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Rail and wheel roughness - implications for noise mapping based on the Calculation of Railway Noise procedure

A report produced for Defra

AEJ Hardy and RRK Jones

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Executive Summary

Under the EC Environmental Noise Directive, noise from major railways and railways in agglomerations is required to be mapped using appropriate models. It is also expected that a similar approach will be taken for England under a Defra-funded pilot scheme. The UK Procedure "Calculation of Railway Noise 1995" (CRN) is considered to be an appropriate model, except that it assumes that the rail head is comparatively smooth, which will tend to under-predict rolling noise. The reason for this is that CRN was developed for application under the Noise Insulation (Railways and other Guided Transport Systems) Regulations for Railways 1996 for new or additional railways, where the assumption is that rails will be new and therefore smooth. The current study was therefore commissioned by Defra to investigate in detail the subject of rail and wheel roughness and its acoustic implications, and to determine whether it was feasible, and of use, to derive back-end corrections for CRN. These corrections would be designed (a) to account for prevailing real levels of rail head roughness in the UK and (b) to allow for the effects of rail grinding strategies to be catered for in the modelling.

The study presents the current state of knowledge of the development of rail and wheel roughness. For wheels, the most significant factor is the damage mechanism that results from the action of cast-iron brakes applied to the rolling surface, due to differential wear at hot spots and material transfer from block to wheel. For rails, the significant factor is the development of corrugation, a periodic wear pattern with a pitch of around 30mm to 80mm and a potential peak-to-peak depth of 120 microns or more. There are several theories for its growth, all based on a combination of "wavelength fixing" due to the combined dynamics of the train and track, and a damage mechanism caused by some form of differential wear.

Rail grinding techniques, ranging from rotating stones to continuous abrasive bands, are reviewed, as are systems for measuring wheel and rail roughness. Roughness measurement systems tend to be based either on probes with some form of displacement transducer (wheels or rails) or on accelerometers drawn over the rail surface, with displacement obtained by double integration of the acceleration signal. Rail roughness severity can also be quantified by measuring the rolling noise under a vehicle as it travels over the network.

The research element of the study is based on the running of a very large number of simulations of typical UK railway situations for rail head roughness levels obtained at random from known distributions and typical mixes of traffic, speeds, times of operation, intensity of service etc. This has enabled a speed-dependent back-end correction for CRN to be derived so that global noise exposure from the current railway network can be more accurately modelled than is currently possible. Following on from this, the effects of grinding strategies have been considered.

An alternative approach is also presented, based on obtaining back-end corrections to the rolling noise element of CRN for prevailing levels at specific locations rather than globally, by means of measurements of rolling noise. The effects of rail grinding on local levels can be accounted for within this technique. This approach is obviously desirable in terms of accuracy of results at a local level, but requires the gathering of rolling noise data over all sections of track that are to be modelled.

Contents

1	Introduction	1
2	Measuring wheel and rail roughness	5
	2.1 INTRODUCTION TO ROUGHNESS	5
	2.2 MEASURING RAIL HEAD ROUGHNESS	6
	2.3 CURRENT RAIL ROUGHNESS SPECIFICATIONS FOR LEGISLATION AND STANDARDISATION	9
	2.4 MEASURING WHEEL ROUGHNESS	10
3	The development and control of rail head and wheel roughness	10
	3.1 THE DEVELOPMENT OF RAIL HEAD ROUGHNESS	10
	3.2 CONTROL OF RAIL HEAD ROUGHNESS	14
	3.3 THE DEVELOPMENT OF WHEEL ROUGHNESS	15
	3.4 CONTROL OF WHEEL ROUGHNESS	16
4	Research study description and results	17
	4.1 THE STUDY APPROACH	17
	4.2 DERIVING THE DISTRIBUTION OF RAIL ROUGHNESS	18
	4.3 MODIFYING THE CRN SOURCE TERMS	21
	4.4 PREDICTION OF THE NOISE LEVELS ON ANY TRACK	22
5	Implications of rail grinding strategies	25
6	Derivation of back-end correction approach	28
7	Conclusions	38
8	References	39
	APPENDIX A	41
	APPENDIX B	46
	APPENDIX C	54
	APPENDIX D	56
	APPENDIX E	58

1 Introduction

Railway operational noise originates from a number of sources. These include the engines and cooling fans of locomotives, the under-floor engines of "diesel multiple units[1]" (self-propelled sets of railway coaches), gears, aerodynamic effects at higher speeds, and the interaction of wheels and rails. The latter source tends to have an influence on overall noise levels at speeds above 50 km/h and is normally predominant at speeds above around 100 km/h.

Wheel/rail noise, or "rolling noise", results from the vibration–excitation of the wheels and track as the wheel rolls on the rail. The excitation is provided by the combined surface roughness at the interface, or "contact patch", between the wheel and the rail. Because the entire wheel and track system is excited by the combined roughness at the interface, it is this combined value that determines the level of rolling noise rather than the individual rail and wheel roughness components.

This phenomenon was first noted in Britain with the introduction of disc-braked Freightliner vehicles in the early 1970s. Prior to this, most railway brake systems consisted of cast-iron blocks that were applied directly to the wheel's rolling surface. This led to efficient braking characteristics, with the added benefit of providing a clean wheel surface for improved adhesion during acceleration and braking. It also maximised electrical conductivity at the interface to maintain "track-circuit" electrical continuity between rails for signalling purposes. One mechanical disadvantage of cast-iron tread brakes is the heating of the wheel during braking, necessitating a wheel design that can expand and contract safely when subject to thermal cycling.

When the Freightliner vehicles were introduced and were obviously quieter than other vehicles, British Rail Research commenced investigations. These investigations, and theoretical work by Remington (1) at around the same time, initiated the process of understanding and modelling wheel/rail noise. Thompson developed the Remington model further at British Rail Research (2) as "Springboard". Further research funding from the European Rail Research Institute allowed the model to be implemented in the program "TWINS" (Track Wheel Interaction Noise Software) (3). Validation of the model from on-track measurements has shown that it can predict the noise from a range of wheel and track designs to within around 2 dB (4).

The TWINS model starts with the individual roughness of the wheel and the rail, expressed in terms of the roughness amplitude spectrum (level vs wavelength). These roughnesses are then combined and used as the basis of a model of the forces that excite the wheels, the rails and the sleepers. The response of these components to the exciting forces, and their resultant acoustic radiation, is then predicted by knowledge of the physical characteristics of the components of the system and the interfaces between them. The reduced surface roughness of wheels that are not subject to cast-iron tread braking therefore results, both within the model and in reality, in a rolling noise that is lower than that resulting from cast-iron tread brakes,

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[1] **See Appendix A for an explanation of terminology and technical concepts**

provided rail roughness is comparatively low. For this reason the Freightliner vehicles discussed previously, and indeed any purely disc-braked vehicle, will tend, on good quality track, to be 8 to 10 dB(A) quieter than cast-iron tread-braked vehicles.

Similarly, the roughness of the rail head can influence the level of rolling noise. The rail head will normally exhibit a “broad-band” surface roughness but at some locations there are periodic wear patterns, known as corrugations, which can have significantly greater amplitudes than the general broad band roughness. They can be seen clearly on some rail heads, in the form of equally-spaced bright patches with a pitch of around 30mm to 80mm (See Figure 1-1). Where wheels are comparatively smooth, the difference between rolling noise on smooth track and on badly corrugated track can be more than 20 dB(A), an approximate quadrupling of perceived loudness. As well as the acoustic implications, corrugations will increase the forces on track components and, in severe cases, can interfere with the coupling of ultrasonic transducers with the rail when non-destructive testing is being carried out.

For both the wheels and the rails, the wavelengths of surface roughness of particular relevance to rolling noise are between 5 and 200mm, although there is a filtering effect for shorter wavelengths at the contact patch due to its size (typically 10-15mm long). The frequency of vibration excited by the roughness is simply related to the roughness wavelength by the equation: Frequency = Velocity/Wavelength.

To illustrate this relationship, roughness wavelengths of 20mm and 200mm will generate a vibration excitation at 1400 Hz and 140 Hz respectively at 100 km/h.

Rail and wheel roughness spectra are normally presented in terms of roughness expressed in decibels vs wavelength. Roughness in decibels relates directly to the unit used to quantify sound, and allows a certain degree of immediate interpretation by the experienced practitioner. This value is obtained from $20 \log_{10}$ ([root mean square roughness amplitude]/[root mean square reference level, normally taken as 1×10^{-6}m ie 1 micron]). Using this decibel scale, a roughness value of 1×10^{-6}m = 0 dB, 3.2×10^{-6}m= 10 dB, 10×10^{-6}m= 20 dB etc.

Figure 1-2 shows a typical presentation of wheel and rail roughness, over the wavelengths of relevance to rolling noise.

Figure 1-1 Rail head corrugation

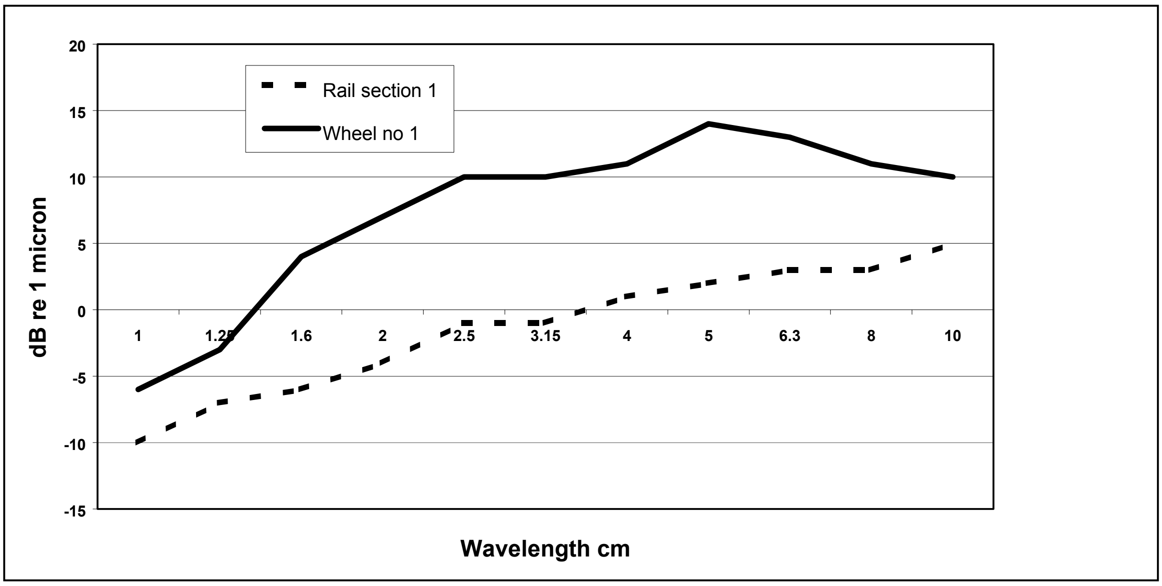

Figure 1-2 Typical representation of rail and wheel roughness.

In Great Britain, a standard method for the prediction of railway environmental noise is available. This is the "Calculation of Railway Noise" (CRN) (5). This procedure was designed primarily for use with the Noise Insulation (Railways and Other Guided Transport Systems) Regulations 1996 (6), particularly for new or additional railways. The procedure predicts the Equivalent Continuous Sound Level (L_{Aeq}) over an 18 hour day or a 6 hour night in order to determine eligibility for sound-attenuating windows, ventilators and doors under the Regulations, although it is a straightforward matter to apply its routines to calculate L_{eq} values for other time periods (day, evening and night), as will be required under the EC Environmental Noise Directive (7). The Directive requires the "day-evening-night level" (L_{den}) to be calculated as follows:

$$L_{den} = 10 \times \log_{10}\left[\left(12 \times 10^{Lday/10} + 4 \times 10^{(Levening+5)/10} + 8 \times 10^{(Lnight+10)/10}\right) \Big/ 24 \right]$$

ie increasing the relative annoyance of noise during the evening by an amount represented by 5 dB and that of night time noise by an amount represented by 10 dB. L_{night} is also required to be considered separately under the Directive but, in this case, without the +10dB weighting.

The CRN procedure requires the railway to be divided into a series of nominally straight sections. The starting point for predictions is to calculate the noise source term for each vehicle type travelling over a track section. This source term is defined in terms of "Sound Exposure Level" (SEL), which is the level at a reception point which, if maintained constant for a period of 1 second, would give the same A-weighted sound energy as is actually received from a given noise event. (A-weighting being a frequency-dependent weighting designed to approximate to the response of the human ear). For rolling noise, the source term is calculated from a chart relating SEL at 25m to train speed, with a vehicle type-specific correction. Although the corrections presented in the procedure are largely empirically derived, the values will strongly depend on the nature of braking on the vehicles in question, for the reasons outlined above. However, the source terms are based on emission levels acquired on track in comparatively good condition to represent the likely situation for a new or additional railway.

