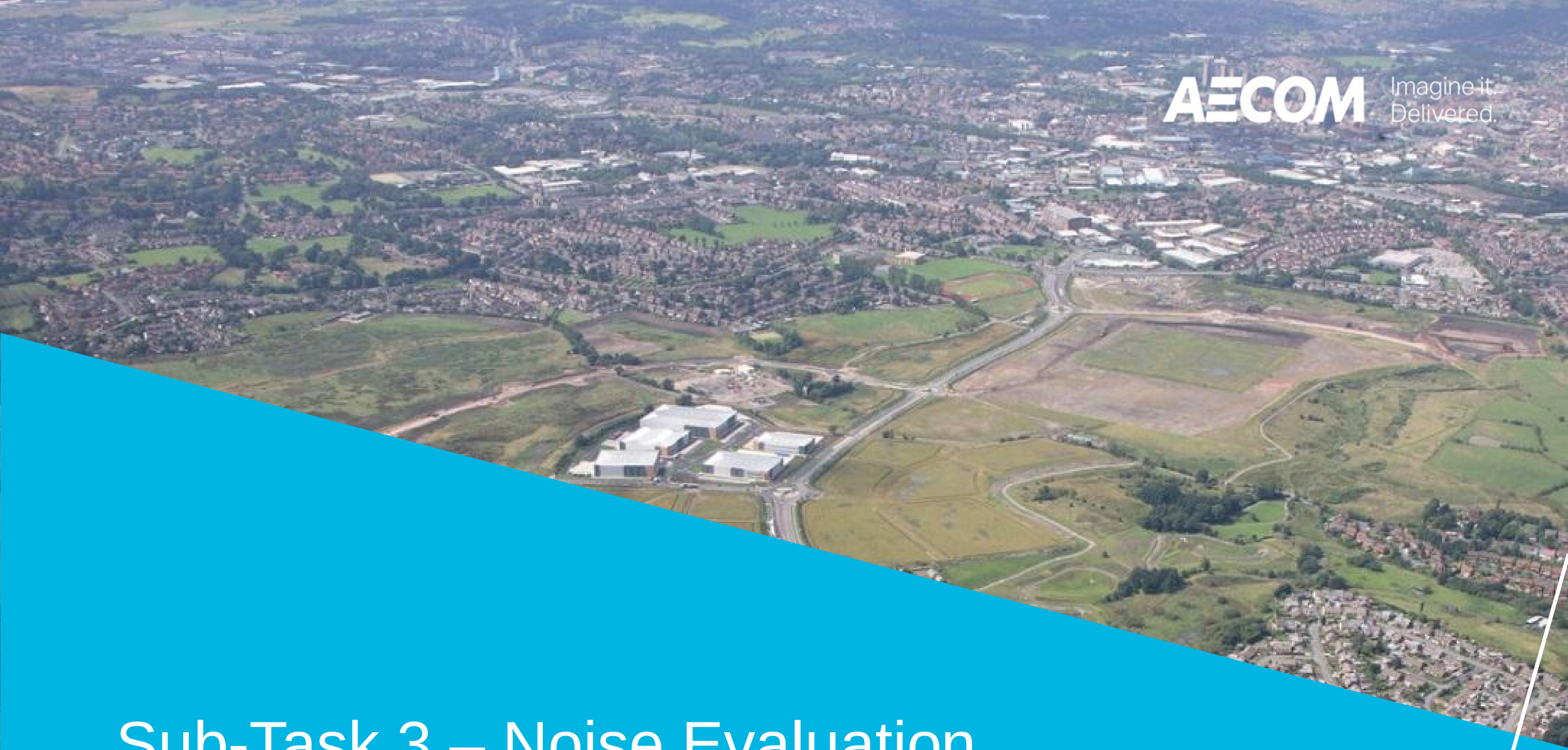

Sub-Task 3 – Noise Evaluation

Task 1-111 Collaborative Research Project

Highways England, Mineral Product Association and Eurobitume UK

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Executive Summary

The impact of road traffic noise can have a significant impact on the quality of life for residents close to major road networks. One of the most effective measures for reducing the noise from road traffic, particularly on high-speed roads, is to ensure the use of a low noise road surface. Research on pavement construction and the measurement of its acoustic properties has shown that significant noise benefits can be achieved through the use of certain road surface types. However certain low noise road surfaces do not exhibit the desired durability associated with more traditional pavements, leading to costly and disruptive maintenance regimes.

As such Highways England, the Mineral Products Association and Eurobitume UK have come together to fund collaborative work into developing a durable low noise pavement. This work will ensure that asphalt surfacings continue to deliver value for money on the UK Strategic Road Network and maximise the benefit from innovation.

As part of this programme of work, this report provides an overview of the mechanisms involved in tyre/road noise generation, how tyre/road noise is measured, the acoustic properties of different road surfaces and how road surfaces may be classified in terms of their impact on traffic noise.

In addition, this report makes recommendations for the future acoustic monitoring and classification of road surfaces, including the new Hot Rolled Asphalt and Premium Asphalt Surfacing System materials developed as part of this programme of work.

1. Introduction

Several studies have examined the health and monetary impact of changes in road traffic noise, either as a consequence of revisions to the vehicle noise test procedures (Watts, et al., 2005), proposed changes to the type approval noise limits for tyres (Muirhead, et al., 2008) or changes to vehicle noise regulations (Muirhead, 2012). Such impacts, particularly in noise sensitive areas, can be significant and highlight the benefits of reductions in road traffic noise. Research on pavement construction and the measurement of its acoustic properties has shown that significant noise benefits can be achieved through the use of certain materials. However, it can be the case that certain quieter surfaces do not exhibit the desired durability associated with more traditional pavement types (Morgan(editor), 2006).

As such, a key component of collaborative work, funded by Highways England (HE), the Mineral Products Association (MPA) and Eurobitume UK, on ensuring that asphalt surfacings continue to deliver value for money on the UK Strategic Road Network (SRN) and maximise the benefit from innovation, is to find a durable low noise pavement. The first part of this programme of work, see (Ojum, 2016), reviewed surfacing materials worldwide with the view to understanding and developing requirements for materials which offer significantly enhanced durability, reduced noise characteristics and improved skid resistance. This knowledge was used to initiate the development of asphalt materials that could meet these requirements. A Hot Rolled Asphalt (HRA) and a Premium Asphalt Surfacing System (PASS) mixture were further developed in the laboratory to establish a proof of concept for the asphalt materials.

This follows up a programme of work looks to perform live trials of these materials on the SRN. One of the consequences of this is the need to understand the acoustic performance of these materials under regular traffic conditions. This report summarises existing knowledge and experience with respect to tyre/road surface noise generation, the acoustic performance of different pavement types and the methods by which the acoustic performance of pavements can be assessed. This will provide useful context when attempting to understand the acoustic performance of the modified HRA and PASS mixtures.

2. Tyre Road Noise Generation

This chapter discusses road surface properties in general and their impact on the acoustic performance of the pavement. A detailed examination of these properties and mechanisms is presented in the SILVIA Guidance Manual (Morgan(editor), 2006) and the tyre/road noise reference book (Sandberg & Ejsmont, 2002). SILVIA was a large European wide programme carried out around 2005 with the aim of evaluating low noise road surfaces and determining how best they could be integrated into existing networks and what associated benefits could be achieved.

2.1 The Tyre/Road Interaction

The mechanisms of tyre/road noise generation are often divided into three classes covering impacts and shocks, aerodynamic processes and adhesion effects respectively.

Impacts and shocks

These describe the interaction forces between the tyre tread and the road surface. The tread block itself is said to be snapping out as it leaves the road surface and returns to its uncompressed state and this tends to generate noise below 1 kHz.

