levels with corresponding levels for a given commonly used road surface type. In this way differences between the surface being tested and the reference surface readily identify whether the test surface is quieter or noisier than the reference and by how much. This approach has been used in the method employed in HAPAS by constructing the Road Surface Influence (RSI), which is essentially the difference in \( L_{Aeq} \) between the surface being tested and a corresponding noise levels generated by traffic travelling on a new condition Hot Rolled Asphalt (HRA) surface. HRA was chosen as the reference surface as this surface is frequently used in the UK on roads where traffic speeds are in the medium to high speed ranges as defined in Table 2.1.
For the high-speed road category the Road Surface Influence, RSI_H is defined as:

\[
RSI_H = 10 \log_{10} \left( 7.8 \times 10^{\frac{L_{v_1,H_1}}{10}} + 0.578 \times 10^{\frac{L_{v_2,H_1}}{10}} + 10^{\frac{L_{v_2,H_2}}{10}} \right) - 95.9
\]  

(2.3)

where:

\( L_{\text{veh},L_1} \) = the ordinate light vehicle noise level calculated at 110 km/h,
\( L_{\text{veh},H_1} \) and \( L_{\text{veh},H_2} \) is the heavy vehicle noise levels (for trucks with two axles and more than two axles, respectively) calculated at 90 km/h.

Note that the noise levels used in Equation 2.3 are maximum levels rather than SEL values. However, since standardised speeds and measurement distances are used across sites this should not affect relative values.

### 2.3.2 France

This section details the two methods that have been adopted in France for the in-situ characterisation of the acoustic qualities of road surfaces (standard NFS 31-119, AFNOR, 1993), the Isolated Vehicle Procedure and the Single Test Vehicle Procedure.

#### 2.3.2.1 Isolated vehicle test procedure

Standard NFS 31-119 describes a procedure in line with the ISO 11819-1 SPB method, known as “véhicule isolé”, translated as “isolated vehicle”. The term “isolated” means that the measured noise of the vehicle considered is not affected by noise from other vehicles. As in the ISO procedure, a sufficient number of vehicle pass-by measurements are taken to obtain linear regression relationships between pass-by noise and the logarithm of vehicle speed for four vehicle types. This is essentially the same as the procedure described in ISO 11819-1 with the exception of the points detailed below.

Firstly, the vehicle categorisation and minimum sample size required for the ISO 11819-1 and French NFS 31-119 procedures differ as can be seen in Table 2.2 and Table 2.3.

<table>
<thead>
<tr>
<th>ISO 11819-1 Vehicle Category</th>
<th>Minimum Category Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Vehicles (Cars)</td>
<td>100</td>
</tr>
<tr>
<td>Dual-Axle Heavy Vehicles</td>
<td>30</td>
</tr>
<tr>
<td>Multi-Axle Heavy Vehicles</td>
<td>30</td>
</tr>
<tr>
<td>Categories 2a and 2b together (Heavy Vehicles)</td>
<td>80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NFS 31-119 Vehicle Category</th>
<th>Minimum Category Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Vehicles (Cars)</td>
<td>80</td>
</tr>
<tr>
<td>Utility vehicles (vans)</td>
<td>80</td>
</tr>
<tr>
<td>Heavy road vehicle transporters (2 or 3 axles)</td>
<td>80</td>
</tr>
<tr>
<td>Road trains / tractor-drawn trailers (4 or 5 axles)</td>
<td>80</td>
</tr>
</tbody>
</table>
The only other notable difference between the French NFS 31-119 and ISO 11819-1 is the use of the two microphone experimental set-up. The French standard states that whenever possible, experimental measurements with two microphones should be used. In these circumstances, the set up displayed in Figure 2.2 should be followed.

![Figure 2.2: French measurement technique with two microphones](image)

The two microphones are placed 15 m apart on either side of the road under test. The microphones are arranged so that the centre line of the road lies at a distance of between 6 m and 9 m from each microphone. ISO 11819-1 denotes the distances $d_1$ and $d_2$ as follows:

$$
d_1 + d_2 = 15\text{ m} \pm 0.20\text{ m}$$
$$d_1 = 7.5\text{ m} \pm 0.1\text{ m}$$
$$d_2 = 7.5\text{ m} \pm 0.1\text{ m}$$

The microphone height of 1.2 m above the test surface remains the same as that used in ISO 11819-1, but the tolerance is reduced from $\pm 0.1\text{ m}$ to a tolerance of $\pm 0.05\text{ m}$ for both the single and dual microphone procedures.

According to NFS 31-119, the corrected noise level may be determined as follows:

$$L_{\text{corrected}} = \frac{L_1 + L_2}{2}$$

This applies to all measured levels (overall and by one-third octave) where $L_1$ and $L_2$ are the noise levels measured simultaneously by the two microphones.

**2.3.2.2 Single vehicle test procedure**

NFS 31-119 also describes a second procedure known as “Franco-allemande vehicules maitrises” (the “Franco-German Controlled Vehicle” procedure) that is used in France to rate various road surfaces with respect to their acoustic performance. It is primarily used to enable the acoustic performance of road surfacings to be compared under identical conditions.
The procedure is conducted using two different light vehicles, each with two different types of tyre. The vehicles must have an odometer reading of less than 30,000 km and they must be fitted with petrol engines that are between 1400 and 2000 cm³ in size. The tyres must have run a minimum distance of 500 km and a maximum distance of 10000 km.

For each configuration, a total of eight measurements must be conducted at vehicle speeds spread uniformly in the range 70 to 110 km/h. The test vehicles are run with their engines operating at a steady speed and with an optimum gearbox ratio according to their road speed (to ensure that engine and exhaust noise is kept to a minimum).

For each pass, the L_{A_{max}} level (maximum sound level) is determined and the vehicle speed is measured. On completion of the measurements, thirty-two speed/L_{A_{max}} pairs are obtained. The relationship between L_{A_{max}} and the logarithm of vehicle speed is then expressed as a regression function in the following form:

\[
L_{A_{max}}(V) = L_{A_{max}}(90\text{km/h}) + a \log\left(\frac{V}{90}\right)
\]  

(2.6)

where L_{A_{max}} (90 km/h) is the sound level corrected for the reference speed of 90 km/h, \( V \) is the speed in km/h and \( a \) is the linear regression coefficient.

Using this equation enables L_{A_{max}} to be determined for any required speed provided it is within the range over which the regression function remains valid.

2.3.3 Germany

The German measurement procedure (GEStro.92) has been developed as part of the German-French collaboration in highways systems and it is also used by the Federal Institute of Highways and the Research Institute for Noise and Vibrations (FIGE) in Herzogenrath for testing noise-reducing surfaces (GEStro.92).

The procedure followed in Germany is virtually the same as that previously described for France. To determine the maximum noise level L_{A_{max}}, either of the two following methods may be used.

The statistical test run method (SV method) is the equivalent to the French NFS 31-119 “isolated vehicle” or ISO 11819-1 SPB procedure. In the SV method, the maximum pass-by noise levels produced by the passage of individual cars and lorries in a stream of traffic is measured.

The controlled test run method (KV method) is equivalent to the French NFS 31-119 “single test vehicle” procedure. In the KV method, the noise produced by the passage of a limited number of private cars on a closed road or the noise on a road that is open to traffic is measured. The KV method is used for producing an order of rank of the various road surfaces in terms of the emission of road traffic noise and the quality control in the acceptance of new road constructions.

As with the French method, a difference between the German GEStro-92 (SV) method and the ISO 11819-1 method relates to the dual microphone measurement set-up (see Figure 2.3). The ideal distance between the centre track of the vehicle and the microphone positions \( d1 \) and \( d2 \) is the same at 7.5m. If this condition cannot be met on both sides of the vehicle, positions can be displaced by up to 1m in order to maintain a distance of 15m between them. The tolerances on the distances of the microphones are slightly different than those in the French version.
The vehicle categorisations and minimum sample sizes required for the ISO 11819-1 (SPB) and German GEStro-92 (SV method) are compared in Table 2.4 and Table 2.5.

Table 2.4: ISO 11819-1 vehicle categories and sample sizes

<table>
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<tr>
<td>Categories 2a and 2b together (Heavy Vehicles)</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 2.5: GEStro-92 vehicle categories and sample sizes

<table>
<thead>
<tr>
<th>GEStro-92 Vehicle Category</th>
<th>Minimum Category Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single microphone</td>
<td>Dual microphone</td>
</tr>
<tr>
<td>Light Vehicles (Cars)</td>
<td>140-200</td>
</tr>
<tr>
<td>Dual-Axle Heavy Vehicles</td>
<td>140-200</td>
</tr>
<tr>
<td>Multi-Axle Heavy Vehicles</td>
<td>140-200</td>
</tr>
<tr>
<td>Categories 2a and 2b together (Heavy Vehicles)</td>
<td>140-200</td>
</tr>
</tbody>
</table>

If simultaneous measurement on both sides of the vehicle is impossible (e.g. in the case of motorways with more than two traffic lanes in each direction), a single microphone technique may be used. The...
measurement distance of 7.5m from the central track of the vehicles in the test lane to just one microphone position may be applied. In the case of measurements taken with a single microphone, double the number of vehicles must be recorded. The Standard notes that measurements taken on both sides of the vehicle may show slightly different noise levels as a result of directional noise radiation from the vehicles.