As well as rolling noise source terms, values are also available for diesel locomotives on power. It should be noted that CRN is not able to predict noise from trains when stationary at signals or in stations, or when squealing around tight curves. It also does not cater for the warning horns mounted on trains, or for audible sounders at level crossings. The standard source term information in CRN is based on the train fleet that operated in 1995, meaning that more recent types of train have not yet been included within the document (except for Eurostar, which was added in 1996 within a supplement). Once source terms have been established, the procedure allows the effects of the number of vehicles in the train, distance from track to receiver, cuttings, embankments, barriers, buildings, angle of view, type of track support structure, joints, points and crossings all to be taken into account to provide a predicted level at the façade of buildings.

Although CRN is the most comprehensive prediction model available for the UK railway, it is obviously not designed to be a complete system for predicting all aspects of railway noise. The reason for this is that it was specifically intended, at the time of its formulation, to be a tool that identified properties entitled to noise insulation, and therefore did not necessarily require wide-ranging applicability.

A major failing of CRN if it is to be used as a general purpose railway noise prediction tool is that it takes no account of the potential effects of variability of rail head roughness. If, therefore, CRN were to be used in its standard form to produce the noise maps required by the Directive, it is possible that specific locations where rail head corrugation is present may be 20 dB + noisier than the procedure would indicate, which could seriously discredit the process. Of equal concern is the fact that Network Rail may propose a rail head grinding strategy to remove corrugations and maintain smooth rails as part of an Action Plan as required by the Directive. Predictions of noise before and after grinding using the current version of CRN would show no change.

Article 6 of the Directive states that "Common assessment methods for the determination of L_{den} and L_{night} shall be established by the Commission…..Until these are adopted, Member States may use assessment methods adapted in accordance with Annex II and based upon the methods laid down in their own legislation. In such case, they must demonstrate that those methods give equivalent results to the results obtained with the methods set out in the paragraph 2.2 of Annex II" In the case of railways, the method identified is the Dutch model Reken-en Meetvoorschriften 96 (8).

The Dutch model categorises trains into one of ten classes ranging from tread-braked freight wagons to high speed passenger trains. Nine track types are accounted for as further categories. Two levels of prediction are available; SRM 1 can only predict dB(A) terms on straight track without barriers, while SRM II allows more detailed source characterisation (spectral content and multiple source heights) and predicts for complex propagation paths, as well as taking meteorological conditions into account. SRM II builds up the railway to be modelled from a series of segments, in a similar way to that adopted within CRN, and uses the train and track categories, combined with speeds and numbers of trains passing, to produce the emission term from each segment. Source terms for this model were acquired on typical non-corrugated track in the Netherlands, and it has no provision for taking rail head roughness into account.

Assuming it is possible for Great Britain to demonstrate the equivalence between CRN and SRM satisfactorily, it is understood that CRN is likely to be used for the first round of EC mapping of railways. This will be for railways with more than 60000 passages per annum and those in agglomerations of more than 250000 inhabitants, and is to be completed by June 2007. It is even more likely that CRN will be used for the England pilot mapping study of railways, expected to commence in mid-2004. In order, therefore, to establish the implications of the true range of rail, and wheel, roughness on predictions using CRN, and to develop, if necessary, a "back-end" correction for the procedure that takes roughness into account, the research study reported in Sections 4 and 5 has been commissioned by Defra. Such a correction will allow the mapped levels of railway noise to be a closer representation of the real environment due to the current railway and is also intended to account for the effects of action plans that lead to smoother rails.

In addition to the research study, Section 2 of this report describes methods for measuring wheel and rail roughness while Section 3 explains how this roughness develops and how it may be controlled.

2 Measuring wheel and rail roughness

2.1 INTRODUCTION TO ROUGHNESS

The roughness of both wheels and rails is characterised by micro peaks and troughs, sometimes with a periodic pattern, and with occasional larger areas of damage such as "spalling" of wheels where small sections of material come away, or "head checking" and "shelling" on rails caused by rolling contact fatigue. The roughness of relevance to rolling noise on both wheel and rails will normally be in the wavelength range of 5 – 200mm, with a roughness level ranging from around 0.3 microns peak-to-peak to around 120 microns peak-to-peak. As explained in Section 1, roughness is normally expressed, for acoustic purposes, in terms of decibels:

Roughness level = $20 \log_{10}$ ([root mean square roughness amplitude]/[root mean square reference level])

Where the reference level is normally taken as 1×10^{-6}m (ie 1 micron, or 1 μm).

Although a roughness peak-to-peak level of 120 microns will increase rolling noise, for a smooth wheel, by up to 20 dB(A) when compared with the noise when running on "smooth" track, it is worth noting that, physically, this is only around $1/10^{th}$ of a millimetre, indicating the unfortunate acoustic efficiency of the wheel/rail system.

To give an indication of typical rail head roughness levels, Figure 2-1 shows values measured on Dutch track, as reported by Dings of AEA Technology Rail BV and Dittrich of TNO (9).

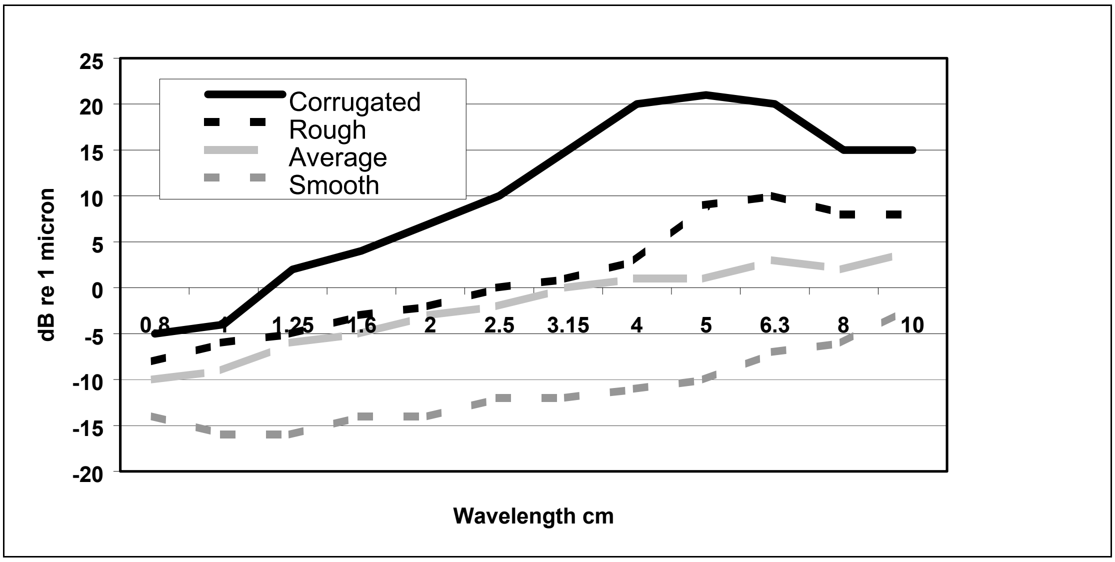

Figure 2-1 Typical rail head roughness values

From the same Dutch study, typical wheel roughness levels were as shown in Figure 2-2.

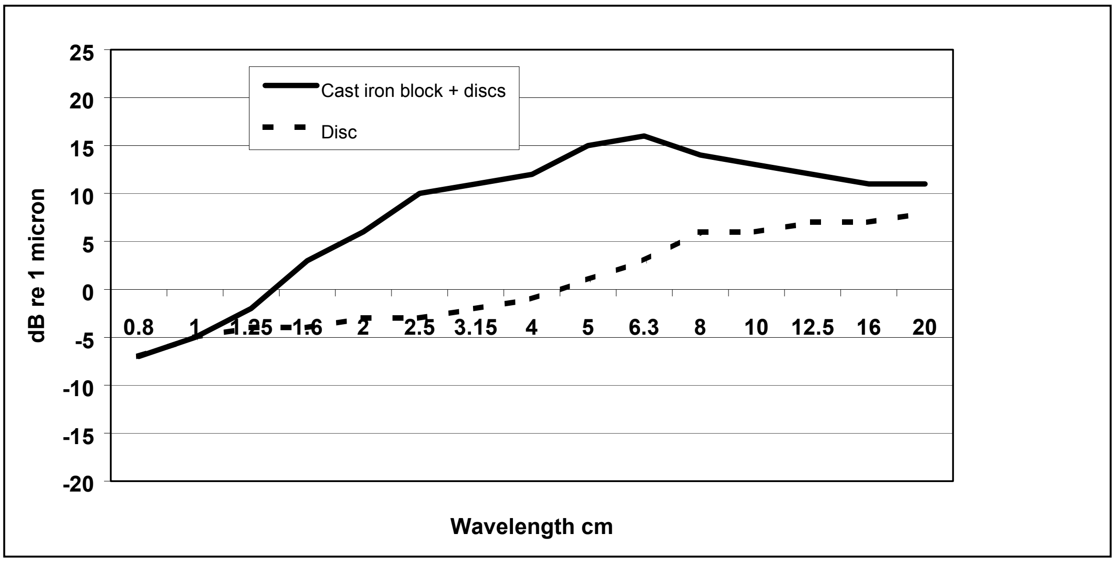

Figure 2-2 Typical wheel roughness values

2.2 MEASURING RAIL HEAD ROUGHNESS

Several types of device have been used since the mid 1980s to measure the surface roughness of rails in connection with noise studies. There are two broad categories of device capable of producing accurate roughness spectra, namely those that are trolley based and able to pass over comparatively long sections of track at around walking pace, and those that comprise a frame clamped over the rail with an integral moving stylus. Trolley systems have been used in the past by SNCF (motorised with displacement transducers), Dutch Railways (NS) (hand propelled with two non-contacting capacitive transducers) and British Railways (motorised trolley, with a steel skid, representing the contact patch of the wheel, attached to an accelerometer).

Two trolley systems still known to be in operation are the "CAT", produced by Grassie, and the AEA Technology Rail trolley, developed from the original BR system. Both of these systems rely on double integration of an acceleration signal from an accelerometer coupled via a contact device to the rail. The CAT is pushed along the rail by a pole and can measure wavelengths between 10mm and 3000mm at a rate of 0.5-1.5 m/s. The self-propelled AEA Technology device can measure wavelengths between 16mm and 3000mm at 1 m/s. A slightly different trolley is also available from Geismar (the PTCT/-D), comprising a sliding 1.2m long shoe with a centrally positioned displacement transducer and able to measure wavelengths from 20mm to 600mm.

There are several frame systems available, eg from Müller BBM, Qualitech and ODS, all of which work in a similar fashion. A displacement transducer passes along the frame in contact with the rail and provides a direct reading of surface profile. The best known of these is the Müller BBM version, developed originally in 1989 for German Railways and upgraded in 1999. This system, the RM1200E, comprises a frame within which a linear voltage displacement transducer with a hard alloy tip of 14mm diameter passes over the rail head, sampling displacement at every 0.5mm travelled. Each pass takes 20 seconds, and practical experience has shown that, realistically, only 500m of rail can be measured per day as the frame has to be moved and set up for every 1.2m section being considered. In order for longer wavelengths to be characterised accurately with this device, the discrete samples from each pass have to be combined during the analytical phase.

An alternative method for identifying stretches of track where rail head roughness is high is to use under-floor microphones to measure rolling noise from a smooth wheel. The increased noise levels caused by rough rail, and especially corrugation, can provide the track owner or maintainer with useful information regarding sections of rail that require attention. German Railways and French Railways use microphones beneath the floors of laboratory coaches for this purpose. AEA Technology has developed a system (NoiseMon) that can be installed on passenger trains routinely traversing the network, with GPS location and cell phone connection to a base station, allowing the track owner or maintainer to monitor the system continuously (10).

Figure 2-3 shows the noise characteristics that are measured over a range of track sections with NoiseMon.