Aerodynamic processes

Air trapped between tyre tread blocks as it passes over the road is compressed and decompressed and this is referred to as air pumping and this tends to generate noise above 1 kHz. Theoretically, this process is a significant source of tyre/road noise for smooth, non-porous surfaces which have fewer avenues for the dissipation of the compressed air. Additionally, cavities in the tyre tread pattern may cause further resonance of the noise. The amplitude of the shorter texture wavelengths in the road texture profile has an important role in determining the level of aerodynamic noise, see Section 2.2.

Adhesion effects

The frictional forces between the tyre and road surface cause vibrations in the tyre which are dissipated by the tyre slipping on the road surface. This noise generation mechanism is partly governed by the small-scale roughness characteristics of the road surface.

These noise generating mechanisms are amplified by the local geometry of the tyre and road surface, at the rear of the contact patch (the area where the tyre touches the surface), and this is known as the horn effect. It can result in substantial amplification of the noise above 1 kHz.

The relative importance of these various mechanisms varies between tyre types and surface designs.

As well as the generation of noise, surface design can influence noise propagation. For example, porous road surfaces (see Section 2.3) can result in destructive interference between the direct sound wave and that which penetrates the surface layer and is reflected back towards the receiver but out of phase with the direct wave, as illustrated in Figure 2.1. In addition, porous surfaces mitigate the amplification of noise caused by the horn effect.

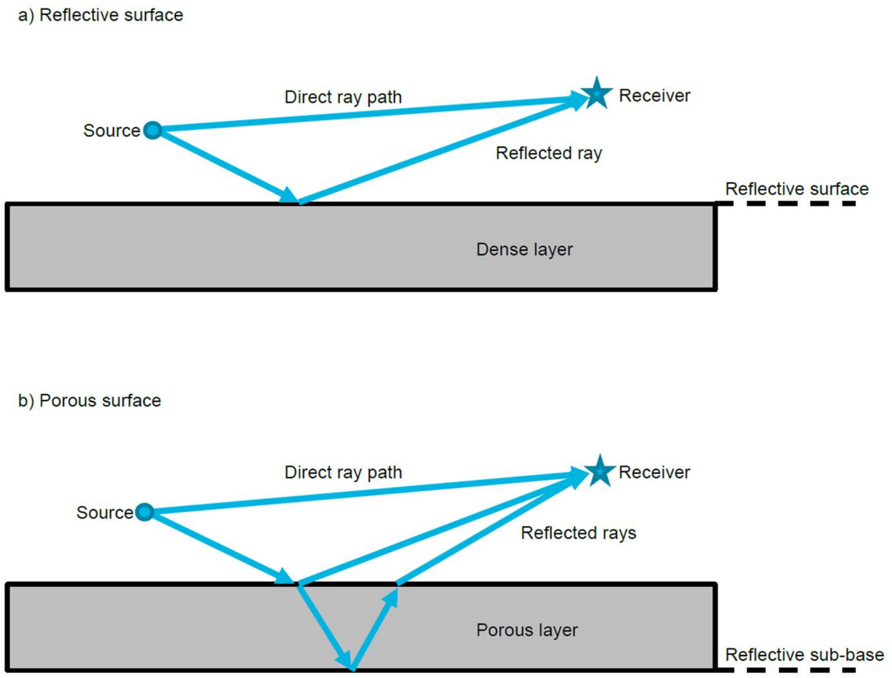

Figure 2.1: Sound Paths over Reflective and Porous Surfaces

2.2 Road Surface Texture

A road surface profile can be visualised by taking a virtual cross section of the pavement and considering how the top layer of this cross section appears. It will consist of a continuous series of peaks and troughs which may be randomised or reasonably well defined depending on the pavement type. This profile shape can be interpreted in terms of the summation of a number of sinusoidal variations of different amplitudes and wavelengths. Each sinusoidal variation is called a waveform and the associated amplitudes and wavelengths are referred to as texture amplitudes and texture wavelengths.

These texture wavelengths may be classified in terms of their size – see Table 2.1.

Research has shown that increasing texture amplitudes at wavelengths between 0.5 and 10mm reduces air pumping noise as the air between the surface and tyre is released more smoothly. However, research has also shown that increasing texture amplitudes at wavelengths between 10 and 500mm increases low-frequency noise as a result of higher vibration levels in the tyre carcass.

Table 2.1: Texture Wavelength Classifications

Texture region	Texture wavelength (mm)
Microtexture	< 0.5
Macrotexture	0.5 – 50
Megatexture	50 – 500
Unevenness	> 500

In addition, the way the texture is applied can have an effect. Research reported in (Morgan(editor), 2006) indicated that noise levels associated with surfaces with transverse texture (i.e. a relatively regular profile across the width of the road surface) are higher than noise levels associated with surfaces with random texture even if the texture amplitudes are similar. This is down to the synchronised forces in the transverse texture enhancing the associated tyre vibrations.

As well as texture amplitudes and wavelengths, road surface profile may be referred to as having either a positive or negative texture. Positive texture refers to a surface where ridges protrude above the plane of the surface whereas negative texture refers to a surface which is largely smooth save for some voids between the aggregate, see Figure 2.2. In general positive texture encourages higher levels of vibration (and therefore noise) in the tyre than negative texture.

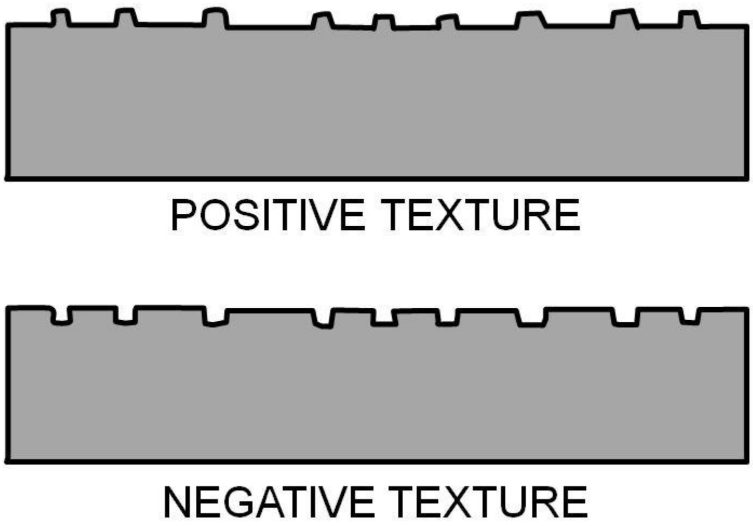

Figure 2.2: Positive and Negative Texture

There has been work carried out to develop a noise model based on texture measurements for particular pavement types, see (McRobbie, et al., 2004). These models generated noise levels that were within 1 dB of the reference measured value 60% of the time but there was not a strong correlation between noise and overall texture for a given surface and there were further corrections required to predict noise levels at different speeds.

2.3 Other Road Surface Properties

The environmental noise from traffic is also influenced by the absorption of the noise generating mechanisms discussed in Section 2.1 and one of the key parameters in this regard is porosity.

Porosity is a measure of the fraction of the volume of voids to the overall volume and, with respect to road surfaces; the residual air void content is the fraction of voids open to the air in a given volume of pavement mix. Generally speaking, dense pavements have an air void content under 10% and porous surfaces have an air void content over 20%.

For tyre/road noise, increased porosity reduces air pumping and generally increases sound absorption, which in turn reduces the horn effect. There are also other parameters which influence sound absorption including the thickness of the porous layer, airflow resistance and tortuosity (a measure of the curved/meandering nature of the air path through the surface layer).

These parameters have complex and interdependent relationships with the air flow through the surface and the frequencies which are mostly absorbed, see (Hamet & Berengier, 1993) (Hamet, et al., 1990). Research in the area of porous surfaces, see Section 4.5, has shown that porosity decreases as the surface becomes clogged. Additionally reducing the mechanical impedance of the road surface will reduce tyre vibration levels and therefore noise generation.