The most significant differences between the French NFS 31-119 "Franco-allemande vehicules maitrises" (single test vehicle procedure) and German GEStro-92 (KV) method are described below. The French Standard NFS 31-119 states that the equivalent test to Germany’s KV procedure must be carried out with vehicles fitted with petrol engines of between 1400 and 2000 cm³ in size. The vehicles are further restricted in that they are only eligible for testing if they have covered less than 30000 km. The German KV method has two different categories – one where the vehicles must be fitted with engines in the range 1400 to 2000 cm³, and a second for vehicles with engines of between 2000 and 3000 cm³. The French method states that test vehicles for the equivalent German KV test must have petrol engines with a cubic capacity of between 1400 and 2000 cm³, with a maximum odometer reading of less than 30000 km. The German KV method allows a maximum odometer reading of up to 60000 km, i.e. twice that of French test vehicles.

Both the French and German methods dictate that four different types of tyre are used on the test vehicles. The German test specifications state that for each vehicle measurements must be carried out with two or four sets of branded tyres of different type, size and tread. Of the four features (brand, type, size and tread), one, at most, out of every two tyres, should be identical. Preference should be given to the following tyres:

<table>
<thead>
<tr>
<th>Tyre Manufacturer</th>
<th>Tyre Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michelin</td>
<td>155/70 SR 13</td>
</tr>
<tr>
<td>Goodyear</td>
<td>175/70 SR 13</td>
</tr>
<tr>
<td>Continental</td>
<td>195/65 HR 15</td>
</tr>
<tr>
<td>Pirelli</td>
<td>205/60 VR 15</td>
</tr>
</tbody>
</table>

If a single microphone is to be used for measurements according to the KV method, measurements must then be conducted in both directions of travel.

2.3.4 **Belgium**

The current ISO standard (ISO 11819-1 (1996) Acoustics – Method for measuring the influence of road surfaces on traffic noise – Part 1: “The Statistical Pass-By method”) is currently used in Belgium for tyre noise measurements. A further method has been developed by the Centre du Research Routiere (CRR) for research purposes.

2.3.5 **The Netherlands**

The measurement of the acoustic performance of road surfaces within the Netherlands also follows the measurement technique detailed in ISO 11819-1 “The Statistical Pass-By Method”. There are differences, however, in the categorisation of vehicles and in the position of the measurement microphones.

In the Dutch standard vehicles are divided into the four categories (Motorcycles, light vehicles, medium heavy vehicles (2- and 3-axled trucks), and heavy vehicles and the height of the measurement microphones is set at 5m above the surface. The higher microphone position is used to reduce the possibility of ground effects interfering with the recorded noise level.
2.3.6 Austria

At time of writing, the specification for tyre/road noise measurement is contained within "Richtlinien und Vorschriften für den Straßenbau – RVS” 8.06.28”. This method for the measurement of the acoustic performance of surface treatments consists of a self contained trailer and microphone arrangement. Figure 2.4 shows a diagram of the trailer showing the positions of the test tyre and measurement microphones.

![Austrian acoustic trailer diagram](image)

### Figure 2.4: Austrian acoustic trailer

**Specifications:**

- **Tyre**
  - Standard 165 R15
- **Tyre pressure**
  - 2.3 bar
- **Test load**
  - 400 kg
- **Microphone position**
  - Directly behind the trailer tyre
- **Minimum surface temperature**
  - 10°C
- **Calibration requirement**
  - Every 12 months

The trailer is fully lined with sound absorbent material in order to minimise the reflection effects from the internal surfaces of the trailer body. In operation, the trailer is attached to the back of a standard vehicle and is towed at a steady speed of 100 km/h. Currently the trailer method is used for testing new surfaces and for the classification of porous asphalt on Austrian roads.
3 Close-Proximity Noise Testing

3.1 Introduction

The close-proximity (CPX) method involves the measurement of tyre noise using a microphone mounted near a tyre loaded on a specially developed vehicle or trailer. Typically the microphone will be located between 200 mm and 500 mm from the tyre. The main advantage of the CPX method over the SPB method is that it is not affected by site layout restrictions. It was noted in Section 2 that SPB measurements must be taken in an ‘open’ area where there are no significant acoustically reflecting surfaces near to the measurement microphone. This requirement means that the SPB method cannot be used as a routine test method to establish noise levels from road surfaces at any arbitrary location on the road network. Although this is not an issue for measurements taken for close proximity measurements, CPX noise levels cannot at present be simply related to traffic noise levels and hence community annoyance. It was shown earlier that SPB noise levels can be used to calculate traffic noise levels.

The difficulty of relating CPX measurements to traffic noise originates in the fact that any measurements taken in close proximity to a test tyre tend to emphasise the directional characteristics of the noise generated. Therefore, the results obtained may not be an accurate representation of the noise propagating to the roadside. A further point is the difficulty in identifying suitable test tyres that provide a representative coverage of the broad range of tyre types currently in service. An ISO working group is currently investigating these issues and is working towards providing a method that will allow SPB levels to be determined from measured CPX noise levels. It is anticipated that the preferred method will require testing with several different ‘standard’ tyres. The results from each test tyre will be combined to determine a composite noise level that is representative of the rolling noise from the traffic stream. The method, when developed would be suitable as a type approval test for road surface noise. It could also form the basis of a suitable conformity of production (COP) test and for monitoring the acoustic condition of the network as part of routine maintenance and replacement strategies.

Previous studies carried out for the Highways Agency investigated the relationship between close-proximity noise levels and roadside SPB measurements for a limited range of road surfaces. A statistically significant correlation was found between SPB and CPX noise levels (Phillips et al, 1996). However, it was concluded that far-field (i.e. roadside) noise levels could not be confidently predicted from the limited data available. The noise levels recorded at the roadside can be substantially affected by the acoustic properties of the intervening road surface. This is particularly the case for absorptive surfaces such as porous asphalt. Despite these concerns, it has been found that by comparing CPX noise measurements with laser texture depth measurements, variations in noise along a road surface can be related to road surface texture. Regression analysis confirmed that there was a statistically significant correlation between noise and sensor measured texture depth (SMTD) values (Viner et al, 1998). This type of result may also be relevant to the development of routine network monitoring applications.

3.2 International CPX experiment

In order to develop the ISO standard for the CPX method, an International Trailer Comparison Experiment was organised in the summer of 1998 by TUV Automotive and M+P Raadgevende Consulting Engineers from the Netherlands. BASt, CROW, RWS and VCRM organised the tests, which were performed on several road surfaces in Germany and the Netherlands and included participants from Europe and Japan. The objectives were to establish the variability of measurement results from different CPX measurement devices developed in various countries, and to examine the degree of correlation between the CPX method and the roadside SPB method.

Eight different trailer/vehicle systems were examined during the trials and between them; three different microphone positions were used. The positions ‘inner and ‘outer’ were defined in the first
committee draft version of the ISO document (International Organisation for Standardisation, 1997b). In the most recent draft version of the ISO standard, the outer positions have been deleted, and only the inner microphone positions remain as mandatory.

<table>
<thead>
<tr>
<th>Microphone layout dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphone position</td>
</tr>
<tr>
<td>Extreme outer</td>
</tr>
<tr>
<td>Outer (M3 M4)</td>
</tr>
<tr>
<td>Inner (M1 M2)</td>
</tr>
</tbody>
</table>

![Diagram of microphone positions](image)

**Figure 3.1: CPX microphone positions used in the International experiment**

Table 3.1 summarises the systems used by the participants of the International Experiment. The TU Gdansk, DWW, TU Berlin and Arsenal Wien (Austrian) trailers consisted of a single test wheel mounted inside an enclosure, which was towed behind a vehicle. In the Austrian trailer, the test tyre itself supported the trailer whilst all the other trailers had supporting wheels. It should be noted that in all cases the test tyre was mounted along the longitudinal centre-line of the trailer. The Austrian trailer was also equipped with two sets of microphones located at the inner and outer positions. Therefore, as shown in Table 3.1, this trailer was given two vehicle identification numbers for the purposes of the study. Examples of the various CPX trailers are shown in Figure 3.2.
Table 3.1: Summary details of test equipment used in the international experiment

<table>
<thead>
<tr>
<th>Type</th>
<th>Participant</th>
<th>Vehicle No.</th>
<th>Microphone Position</th>
<th>Wheel Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-wheeled trailers</td>
<td>TU Gdansk, Poland</td>
<td>1</td>
<td>Inner</td>
<td>Centre</td>
</tr>
<tr>
<td></td>
<td>DWW, Netherlands</td>
<td>2</td>
<td>Outer</td>
<td>Centre</td>
</tr>
<tr>
<td></td>
<td>TU Berlin, Germany</td>
<td>4</td>
<td>Outer</td>
<td>Centre</td>
</tr>
<tr>
<td></td>
<td>Arsenal Wien, Austria</td>
<td>8</td>
<td>Inner</td>
<td>Centre</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>Outer</td>
<td>Centre</td>
</tr>
<tr>
<td>Two-wheeled trailers</td>
<td>M+P, Netherlands</td>
<td>5</td>
<td>Outer</td>
<td>Off-side</td>
</tr>
<tr>
<td></td>
<td>TUV Automotive, Germany</td>
<td>7</td>
<td>Extreme Outer</td>
<td>Both</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>Outer</td>
<td>Nearsidde</td>
</tr>
<tr>
<td>Single vehicle</td>
<td>JARI, Japan</td>
<td>3</td>
<td>Inner</td>
<td>Off-side</td>
</tr>
<tr>
<td></td>
<td>TRL, UK</td>
<td>6</td>
<td>Inner</td>
<td>Near-side</td>
</tr>
</tbody>
</table>

The TÜV Automotive trailer, shown in Figure 3.3 had two axles although during each test only one of the axles was lowered. Unlike the M+P trailer, the test tyres mounted on each axle were not acoustically isolated from each other, the principle of noise measurement being that the contribution from each of the two tyres on the axle (one in each wheel-track) was recorded by the microphones in the extreme outer position.