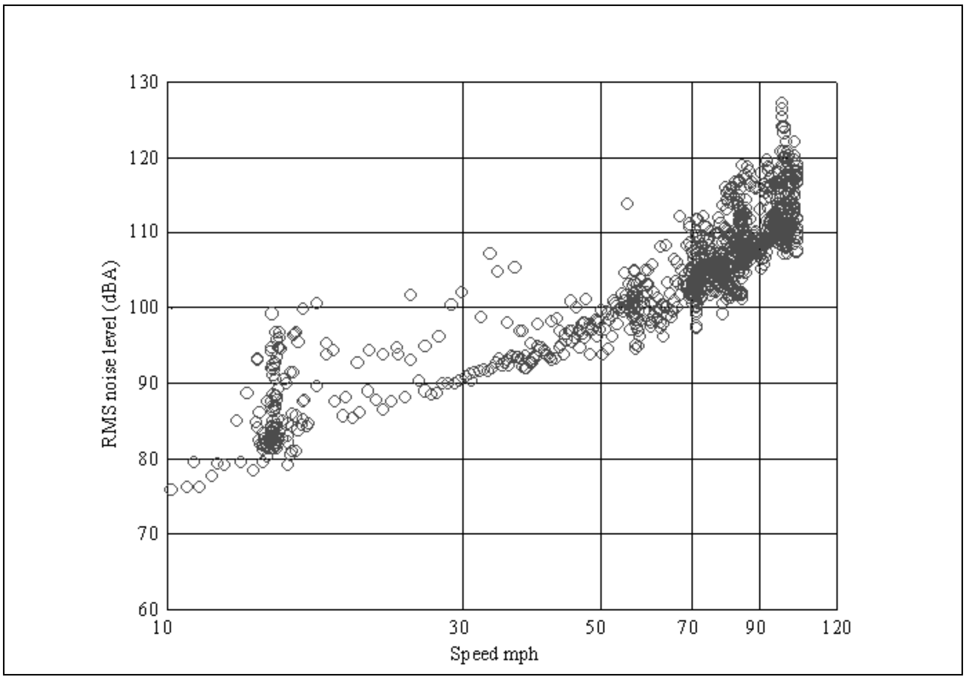

Figure 2-3 Under-floor noise level vs speed

It can be seen that at any given speed there is a range of values, with a lower bound representing the smoothest track likely to be encountered. The highest value at each speed will represent rough, or corrugated, track. For a section of track with a known roughness the speed dependence of the under-floor noise level can be represented by:

$$L_2 = L_1 + 10 \times n \times \log_{10}(v_2 / v_1)$$

Where, L_1 is the noise level at speed v_1, L_2 is the noise level at speed v_2 and n is the "speed exponent".

For the data in Figure 2-3 the speed exponent is 3.4.

If L_1 and v_1 are measured values then by fixing v_2 (usually at 160 km/h) the equation can be used to calculate the level (L_2) "normalised" to this standard speed.

NoiseMon can display these speed-normalised data in a number of ways, including the form of plot shown in Figure 2-4.

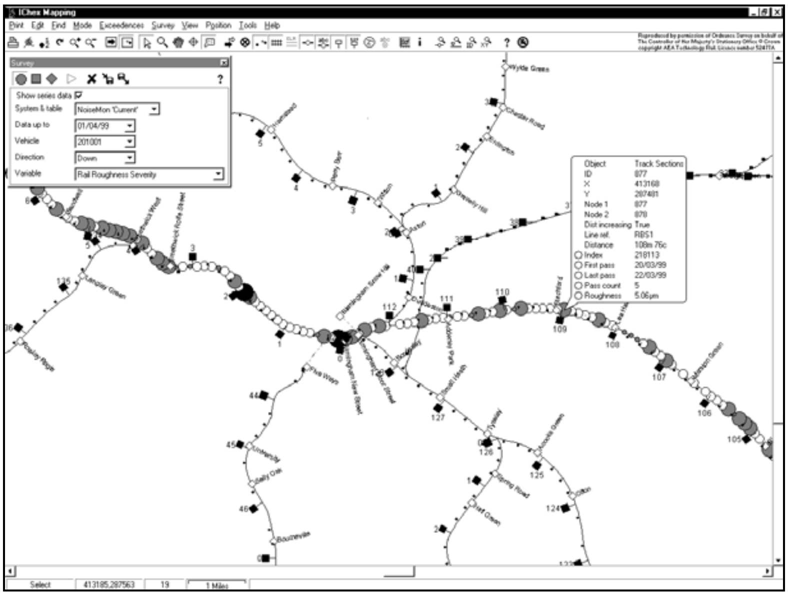

Figure 2-4 Plot of roughness level over a section of the railway network.

The NoiseMon approach provides a very effective overview of the rail head condition on a network. The information thus acquired can also be used in predicting the true wayside noise emission from the railway, by providing correction factors for source terms based on the true rail head condition rather than an idealised assumed situation. It does not, however, provide the spectral information that the other systems described above can offer.

Similarly, axle box (bearing housing) accelerometers are sometimes used to identify corrugated rail, relying on the increased vibration levels transmitted from the track to the axle box when the rail is rough to provide this indication. This is not always satisfactory as the vibration modes of the wheelset will introduce resilience between rail and accelerometer, with unpredictable consequences.

2.3 CURRENT RAIL ROUGHNESS SPECIFICATIONS FOR LEGISLATION AND STANDARDISATION

There are currently three rail head roughness specifications being used within international legislation and standardisation to endeavour to minimise the influence of rail roughness on train pass-by noise when testing trains. These are the requirements of the draft ISO 3095 (11) for measuring the external noise from trains, the values specified for testing compliance of trains with the EC High Speed Technical Specification for Interoperability (TSI) (12) and the values currently proposed for testing the compliance of trains with the Conventional Stock TSI. The ISO 3095 values are likely to be achievable on good quality sections of track on most railway administrations, but the High Speed TSI values are more stringent, while the proposed Conventional Stock values are considered by some railway administrations to be unachievable at certain wavelengths. This latter specification may therefore change before publication of the TSI. The three specifications are shown in Figure 2-5, which also shows, for comparison, the smoothest characteristics found on Dutch track (9).

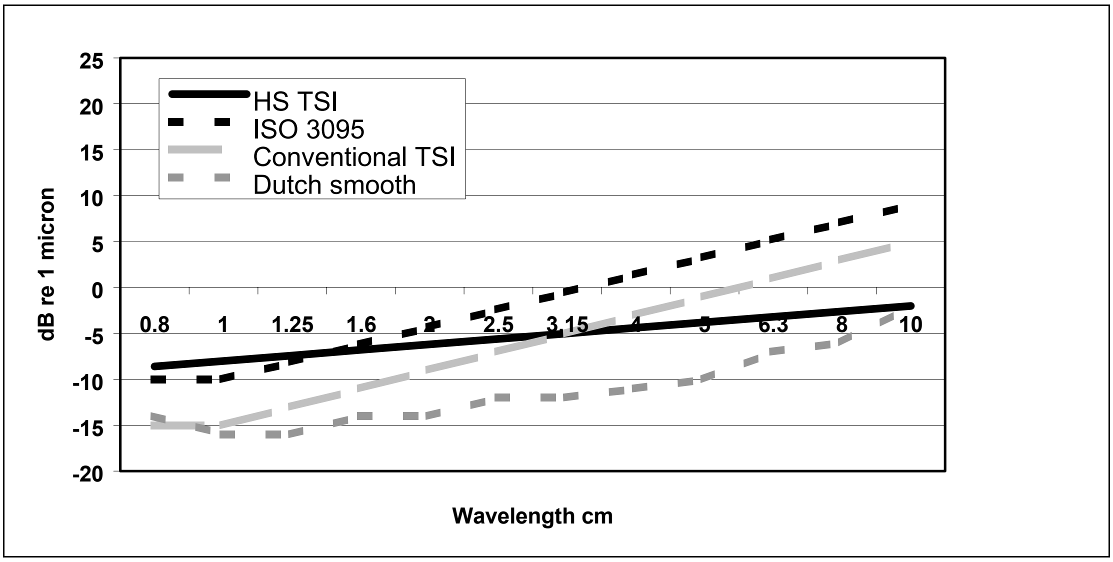

Figure 2-5 The three current standards being proposed for rail head roughness, with Dutch "smooth" track for comparison.

2.4 MEASURING WHEEL ROUGHNESS

All wheel roughness devices currently in use for acoustic purposes are based on contacting linear voltage displacement transducers, bearing against the wheel while it is rotated, normally while still on the vehicle (which is jacked up). One such system, manufactured by SNCF and also used by AEA Technology, drives the wheel with an electric motor. Other systems, such as the Dutch TNO device, the Müller BBM RMR 1435 and the Danish ODS RRM 01, rely on the wheel being turned by hand.

3 The development and control of rail head and wheel roughness

3.1 THE DEVELOPMENT OF RAIL HEAD ROUGHNESS

As indicated in Section 1, rail head roughness typically has a broad band wavelength characteristic with, in some instances, a superimposed periodic wear pattern known as corrugation. Theoretical studies and models, however, tend to concentrate on the latter phenomenon because it is more straightforward to postulate theories about periodic characteristics and because corrugation has generally greater implications for track integrity and for rolling noise emission.

Grassie (13) provides the following assessment of rail corrugation. There are 6 forms of corrugation on rail tracks. These are

- Heavy Haul, with a pitch of 200mm-300mm, associated with heavy haul loads, resulting from gross plastic flow of material
- Light rail, with a pitch of 500mm-1500mm, resulting from plastic bending
- Rolling contact fatigue, with a pitch of 150mm – 450mm, tending to occur on curves, with a flaked surface and possible plastic flow
- Booted sleeper, with a pitch of 45mm – 60mm occurring on severe curves, due to wear, plastic flow and micro-cracking
- Rutting, with a pitch of around 200mm for metro systems and around 50mm for trams, due to wear and longitudinal slip of the wheel relative to the rail
- Roaring rails, with a pitch between 25mm and 80mm, due to wear (possibly lateral), principally a problem for relatively high speed railways and straight track or on gentle curves. One or two bands of martensitic "white phase" (white etching layer) steadily build up on the rail head. The mechanism is not fully understood, but it is most plausibly associated with wheel slip (possibly from driven axles). The periodic wearing away of one of the bands of white phase leaves "islands of white phase in a sea of darker oxidised material"

It is the phenomenon termed roaring rail that is the principal concern of the current study. All models for this form of corrugation concentrate on two aspects of its development, the damage (or wear) mechanism and the "wavelength fixing" mechanism. For wavelength fixing, Grassie speculates that this is possibly a stick-slip phenomenon at the wheel/rail interface and/or a function of the pinned-pinned resonant frequency of the rail between sleepers. The work of Nielsen (14) is also based on similar hypotheses. His theory is that the initial track roughness acts as an input to the dynamic train/track system resulting in fluctuating contact forces, creepages (relative movement between wheel and rail) and contact patch dimensions. If a large number of wheelsets pass at uniform speed this process becomes self-perpetuating.

The damage mechanism is generally considered to be due predominantly to wear with some elements of plastic flow (13, 14, 15, 16). Grassie (13) suggests that this wear may be lateral. Internal work within BR Research has suggested that longitudinal creepage due to traction, braking and torsional wind up of the wheelsets could all contribute to differential wear patterns on the rail head.

None of these models and theories is well validated, although the work of Nielsen (14) considered Netherlands data acquired over several years, and appears capable of producing a reasonably good prediction of roughness growth.

Data on rail roughness in general are not readily available. In fact, the recent report by Wölfel for the EC on the interim computation methods (17) states that "After doing some search of existing rail roughness data at different European countries, very few data has been found. Actually neither Germany, Austria, Spain, nor Belgium has statistical relevant roughness data. There is no Dutch national average data". Rates of growth are highly variable and without detailed study of all the parameters involved, very difficult to predict. Dutch data (9) have in fact shown that the smoothest rail to be found had been in place for 18 years, while other sites show growth at corrugation wavelengths of between 1 and 4 dB per annum. It is clear, however, that at sites where corrugation occurs, gross tonnage of traffic is an important factor in growth.

Another problem when trying to understand the growth of roughness is that not all the data are measured in the same way. For example, indirect systems such as NoiseMon measure a single figure, and direct measuring systems measure roughness as a function of wavelength. To compare the few sets of rail head roughness data that were available the **noise** levels produced for the various levels of rail head roughness were calculated assuming a "Mk 3" disc-braked wheel. NoiseMon data from typical UK locations could then be adjusted to enable comparison[2]. It was therefore possible to calculate the rate of growth of the **noise** at the sites where data were available, over successive years, as follows:

Hölzl (18)	4.7 dB/year
	1.1 dB/year
	0.6 dB/year
	1.7 dB/year
Silent Track (19)	6.4 dB/year
Nielsen (14)	3.2 dB/year
	2.1 dB/year
	1.2 dB/year
	1.5 dB/year
Silent Track (20)	-0.6 dB/year
NoiseMon	2.5 dB/year
	9.5 dB/year
	1.2 dB/year

It can be seen that the growth rate varies from a reduction of 0.6 dB/year to a growth of 9.5 dB/year. However, it was found that at least some of the growth rates depended on the initial conditions as can be seen in Figure 3-1.