Of course, these considerations for a low noise pavement need to be balanced with the non-acoustic requirements for the pavement. These include skid resistance, rolling resistance and durability. It is not the intention of this report to look at these requirements in close detail but a brief summary of how they relate to the pavement parameters discussed in this chapter is provided below.

Skid resistance requires a degree of surface texture amplitude over a wide range of texture wavelengths. Increasing texture amplitudes in the microtexture and macrotexture range is less likely to have a detrimental effect on the noise generation than increased texture amplitude in the megatexture range. Achieving the desired texture amplitudes for skid resistance at the texture wavelengths that do not adversely impact the noise generation is the key to having a low noise surface that meets the necessary safety requirements.

Rolling resistance and noise are more closely related and reducing texture amplitudes in the megatexture range tends to be beneficial for both properties. For a comprehensive review of the literature on rolling resistance see (Bendtsen, 2004).

These texture wavelengths that influence these properties are shown in Figure 3.3 of the SILVIA guidance manual, reproduced here as Figure 2.3.

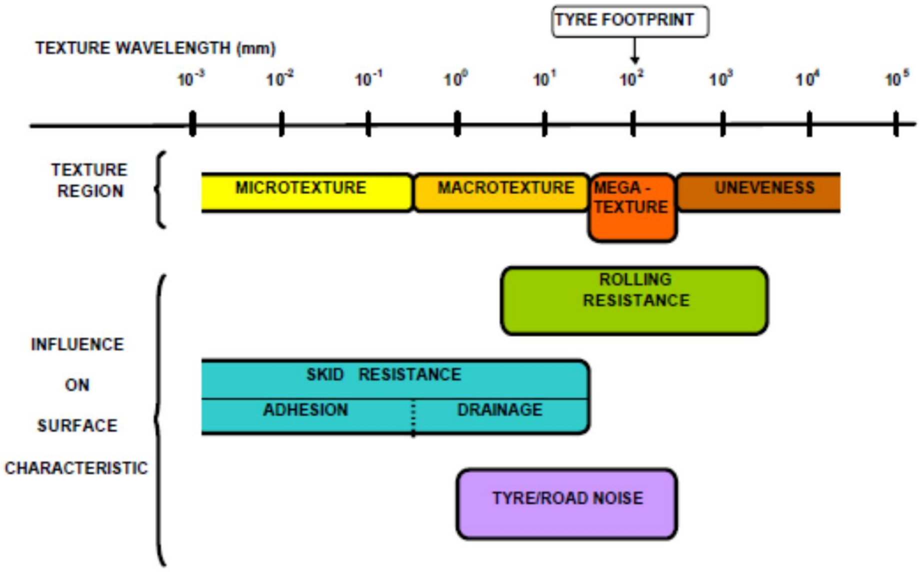

Figure 2.3: Texture Wavelengths and Influence on the Surface Characteristics[1]

The durability of a road surface reflects its ability to retain its structure over time and resist the forces applied to it from traffic and weather. For example, traffic can wear down the texture amplitudes associated with shorter texture wavelengths, increasing aerodynamic noise. Porous surfaces are particularly susceptible to degradation as the high void content can result in the surface becoming clogged, reducing acoustic absorption and causing the surface layer to break apart. Other surface characteristics, such as the grooves in grooved concrete, are also liable to wear which can increase noise levels.

Acoustic measurement methods for pavements are presented and discussed in the next chapter and the noise performance over time of a variety of pavements is discussed in Chapter 4. There, some results from acoustic measurement programmes are presented which can be compared with the theoretical treatment of the noise generating mechanisms discussed above.

[1] Figure taken from P. Morgan(editor), "Guidance manual for the implementation of low-noise road surfaces," FEHRL SILVIA Report 2006/02, Brussels, Belgium, 2006.

3. Road Surface Noise Measurement

3.1 Measurement Methods

Whilst some acoustic properties of a pavement can be measured in the laboratory, this is no guarantee of their acoustic performance on the road. For example, the first part of this programme of work (Ojum, 2016) tested core samples of various materials according to ISO 13472-2:2010 (BSI, 2010) in order to determine the sound absorption characteristics. This was also looked at as part of the SILVIA programme (Morgan(editor), 2006).

In order to get a full picture of how a road surface performs in practice however in-situ measurement programmes involving vehicles are required and these form the focus of this chapter.

When looking to assess the acoustic performance of a road surface it is useful to consider the primary reason for the assessment as well as the location and extent of the surface as laid. For example, it may be useful to consider the following factors:

- Where is the surface to be laid and over what length of road is the surface to be assessed?
- What is the typical speed and composition of traffic on the proposed test section(s)?
- Is the intention of the measurement to classify the road surface purely at the test location or is the intention to classify the road surface type and infer its performance elsewhere on the network?
- Is the intention to rank the surface’s acoustic performance against other surface types?
- Are there performance metrics for the surface and/or traffic noise at the test or other sites?
- What is an acceptable level of uncertainty for the measurement?
- Are the results required for use in calculating environmental noise levels at residential properties?

There are different methods of measuring the acoustic performance of road surfaces and such considerations as highlighted above may influence which of the methods is best suited for a particular measurement programme.

The following paragraphs provide a brief overview of the measurement methods followed by more detailed discussions of the two prominent methods, the Statistical Pass-By (SPB) and Close ProXimity (CPX) methods in Sections 3.2 and 3.3 respectively, see also (Morgan(editor), 2006) and (Haider & Descomet, 2006).

The simplest way to measure road traffic noise is to record average noise levels at the side of a road and, where the average traffic speed is not low (>50 km/h say) and tyre/road noise dominates over engine noise, this can be a reasonable proxy for the acoustic performance of the road surface. Additionally, for a fixed set of conditions, these measurements are very repeatable. The problem with this approach is that there are too many variables which are not accounted for such as vehicle speed, traffic composition, measurement averaging time and the environment which can all have a significant effect on the results. Therefore, whilst this method can be useful for directly comparing the relative acoustic performance of different test sections laid next to each other and subject to the exactly the same traffic stream, it is not appropriate for any other application.

Controlled Pass-By (CPB) measurements limit the number of variables by measuring the cruise-by noise level of a test vehicle at specified speeds. Whilst this accounts for vehicle speed it is not representative of the noise emissions from all types of vehicles, such as Heavy Goods Vehicles (HGVs), which will respond differently due to differences in engine performance and tyre tread characteristics. Additionally, it only assesses the acoustic performance of the road surface positioned alongside the microphone, it can be time consuming to perform and can be difficult to find roads with the limited amount of traffic needed to ensure that the noise from the test vehicle as it passes the microphone is not contaminated by noise from other vehicles in the traffic stream.

In situations where a CPB measurement may be required it is nearly always preferable to perform a series of SPB measurements instead. This method involves measuring the speed and maximum pass-by level of a number of cars and HGVs and performing a regression analysis to determine a reference noise level at a given speed. This procedure is discussed in detail in Section 3.2.

The final measurement method for determining the acoustic performance of a road surface, the CPX method, records the tyre/road noise in the near field through the use of microphones placed close to the tyre of a test vehicle or trailer and enclosed in a semi-anechoic chamber. These direct measurements are arguably the best way to understand the levels of noise generated by the mechanisms discussed in Chapter 2 but are more difficult to relate to traffic noise levels experienced by residents close to the road. This measurement procedure is discussed in detail in Section 3.3.

3.2 Statistical Pass-By (SPB) Method

3.2.1 Overview of Methodology

The SPB method is described in ISO 11819-1 (BSI, 2001) and involves measuring the speed and maximum A-weighted[2] sound pressure level (L_{Amax}) of a statistically representative number of vehicles from the following categories:

- *Vehicle Category 1:* Passenger cars
- *Vehicle Category 2a:* Dual-axle heavy vehicles (>3.5t) with more than 4 wheels, including commercial trucks, buses and coaches
- *Vehicle Category 2b:* Multi-axle heavy vehicles (>3.5t) with more than 2 axles including commercial trucks, buses and coaches.