The Japanese Automobile Research Institute (JARI) participated with a medium sized passenger car fitted with two microphones at the inner positions measuring noise at the left-hand rear wheel. Unlike the other participants, this vehicle required the use of a 6-inch wide wheel rim rather than the standard 5.5-inch rim. TRL also participated in the experiment with a passenger car, but noise measurements were taken at the right-hand rear wheel. The TRL vehicle included tyre monitoring equipment which allowed the temperature and inflation pressure of the test tyres to be continually monitored. The vehicle was also fitted with a video camera system that monitored the test tyre; the main purpose of this was to determine the lateral location of the tyre relative to the white marker lines on the roadside. This allowed the influence of minor deviations from the wheel track to be determined. However, because only one other vehicle (M+P) was able to routinely measure from one tyre in the same, nearside wheel-track, the results of this aspect of the experiment are not reported here. The TRL vehicle was converted to front wheel drive to ensure that tyre noise was not affected by torque or steering forces.
Four test tyres were selected for use with most of the participating systems. These were essentially the test tyres, A, B, C and D specified in the proposed International Standard, ISO/CD 11819-2 (International Organisation for Standardisation, 1997b). The test tyres are illustrated in Figure 3.4. It should be noted that the standard ISO reference tyre A was not available for the trials and was replaced by a similar style of tyre which was also called “A” for the study. In addition measurements carried out with Trailer 7 (TÜV) were also conducted using a set of tyres that have been standardised in Germany. These are known as the GEStrO tyres (Bundesministerium Fur Verkehr, 1992) and were used for comparison with the existing German database of results.
Thirteen test surfaces were selected for the trial. The surfaces represented a range of types commonly found in Germany and the Netherlands. These included surfacings such as stone mastic asphalt (SMA), porous asphalt (single and twin layered), concrete (exposed aggregate and brushed), Guss-asphalt and surface dressing. Most of the test surfaces were located in the Netherlands, although four of the surfaces were in Germany. Dual and single carriageway roads were included amongst the selected surfaces and Statistical Pass-by measurements were performed at one location on each of the test surfaces. In addition, measurements of the surface texture over the length of the different test tracks were made by KOAC•WMD, using a device called the Automatic Road Analyser (ARAN). This device was equipped with two lasers, one measuring the texture profile in the right wheel track, the other in the track between the wheels.

Unfortunately, during the period of the International Experiment poor weather in the vicinity severely affected the measurement programme. Nevertheless a substantial amount of testing was still carried out over a two-week period.

The basic test routine involved the measurement of each of the thirteen test sections using the CPX method at three different speeds. The three speeds selected were 50, 80 and 110 km/h and it was envisaged that the measurements at each speed would be repeated at least once.
3.2.1 Summary findings from the international experiment

All of the participants recorded the average A-weighted sound pressure levels, one-third octave band sound levels and vehicle speeds over the various test sections lengths. The length of the test sections ranged from 70 m to 270 m. The participants were also able to monitor the variation in noise and speed over the test section by dividing the road sections into ten metre segments. Early on in the test programme, it was found that TRL’s vehicle, which had been specially modified for the experiment, was not able to accelerate to the highest test speed on many of the test tracks. Consequently, testing with this vehicle (Vehicle 6) was often restricted to speeds of 50 km/h and 80 km/h only.

During analysis, the average sound pressure levels for each test section for each tyre and trailer combination were regressed against the logarithm of the average speed. An example of this analysis is shown in Figure 3.5.

In general it was found that the noise levels at the front microphone positions were higher than those found at the rear microphone for both the inner and outer positions. It was noticeable that the differences in the noise levels at the two microphone positions decreased at higher test speeds. The differences between front and rear microphones were greatest for Tyres A and D, which were the tyre with the directional tread pattern and the aggressive winter tyre respectively. Rougher road surfaces were also associated with greater differences between front and rear noise levels.

Examination of the average speeds at which measurements were taken showed that, inevitably, there was some deviation from the targeted values. At the time the international experiment was conducted, the ISO proposal, ISO/CD 11819-2, required that the measured average speed over the road section had to fall within 5 km/h or 3% of the target speed, whichever was the greatest. In the International Experiment, it was found that, although some traffic management was in place in an attempt to provide uninterrupted running for the participants, at least 4% of test runs were invalid due to the vehicle speed falling outside the target range. This is probably an underestimate of the problem as it does not include tests that were abandoned by the operators when, for example, a 110 km/h test run was halted because of slow vehicles in the test lane.

![Figure 3.5: Sound pressure level and speed measured at the front microphone position for the four test tyres (Vehicle 1)](image-url)
Analysis (carried out by TUV) of actual vehicle speeds that occurred during testing showed that even though the average vehicle speed for the run was found to be acceptable in terms of the tolerances allowed by the proposed Standard, actual vehicle speeds in specific ten-metre segments often deviated substantially from the target speed. In some cases a standard deviation in the test speed of approximately 6 km/h were found. For example, one test run with a target speed of 80 km/h included individual 10 m sections where the speeds ranged between 65 and 86 km/h.

However if the ISO test requirement (i.e. no more than 5 km/h or 3% from the target speed) was applied to each of the individual 10 m section, then more than 13% of the test runs would be judged to have been invalid.

As a consequence of these findings, the draft standard was revised to allow the measured speed over a road section to deviate by up to ±5% of the reference speed. In addition, the speed on individual road segments may deviate by up to ±20% or ±15 km/h (whichever is greater) of the reference speed.

Because of the variability in speed two alternative methods of analysing the test data were examined. Both of these involved the regression of the noise and speed associated with each 10m segment of the test surface. The simplest of these methods allows the average noise level along the entire length of the road section to be determined. In this case, shown in Figure 3.6 the noise level for each tyre on each ten-metre road segment has been correlated against the speed of the vehicle over that ten-metre segment. Regression analysis is then performed using the noise-speed data pairs for each individual road segment to arrive at a noise level that characterises the whole section of road being assessed. Such an approach allows testers to accept a wider range of speeds and could be suitable for some forms of tests.

However, this very simple method of analysis does not allow the homogeneity of the road surface (in terms of its acoustic performance) to be examined. Therefore an alternative method was also examined which allowed the variation in the noise levels between consecutive ten-metre segments to be determined. This analysis consisted of calculating the regressed noise levels for each individual segment using data from a number of test runs. An example of this is shown in Figure 3.7 for the same test section shown in Figure 3.6.

![Figure 3.6: Regression of measured CPX noise levels against speed](image_url)
In Figure 3.7 six separate test runs have been included. Three of these were carried out at a target speed of 50 km/h and the remainder at 80 km/h. It can be clearly seen there was some variation in measured noise level along the test section for each run, but that the variation was not necessarily repeatable. In fact for one of the runs where the target speed was 80 km/h the levels are considerably lower because the test speed could not be maintained and the average speed for the entire run fell to 75 km/h. However, by calculating the regression statistics between measured noise levels and the vehicle speed separately for each 10 m segment of the test surface noise levels for the target speed can then be determined from the regression relationship.

3.2.2 Development of draft ISO11819-2

Following the international CPX experiment a number of changes have been made to the specification of the draft standard. The changes have focussed on achieving the main objectives of the standard. These are that it provides a method for characterising road surfaces at almost any arbitrary site; that the method can be used to check the acoustic condition of a surface and to identify the effects of wear and maintenance requirements; and that it can be used to check the longitudinal homogeneity of a road section.

3.2.2.1 General

It was found that significant differences in the design of the different test systems led to considerable variations in the results obtained from different vehicles. Some of the vehicles had test wheels located in the wheeltrack whilst others had a test wheel located between the wheel tracks of the road surface. Some of trailer designs had a single test wheel whilst others had two. The different vehicles also employ a variety of different microphone positions. As a result of these findings, the draft ISO standard was amended to stipulate that the test tyre must run in the wheel track of the surface under study.