It should be noted that the quantity for the x-axis in Figure 3-1 is the Acoustic Track Quality (ATQ).

$$ATQ = L_{160,x} - L_{160,CRN}$$

Where, $L_{160,x}$ is the noise level measured by NoiseMon at location x and normalised to 160 km/h and $L_{160,CRN}$ is the noise level that would be measured by NoiseMon at 160 km/h while running on rails with a surface roughness at the level that is implicit within CRN.

[2] How this was done is covered in more detail in section 4.

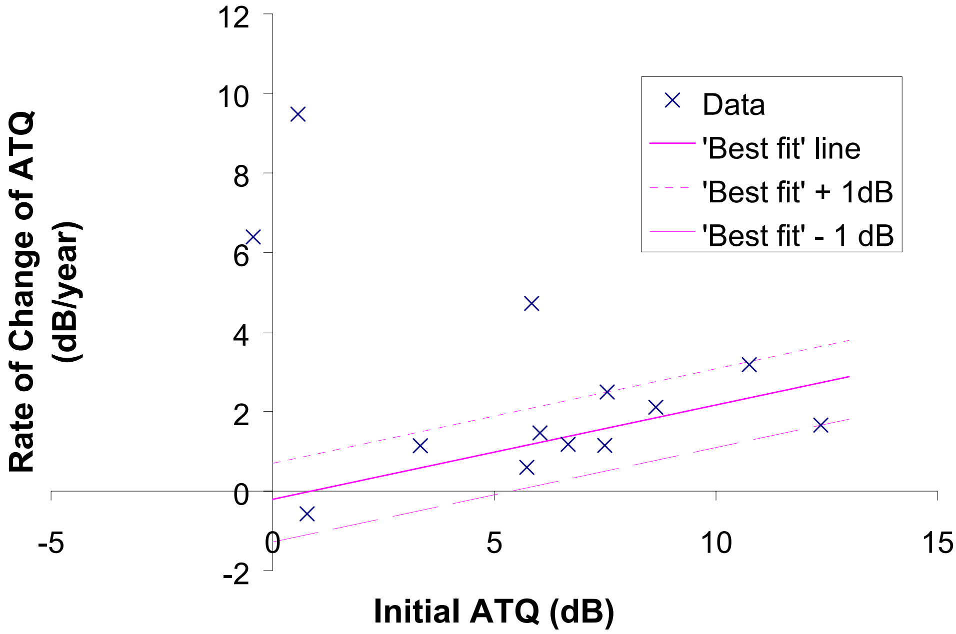

Figure 3-1 Effect of the initial ATQ on the rate of change of noise levels

The majority of the growth rates can be seen to lie close to the 'Best fit' line. This change in the growth rate means that as roughness grows so does the rate of growth. It also suggests that the initial growth rate will determine how soon the rail surface gets very rough. What this means in practice is shown in Figure 3-2.

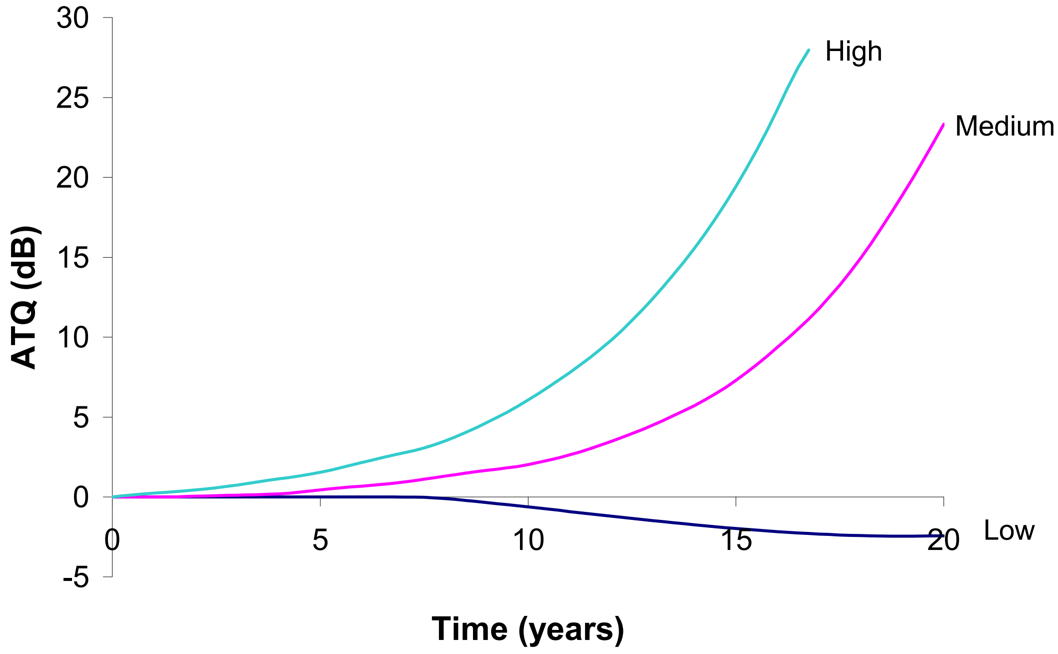

Figure 3-2 Growth of roughness (as measured by ATQ)

In practice, the actual growth rate may well depend on the amount of traffic. However, Figures 3-1 and 3-2 do illustrate that small changes in the initial conditions can produce large differences over the life of a rail. Furthermore, Figure 3-1 shows that at some locations the growth rate of roughness-related noise is so high that the roughness may have grown, assuming it approximates to an exponential growth, by more than 30 dB in under 5 years.

Figure 3-3 shows roughness growth at one main line site before and after grinding (see Section 3.2), as measured with the microphone-based "NoiseMon" system and displayed in the AEA Technology "Trackmaster™" format.

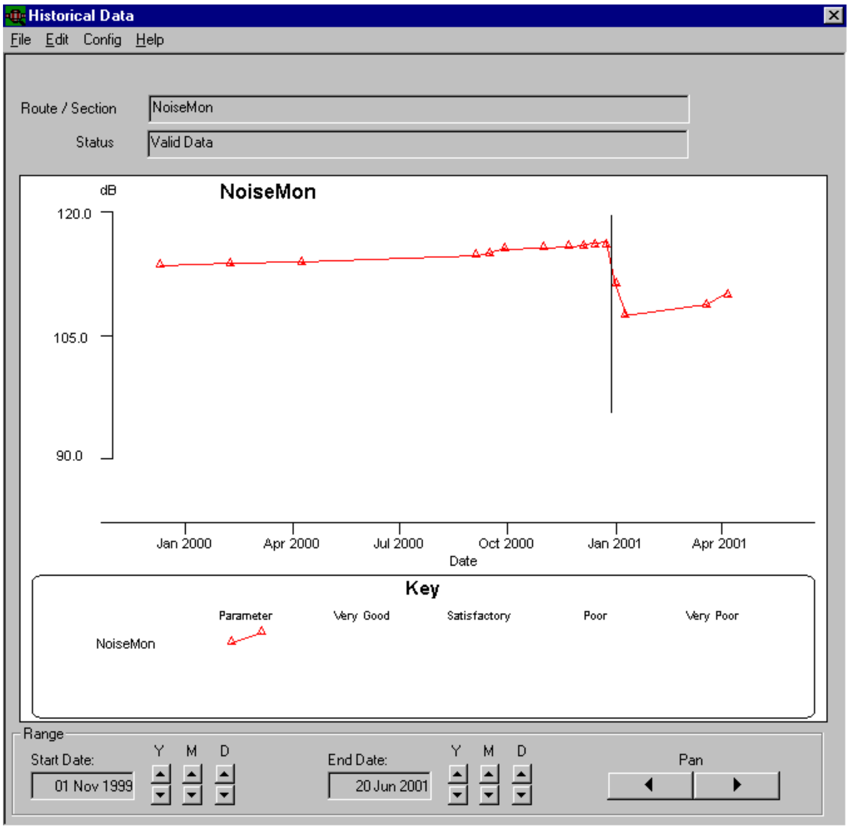

Figure 3-3 Rail head roughness as measured using an under-floor microphone, showing growth with time before and after rail head grinding (indicated by the vertical line in Jan 2001)

3.2 CONTROL OF RAIL HEAD ROUGHNESS

Ideally, the growth of roughness, and particularly corrugation, should be controlled by discouraging its formation. The following have all been suggested as helping in reducing growth: use welds of equal hardness to the parent material; increase rail support resilience; increase rail damping; reduce sleeper spacing or use continuous support; avoid rail irregularities; reduce the unsprung mass of vehicles; reduce plastic flow and wear by using hard rail material; ensure wheel and rail transverse profiles are kept well within specification; reduce stick-slip effects by increasing lateral dynamic track stiffness; reduce speeds; vary traffic loads and speeds; increase rail cross sectional area. Some of these options are impractical, and there is no guarantee that any of them will significantly reduce roughness growth with the current state of knowledge.

Once a rail has reached an unacceptable level of roughness the remedy is to grind its surface. Grinding is carried out for a number of reasons by railway administrations. "Preventive grinding" delays corrugation initiation by removing irregularities that could "seed" the process. "Corrective grinding" removes discrete rail head damage, removes corrugation, restores the transverse profile and improves the geometry of welds. A range of grinding trains and techniques is available, all of which remove a certain amount of material by means of sets of rotating or oscillating grinding stones, or continuous bands. Rail head grinding to remove corrugation on the running surface tends to flatten the rail head, thus altering the transverse profile of the rail and potentially affecting the ride of trains. It may then be necessary to grind again to restore the transverse profile. A typical grind to remedy corrugation requires around 0.2 – 0.5mm of material to be removed.

Grinders with horizontally rotating stones capable of restoring transverse profiles (eg devices from Speno, Loram and Scheuchzer) are aggressive and leave transverse grooves on the rail. Longitudinally oscillating stones (eg Plasser GWM) remove less material and leave longitudinal grinding grooves. Speno have also developed a finishing unit equipped with an abrasive band to provide a very smooth rail head finish. It is sometimes found that the grinding itself leaves a periodic pattern on the rail head, capable of producing tonal noise as trains pass. However, this is found to "roll out" in a comparatively short time.

Typical grinding machines are (21):

Scheuchzer MRK 4. 32 cup wheels around a vertical axis correct the profile from the outer side to the inner side of the rail. 4 peripheral wheels around a horizontal axis, which are applied to the upper part of the rail head and tend to flatten it, to provide fine grinding, both at 3600 rpm.
GWM Ameba (based on Plasser method) Stones oscillating along the rails in a longitudinal direction – not capable of reprofiling transverse profile.
Speno RR 24 MC-7, 24 grindstones around an axis that can vary between +30 deg to –70 deg towards the inner side.
MIB GWM 220, based on Plasser system. Vibrating grindstones oscillating in longitudinal direction, cannot reprofile transverse profile.
Speno RPS 32-1 32 grinding motors (16/rail) can be aggressive if required. Angle of grinding is variable.

German Railways have a special arrangement "Besonders Überwachtes Gleis" (BÜG), whereby sections of the network are annually monitored with their roughness-measuring laboratory coach, and ground as appropriate. The railway administration is given a nominal 3dB environmental impact bonus for legislative purposes on sections where this is carried out.

3.3 THE DEVELOPMENT OF WHEEL ROUGHNESS

Wheel roughness falls into two main categories. Smoother wheels tend to be those that are either disc-braked or fitted with tread brakes made from a composition material similar to those used for car brake pads. Rough wheels are those with cast-iron tread brakes. Wheels with tread brakes of sintered material tend to be smooth, but can produce aggressive concave wear which leads to anomalous (unexpectedly noisy) acoustic behaviour. Although these are comparatively rare at present, there is a possibility that the UK freight operators may wish to use them in the future and therefore the situation needs to be monitored.

In general, the roughness of wheels tends to remain fairly static at the wavelengths of relevance to noise (in the case of tread-braked stock following only a few brake applications). Gross damage may occur, for example as a result of a wheel slide during braking when a "flat" is formed, and there can be a certain amount of polygonisation with some braking combinations such as cast-iron tread + discs. Driven wheels can also have greater levels of roughness due to tractive forces.

The roughness created on the surface of a wheel due to tread brakes, particularly those of cast-iron, has been studied in the "Eurosabot" EC Brite Euram project (22) and by Vernersson (23). From rig and field tests, wheel roughness has been found to be due to the creation of hot spots during braking. They expand above the general wheel surface and therefore are worn down so that, upon cooling, pits are formed and hence rough wheels. The dominant wavelength of roughness is 5-7cm. In addition, a wear regime known as galling occurs, where block material is transferred to the wheel surface. Similar hot spot effects occur with composition materials, but they are less severe and do not therefore cause such extreme tread damage, with a dominant wavelength of roughness of around 13cm. However, they do impose higher thermal loads and their braking performance is less stable.