The requirement is to capture at least 100 category 1 vehicles and at least 80 category 2 vehicles with at least 30 vehicles from category 2a and category 2b respectively.

In taking the measurements the microphone is to be placed 7.5m back from the centre of the running lane and 1.2m above the road surface. There are also a number of conditions on the local environment such as there should not be any reflecting surfaces within 10m of the microphone[3], the road surface should be dry and the road surface should be reasonably straight and level.

Depending upon the mean speed of the captured vehicles in each category, the road is classified as either a medium or high-speed road and corresponding reference speeds for each vehicle category are defined as follows:

- Medium Speed Road: Category 1 80km/h, Category 2 70km/h
- High Speed Road: Category 1 110km/h, Category 2 85km/h.

Reference noise levels for each vehicle category, for a given reference speed, are derived from a regression analysis of the maximum pass-by noise levels and the logarithm of the vehicle speeds. The exact form of the analysis varies slightly depending upon whether or not the procedures outlined in the Highways Authority Product Approval Scheme (HAPAS) Appendix A8 (British Board of Agrement, 2008) are followed. For example, the HAPAS procedure applies a temperature correction to the noise levels from category 1 vehicles and uses a different reference speed, 90km/h, for category 2 vehicles on high-speed roads. The temperature correction reflects research which has indicated that higher noise levels are measured at lower temperatures. It is described in HAPAS as a tentative correction based upon ongoing analysis but has not changed since it was first introduced.

[2] The frequency response of human hearing to sounds in the frequency range 20 to 20k Hz is not constant. The ear is more sensitive to sounds at frequencies centred on about 2.5k Hz compared with sounds at higher or lower frequencies. The frequency response of instruments designed to analyse noise are filtered or weighted accordingly to match that of the human hearing system and is referred to as A-weighted sound pressure levels dB(A).
[3] If this cannot be achieved the SPB can be performed with a backing board for the microphone which is then placed at 5m, rather than 7.5m, from the centre of the measured lane, see (Abbott, et al., 2004)

If following the HAPAS procedure two sets of measurements are taken (at least 100m apart or on opposite carriageways) and the derived SPB levels are fed into an equation designed to provide an indication of the overall acoustic performance of the road surface, called the Road Surface Influence (RSI). For medium speed roads:

$$RSI_M = 10log_{10}\left(11.8 \times 10^{\frac{L_{veh,L}}{10}} + 0.629 \times 10^{\frac{L_{veh,H1}}{10}} + 0.157 \times 10^{\frac{L_{veh,H2}}{10}}\right) - 92.3$$

and for high-speed roads:

$$RSI_H = 10log_{10}\left(7.8 \times 10^{\frac{L_{veh,L}}{10}} + 0.578 \times 10^{\frac{L_{veh,H1}}{10}} + 10^{\frac{L_{veh,H2}}{10}}\right) - 95.9$$

where $L_{veh,L}$, $L_{veh,H1}$ and $L_{veh,H2}$ are the derived maximum noise levels for each vehicle category at the corresponding reference speed. The resulting RSI level provides an indication of the acoustic performance of the surface with respect to a reference equivalent to a newly laid HRA with 20mm chippings. A negative RSI indicates a quieter surface and Table NG 9/30 in the Manual of Contract Documents for Highway Works (MCHW) (Manual of Contract documents for Highway Works, 2008) lists a classification of these in terms of levels.

It is important to note that the derived RSI levels are based on both the associated reference speeds as well as a traffic composition implicit in the RSI equation (the ratio of the multiplying coefficients of the three terms in the brackets)[4]. At other traffic speeds and compositions, the actual acoustic performance of the surface may differ. Some unpublished research (Muirhead, 2013) provides a theoretical framework for how these differences may be quantified but at present derived values for RSI are used directly in road traffic noise calculations. It is worth noting that while changing traffic conditions can mean that only a fraction of the measured benefit of the surface may be realised in practice these changes do not tend to alter the ranking of the relative performance of different surface types. In other words, if surface A is quieter than surface B as measured through a high-speed SPB then there is no reason to believe it will not be quieter at lower speeds even if the absolute benefit may be reduced.

It is also worth noting that when referring to traffic noise calculations and exposure to traffic noise this exposure is measured in terms of an average noise level over a period of time whereas the RSI metric is derived from a selection of maximum (i.e. relatively instantaneous) noise levels. Fortunately, work carried out in the development of ISO 11819-1 and reported in the SILVIA guidance manual (Morgan(editor), 2006), there is a good correlation between the two metrics for traffic noise.

3.2.2 Advantages and Disadvantages

The SPB method is still the most commonly used measurement procedure for classifying the acoustic performance of road surfaces in the UK. No doubt this is partly down to its entrenchment in several key documents such as HAPAS (British Board of Agrement, 2008), Design Manual for Roads and Bridges (DMRB) (Transport, 2011) and MCHW (Manual of Contract documents for Highway Works, 2008) but it does have other clear benefits such as:

- It is measuring the roadside noise level from actual traffic using the road in question and is therefore usually a very good indicator of the impact the tyre road noise from that surface is having on those exposed to it.
- The derived metrics, such as RSI, can easily be incorporated into the current procedure for modelling road traffic noise, as described in DMRB, and allow the mitigation provided by the use of low noise surfaces to be fully assessed.
- The equipment required to perform the measurements is relatively straightforward and inexpensive and measurements at one location can usually be completed in 2-3 hours.
- The measurement programme involves recording the noise from a representative sample of vehicles within a number of acoustically similar groups to ensure that the results are not unduly influenced by atypical tyres or engines.

[4] The implicit traffic conditions assumed in deriving RSI are based on typical traffic compositions for medium and high speed roads in the late 1990s.

Nevertheless, there are also some disadvantages to the SPB method which should be borne in mind in order that the results are not misused or misinterpreted in any way. In Section 3.2.3 the repeatability and reproducibility of the method are discussed and can be considered together with the following limitations:

- The SPB method only assesses the road surface at the measurement location. As such, there is no assessment of the conformity of production. If there are any inconsistencies in the laying of the surface these are not picked up by the SPB measurements and therefore the results can only ever be indicative of the acoustic performance of the surface.
- There can be relatively large variations in the noise of HGVs which is usually only loosely correlated with speed over the sorts of speed ranges captured during a set of measurements. As such there can be some uncertainty with the reported SPB values for category 2 vehicles.
- As mentioned above RSI values are only really representative of the influence of the road surface at the reported reference speeds and traffic compositions implicit in the RSI equations and therefore results need to be treated with caution if they are used to infer the performance of the road under different traffic conditions.
- Because the measurement method relies on far field noise measurements environmental factors such as wind speed, temperature and the proximity of other vehicles cannot be discounted. Although the standards governing the method do apply constraints to reduce the influence of these factors, nevertheless, they may still impact on the test repeatability.
- The conditions required for the successful completion of an SPB measurement can sometimes be difficult to achieve:
  - The road needs to be straight and level.
  - There needs to be sufficient traffic to allow the capture of enough vehicles within each vehicle category to ensure a statistically representative sample.
  - There must be sufficient space to the side of the road to allow for the measurement microphone to be placed in the correct position and to accommodate the required safety protocols.
  - The measurement vehicle must be positioned safely and appropriate weather conditions must prevail – a dry surface, a wind speed less than 5m/s and an air temperature between 5°C and 30°C.

3.2.3 Repeatability and Reproducibility

Confidence in the robustness of the reported acoustic performance of the road surface is important in fully understanding how best to interpret the results of a set of measurements and therefore knowing the repeatability and reproducibility of the method is useful information in this regard. In this context repeatability refers to the measurements being conducted again by the same team with the same equipment and reproducibility refers to the measurements being conducted by a different team with an alternative set of equipment.