Figure 3.7: Regression of noise levels against speed along a test section
Actual variations in vehicle speed over the course of a test run were found to be much greater than allowed by the original draft proposal for ISO 11819-2. As a result of this finding, the draft ISO standard has been amended to allow greater speed variation, and analysis techniques that allow the regressed noise level for specific road segments to be determined have also been incorporated into the draft standard.

Difficulties were encountered in measuring accurately test sections of 10m. This has been increased to 20m in the revised draft standard.

ISO 11819-2 uses specially modified vehicles in order to assess the acoustic performance of road surfaces. The original draft standard specifies certain criteria that test vehicles must comply with, but it still allowed a wide variety of different types of vehicle to be used. The ISO standard permitted CPX measurements to be taken using either a self-powered vehicle or a towed trailer. The standard specified that the test tyre may be located within an enclosure in order to shield it from background noise and other interference. However, there was no obligation in the draft standard for vehicles to be fitted with an enclosure. In the revised wording, the influence of extraneous noise levels at the test tyre(s) must be controlled to the extent that background noise levels (e.g., from the vehicle power train, from other tyres on the vehicle, or from other vehicles in the traffic stream) do not influence noise levels measured at the test tyre(s) by more than 1 dB in the 500 to 4000 Hz frequency range, and by not more than 2 dB in the 315 to 400 Hz range.

3.2.2.2 Microphone positions

ISO 11819-2 requires that at least two measurement microphones shall be used for determining CPX noise levels from the test tyre. Three further optional microphone positions have been added to the draft standard. Figure 3.8 below details the positions of the mandatory microphones M1 and M2 and the optional microphones M5, M6 and M7. The outer microphone positions M3 and M4 that were considered in the International experiment, see Fig 3.1, are not included in the draft standard.

![Diagram of CPX microphone positions](image-source)

Figure 3.8: CPX microphone positions (diagram sourced from ISO/DIS 11819-2)
3.2.2.3 Reference tyres

The standard specifies a set of “reference tyres” to be used for all CPX measurements. Reference tyres are necessary because the noise levels generated on a particular surface are dependent on the design of the tyre used in the test. Having a set of reference tyres allows CPX tests to be readily reproduced. The four reference tyres selected for use in the standard were chosen for the good reproducibility characteristics and their long-term stability. Three of the four reference tyres (tyres A, B, and C) were chosen to be representative of light vehicle tyres currently in use. Tyre D, which is a winter mud and snow car tyre, was chosen to be representative of truck tyre noise. A real truck tyre was not used for Tyre D as it was deemed unlikely that CPX test vehicles would be able to run on both passenger car and truck tyres.

3.2.2.4 Investigatory and Survey methods

Two variants of the CPX technique have been developed by the ISO Working Group in order to allow a certain level of flexibility in the type of tests required to obtain standardised measurement results. The two methods differ in the number of reference tyres used to determine the CPX sound levels. The investigatory method was developed as the main CPX method and is intended to be used in situations where the number of measurements or the distance travelled during testing is not excessively high. The investigatory method makes use of all four reference tyres. The survey method (in which only tyres A and D are used), was developed for situations that involve taking measurements over very large distances or where large numbers of test runs are required. By using only two of the four reference tyres, the survey method significantly reduces the cost and time associated with such measurements.

3.2.2.5 Measurement techniques

The method used for measuring the influence of road surfaces on traffic noise relies on taking measurements of average CPX noise levels at regular intervals using each of the test tyres. The technique can only be used on sections of road surface that are 100 m in length or greater. All noise level measurements are recorded with the test vehicle travelling at a constant speed, or as close to a constant speed as possible. Sections of road are divided up into segments, each of which is twenty metres in length, and the energetic average noise level (equivalent continuous noise level, $L_{Aeq}$) is determined for each segment at each microphone position. The $L_{Aeq}$ levels at the two mandatory microphone positions are then arithmetically averaged to give a single noise level value for each road segment, known as $L_{meas}$. Values of $L_{meas}$ are then corrected for variations in speed using the following equation:

$$L_{corr} = L_{meas} + B \log \left( \frac{v_{ref}}{v} \right)$$  \hspace{1cm} (3.1)

where: $v$ is the actual speed  
$v_{ref}$ is the target test speed  
$B$ is the slope of the noise noise-speed relationship. This has a default value of 35 where this is unknown for a particular surface.

The values determined for each segment of the road section are then arithmetically averaged to give a single noise level value for the whole section of road under study. The whole procedure is then repeated at least once, and the resultant road section noise levels are averaged to give $L_{tr}$, the Tyre/Road Sound Levels (TR level) for a particular reference tyre on a road section.
Alternatively, average noise levels can be determined for individual segments of a road section. In this case, the speed corrected noise levels for a particular segment obtained on different test runs are arithmetically averaged to give the average sound level for a segment.

### 3.2.2.6 CPX sound indices

The CPX procedure allows for a number of indices to be determined that characterise the influence of a road surface on traffic noise. These indices take into account differences in traffic composition and the types of tyres in use on the roads. These indices are CPX\textsubscript{L}, which represents light vehicle traffic, CPX\textsubscript{H}, which is used for heavy vehicle traffic, and CPX\textsubscript{I} which represents a mixture of light and heavy vehicles in the traffic stream. The method used for calculating each of these indices varies depending on whether the investigatory method or the survey method is being used. For the investigatory method, the following equations apply:

\[
\text{CPX}_L = 0.25L_A + 0.25L_B + 0.25L_C + 0.25L_D \quad [\text{dB}] \\
\text{CPX}_H = 1.00L_D \quad [\text{dB}] \\
\text{CPX}_I = 0.20L_A + 0.20L_B + 0.20L_C + 0.40L_D \quad [\text{dB}]
\]

(3.2) (3.3) (3.4)

To calculate these indices when the survey method is used, the following equations apply:

\[
\text{CPX}_L = 1.00L_A + 1.00 \quad [\text{dB}] \\
\text{CPX}_H = 1.00L_D \quad [\text{dB}] \\
\text{CPX}_I = 0.50L_A + 0.50L_D + 0.5 \quad [\text{dB}]
\]

(3.5) (3.6) (3.7)

L\textsubscript{A}, L\textsubscript{B}, L\textsubscript{C} and L\textsubscript{D} are the Tyre/Road Sound Levels for tyres A, B, C and D respectively.
4 Correlation of SPB with CPX Measurements

The main part of this project was concerned with providing a method of correlating noise levels obtained using the CPX method with corresponding noise levels taken using the SPB method. It is anticipated that the ability to estimate SPB noise levels from CPX data would be of particular value in relating the acoustic characteristics of road surfaces with roadside traffic noise levels and, hence, community noise impact. The greater efficiency of the CPX method would potentially allow large sections of the network to be monitored in this manner which could then be used for assessing road condition and informing road surface replacement and maintenance programmes.

The objective of examining the correlation between the two types of measurements was achieved by carrying out a series of measurements on different road surfaces using both measurement methods. A brief description of the location of the sites selected for measurement is given in section 4.1 below. The statistical correlation between the data was then examined and is described in section 4.2.

4.1 Experimental procedure

Seventeen different (SPB) sites located on thirteen different road sections were included in the measurement programme. The range of surface types included porous asphalt (PA), stone mastic asphalt (SMA), hot rolled asphalt (HRA), exposed aggregate concrete (EAC) and brushed concrete (BC). The approximate location of the different road sections are given below in Table 4.1.

<table>
<thead>
<tr>
<th>Road</th>
<th>Surface Type</th>
<th>Length of road in section (metres)</th>
<th>Direction of travel</th>
<th>Number of SPB sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>M40</td>
<td>Porous asphalt</td>
<td>1260</td>
<td>North</td>
<td>2</td>
</tr>
<tr>
<td>M40</td>
<td>Stone Mastic Asphalt</td>
<td>1000</td>
<td>North</td>
<td>1</td>
</tr>
<tr>
<td>M23</td>
<td>Exposed Aggregate Concrete</td>
<td>300</td>
<td>North</td>
<td>2</td>
</tr>
<tr>
<td>A50</td>
<td>Exposed Aggregate Concrete</td>
<td>2500</td>
<td>East</td>
<td>3</td>
</tr>
<tr>
<td>A50</td>
<td>Exposed Aggregate Concrete</td>
<td>2260</td>
<td>West</td>
<td>1</td>
</tr>
<tr>
<td>A50</td>
<td>Hot Rolled Asphalt</td>
<td>2500</td>
<td>West</td>
<td>1</td>
</tr>
<tr>
<td>M18</td>
<td>Exposed Aggregate Concrete</td>
<td>220</td>
<td>North</td>
<td>1</td>
</tr>
<tr>
<td>M18</td>
<td>Exposed Aggregate Concrete</td>
<td>200</td>
<td>South</td>
<td>1</td>
</tr>
<tr>
<td>M18</td>
<td>Hot Rolled Asphalt</td>
<td>400</td>
<td>North</td>
<td>1</td>
</tr>
<tr>
<td>M18</td>
<td>Hot Rolled Asphalt</td>
<td>400</td>
<td>South</td>
<td>1</td>
</tr>
<tr>
<td>A34</td>
<td>Hot Rolled Asphalt</td>
<td>2220</td>
<td>South</td>
<td>1</td>
</tr>
<tr>
<td>A34</td>
<td>Brushed Concrete</td>
<td>6420</td>
<td>South</td>
<td>1</td>
</tr>
<tr>
<td>A34</td>
<td>Brushed Concrete</td>
<td>7220</td>
<td>North</td>
<td>1</td>
</tr>
</tbody>
</table>

CPX data using all four reference tyres was obtained for each road section. The measurements were carried out using TRL’s CPX vehicle (TRITON). A full description of TRITON including some details of the work carried out to validate the measurement system incorporated in TRITON is given in Appendix A.