3.4 CONTROL OF WHEEL ROUGHNESS

Wheels are "turned" on a lathe periodically to restore transverse profile and concentricity. They may also be turned if discrete tread damage, such as a wheel flat due to sliding during braking, occurs. Because roughness of wheels does not normally grow at a significant or predictable rate (once tread brakes have been applied a small number of times), there is no turning strategy that can be recommended from an acoustic point of view. It is desirable to minimise the number of discrete faults and flats that are present, and therefore it would be acoustically advantageous to turn wheels whenever such features become apparent, but this would prove costly for train owners and maintainers (wheelset maintenance is already a major element of the overall maintenance cost for leasing companies).

In general, the ideal wheel in terms of roughness is one that is disc-braked and without any flats or discrete areas of damage. Wheels with composition tread brakes are almost as smooth as those with disc-brakes and are therefore also acoustically attractive. The most effective control for wheel roughness is therefore by the use of disc-braked or composition tread-braked stock (which is the general trend anyway). However, it should be noted that disc-braking systems are considerably more expensive than tread braking systems, and also that there is currently no composition tread brake block that can be directly substituted for cast-iron blocks while maintaining brake performance. The design of such a block, named the LL block, has been striven for over several years, to date with little success.

4 Research study description and results

4.1 THE STUDY APPROACH

The aim of this study was to consider the implications on noise predictions of a level of rail roughness different from that assumed in the 'Calculation of Railway Noise 1995' (CRN) (5) because it is known that some track is more than 20 dB noisier than that assumed for CRN. However, because such very noisy track occurs comparatively infrequently, is often only one of two or more tracks at that location, and has trains passing over it at a range of speeds, the implications are complex. In this study a statistical approach has been followed, where the measured current variation in the condition of the running surface of the rail is combined with the types and speeds of trains found at a number of locations within the UK. These locations were chosen to represent the wide range of railway traffic types found in the UK and to include sites with only diesel trains, those where multiple units dominate and those where electric trains dominate.

Figure 4.1 is a flow diagram of the basic steps involved in the calculations.

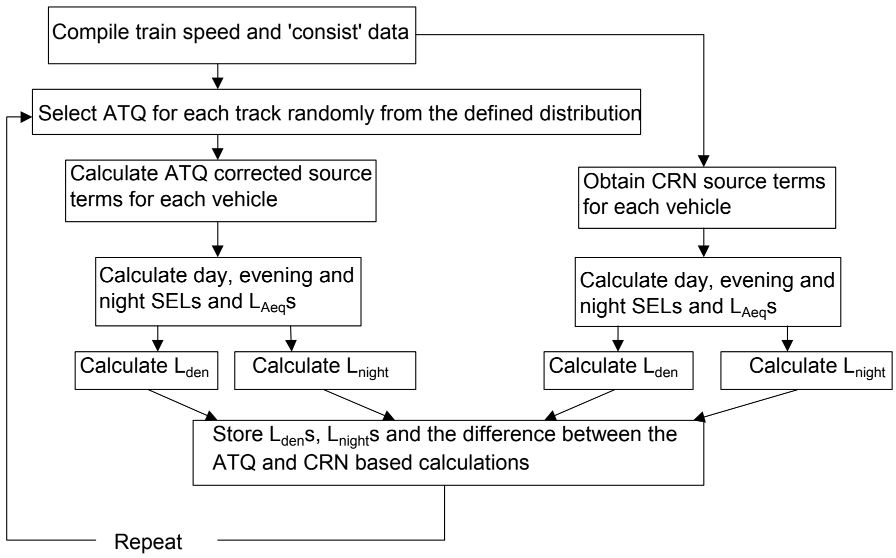

Figure 4-1 Flow diagram of steps used in calculations

Details of the selected sites are given in Appendix B.

Because CRN contains data for a limited number of types of railway vehicle, additional data in AEA Technology Rail's archives, measured under appropriate conditions, were used when available. However, there remained some vehicles with no CRN, or measured, data available (or where the measured data were not made under the CRN conditions). In this case, levels were predicted. For rolling noise this was done by using the fact that the noise level depends largely on the number of wheels and whether or not the train has cast-iron tread brakes. From experience, comparison of the levels predicted in this way shows very good agreement with measurements. Because CRN contains very little information for traction equipment, and none for the most recent diesel locomotives, data from AEA Technology Rail's archives were particularly useful for this source.

At each site, the condition of the rail was selected at random from the distribution measured over major sections of the UK network with an under-floor microphone. Using a technique developed by AEA Technology Rail in connection with the West Coast Main Line upgrade the available train noise source data were adjusted for the condition of the rail. These adjusted data were then used to predict the noise levels at each site using the techniques in CRN. These predicted levels were then compared with the level obtained from the standard application of CRN. This process was repeated over a million times at each site (with each step involving around 100 million calculations) so that a statistically significant measure of the average effect of the condition of the rail could be obtained. From these data a correction was derived that allows CRN predictions to be adjusted so that they reflect the levels that would be found at an 'average' location in the UK.

4.2 DERIVING THE DISTRIBUTION OF RAIL ROUGHNESS

The direct measurement of rail roughness is a relatively slow process and therefore it is impractical to obtain enough data to produce a meaningful distribution using this approach. With train-borne indirect measurement techniques, it is possible to measure a large amount of track, which is why data obtained using this approach were used as a basis of these predictions. Furthermore as, in this case, the indirect roughness measurements are based on under-floor noise measurements, it was relatively easy to obtain a relationship between the on-train measurements and the noise measured at the track side. This in turn made it a relatively simple task to determine the level measured by the instrumentation on the train that produces a noise level equivalent to that predicted by CRN. This avoided the need to rely on predicted noise levels, which would have been necessary if directly measured roughness data had been used. Instead, the relationship between the noise measurements on the train and the levels predicted by CRN were obtained by a measured transfer function.

Ideally, the transfer function should be obtained by measuring the noise under the train and at the track side simultaneously. However, this does create the following practical problems:

- The instrumented vehicle is only one part of a complete train and it is difficult to measure the pass-by noise from a single vehicle within a train.
- Even if the noise from the individual vehicle were measured the results would not be statistically reliable (24).
- The train with the instrumented vehicle will only pass a site a few times a day.

Instead, the noise was measured from acoustically identical vehicles passing the site and compared with the noise measured on the train at that location. It should be noted that at any site the different tracks are likely to produce different noise levels. However, this improves the statistical reliability when calculating the transfer function.

Because the trains containing the acoustically identical vehicles always have a locomotive it is necessary to extract the contribution to the train pass-by from the coaches. How this was done is presented in Appendix C.

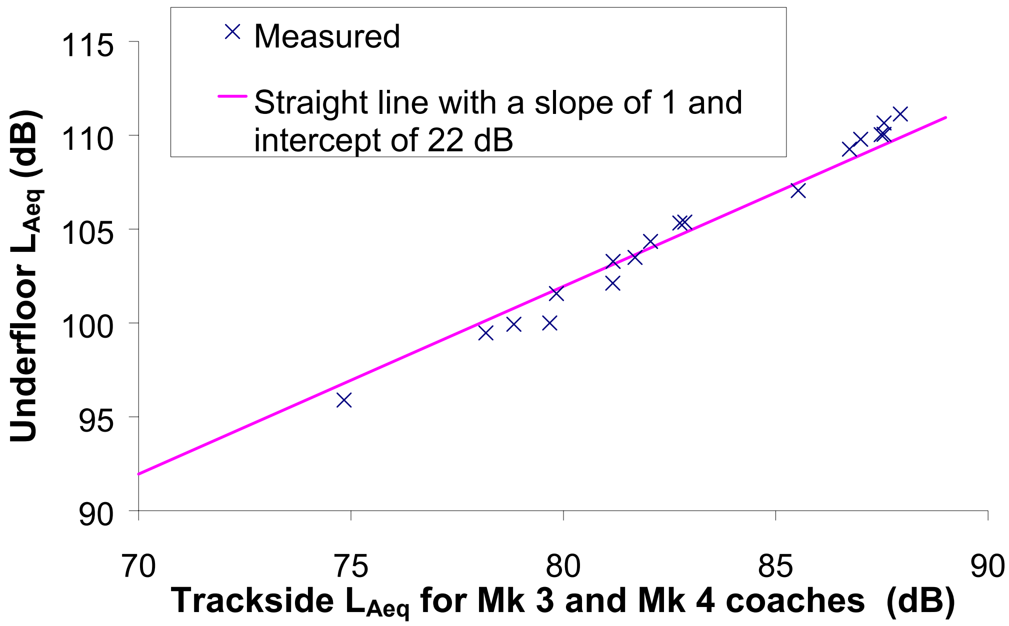

Figure 4-2 Measured Transfer Function for microphone under a disc-braked train to noise measured at the track side, 25 metres from the nearest rail

Figure 4-2 is the measured relationship between the L_A 25m from acoustically similar vehicles and the L_A measured under the vehicle at that location. As the measurements at the track side are taken from different trains and as these will be running at different speeds, the under-floor data have been adjusted for speed.

It should also be noted that because the trains have a locomotive that has cast-iron tread brakes the track side noise measurements are only for the part of the train with the disc-braked vehicles. This was done by ignoring the locomotive and the vehicle nearest to it and only considering the sound produced by the rest of the train.

The noise measured at the track side comprises the noise originating from a length of track and not just a short section nearest to the measurement position. Therefore, the under-floor data were averaged over a 200 m length of track.

Figure 4-2 includes a straight line that has a slope of 1 and a constant equal to the average difference between the speed-adjusted under-floor and track side measurements. The slope of 1 means that for every 1 dB change in the noise levels measured under the train there is a corresponding 1 dB change in the noise at the track-side. As the measured data closely follow this line, the intercept of 22 dB can safely be taken as the transfer function for this particular under-floor microphone position[3].

Having established the relationship between the under-floor and track side noise data the under-floor noise level that produces a pass-by noise level equal to the value produced by CRN can be calculated. This was done by calculating the Transit Exposure Level (TEL) from the Sound Exposure Level (SEL) predicted by CRN.

$$TEL = SEL - 10 \times \log_{10}(T_p)$$

where T_p is the time the train takes to pass ("buffer to buffer").
The advantage of using the TEL is that it is independent of the number of vehicles in the train and approximates to the measured pass-by L_{Aeq} of part of the train. If the train comprises identical vehicles, then the TEL can be derived from the measured SEL.

Using CRN, the TEL at 25 m from the track for a rake of Mk 3 coaches travelling at 160 km/h is 84 dB. Using the difference calculated from the data shown in Figure 4-2 the under-floor L_{Aeq} that gives a level at the track-side that would agree with CRN is 106 dB.

Because a change in the noise under the train produces a corresponding change in the rail/wheel noise at the track-side the amount by which the speed-normalised (to 160 km/h) under-floor level exceeds 106 dB is a measure of how much a Mk 3 or Mk 4 coach would exceed the level predicted by CRN at that location. This difference is known as the Acoustic Track Quality (ATQ) and is plotted in Figure 4-3 in terms of its distribution over a large section of the UK network.

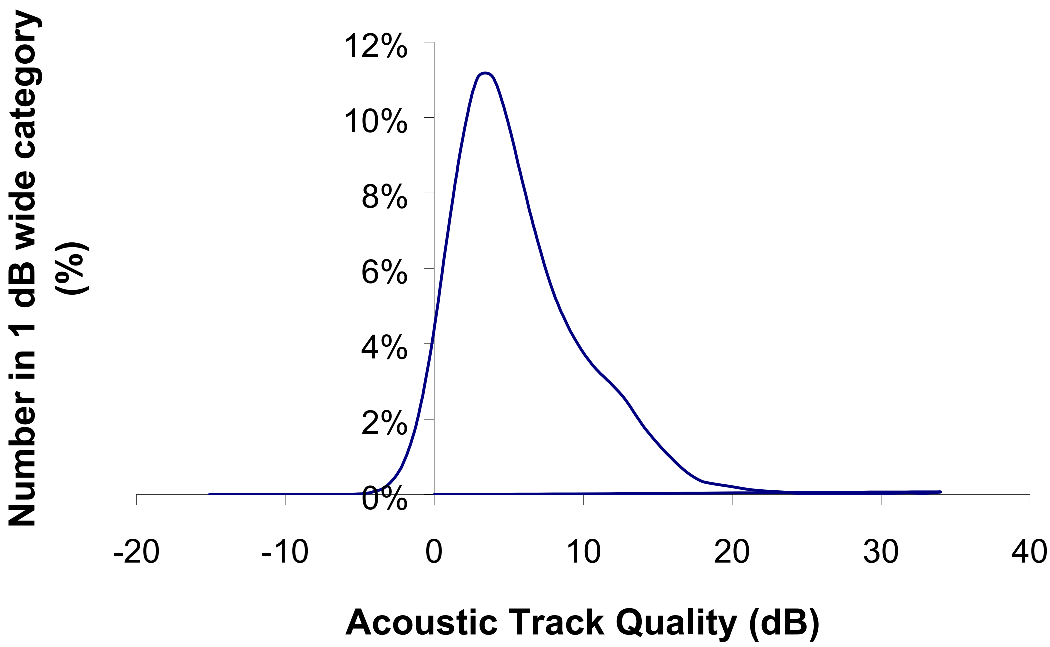

Figure 4-3 The distribution of the Acoustic Track Quality on typical UK track

[3] It should be noted that the transfer function will depend on the measurement arrangement used. In particular the position of the microphone under the train means that different measurement set-ups will produce different transfer functions.