Statistical studies on the repeatability and reproducibility of the SPB method are relatively few and far between however, there has been some work done in this area a summary of which is presented here. A study carried out in 2001 is reported on in (Morgan(editor), 2006) as finding a standard deviation of 0.3 dB for light vehicles and 0.5 dB for heavy vehicles, leading to a repeatability of 0.8 dB and 1.3 dB respectively using 80% coverage factors. The corresponding values for reproducibility were found to be 1.1 dB and 1.8 dB. This means that there was considered to be an 80% confidence that the measured results were accurate to within +/- the quoted repeatability value, see (Bell, 2001).

A small study was carried out as part of the SILVIA programme involving two teams taking two sets of SPB measurements each and this found peak-to-peak repeatability differences of 0.2 and 0.4 dB for light and heavy vehicles and corresponding peak-to-peak reproducibility values of 0.4 and 0.6 dB. It was concluded that the main cause of uncertainty was inherent in the measurement procedure itself rather than as a result of different operators.

A statistical analysis of repeatability and reproducibility tests carried out in the US is reported in (Dick, et al., 2015). These tests looked at the American Association of State Highway and Transportation Officials (AASHTO) TP 98: Statistical Isolated Pass-By (SIP) Method, which is essentially the SPB method and involved 5 operators across 4 sites. Overall repeatability and reproducibility standard deviations were slightly higher at 0.5-0.7 dB.

The experience of the author, having conducted numerous SPB measurements across the UK, is that measurements at the same location are nearly always within 1 dB and usually within 0.5 dB.

Additionally, some work has been carried out, both as part of SILVIA and at TRL, looking at the distribution of noise levels amongst HGVs. The general conclusions are that the spread of results can potentially be reduced by further restricting the defined classes but this does not tend to improve the accuracy of the overall result and therefore does not warrant an update to the standard.

3.3 Close ProXimity (CPX) method

3.3.1 Overview of Methodology

The CPX method is described in ISO/FDIS 11819-2:2016 (BSI, 2016) and involves measuring the tyre / road noise at two microphone positions close to the contact patch of the tyre. The test tyre rolls freely over the road surface (i.e. does not have a drive axle) and the measurements are taken 20cm from the tyre wall, 20cm in front and behind the contact patch, and 10cm above the road surface. Results are averaged over 20m road sections and across the two microphone positions.

There are standard reference tyres for cars and trucks and these are defined in ISO 11819-3 (BSI, 2017) as a Uniroyal Tigerpaw 225/60 R16 tyre and Avon Supervan AV4 195-R14C tyre respectively.

The test tyres are usually enclosed within a semi-anechoic chamber to ensure that other noise sources do not influence the levels recorded at the microphones by more than 1 dB. CPX measurements are carried out at references speeds of 50, 80 or 110km/h.

3.3.2 Advantages and Disadvantages

The CPX method is used extensively in some European countries such as Germany and the Netherlands and is becoming increasingly prevalent as the latest versions of the ISO standards 11819-2 and 11819-3 are due to be formally published. This approach has some clear benefits when assessing tyre/road noise such as:

- The method provides a direct measure of the influence of the road surface on the generation of tyre noise. The close proximity of the microphone to the contact patch of the tyre within a semi-anechoic enclosure reduces the influence of other extraneous noise sources affecting the results.
- The method can be used to assess any length (>100m) of road surface relatively quickly and economically, making it ideal for performing Conformity of Production (CoP) checks
- Aside from free-flowing traffic conditions and a dry road surface, there are few practical constraints on performing CPX measurements.

There are however a few limitations of the method, some of which may act as obstacles to its widespread adoption in the UK. Section 3.3.3 discusses the repeatability and reproducibility of the method which has the following constraints:

- The results are not easily transferable into a form which can be readily used in traffic noise calculation and/or environmental noise assessment. Engine noise, for example, is not measured and there may be some directivity to the noise generation and absorption characteristics of the surface that are not fully captured. It is possible to make use of relationships between CPX and SPB measurements values, derived from statistical studies of measurement data collected by both methods on the same road surface see Section 5.2, but this adds an extra layer of uncertainty to the accuracy of results used in traffic noise calculation procedures.

- The test is carried out at a given reference speed and therefore either further tests need to be carried out at other speeds or the impact of the surface on tyre/road noise at other speeds needs to be inferred.
- The test is carried out with a standard reference tyre for either light or heavy vehicles and whilst every effort has been made to ensure this is representative of the vehicle class different tyre widths and tread will result in some difference to the noise levels. Additionally changes in the properties of the reference tyre, as a result of storage and/or ageing, can affect the results although these are mitigated somewhat by requirements for the tyre properties, such as hardness, to meet defined criteria as specified in the standards.
- The test requires a specialised, instrumented vehicle or trailer and TRL's Triton is the only such piece of equipment currently in use in the UK. Also as an HGV, it cannot perform the CPX measurements at 110 km/h and, on some roads, cannot perform measurements at 80 km/h either.

3.3.3 Repeatability and Reproducibility

The repeatability and reproducibility of the CPX method have been examined in studies carried out in 1997-1998 and 2005-2006, reported in (Morgan(editor), 2006) and 2011, reported in (Derksen & Roo, 2012).

Repeatability measurements from the first two studies found typical discrepancies between measurements on the same surface of around 0.2-0.3 dB, with maximum differences observed of around 1 dB. This was backed up by the round robin test in 2011 which found a standard deviation for repeatability measurements of 0.4 dB.

Reproducibility results from the original set of tests were highly scattered because of the relative freedom of microphone positions allowed at the time which has led to a more stringent specification of the measurement systems and microphone positions in the standard. Between the four different systems using the same reference tyre in the SILVIA round robin tests, the standard deviations in the CPX index ranged between 0.3 and 1.3 dB across the different surfaces in the study with typical values around 0.6-0.7 dB. The largest difference between results was 2.9 dB. Similar results were obtained from the 2011 round robin tests where a standard deviation of 0.8 dB was calculated, from tests with 9 trailers across 5 different surfaces, and peak-to-peak variances of +/- 1 dB.

These results show that the whilst the repeatability of the CPX method is slightly better than for the SPB method, likely due to the relatively controlled environment close to the tyre, the reproducibility of both methods is of a similar magnitude, likely due to changes in the tyre properties between measurement systems.

4. Pavement Types

4.1 Overview

Both the age and composition of a pavement can have a huge impact on the associated traffic noise, especially at high vehicle speeds. Measurements taken on the SRN have revealed differences of over 10 dB between the best and worst performing surfaces (Muirhead, et al., 2010). In terms of perception, a 10 dB reduction represents a halving in the loudness of the noise from a passing vehicle and in terms of noise exposure it is the equivalent of taking 90% of the vehicles off the road.

The SILVIA guidance manual (Morgan(editor), 2006) includes a comprehensive discussion of the majority of pavement types found in Europe including their construction and surface properties. In this chapter, several common pavement types are categorised into four different groups and their acoustic properties are discussed. This discussion focusses on their intrinsic acoustic performance and the impact on this over time, touching on their construction and texture were relevant to the acoustic properties of the surface.

The EU project QUESTIM reports on a summary from around Europe of measured road surface noise over time across several different surface types, see (Blokland, et al., 2014). Whilst this showed that the acoustic performance of road surfaces did not deteriorate as quickly in central and southern European countries compared to parts of the UK and Scandinavia it also confirmed that quiet surfaces, such as porous asphalt and thin layer systems with relatively small chip size, are subject to a faster drop off in acoustic performance compared to surfaces such as concrete and HRA.