At each site the CPX measurements were taken along the 20m section located directly in front of the sites chosen for the SPB measurements. The CPX levels were determined over a range of speeds from 60 km/h to 110 km/h in approximately 5km/h increments. This data was used to establish the relationship between CPX noise levels and speed in each case.
4.2 Statistical analysis of the data

Using the data gathered from the measurements a statistical analysis was carried out to examine the relationship between various SPB noise indices related to high-speed roads with a range of CPX indices. The objectives of this analysis were as follows:

1. To initially examine the correlation between the SPB indices for high-speed roads as described in HAPAS with a selection of CPX indices as described in the Draft International Standard, ISO 11819-2 derived from measurements at the mandatory microphone positions, M1 and M2.

2. To compare the predictive accuracy of the corresponding regression equations between the investigatory method based on the measurement of all four reference tyres and the survey method which uses only two reference tyres.

3. To examine separately the correlation between the SPB indices related to light and heavy vehicles and the Tyre/Road Sound Level values recorded for each reference tyre.

4. To explore the possibilities of simplifying the CPX method without reducing the predictive accuracy in estimating the SPB index, RSI_{HI}

5. To investigate the influence of the absorption characteristics of the road surface on the correlation between the SPB and CPX indices. The characteristics of porous asphalt influence both the generation and propagation of tyre/road noise and may affect the correlation.

4.2.1 Relationship between RSI_{HI} and CPX_{fi}

Table 4.2 shows the linear regression statistics obtained when correlating RSI_{HI} against CPX_{fi}.

The table includes regressions for CPX_{fi} calculated at two speeds, 110 and 80 km/h, for both the investigatory method where all four reference tyres are required to be measured and the survey method where reference tyres A and D are only used. The results shown in brackets are the corresponding values obtained when the two porous asphalt surfaces are excluded from the analysis.

The results show that there is a good correlation between RSI_{HI} and CPX_{fi} derived from both methods at 110 and 80 km/h for the surfaces selected. Comparing the variance (R^2) and the standard errors between the investigatory and survey methods indicate little benefit in prediction accuracy by including all the reference tyres in the measurement. The results also indicate that there is little difference in prediction accuracy between the two speeds used in the measurement of CPX_{fi} and that therefore CPX_{fi} values obtained using the lower speed of 80km/h may provide a better alternative bearing in mind the difficulties of maintaining higher speeds during normal traffic conditions. Clearly, however, there is a significant improvement in the variance and standard errors after the porous surfaces were excluded from the analysis. The results in the table show that about 75% of the variance between RSI_{HI} and CPX_{fi} can be explained from the regression analysis when the data includes porous asphalt whereas by excluding the porous asphalt surfaces from the analysis, the explained variance increases to over 90% and the standard error is reduced by about 50%.
### Table 4.2: Comparing regression statistics of RSI\(_{11}\) and CPX\(_{1}\) with and without Porous Asphalt

<table>
<thead>
<tr>
<th>Method</th>
<th>Regression Statistic</th>
<th>Investigatory 110 km/h</th>
<th>Survey 110 km/h</th>
<th>Investigatory 80 km/h</th>
<th>Survey 80 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope</td>
<td>1.19</td>
<td>1.23</td>
<td>1.59</td>
<td>(1.1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.1)</td>
<td>(1.17)</td>
<td>(1.53)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intercept</td>
<td>-126</td>
<td>-131</td>
<td>-162.6</td>
<td>(-116)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-116)</td>
<td>(-124.6)</td>
<td>(-156.2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R(^2)</td>
<td>0.79</td>
<td>0.71</td>
<td>0.71</td>
<td>(0.9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.9)</td>
<td>(0.89)</td>
<td>(0.91)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Standard error</td>
<td>1.3</td>
<td>1.5</td>
<td>1.5</td>
<td>(0.79)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.79)</td>
<td>(0.85)</td>
<td>(0.75)</td>
<td></td>
</tr>
</tbody>
</table>

1 Values in brackets show the corresponding results when the porous asphalt surfaces have been omitted from the analysis.

The reason for the reduction in prediction accuracy when porous surfaces are included in the regression analysis correlating RSI\(_{11}\) and CPX\(_{1}\) is likely to be due to the influence of the absorptive characteristics of the porous surface on noise propagation. The SPB procedure can take both of these factors into account as measurements are taken at the roadside, a distance of 7.5 m from the centre of the measurement lane. However, CPX measurements are recorded in close-proximity to the tyre/road interface and the effects that porous surfaces have on the propagation of tyre/road noise to the roadside may not be fully taken into account. As a consequence, it was decided to examine whether CPX indices based on noise levels collected at other microphone positions could provide more significant correlations. In this report the results from the optional microphone positions described in the Draft International Standard, positioned at the rear and in front of the contact patch, M6 and M7 respectively, were included in this analysis.

### Table 4.3: Regression statistics of RSI\(_{11}\) and CPX\(_{1}\) derived from averaging noise levels at microphone positions M6 and M7

<table>
<thead>
<tr>
<th>Method</th>
<th>Regression Statistic</th>
<th>Investigatory 110 km/h</th>
<th>Survey 110 km/h</th>
<th>Investigatory 80 km/h</th>
<th>Survey 80 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope</td>
<td>1.07</td>
<td>1.17</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.3</td>
<td>1.17</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intercept</td>
<td>-110</td>
<td>-119.9</td>
<td>-138.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-127.8</td>
<td>-119.9</td>
<td>-138.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R(^2)</td>
<td>0.89</td>
<td>0.89</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.9</td>
<td>0.9</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Standard error</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 shows the results from the regression analysis correlating RSI\(_{11}\) and CPX\(_{1}\) where CPX\(_{1}\) values were calculated using averaged noise levels measured at microphone positions M6 and M7 and
includes the results from the porous asphalt surfaces. These results show a clear improvement in accuracy over those given in Table 4.2 for regressions including data from porous asphalt surfaces. The improvement in the correlation obtained when using microphone positions M6 and M7 can also be seen in Figure 4.1 which compares the regression equations derived from the correlation between RSI_H and CPX_I using the survey method at a speed of 80 km/h.

\[
\text{Regression equation } RSI_H = 1.59 \times CPX_I - 162.6 \text{ dB(A)} \\
R^2 = 0.71
\]

\[
\text{Regression equation } RSI_H = 1.41 \times CPX_I - 138.7 \text{ dB(A)} \\
R^2 = 0.91
\]

![Figure 4.1 Comparing the regression relationship between RSI_H and CPX_I derived from averaged noise levels at M1M2 and M6M7 for the survey method at 80 km/h.](image)

The regression derived from the average noise levels at positions M6 and M7 suggests that for these positions, measurements of CPX_I can explain over 90% of the variance in RSI_H levels compared with only 71% when using microphone positions M1 and M2. The figure clearly shows that results for porous asphalt are better aligned with the regression for M6M7 than that for the M1M2 data. The improvement in the correlation for sound absorbing surfaces could be explained by the fact that sound levels recorded at positions to the rear and in front of the contact patch will be influenced by the absorption properties of the road surface due to the so called “horn effect”. This refers to the amplification of the sound due to multiple reflections occurring between the road surface and the tyre tread either side of the contact patch (Phillips et al, 2003). The absorption characteristics of the porous asphalt surface significantly reduce the amplification of the noise generated at the front and rear of the contact patch and therefore noise levels recorded at microphone positions M6 and M7 are more likely to be influenced by this effect than at microphone positions M1 and M2.

However, under controlled pass-by conditions it was found that under a range of porous and non-porous surfaces that the average of microphone positions 1 and 2 produced the best correlations (Abbott and Watts, 2004). Clearly the issue of the optimum position of the measurement microphones requires further study before definite conclusions can be reached.
4.2.2 *Relationship between SPB vehicle noise indices and Tyre/Road Sound Levels*

The following sections describe the relationships between the SPB vehicle noise indices $L_{vehL1}$ for light vehicles and $L_{vehH2}$ for heavy vehicles at a reference speed of 110km/h and 90km/h respectively with the Tyre/Road Sound Levels (TR levels, $L_{tr}$) for each reference tyre at 80 km/h. A similar approach as that followed in the previous section has been used.