4.3 MODIFYING THE CRN SOURCE TERMS

The ATQ curve can be used to adjust the CRN source term for vehicles with smooth wheels (such as the Mk 3 and Mk 4 coaches) simply by adding the ATQ value to the CRN source term. For wheels that have a roughness that makes a significant contribution to the total surface roughness the situation is more complex. At low levels of rail roughness, the difference between smooth and rough wheels will remain relatively constant. However, at very high levels of rail roughness, when the surface roughness of the rail dominates, the roughness of the wheel is no longer significant and the noise from smooth and rough wheels will be approximately the same.

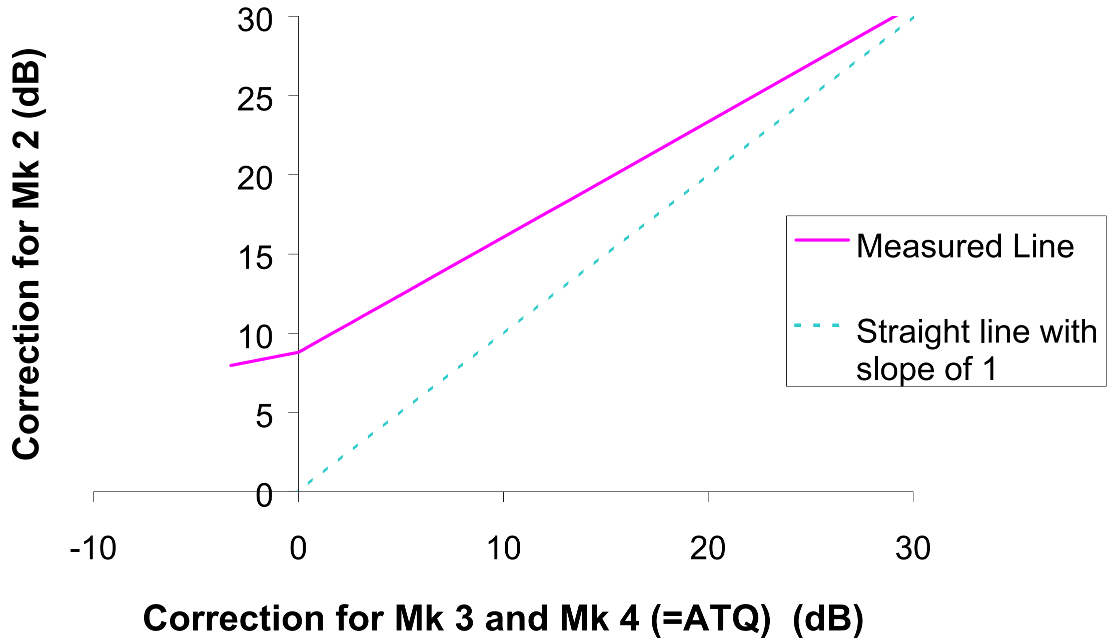

Figure 4-4 The relationship between the CRN correction required for a cast-iron tread-braked coach (Mk 2) and the correction required for a disc-braked (Mk 3 or Mk 4) coach

Figure 4-4 shows that the "measured line" (best fit to available data) crosses the vertical axis at 8.8 dB, which is the difference between the CRN corrections for a Mk 2 and Mk 3 coach. Because there are few measured noise data available for track with very low roughness some of the data shown have been derived from directly measured roughness.

The 'Straight line with a slope of 1' represents the relationship that occurs when rail roughness dominates (for example when rail roughness is very high). It can be seen in Figure 4-4 that the 'Measured line' approaches the 'Straight line' when the correction level is high.

Figure 4-4 can be considered to show the relationship between the ATQ and the CRN-type correction for a Mk 1 or Mk 2 cast-iron tread-braked coach. In practice, similar curves can be derived for other types of vehicle. Figure 4-5 shows the relationship between the ATQ and the corrected CRN source for a range of vehicles. Because HAA wagons only have two axles the '2 HAA' source term is for two HAA wagons. This ensures that all the vehicles in Figure 4-5 have the same number of axles.

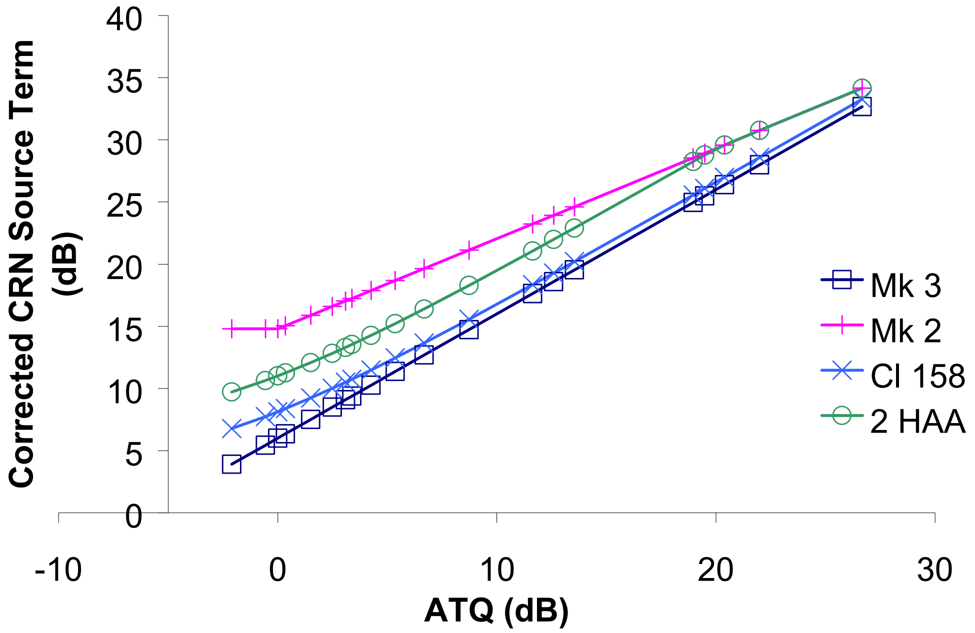

Figure 4-5 The relationship between ATQ and the corrected CRN source terms[4]

The Class 158 is a Diesel Multiple Unit with disc brakes. Because the powered axles are not as smooth as the unpowered ones the source term is higher than for a MK 3 coach.

HAA (Merry Go Round) wagons have a mixture of cast iron tread and disc brakes. The disc brakes are used for the majority of the braking. Interestingly, the source terms for two wagons (to give the same number of axles as the other vehicles) falls between the disc braked Mk 3 and the cast iron tread braked Mk 2.

As the surface roughness of the rail increases, the ATQ increases and Figure 4-5 shows how the Corrected Source Terms converge.

The ATQ-corrected source terms for a selection of vehicles given in CRN are given in Appendix E.

4.4 PREDICTION OF THE NOISE LEVELS ON ANY TRACK

If the ATQ is known for all the tracks at a site then, by using the principles outlined above, it is possible to derive a modified CRN correction for all types of train. However, the ATQ is rarely known for all locations and even if it were, it might well change with time. Instead, the possibility of producing an 'average' correction has been investigated

[4] NB, the y-axis in Figure 4-5 is the Corrected CRN Source Term and in Figure 4-4 it is the Correction to the CRN Source Term.

To derive this correction a number of typical sites were selected that included a mixture of diesel and electric traction, locomotive hauled passenger, multiple unit and freight trains, plus a range of average speeds. The initial train speeds and type of trains were obtained from the traffic previously observed at a number of sites. These were supplemented by information on other trains that are subsequently known to pass a site. For example, at one site a number of HSTs (Intercity 125) operated by Virgin Cross-Country were observed previously. These have subsequently been replaced by Virgin Voyager trains. Furthermore, there was previously one Virgin HST every hour while there are now two Voyagers every hour.

Details of the selected sites are given in Appendix B.

The information on the speeds and types of train was only available for a few hours of operation. However, because trains are often timetabled on a cycle that repeats every few hours, provided the sample time is long enough, and using information from the timetables, it is possible to establish the numbers and types and speeds of train passing a site through the day and night.

At each site, the ATQ for each track was selected at random using the distribution given in Figure 4-3. The CRN source term for each type of vehicle was then derived for the ATQs for each track[5]. Using these data the L_{den} and the L_{night} were calculated for a site 25 m from one side of the railway using both the CRN source terms and the corrected CRN source terms. The difference between the levels predicted using the corrected CRN source terms and the uncorrected source terms is a measure of the impact of the ATQ.

By repeating this process over a million times per site the difference between the levels predicted using the standard CRN and the corrected source terms was calculated.

Because of the effect of averaging over a range of trains travelling at different speeds on different tracks the spread of these predicted L_{den} and L_{night} values will be less than that presented in Figure 4-3. This is illustrated in Figure 4-6 where the uncorrected CRN prediction of L_{den} has been subtracted from the corrected L_{den} for four sample sites.

[5] CRN does not contain source terms for all the types of vehicle found at the sites. However, because the rolling noise source terms depend on only a few parameters (eg the types of brakes, the number of axles and whether the vehicle is a freight wagon) it is possible to predict the source terms for other rolling stock. In addition, AEA Technology Rail has measured data of the rolling noise for some of these vehicles and when appropriate these were used in preference to the predicted source terms. Where traction noise was not available in CRN, measured data were used.

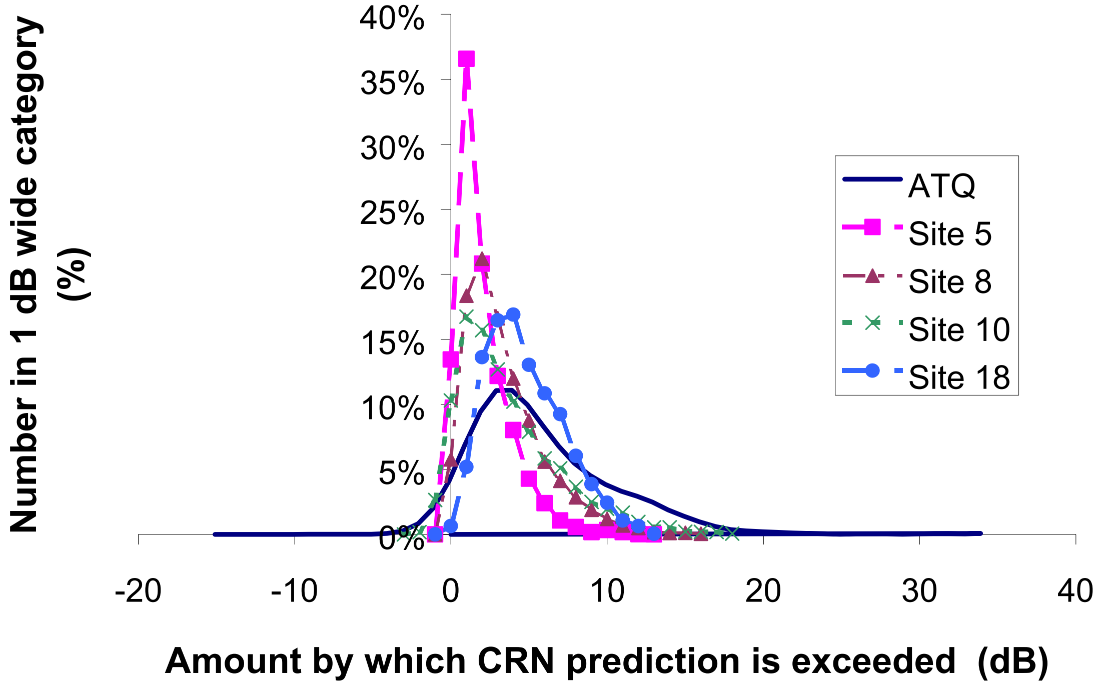

Figure 4-6 Distribution of the amount by which the CRN-based prediction of L_{den} is exceeded using a random selection of ATQ at 4 sample sites

The differences in the shapes of the distributions in Figure 4-6 are a result of the different mixture of trains and train speeds at the various sites. In practice, the selected sites had a range of trains, train speeds and ratios of cast-iron tread brakes. To assess the impact of the cast-iron tread brakes, additional predictions were made assuming all the trains at each site had either 100% or 0% cast-iron tread brakes. The results from these predictions show that although the difference to the L_{den} and the L_{night} between the situations with 100% and 0% of trains having cast-iron tread brakes can be up to 7 dB, the amount of traction noise at low speed sites means that the difference can be negligible at some locations. In reality, it is the high speed trains that are most unlikely to have cast-iron tread brakes on passenger coaches.