4.2 Hot Rolled Asphalt

HRA has been widely used on the SRN and is a durable surface that can last over 20 years, however, it results in higher levels of traffic noise than most other randomly textured surfaces including thin surfacings and porous asphalt. The HAPAS Appendix A8 classifies road surface noise through the Statistical Pass-By (SPB) method, see Section 3.2, and references the noise performance with respect to a surface acoustically equivalent to a newly laid HRA with 20mm size pre-coated chipping (PCC); hereafter HRA surface. This level of acoustic performance is also a reference for Calculation of Road Traffic Noise (CRTN), the national methodology for calculating traffic noise used by highways authorities for assessing noise from road traffic and which forms the basis of the method described in DMRB (Transport, 2011). As such, when referring to the noise performance of road surfaces in this chapter, a new HRA surface is used as a reference point. For example, if a surface is referred to as providing a benefit of 3 dB this is to be interpreted as with respect to a new HRA surface.

Measured SPB levels on an HRA surface over the course of 12 years, reported in (Muirhead, et al., 2010), show that the pavement had an RSI slightly below 0 when new and exhibited an acoustic decay of around 0.2 dB / year.

4.3 Thin Surfaces

Thin surface course systems have been used on the SRN since the late 1990s and encompass a variety of bituminous products with a surface layer less than 50 mm deep. These surfaces tend to be classified either according to their surface thickness or in terms of the aggregate size used. Ultra-thin asphalt concrete has an average design thickness of 10-20 mm, very thin asphalt concrete surfaces are laid with a nominal thickness of 18-25 mm and Stone Mastic Asphalt (SMA) surfaces have a typical thickness of 25-50 mm. The nominal aggregate size used in these surface layers is in the range 6-14 mm and the open and smooth surface texture lends itself to low noise performance.

There have been numerous studies involving thin surface layers, such as (Bendtsen, et al., 2005) (Thomsen, et al., 2006) (Andersen, et al., 2006) (Muirhead, et al., 2010), and in general, and as discussed in Chapter 2, thinner layers and smaller aggregate sizes result in quieter surfaces with less durability and greater deterioration in acoustic performance over time (Muirhead, et al., 2010).

The SILVIA guidance manual (Morgan(editor), 2006) notes that thin surfaces have negative texture resulting in lower noise levels and less spray than a traditional surfacing material. However, it is also noted that it may be more difficult to achieve required skid resistance requirements.

An overview of the acoustic performance of thin surface layers in the UK can be gleaned from (Muirhead, et al., 2010) where measured RSI levels were between -3 (14 mm aggregate size) and -8.5 dB (6 mm aggregate size) for new surfaces and acoustic performance degraded by around 0.5 dB / year. Despite this higher decay rate in acoustic performance thin surfaces layers were, in general, still found to be quieter than a new HRA surface after 10 years. Acoustic measurements over time on thin layers were also collated as part of the EU QUESTIM programme and reported in (Blokland, et al., 2014); these results, from across Europe, showed an improved level of acoustic degradation of around 0.2 dB /year. This discrepancy between degradation rates is likely to be due to the differences in the degree of trafficking affecting the wearing process on the roads sampled between the two studies as well as differences in climatic conditions affecting the ageing process.

4.4 Concrete

Exposed Aggregate Concrete (EAC) and brushed concrete are no longer laid on the SRN but sections of the network still have these surfaces in use. Measurements of EAC, see (Hewitt, et al., 1997) and (Muirhead, et al., 2010), have shown it to be around 2 dB quieter than HRA surface with a similar rate of deterioration in acoustic performance.

Brushed concrete is associated with high levels of vehicle noise, around 1-2 dB louder than HRA surface (Hewitt, et al., 1997), however recent measurements of brushed concrete with longitudinal grooves have shown that the grooving can provide around 4-5 dB of benefit to vehicle noise. What has not yet been determined is how this benefit changes over time as the grooves become frayed from the exposure to traffic.

As discussed in Section 2.2, the lower noise levels of EAC and HRA surface when compared to brushed concrete are likely partially because of the random textures in EAC and HRA compared to the transverse texture of brushed concrete. As reported in (Hewitt, et al., 1997), the increased noise levels are largely above 1.25 kHz and are also associated with increases in texture amplitude in the megatexture wavelength region.

4.5 Porous Asphalt

Porous asphalt surfaces can be constructed with either a single layer or two layers usually around 40 mm thick; sound absorption is achieved by a gap-graded aggregate distribution resulting in a high void content. They are common low noise surfaces in Denmark and the Netherlands and their acoustic properties have been investigated in several studies, see for example (Kragh, 2008) (Kragh, 2005) (Blokland, et al., 2014) (Raaberg, et al., 2001). They are not commonly laid in the UK however as they do not exhibit good durability because of the rapid ageing of the binder and the clogging of the voids. The surface also requires more frequent salting in winter conditions and surface repairs are more problematic (Morgan(editor), 2006).

Reported measurements indicate that high initial noise benefits, around 5 dB quieter than some SMA thin surfaces, are achievable but that the clogging of the voids in the surface leads to most of this benefit disappearing over the first 5-6 years of the surface's life. Also, noise levels are reported to increase by around 3.5 dB in wet weather and the surface takes longer than other surfaces to dry out, see (Phillips & Abbott, 2001).

5. Pavement Classification

5.1 Current Procedures

In the UK the HAPAS guidelines (British Board of Agrement, 2008) include an optional noise test for labelling and procurement. The noise test comprises two sets of SPB measurements together with some additional procedures as explained in Section 3.2.1. The MCHW (Manual of Contract documents for Highway Works, 2008) clarifies that quiet surfaces are only required in noise sensitive areas and Table NG 9/30 lists a classification of these results in terms of levels as defined in Table 5.1.

Table 5.1: Road Surface Noise Levels from MCHW

Level	Description	RSI (dB(A))
3	Very quiet surfacing material	-3.5
2	Quieter than HRA surfacing materials	-2.5
1	Equivalent to HRA surfacing materials	-0.5
0	No requirement	No requirement

Additionally, HE guidance in the DMRB (Transport, 2011) suggests, in the absence of measured data, an existing thin surface on the SRN to be classified as Level 2 and new thin surfaces to be Level 3.

Noise mapping, conducted in response to the Environmental Noise Directive (European Commission, 2002), has not imposed any additional or alternative procedures for classifying the noise from road surfaces. Instead, default acoustic corrections were used for three common surface types; see (Jones, et al., 2015). The Environment Agency is responsible for round 3 of the environmental noise mapping and they have merely requested that the procedures of round 2 be followed.

Classification procedures for the Netherlands and Germany, as reported in (Morgan(editor), 2006), make use of different reference surfaces and reporting requirements but as with the UK do not mandate CoP measurements or routine monitoring to determine acoustic ageing.

Proposals have been made for classification procedures which account for such factors and these are discussed in Section 5.3. In order to evaluate these proposals effectively it is necessary to understand the relationship between SPB and CPX measurements and therefore this is discussed next, in Section 5.2.

5.2 The SPB and CPX Relationship

Due to the advantages of the CPX method in being able to cover much larger sections of the road network, and the ISO 11819-2 finally formally accepted for publication, it is increasingly becoming the preferred method of assessing the acoustic performance of pavements in many parts of Europe. However, as discussed in Chapter 3, whilst CPX measurements are useful for understanding the acoustic performance of road surfaces they are not as useful as roadside noise levels for the calculation of environmental noise exposure from traffic.

Therefore, in order for a pavement classification system to be of use in helping to calculate noise exposure and its relative benefit or disbenefit to society, it is important to be able to relate the CPX measurement index to roadside traffic noise levels. Fortunately, this is exactly what the SPB method measures[5] and therefore data from road surfaces subject to both SPB and CPX measurement make an ideal starting point for understanding this relationship.

[5] Albeit in terms of maximum noise levels rather than noise exposure but, as mentioned in Section 3.2.1, the two are well correlated.

A study on this relationship, from six different sources and covering several different CPX systems, was performed as part of the SILVIA project (Morgan(editor), 2006). The mean difference between corresponding SPB and CPX measurements was found to be 21.2 dB with a spread of 0.8 dB, however, the slope of the regression did differ from a one-to-one relationship between the measurements and varied from 0.8 to 1.2 depending upon which sets of data were examined. At the time (2006) it was felt that the CPX method could not, therefore, be used in isolation as it lacked a clear unambiguous relationship with roadside noise levels. Hence it was suggested to use both methods in parallel for road surface classification, see Section 5.3.