4.2.2.1 *SPB light vehicle noise index $L_{vehL1}$*

Table 4.4 compares the regression statistics between the SPB index for light vehicles, $L_{vehL1}$, and the TR levels, $L_{tr}$, derived from the average CPX noise levels measured at positions M1 and M2 for each reference tyre. The results show that when the porous surfaces are included in the analysis there is reasonable correlation between the indices for all the tyres. Although there is no significant difference in the correlation between each of the tyres the results indicate that Tyre B marginally performs better than the other tyres and that not perhaps surprisingly, Tyre D performs marginally worst in estimating the SPB index, $L_{vehL1}$. As was shown in the previous section, when the porous surfaces are removed from the analysis, the predicted accuracy between the indices significantly improves but the relative performance between the reference tyres remains fairly constant with Tyre B providing the highest correlation with over 90% of the variance explained by the regression equation and Tyre D performing marginally worst with 84% of the variance explained.

<table>
<thead>
<tr>
<th>Regression Statistic</th>
<th>Results for each reference tyre where $L_{tr}$ is derived from M1 and M2 data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L_A$</td>
</tr>
<tr>
<td><strong>Slope</strong></td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>(1.41)$^1$</td>
</tr>
<tr>
<td><strong>Intercept</strong></td>
<td>-64.1</td>
</tr>
<tr>
<td></td>
<td>(-58.3)</td>
</tr>
<tr>
<td><strong>$R^2$</strong></td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>(0.86)</td>
</tr>
<tr>
<td><strong>Standard error</strong></td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>(0.93)</td>
</tr>
</tbody>
</table>

$^1$ Values in brackets show the corresponding results when the porous asphalt surfaces have been omitted from the analysis.

The analysis was repeated but with TR levels calculated by averaging the noise levels recorded at position M6 and M7. Table 4.5 shows the results obtained. It can be seen that, similar to the results reported in the previous section, the CPX results obtained at microphone positions M6 and M7 provide an improvement in the correlation between the SPB index $L_{vehL1}$ over that obtained by correlating SPB levels with CPX levels derived from measurements taken at microphone positions M1 and M2.
Table 4.5: Regression statistics of $L_{vehL1}$ and $L_{tr}$ (M6 and M7)

<table>
<thead>
<tr>
<th>Regression Statistic</th>
<th>$L_A$</th>
<th>$L_B$</th>
<th>$L_C$</th>
<th>$L_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>1.38</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Intercept</td>
<td>-50</td>
<td>-21.7</td>
<td>-33.2</td>
<td>-38.3</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.88</td>
<td>0.89</td>
<td>0.83</td>
<td>0.81</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.96</td>
<td>0.92</td>
<td>1.12</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Figure 4.2. shows the regression relationships derived from the analysis of the data from microphone positions M6 and M7. The data from porous surfaces are shown as ‘solid’ data points for each test tyre. It can be seen that, in general, the TR levels for all the reference tyres travelling at 80 km/h correlate reasonably well with noise emissions from light vehicles travelling at high speeds.

Figure 4.2 Comparing the regression relationship between SPB index, $L_{vehL1}$ and TR Level, $L_{tr}$, derived from averaged noise levels at M6 and M7 at 80 km/h.

4.2.2.2 SPB heavy vehicle noise index, $L_{vehH2}$

Similar analysis to estimate the SPB index for heavy vehicles, $L_{vehH2}$ at the reference speed of 90 km/h for high-speed roads was carried by regression analysis with measured TR levels derived from the average noise at positions M1 and M2 for each reference tyre at 80 km/h. Table 4.6 compares the results of this analysis for all the surfaces examined and also with the porous surfaces excluded from the analysis. The results show that when the porous surfaces are included in the analysis there is reasonable correlation between the indices for all the tyres. Although statistically there is no significant difference in the correlation between each of the tyres, the results indicate that Tyre B and
Tyre D, which was selected to represent noise levels from heavy vehicle tyres, performs marginally better in estimating the SPB index, \(L_{vehH2}\). As was shown in the previous analysis for estimating noise from light vehicles, when the porous surfaces are removed from the analysis, the predicted accuracy between the indices significantly improves but the relative performance between the reference tyres remains fairly constant with Tyre B and Tyre D both providing the highest correlation with over 90% of the variance explained compared with corresponding values of 85% and 81% for tyres C and A, respectively.

**Table 4.6: Comparing regression statistics of \(L_{vehH2}\) and TR Level, \(L_{tr}\) with and without Porous Asphalt (M1 and M2)**

<table>
<thead>
<tr>
<th>Regression Statistic</th>
<th>LA</th>
<th>LB</th>
<th>LC</th>
<th>LD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>1.54</td>
<td>1.32</td>
<td>1.4</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>(1.49)(^1)</td>
<td>(1.25)</td>
<td>(1.32)</td>
<td>(1.63)</td>
</tr>
<tr>
<td>Intercept</td>
<td>-67.8</td>
<td>-46.8</td>
<td>-53.5</td>
<td>-81.1</td>
</tr>
<tr>
<td></td>
<td>(-62.2)</td>
<td>(-39)</td>
<td>(-45.5)</td>
<td>(-74.7)</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.66</td>
<td>0.76</td>
<td>0.72</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>(0.81)</td>
<td>(0.89)</td>
<td>(0.85)</td>
<td>(0.9)</td>
</tr>
<tr>
<td>Standard error</td>
<td>1.7</td>
<td>1.4</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>(1.2)</td>
<td>(0.9)</td>
<td>(1.1)</td>
<td>(0.87)</td>
</tr>
</tbody>
</table>

\(^1\) Values in brackets show the corresponding results when the porous asphalt surfaces have been omitted from the analysis.

As in the previous sections, the analysis was repeated but with TR levels calculated by averaging the noise levels recorded at position M6 and M7. Table 4.7 shows the results obtained. Again, it can be seen that deriving TR levels from noise measured at positions M6 and M7 provides an improvement in the predictive accuracy in estimating the SPB index \(L_{vehH2}\) compared with measures derived from M1 and M2, particularly for porous surfaces.

**Table 4.7: Regression statistics of \(L_{vehH2}\) and TR level, \(L_{tr}\) (M6 and M7)**

<table>
<thead>
<tr>
<th>Regression Statistic</th>
<th>LA</th>
<th>LB</th>
<th>LC</th>
<th>LD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>1.5</td>
<td>1.18</td>
<td>1.34</td>
<td>1.44</td>
</tr>
<tr>
<td>Intercept</td>
<td>-57.5</td>
<td>-28.1</td>
<td>-41.7</td>
<td>-50.2</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.92</td>
<td>0.95</td>
<td>0.9</td>
<td>0.91</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.85</td>
<td>0.67</td>
<td>0.91</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Figure 4.3 shows the regression equations obtained for each test tyre and shows that in general, TRSL for all the reference tyres travelling at 80 km/h correlate reasonably well with noise emissions from heavy vehicles travelling at high speeds.

Figure 4.3 Comparing the regression relationship between SPB index, L_{vehH2} and TR Level, L_{tr}, derived from averaged noise levels at M6M7 at 80 km/h.

4.2.2.3 Simplifying the procedure for estimating the SPB index, RSI_H, from CPX measurements

In developing a simplified procedure for estimating the SPB index, RSI_H from the TR levels for the four reference tyres, a stepwise multiple regression analysis was carried out. The TR levels for each of the reference tyres at 80 km/h were used as independent variables to correlate against RSI_H values. Using SPSS to pick only the variables that were statistically significant resulted in the following relationship between RSI_H and TR levels.

Road surface influence derived from TR levels by averaging noise levels at M1 and M2 at 80 km/h

All surfaces:

\[
\text{Estimated } RSI_H = 1.2 \left[ L_B \right] - 128.3 \text{ dB}(A) \quad (R^2 = 0.75 : \text{SE} = 1.4) \quad (4.1)
\]

Non-porous surfaces:

\[
\text{Estimated } RSI_H = 1.2 \left[ L_B \right] - 120.7 \text{ dB}(A) \quad (R^2 = 0.91 : \text{SE} = 0.75) \quad (4.2)
\]
Road surface influence derived from TR levels by averaging noise levels at M6 and M7 at 80km/h

All surfaces:

\[
\text{Estimated } RSI_H = 1.1[L_B] - 109.4 \quad \text{dB}(A) \quad (R^2 = 0.91 : \text{SE} = 0.81) \quad (4.3)
\]

The results from these stepwise regression showed that the TR levels for reference tyre B were found to provide the most statistically significant correlation with RSI_H irrespective of whether TR levels were derived from averaging the noise levels at M1M2 or M6M7 and that the TR levels for the other three reference tyres were found not to significantly contribute to the correlation and were therefore eliminated from the analysis.