Real sites often have:

- A range of speeds
- A mixture of multiple units and locomotive-hauled trains
- A mixture of electric and diesel traction
- A mixture of passenger and freight trains

The result of this mixture is that the relationship between the number of wheels with cast-iron tread brakes and the L_{den} and L_{night} is very complex.

In addition to the train speed and type data for the original sites, predictions were made for similar sites with the same trains travelling at different speeds. These speeds were limited by the maximum speed allowed for each type of train.

The result of these simulations enabled a large amount of data on the difference between the levels predicted for a typical UK site and one with track that has CRN quality to be produced.

These were then used to derive a 'back end' correction that can be applied to a complete CRN prediction, as presented in Section 6.

5 Implications of rail grinding strategies

By grinding the rail head it should be possible to modify the shape of the ATQ distribution. This is because the track can be ground to produce a smoother rail head[6]. The simulations could then be re-run to find the overall effect of this grinding. However, a difficulty arises in establishing what the consequences of grinding are and how quickly roughness will subsequently develop. As already discussed, the rate of rail roughness growth is very variable and cannot be easily predicted. One "worst case" assumption is that after a short period of time the newly ground rails will have levels of ATQ with the highest levels removed and the remainder distributed throughout the rest of the existing distribution. This is probably what would happen if grinding were based purely on a trigger value of ATQ.

It is worth noting that no equivalent strategy can be applied to the wheels. This is because, when wheels are turned, they very quickly develop a stable level of roughness that depends largely on whether they are subject to cast-iron tread braking.

When the track is ground initially the rail roughness will be determined by the grinding marks. These grinding marks quickly roll out and the rail head is smooth. However, the roughness soon starts to develop at different rates. For this study it was necessary to decide what will be the distribution of the ATQ of the ground track over a period of time. One scenario is to assume that the ground track has the same distribution as all the unground track below the trigger point. An alternative scenario is that the ground track remains smooth.

When deciding to grind based on the ATQ there will be some deterioration between the time at which the track reaches the trigger point and the point at which it is ground. This will mean that, instead of the distribution being truncated at the trigger level, there will be a smooth transition towards the x-axis. The point where the distribution meets the x-axis will depend on the maximum increase in the ATQ that can occur in the time between the trigger point being reached and the track being ground. To assess the impact of this delay the following two cases have been considered:

- The ATQ deteriorates by up to 3 dB before grinding
- The ATQ deteriorates by up to 10 dB before grinding

In each case, it is assumed that there will be a relatively smooth transition between the trigger point and the upper limit.

[6] Track is not currently ground to produce a smooth running surface for acoustic reasons. However, it is often found that, despite the grinding leaving noticeable grinding marks across the rail head, these quickly roll out and the rail head, at least for a short time, becomes relatively smooth.

The shape of the distributions will depend on the grinding trigger point. Figure 5-1 shows the distributions for a trigger point of ATQ = 6 dB which represents grinding 33% of the noisiest track. In practice, it may prove difficult to grind this amount of track. However, it does illustrate the effect of the different grinding strategies.

How these alternative distributions were derived is covered in more detail in Appendix D.

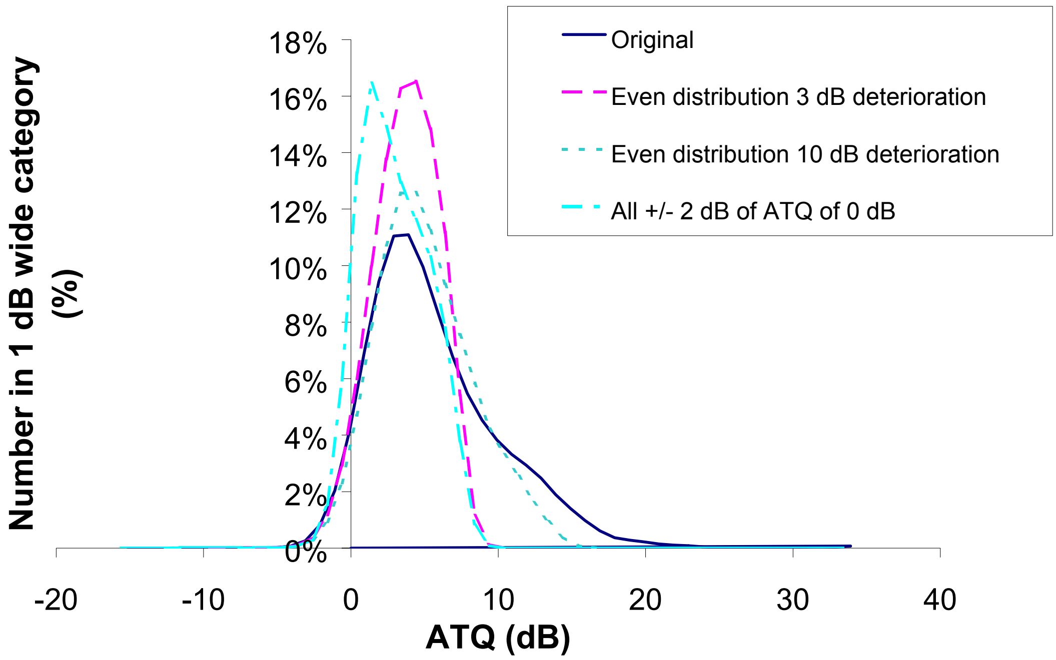

Figure 5-1 Distribution of the ATQ for different rail grinding strategies with an ATQ threshold of 6 dB (33% of the current track would require grinding)

Clearly, grinding the track with the highest ATQ and maintaining it at around 0 dB moves the distribution of the left and is likely to produce the maximum benefit. However, as this would require frequent light grinding to maintain the track in this condition this is the strategy that is the most difficult to apply in practice.

Figures 5-2 and 5-3 show the impact of different trigger levels on the 'Even distribution, 3 dB deterioration'.

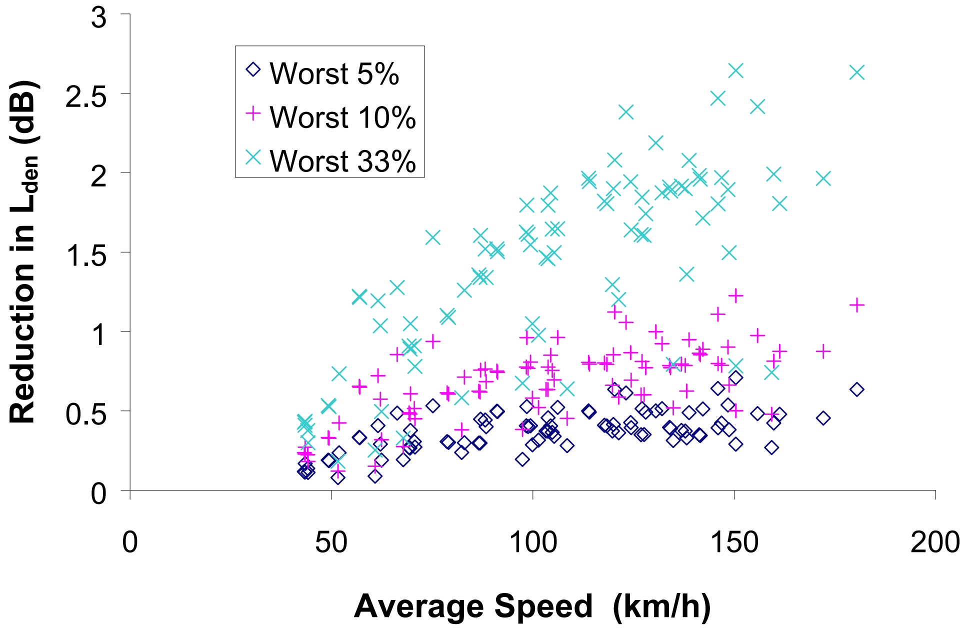

Figure 5-2 The reduction in the L_{den} achieved with different trigger levels for the 'Even distribution, 3 dB deterioration'

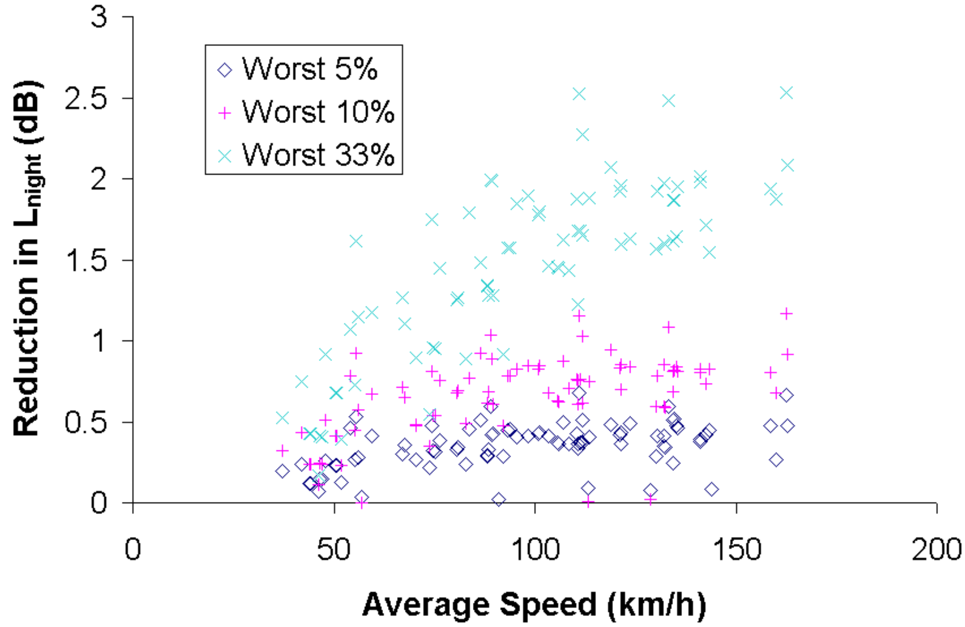

Figure 5-3 The reduction in the L_{night} achieved with different trigger levels for the 'Even distribution, 3 dB deterioration'

Clearly, the differences between the two figures are small with the L_{night} tending to increase marginally more slowly than the L_{den} as the average speed rises. However, the differences are negligible over the normal range of speeds.

Using the other scenarios shown in Figure 5-1 produces a similar distribution of data to those shown in Figures 5-2 and 5-3. However, the grinding strategy does have some effect on the average reduction. At around 160 km/h the annual reductions for L_{den} and L_{night} are:

	Even distribution, 3 dB deterioration between trigger and grind (dB)	**Even distribution, 10 dB deterioration between trigger and grind (dB)**	**All within ± 2 dB of an ATQ of 0 dB (dB)**
Grind worst 5%	0.5	0.2	0.6
Grind worst 10%	0.9	0.4	1.2
Grind worst 33%	2.2	1.2	2.7

6 Derivation of back-end correction approach

Using the data from the predictions, a range of parameters was examined to see how well they correlated with the ATQ-corrected predictions minus the CRN predictions. These parameters included the L_{den} and L_{night} predicted using CRN, the average speed of trains past the site, the number of wheels with cast-iron tread brakes, the number of wheels that were powered, the number of diesel locomotives and the number of multiple units. Figures 6-1 and 6-2 show data for the two parameters that have the best correlation with the ATQ prediction minus the

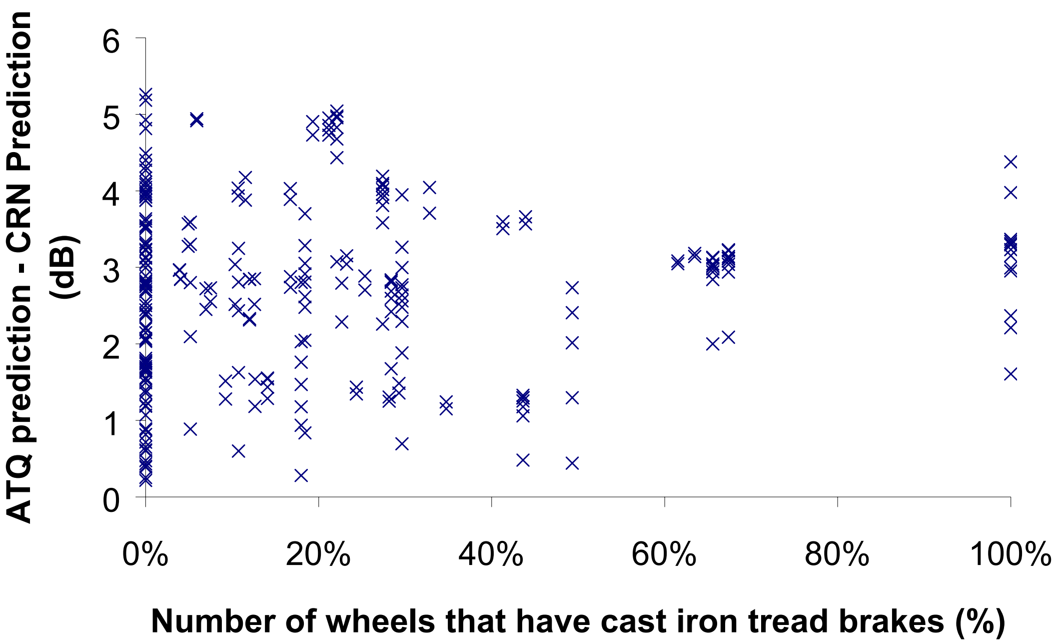

Figure 6-1 Relationship between number of wheels with cast-iron tread brakes and the ATQ-corrected prediction minus the CRN prediction for the L_{den}

CRN prediction. Clearly, only Figure 6-2, considering average speed, shows any discernible trend. The L_{night} data produce very similar result results.