Since this time much more data have been collected in this area and a comprehensive summary of this information has been reported in the ROSANNE project, see (Kragh, 2014). Data were collected from eight different European countries[6] on a variety of road surfaces and normalised levels for light vehicles, shown in (Kragh, 2014), are reflected here in Figure 5.1.

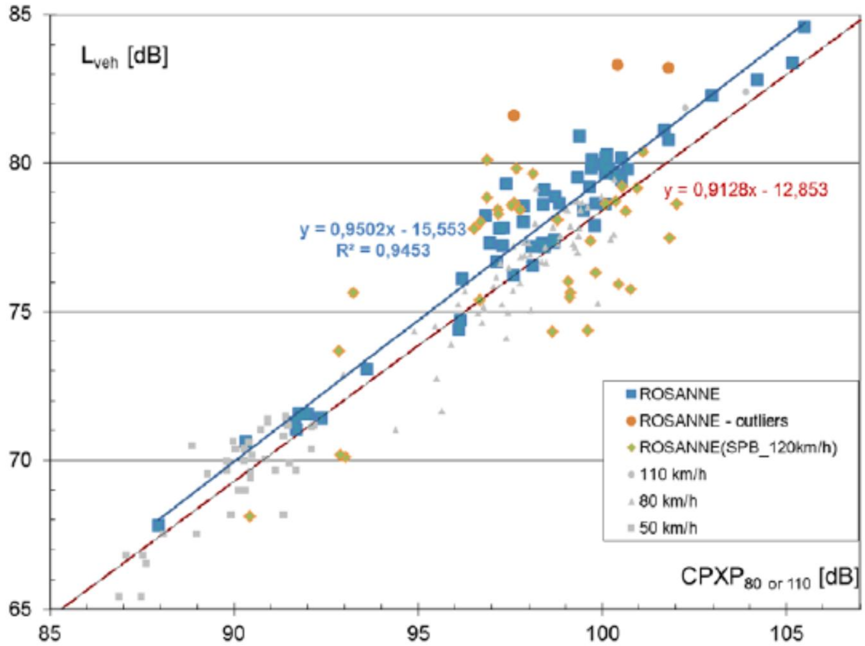

Figure 5.1: Normalised CPX and SPB Data, for Category 1 Vehicles, Collected from the ROSANNE Project[7]

In the figure the blue points represent the data collected on the ROSANNE project itself, the orange points represent some outlining data, the green points represent some cases where SPB measurements were taken at 120 km/h and normalised to 110 km/h using theoretical relationships between noise and speed and the grey points represent data collected by the Danish Road Institute on a different study in 2010-2011. The blue line is the regression line for the ROSANNE data while the red dotted line is the regression line from the earlier Danish study.

The suggested relationship between the two metrics was derived from the blue line as:

$$L_{AFmax} = 0.95 \times CPX_I - 15.6$$

where L_{AFmax} is the measured SPB level for category 1 vehicles and CPX_I is the corresponding CPX index measured with the standard reference tyre for category 1 vehicles at the same reference speed. This implies an average difference between the two indices of 20.5 dB which is similar to the value found during the SILVIA project, and almost 90% of all the data is within 1 dB of the trend line. It was noted in (Kragh, 2014) that this relationship does not apply very well when SPB and CPX measurements are taken at different speeds and normalised.

[6] Austria, Germany, Belgium, Denmark, France, UK, Poland and Norway.
[7] Figure taken from Kragh (2014) Report on the analysis and comparison of existing noise measurement methods for noise properties of road surfaces, FP7-SST-2013-RTD-1, ROSANNE D2.3.

Data from heavy vehicles were provided by Germany and Norway for the ROSANNE project and a tentative relationship between measured SPB levels for category 2a vehicles at 80 km/h and CPX measurements at the same reference speed using the standard truck tyre was given as:

$$L_{AFmax} = 0.65 \times CPX_H + 24$$

Although there was more spread in the data than for light vehicles. This is to be expected since SPB measurements show that there is more spread in the data for category 2 vehicles since the tyre/road noise component for these vehicles is not as dominant over the engine noise as it is for cars and the vehicle category covers a wide range of vehicle weights, tyre sizes and treads and (for category 2b vehicles) number of axles.

5.3 Proposed Procedures

As alluded to in Section 5.2, the SILVIA programme recommended a road noise classification procedure based on both SPB and CPX measurements (Morgan(editor), 2006). The steps involved in the procedure include:

- Selecting a trial site between 100m and 1000m
- Determining a CPX measurement index for the trial section, ensuring that there is no more than a 0.5 dB peak-to-peak variation between the index for 90% of the 20m sections and the mean value
- Carrying out an SPB measurement half way along a selected 100m section of the trial site and calculate a L_{Amax} value for each vehicle category at 10 km/h intervals in the valid speed range[8]
- Reporting two label values where the first is the average L_{Amax} at a chosen reference speed for each vehicle category and the second is the average CPX index for the trial length.

CoP measurements using the CPX method and routine monitoring every 2-5 years were also recommended. The pros and cons of selecting different metrics for the requirements of low noise surfacing were discussed, reflecting the many of the advantages and disadvantages of the underlying methodologies, as presented in Chapter 3. No definitive conclusions were drawn although procedures for how the label values could be used in environmental noise calculations were created.

The concept of a new classification procedure for road surfaces was revisited in the ROSANNE project (Conter, 2016) and a metric called the Road Surface Noise level (RSNL) was suggested. As a result of increased confidence in the relationship between the measurement methods, see Section 5.2, the RSNL is based solely on CPX measurements using both reference tyres and also factors in the ratio of light to heavy vehicles in the traffic stream and the speed category of the road, going some way towards reflecting the performance of the surface in practice rather than just under measurement, as discussed in Section 3.2.1.

It was suggested that at least 3 sections, with a minimum length of 200m, be tested between 2 and 6 months after paving. Similar homogeneity conditions to those recommended in the SILVIA programme were proposed and routine monitoring was suggested as approximately every 3 years for dense surfaces and approximately every 2 years for porous surfaces.

[8] The valid speed range is determined in terms of a limit on the width of the 95% confidence interval for the SPB data. It is defined as +/-0.3 dB for category 1 vehicles and +/-0.7 dB for category 2 vehicles.

6. Conclusions and Recommendations

This report has provided an overview of the mechanisms involved in tyre/road noise generation, how the noise is measured, the acoustic properties of different surface types and how surfaces may be classified in terms of their impact on traffic noise.

The wider programme of work has developed new HRA and PASS materials to be tested with respect to low noise performance and increased durability. In addition to the testing carried out in 2017 as part of this programme, it is essential that the acoustic performance of these surfaces is also measured in future years in order to determine its long-term noise performance. Only then will it be seen if the lessons learned from understanding the mechanisms of pavement noise and durability have been successfully translated into practice.

In addition, there is some background information in this report which should enable the discussion of the acoustic classification procedure for road surfaces and, in particular, if there is scope for CoP and long-term monitoring measures which are not currently required. Such procedures and monitoring measures have been proposed in the past, from the SILVIA and ROSANNE EU programmes of work for example, but not incorporated into requirements for surfaces laid in the UK.

Rather than promote another classification procedure it is recommended that the ROSANNE methodology be given consideration for use in the UK and in the meantime existing knowledge on the performance of surfaces within the UK over time (Muirhead, et al., 2010) and under different traffic conditions (Muirhead, 2013) be exploited in traffic noise modelling and guidance.

7. References

Abbott, P. G., Morgan, P. A., Balsom, M. & Taylor, K., 2004. *Extension of CRTN road surface correction to lower speeds,* Wokingham, UK: PR SE/707/03 TRL Limited.