The results of the regression analysis on this dataset again illustrates that for TR levels derived from averaging noise levels from microphone positions M1 and M2 there is a significant reduction in the predictive accuracy in estimating RSI_H values when porous surfaces are included in the analysis. Comparing the regression equations 4.1 and 4.2 shows that about 75% of the variance between RSI_H and L_B can be explained from the regression analysis when the data includes porous asphalt whereas by excluding the porous asphalt surfaces from the analysis, the explained variance increases to over 90% and the standard error is reduced by about 50%. However, when L_B is derived from averaging noise levels from microphone positions M6 and M7, the explained variance is over 90% and the standard error is 0.81 dB(A) when all the surfaces including porous asphalt are used in the regression analysis.

Comparing the results from the above analysis with those described in section 4.2.1 indicate the possibility of significantly simplifying the procedure for estimating RSI_H values based on CPX measurements from the single reference tyre B without a significant reduction in prediction accuracy. These results are particularly relevant as the availability of the reference tyres are becoming more difficult. For example, reference tyre D is no longer manufactured and the condition of the remaining stock of these tyres are rapidly failing the specification required as described in the Draft International Standard, ISO 11819-2.

4.2.3 Influence of the sound absorption properties of the road surface on CPX levels

The results from the preceding sections have illustrated that the relationship between the various SPB indices and CPX indices is dependent on which CPX microphone positions are used and on the sound absorption properties of the road surface. Noise levels monitored at the mandatory positions described in the Draft International Standard, ISO 11819-2 and referred to as M1 and M2 in this report are less sensitive to the sound absorption characteristics of the road surface than compared with the optional microphone positions M6 and M7 which are situated to the rear and in front of the contact patch of the reference tyre, respectively, as illustrated in Figure 3.8.

An analysis of the relative sound pressures at the different microphone positions was carried out to investigate the possibility of developing a method which may allow TRITON to be used for classifying different surfaces according to their sound absorption properties of the road surface. Although the sound absorption characteristics of the road surfaces selected in this report were not directly measured it is possible to rank order the surfaces according to their sound absorption properties by their generic type. For example, the porous asphalt surfaces are likely to provide the highest sound absorption characteristics followed by the remaining bituminous surfaces, SMA and HRA with the concrete surfaces EAC and BC providing the least sound absorption properties. The analysis showed that examining the relative difference between the sound levels at the microphone
position directly alongside the centre of the contact patch of the tyre (M5) with those recorded at the rear of the contact patch (M6) as illustrated in Figure 3.8, provided the most promising results.

Figure 4.4 shows the results from this analysis. For each of the reference tyres the average difference between the sound levels recorded at M5 and M6 for each surface type were calculated and plotted against surface type ranked ordered in terms of the likely sound absorption properties of the surface. The figure illustrates that there is a general trend across all the reference tyres that as the sound absorption properties of the road surface reduces the average difference in sound levels (M5-M6) becomes smaller.

![Figure 4.4 Relative differences between sound levels recorded at positions M5 and M6 for each reference tyre averaged according to the type of surface](image)

For the porous asphalt surfaces, the average difference between the sound levels at position M5 and M6 is about 6 dB(A) compared with differences of about 1 dB(A) for the highly reflective brushed concrete surfaces. Comparing the results for the different reference tyres indicate that tyres A and B provide the largest difference in sound levels across the range of surfaces examined, and therefore, are more likely to provide a better indicator of the sound absorption properties of the road surface compared with tyres C and D.
5 Summary and Conclusions

TRL were commissioned by Traffic Safety and Environment Division of the Highways Agency to examine methods for assessing the acoustic performance of road surfaces and to examine possible interrelationships between the main methods. The findings and conclusions are summarised below;

1. Currently, the most widely used test method is the Statistical Pass-by (SPB) technique. This method involves establishing the average noise levels from individual vehicle types at a standard distance and passing speed. The results obtained allow the noise effects of different surfaces to be compared in a form that can be directly related to roadside traffic noise levels. An International Standard SPB method has been developed. This standard has been adopted in many countries although some countries have introduced additional features. For example, France and Germany, have standardised their own variants.

2. The main disadvantage of the SPB method is that the acoustical requirements of the test site can restrict the ability to measure at arbitrary locations. A further disadvantage is that the results of measurements taken with the SPB method are not solely dependent on road surface characteristics but also depend upon the characteristics of the vehicles in the traffic stream. SPB measurements taken in the future may be affected by changes in vehicle and tyre design, thereby making it difficult to compare such measurements with historical SPB data.

3. To overcome some of these difficulties, a supplementary method, known as the Close-proximity (CPX) measurement method is currently under development as an ISO standard. This method requires the measurement of tyre/surface noise using microphone receptors located in close proximity to a standard tyre. This type of measurement attempts to isolate the noise specifically from the tyre/surface and therefore overcomes some of the potential difficulties encountered with the SPB method. It also offers the advantage that, with suitable equipment, measurements can be taken at traffic speeds allowing long sections of road to be examined. Its main disadvantage is that the results obtained cannot be simply related to roadside traffic noise levels and that it is fundamentally a more complex type of measurement, requiring the use of specially developed trailer systems or vehicles.

4. The study included an examination of the correlation between various measures of CPX noise levels and SPB noise levels. It is anticipated that the ability to reliably estimate SPB noise levels from CPX data would be of particular value in relating the acoustic characteristics of road surfaces with roadside traffic noise levels and, hence, community noise impact. The greater efficiency of the CPX method would potentially allow large sections of the network to be assessed in this manner which could then be used for assessing road condition and informing road surface replacement and maintenance programmes. The method is also not susceptible to changes over time resulting from a changing vehicle fleet.

5. The objective of examining the correlation between the two types of measurements was achieved by carrying out a series of measurements on different road surfaces using both measurement methods. The statistical correlation between the data was then examined. Seventeen different (SPB) sites located on thirteen different road sections were included in the measurement programme. The range of surface types included porous asphalt (PA), stone mastic asphalt (SMA), hot rolled asphalt (HRA), exposed aggregate concrete (EAC) and brushed concrete (BC).

6. Linear regression analysis between the high-speed road surface influence, RSIH, and the close-proximity index, CPXl, as described in in the Draft International Standard, ISO 11819-2 provided the following results:
   • The correlation between RSIH and CPXl was not significantly different whether CPXl was derived from the investigatory method (tyres A, B, C and D) or the survey method (tyres A and D only). Similarly, the correlations were not significantly affected whether the measurements were carried out at 110 km/h or 80 km/h. This provides scope for simplifying a method of estimating RSIH from CPXl measurements particularly where
measurements at the higher speed of 110 km/h are not possible due to speed limit restrictions.

- The correlation between $RSI_H$ and $CPX_t$ was significantly affected by the absorptive characteristics of the road surface. When the regression analysis excluded the porous asphalt surfaces the explained variance provided by the regression equation increased from about 75% to over 90% with a corresponding reduction in the standard error from about 1.4 dB(A) to about 0.8 dB(A).

- The reduction in prediction accuracy in estimating $RSI_H$ values for porous surfaces can be attributed to the close-proximity of the CPX receptor microphones to the test tyre. Noise levels received at these microphone positions are relatively unaffected by the influence of the absorption properties of the road surface on noise propagation whereas the far-field SPB measurements taken at 7.5m from centre of the test surface will be influenced by these propagation effects.

- Repeating the analysis using averaged sound levels recorded at the optional microphone positions at the rear and in front of the contact patch of the tyre, M6 and M7, provided a regression equation which highly correlated $RSI_H$ with $CPX_t$ noise levels and which included the porous asphalt surfaces. The explained variance provided by the regression equation was about 90% with a standard error of about 0.9 dB(A).

- Sound levels recorded at positions to the rear and in front of the contact patch will be influenced by the absorption properties of the road surface due to the so called “horn effect” which refers the amplification of the sound due to multiple reflections occurring between the road surface and the tyre tread either side of the contact patch.

7. Linear regression analysis between SPB vehicle noise indices for high-speed roads and the Tyre/Road Sound Levels (TR level), $L_{tr}$, for each reference tyre at a speed of 80 km/h as described in the Draft International Standard, ISO 11819-2 showed that:

- The correlations between the SPB vehicle noise index for light vehicles, $L_{vehL1}$, with $L_{tr}$ for each reference tyre were again significantly effected by the absorptive characteristics of the road surface. When the regression analysis excluded the porous asphalt surfaces the explained variance provided by the regression equations increased from between 66-75% to 84-91% dependent on the reference tyre with a corresponding reduction in the standard error from about 1.4 dB(A) to about 0.8 dB(A). Reference tyre B performed marginally better in estimating $L_{vehL1}$ than the other reference tyres.

- Similar results were obtained when correlating the SPB vehicle noise index for heavy vehicles $L_{vehH2}$ with $L_{tr}$ for each reference tyre with correlations improving when porous surfaces were excluded from the analysis. Reference tyres B and D performed marginally better in estimating $L_{vehH2}$ than tyres A and C.

- Repeating the analysis using averaged sound levels recorded at the optional microphone positions at the rear and in front of the contact patch of the tyre, M6 and M7, provided regression equations which highly correlated SPB vehicle noise indices, $L_{vehL1}$ and $L_{vehH2}$ with $L_{tr}$ for each reference tyre. Reference tyre B provided a better overall performance than the other tyres in estimating the SPB vehicle noise indices, $L_{vehL1}$ and $L_{vehH2}$.

- The results of the above analysis suggest the possibility of simplifying the procedure in estimating $RSI_H$ from CPX measurements using a reduced number of reference tyres.

8. A multiple regression analysis between the high-speed road surface influence, $RSI_H$ and the TR level, $L_{tr}$, for each reference tyre at a speed of 80 km/h as described in the Draft International Standard, ISO 11819-2 showed that:

- Results from the stepwise regression showed that the TR level of reference tyre B was found to provide the most statistically significant correlation with $RSI_H$ irrespective of whether the TR levels were derived from averaging the noise levels at M1 and M2 or M6.
and M7 and that the TR levels for the other three reference tyres were found not to significantly contribute statistically to the correlation and were therefore eliminated from the analysis.

- These results provide scope to simplify the procedure for estimating RSI\textsubscript{H} values based on CPX measurements from the single reference tyre B without significantly reducing the accuracy of prediction. These results are particularly useful at the present time as it is becoming increasingly difficult to obtain a full set of reference tyres that conform to the requirements of the standard. For example, reference tyre D is no longer manufactured and the condition of the remaining stock of these tyres is deteriorating to the point where issues related to the age of the tyre preclude their use in tests carried out to the Draft International Standard, ISO 11819-2.

9. Additional analysis comparing the relative sound pressures at different microphone positions was carried out to investigate the possibility of developing a method which may allow TRITON to be used for identifying different surfaces according to their sound absorption properties. The results from this analysis were as follows:

- Examining the difference between the sound levels at the microphone position directly alongside the centre of the contact patch of the tyre (M5) with those recorded at the rear of the contact patch (M6) showed that the sound absorption properties of the road surface were correlated with the average difference in sound levels (M5-M6) for all the reference tyres.

- Comparing the results for the different reference tyres indicate that tyres A and B are likely to provide a better indicator of the sound absorption properties of the road surface compared with tyres C and D.

10. Overall the results of the analysis of the correlation between CPX and SPB noise levels indicate that it is possible to achieve reliable estimates of SPB noise levels from appropriate measures of CPX noise levels. In addition, it might be possible to simplify the procedure such that measurements are only taken on one reference tyre (tyre B appears to be a suitable candidate) and at a single passing speed without significantly reducing the accuracy of estimating the roadside values of SPB noise levels.

11. It would appear that the problems of taking CPX measurements on porous road surfaces can be largely overcome by using close-proximity microphone positions located at the optional positions perpendicular to and in line with the tyre rather than at the currently recommended mandatory 45 degree positions as described in the draft standard.

Recommendation for further work:

- The results described above were obtained from measurements at a limited number of sites (17) for a small range of different surface types (5). It is recommended that further surveys are carried out to extend the range of surfaces to include thin surfaces and surface dressings so that a more robust relationship between SPB and CPX indices can be derived. The results from these additional surveys would help to establish whether the CPX method as described in the Draft International Standard, ISO 11819-2, could be simplified by reducing the required number of reference tyres. A particular objective would be to eliminate the need to find a replacement for reference tyre D which has now become obsolete and to explore the possibility of simplifying the procedure by recommending a single reference tyre. The results from this work suggests that reference tyre B is a good candidate but further work to extending the range of surface types is necessary to support this conclusion.

- To further supplement the data described in this report similar data exists from other research programmes carried out by TRL for the Highways Agency which could be incorporated into the analysis.
The work described in this report has examined the relationship between SPB and CPX indices for high speed roads. It is therefore recommended that similar relationships should be examined for medium and low speed roads so that a comprehensive understanding of the relationship between SPB and CPX indices can be established.

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References


Franklin R E, D G Harland and P M Nelson (1979). Road surfaces and traffic noise. TRRL Laboratory report LR 896. Transport and Road Research Laboratory, Crowthorne, England


Appendix A. Triton Close-Proximity Test Vehicle

A.1 Vehicle specification

The TRL TRITON tyre/road noise test vehicle was specially designed for the purpose of taking CPX measurements from tyres and road surfaces and is shown in Figure A.1.

![TRITON Vehicle](image)

**Figure A.1: TRITON**

TRITON is based on a 10 tonne DAF 45.210 truck, down-plated to 7.5 tonnes. This vehicle registration was chosen to ensure that TRITON could be used for test purposes on the UK road network at speeds up to and including the maximum legal UK motorway speed of 70 mph (112 km/h). On a closed test tracks (or unopened roads), TRITON can actually be operated at speeds of up to 80 mph (130 km/h).

The key features of the vehicle are an acoustic enclosure and special suspension system to control the operating environment around the test tyre. The enclosure and suspension were designed to accommodate the full range of passenger car and van tyres being investigated in this study. The suspension system allows the test wheel to be raised and lowered whilst TRITON is moving as well as controlling wheel load, camber and steer angles. The enclosure isolates the microphones from other sources of noise on TRITON and from other vehicles on the road.

A.2 Triton's enclosure

The enclosure that houses the test wheel/tyre and suspension system had to fulfil strict acoustic specifications and had to attenuate noise generated by the power train and the tyres of the vehicle so that measurements taken from the test tyre were not contaminated by these other sources. This was partly achieved by making the enclosure as large as possible. The size of the enclosure was a major
consideration when choosing the base vehicle from which to develop TRITON. The DAF truck has a long wheelbase and the enclosure fills all of the available space between the front and rear wheels on the left-hand side of the vehicle. To minimise sound reflection in the enclosure, the inner faces are lined with 100 mm thick lightweight melamine-based foam with a sound absorption coefficient of 0.9 at 250 Hz. Additional detachable sound absorption panels cover the rubber curtains down to 25 mm from the road surface and the suspension components within the enclosure are treated with absorptive foam where necessary.

In order to easily vary the load applied to the test tyre, a relatively sophisticated suspension system has been utilised (see Figure A.2). The suspension set-up allows the load on the test wheel to be varied up to a maximum of 1000 kg via an air spring and pneumatic cylinder system. The air spring ensures that load variations experienced at the test wheel are minimised when the vehicle encounters bumps in the road. A high-precision pneumatic regulator controls the air spring pressure. The pneumatic cylinder system allows the test wheel to be lifted off the road whilst maintaining the wheel load settings.

![Figure A.2: TRITON test wheel suspension system](image)

The test wheel is longitudinally located by means of a parallelogram linkage, whilst lateral location is provided by the wheel carrier and the upper suspension member. The suspension system includes equipment to monitor conditions during testing, thereby allowing a range of properties to be measured in addition to noise levels. A load cell in the wheel hub carrier measures the vertical load on the test wheel, whilst horizontal loads are recorded by a similar device located in the lower link. In addition, on-board instruments record tyre inflation pressure and temperature, air temperature and road surface temperature as well as test wheel speed.

### A.3 Validation of the acoustic performance of TRITON’s enclosure

Before TRITON could be used as a CPX test vehicle, it was necessary to prove that the acoustic enclosure on TRITON which covers the test wheel mechanism and microphone arrangement had no effect on noise levels measured in the vicinity of the wheel. The validation has been carried out in accordance with ISO/DIS 118119-2 (2000), which bases the validation on levels recorded at the mandatory microphone positions. This draft standard states that the levels inside the enclosure shall be
within ~1.0 dB of those in the absence of the enclosure, although a limit of ~3.0 dB is acceptable providing that certain reporting conditions are met when the enclosure is used operationally.

TRITON’s mode of construction meant that the enclosure could not be removed for isolated testing. Consequently, conditions in the absence of the enclosure were replicated by taking measurements using a static, freestanding tyre/wheel assembly and an artificial noise source in TRL’s semi-anechoic chamber.

The noise source consisted of a pink noise generator and amplifier connected to the drive-unit of a loudspeaker fitted to a length of heavy duty rubber hose, which was representative of a point source in free-field conditions. Microphones were located at twenty-four positions around the test tyre (see Figure A.3), two of which corresponded with the CPX microphone positions mandated in ISO/CD 11819-2. All measurements were carried out with the noise source at ground level to eliminate ground reflections. Tests were carried out with the noise source first positioned at the leading edge of the tyre contact patch and then at the trailing edge. In each case, one-third octave band sound pressure level measurements were taken at each of the twenty-four microphones.

Figure A.3: Experimental arrangement for source validation (source shown at trailing edge of contact patch). Dimensions in mm

This procedure was repeated using TRITON. In this case, the test tyre/wheel combination was mounted on TRITON’s suspension system and the enclosure was closed. The artificial noise source
and the microphones were positioned around the tyre in the same manner as for the semi-anechoic chamber tests. One-third octave band sound pressure levels obtained from both microphone positions in this exercise were averaged and compared with the corresponding average sound pressure levels in the semi-anechoic chamber. As can be seen from Figure A.4, the differences in level between TRITON’s enclosure and free-field conditions were less than 1 dB(A) for each one-third octave band.

**Figure A.4: Difference in one-third octave band sound pressure level between free-field levels and levels in TRITON’s acoustic enclosure at the two ISO microphone positions**