Andersen, B., Kragh, J. & Bendtsen, H., 2006. *Acoustic performance - low noise road pavements,* Copenhagen, Denmark: Danish Research Institute Technical Note 44.

Balsom, M. H., Kolamthodi, S., Phillips, S. M. & Abbott, P. G., 2004. *Measurement of the acoustic performance of road surfaces,* Wokingham, UK: PPR021 TRL Limited.

Bell, S., 2001. *A Beginner's Guide to Uncertainty Measurement,* Teddington, UK: National Physical Laboratory.

Bendtsen, H., 2004. *Rolling resistance, fuel consumption and emissions: A literature review,* Brussels, Belgium: SILVIA-DTF-ATKINS-007-02-WP3.

Bendtsen, H., Raaberg, J. & Thomsen, S. N., 2005. *International Experiences with Thin Layer Pavements,* Copenhagen, Denmark: Danish Road Institute Technical Note 29.

Blokland, G. v. & Stahlfest, R., 2016. *Uncertainty in the CPX method (ISO 11819-2/3) and its implications for pavement evaluation,* Hamburg, Germany: Internoise.

Blokland, G. v., Tollenaar, C. & Loon, R. v., 2014. *Modelling of acoustic ageing of road surfaces,* Brussels, Belgium: CEDR QUESTIM D2.2.

British Board of Agrement, 2008. *Guidelines document for the assessment and certification of thin surfacing systems for highways,* Watford, UK: British Board of Agrement.

BSI, 2001. *Acoustics - Measurement of the influence of road surfaces on traffic noise - Part 1: Statistical Pass-By method,* London: British Standards Institute BS ISO 11819-1.

BSI, 2010. *Acoustics -- Measurement of sound absorption properties of road surfaces in situ -- Part 2: Spot method for reflective surfaces,* London: British Standards Institute BS ISO 13472-2.

BSI, 2016. *Acoustics -- Measurement of the influence of road surfaces on traffic noise -- Part 2: The close-proximity method,* London, UK: British Standards Institute BS ISO 11819-2.

BSI, 2017. *Acoustics -- Measurement of the influence of road surfaces on traffic noise -- Part 3: Reference tyres,* London, UK: British Standards Institute BS ISO 11819-3.

Centre, M., 2014. *Outline of a draft standard for a procedure for the characterization of noise properties of road surfaces,* Brussels, Belgium: FP7-SST-2013-RTD-1 ROSANNE D2.1.

Centre, M., 2016. *Measurement methods for the noise emission properties of road surfaces,* Sterrebeek, Belgium: ROSANNE Final Event 11 October 2016 BRRC.

Derksen, G. B. & Roo, F. d., 2012. *CPX trailer comparison round robin test data analysis,* Ede, The Netherlands: CROW Report D12-02.

Dick, E., Casey, T., Raad, M. & Nachtsheim, C., 2015. *Precision and Bias Statements for AASHTO Standard Methods of Test TP98 and TP99,* Washington, USA: Transportation Research Board.

European Commission, 2002. *Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise,* Brussels, Belgium: OJ L 189, 18.7.2002, p. 12–25.

Haider, M. & Descomet, G., 2006. *Noise classification methods for urban road surfaces: Classification methodology,* Brussels, Belgium: SILENCE F.D13.

Hamet, J.-F. & Berengier, M., 1993. *Acoustic characteristics of porous pavements: a new phenomenological model.* Leuven, s.n.

Hamet, J.-F., Berengier, M. & Jacques, M., 1990. *Acoustic performance of pervious surfaces.* Gothenburg, Sweden, s.n.

Hewitt, A. P., Abbott, P. G. & Nelson, P. M., 1997. *Alternative texture for concrete roads: results of M18 and A50 trials,* Wokingham, UK: TRL Report 291 TRL Limited.

Jones, N., Burdett, M., Joubert, S. & Williams, M., 2015. *Round 2 strategic noise mapping - data production process,* London, UK: Extrium P054.

Kragh, J., 2005. *Traffic noise at two-layer porous asphalt - Oster Sogade, Year No.6,* Copenhagen, Denmark: Danish Road Institute Technical Note 30.

Kragh, J., 2008. *Road Surfacings - Noise reduction time history,* Copenhagen, Denmark: Danish Research Institute Report 161.

Kragh, J., 2014. *Report on the analysis and comparison of existing noise measurement methods for noise properties of road surfaces,* Brussels, Belgium: FP7-SST-2013-RTD-1 ROSANNE D2.3.

Manual of Contract documents for Highway Works, 2008. *Volume 2: Notes for guidance on the specification for highway works,* s.l.: Series NG900 Road pavements - bituminous materials.

McRobbie, S. G., Viner, H. & Wright, M. A., 2004. *The use of surface texture measurements to predict pavement surface type and noise characteristics,* Wokingham, UK: PR/CSN/32/03 TRL Limited.

Morgan(editor), P., 2006. *Guidance manual for the implementation of low-noise road surfaces,* Brussels, Belgium: FEHRL SILVIA Report 2006/02.

Morgan, P. A., Phillips, S. M. & Watts, G. R., 2007. *The localisation, quantification and propagation of noise from a rolling tyre,* Wokingham, UK: PPR104 TRL Limited.

Muirhead, M., 2012. *Assessment of the environmental impact of changes to vehicle noise regulations,* Wokingham, UK: TRL PPR629 TRL Limited.

Muirhead, M., 2013. *CRTN revision - technical note,* Wokingham, UK: TRL Limited.

Muirhead, M., Abbott, P. G. & Burdett, M., 2008. *An examination of the monetised benefit of proposed changes to the type approved noise limits for tyres,* Wokingham, UK: TRL PPR394 TRL Limited.

Muirhead, M., Morris, L. & Stait, R. E., 2010. *The performance of quieter surfaces over time,* Wokingham, UK: PPR485 TRL Limited.

Ojum, C., 2016. *Collaborative Research into the Next Generation of Asphalt Surfacings,* Nottingham, UK: 409(4/45/12) ARPS.

Phillips, S. M. & Abbott, P. G., 2001. *Factors affecting statistical pass-by measurements,* The Hague, The Netherlands: Proceedings of Inter-Noise, 2031-2036.

Phillips, S. M., Kollamthodi, S., Nelson, P. M. & Abbott, P. G., 2003. *Study of medium and high speed tyre/road noise,* Wokingham, UK: PR SE/849/03 TRL Limited.

Raaberg, J., Schmidt, B. & Bendtsen, H., 2001. *Technical performance and long term noise reduction of porous asphalt pavements,* Copenhagen, Denmark: Danish Research Institute Report 112.

Sandberg, U., 2014. *Temperature influence on measurements of noise properties of road surfaces and possible normalization to a reference temperature,* Brussels, Belgium: FP7-SST-2013-RTD-1 ROSANNE D2.2.

Sandberg, U. & Ejsmont, J. A., 2002. *Tyre/road noise reference book.* Sweden: Informex.

Stahlfest, R., 2016. *Analysis and comparison of methods, CPX and SPB, for measuring noise properties of road surfaces,* Hamburg, Germany: Internoise.

Thomsen, S. N., Bendtsen, H. & Kragh, J., 2006. *Test of thin layers on highway,* Copenhagen, Denmark: Danish Research Institute Technical Note 35.

Transport, D. f., 2011. *Design Manual for Roads and Bridges: Volume 11 Section 3 Part 7: HD213/11 Revision1: Noise and vibration,* London: The Stationery Office.

Watts, G., Nelson, P., Treleven, C. & Balsom, M., 2005. *An examination of vehicle noise test procedures,* Wokingham, UK: TRL PPR044 TRL Limited.

Watts, G. R. & Abbott, P. G., 2005. *Tyre and road surface parameters affecting tyre/road noise,* Wokingham, UK: Extension of PRSE849 TRL Limited.

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