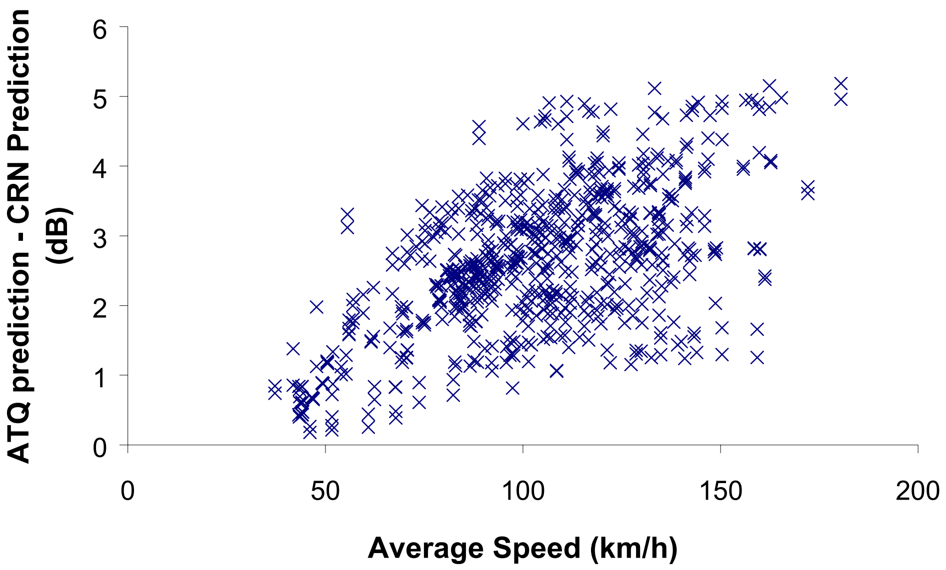

Figure 6-2 The relationship between the average site speed of the trains and the ATQ-corrected prediction minus the CRN prediction for the L_{den}

Figure 6-2 does show a clear trend with the average site speed. However, the spread is still large. Attempts to improve the correlation by using multiple dependent variables produced no statistically significant improvement in the correlation.

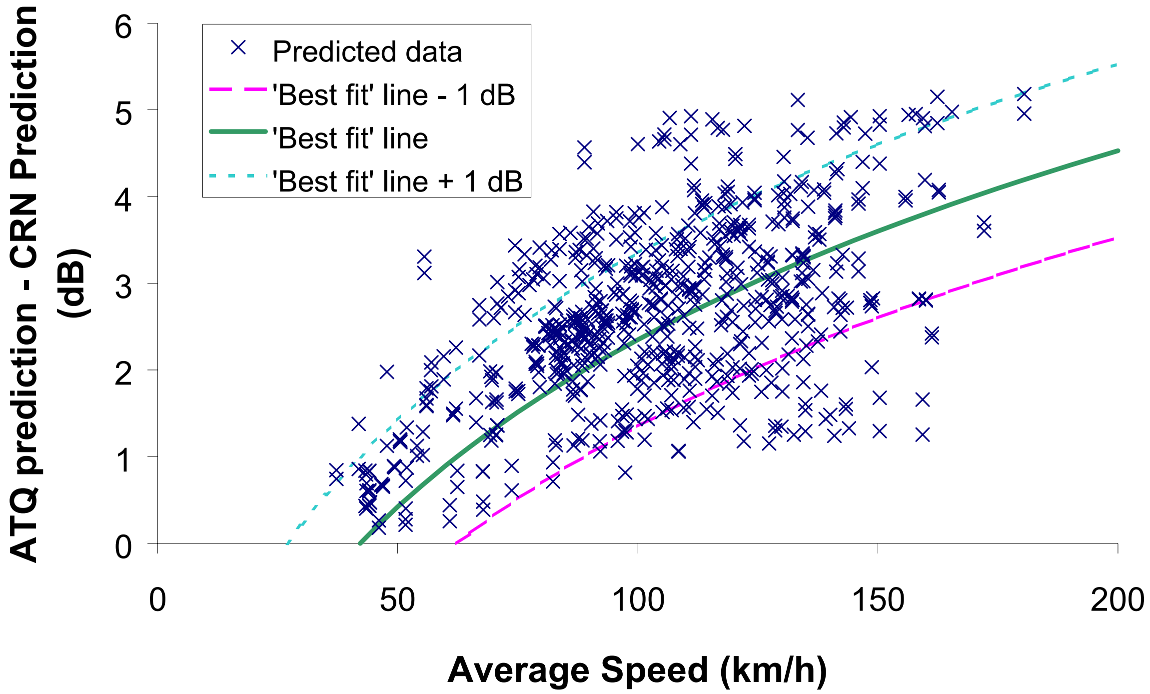

Figure 6-3 The relationship between the average speed of the trains and the ATQ-corrected prediction minus the CRN prediction for the L_{den} with 'Best Fit ' line

The range of ±1 dB contains over 70% of the data and a range of ± 2 dB includes 95% of the data. Given the other likely errors in any form of prediction this is an acceptable tolerance.

Carrying out the same exercise with the L_{night} produces essentially the same result. Figure 6-4 shows the relationship between the differences between the ATQ-corrected predictions and the CRN predictions for the L_{den} and the L_{night}.

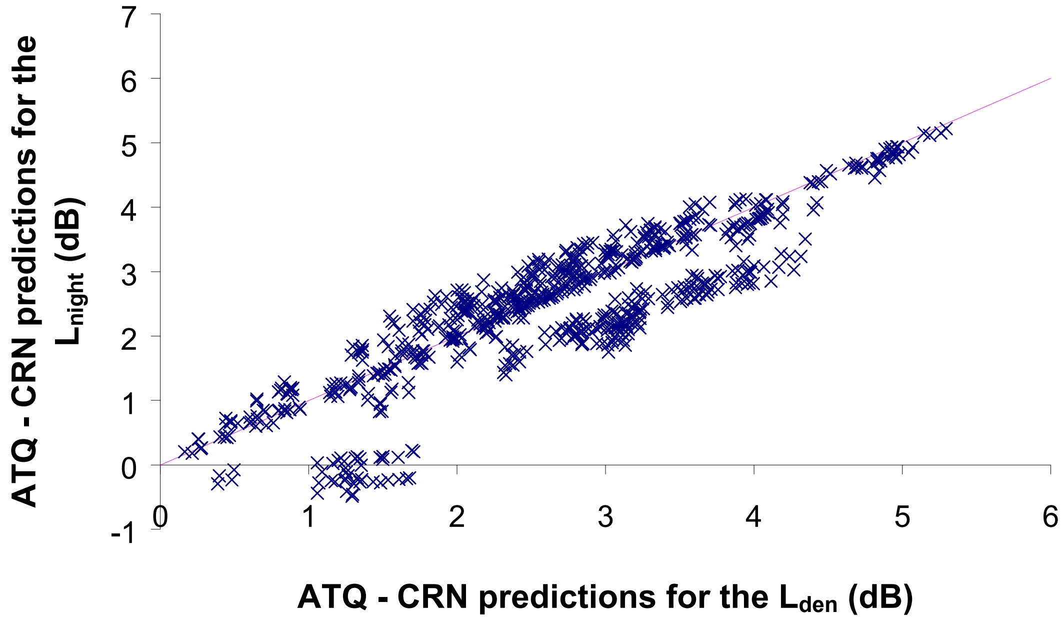

Figure 6-4 Correlation between the ATQ-corrected predictions minus the CRN predictions for L_{den} and L_{night}[7]

Compared with the other variables there is clearly a very close relationship between the ATQ-corrected predictions and the CRN predictions for the L_{den} and the L_{night}. This is probably because the L_{den} is often dominated by the night time contribution and because both sets of data are differences rather than absolute levels.

Based on these findings the following single back-end correction to the complete CRN prediction was derived for all the data.

$$\text{Correction} = 8.33 \times \log_{10}(\bar{v} + 21) - 15 \text{ dB} \quad \text{(Above 42 km/h)}$$
$$\text{Correction} = 0 \text{ dB} \quad \text{(Below 42 km/h)}$$

Where, $\bar{v}$ is the average speed of all the individual trains passing the site in km/h

Figure 6-5 shows the back-end correction in graphical form.

[7] The data plotted in Figure 6-3 and 6-4 are for the difference between the levels predicted using CRN with an ATQ correction and those predicted using the standard CRN. This means that although the Lnight does not have the 10 dB correction used for the night time noise levels in the Lden the data plotted in Figure 6-4 will tend to pass through the origin.

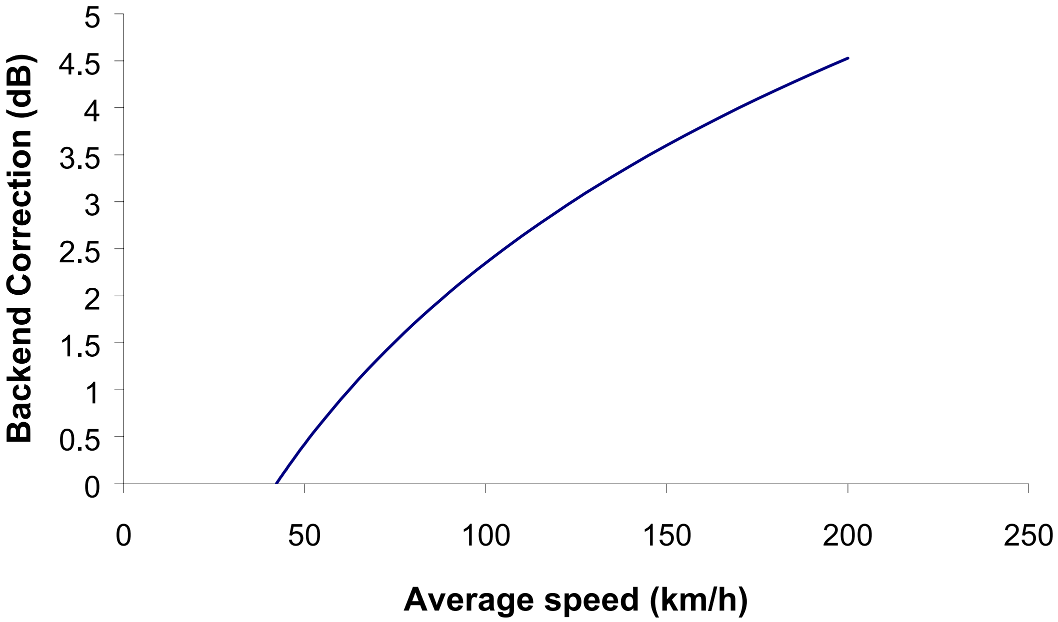

Figure 6-5 Back-end correction to be applied to CRN prediction to allow for the 'Average' variation in the Acoustic Quality of the Track

At low speeds, the noise from the traction equipment will dominate and this is why there is no correction below 42 km/h.

Clearly, the largest correction occurs at the highest speeds because rolling noise will dominate at these locations.

When the back-end correction is applied after the L_{Aeq}s have been calculated using CRN it will make the predicted levels at that site closer to those for an average ATQ. However, as shown by Figure 6-6 the shape of the distribution of the possible levels remains the same.

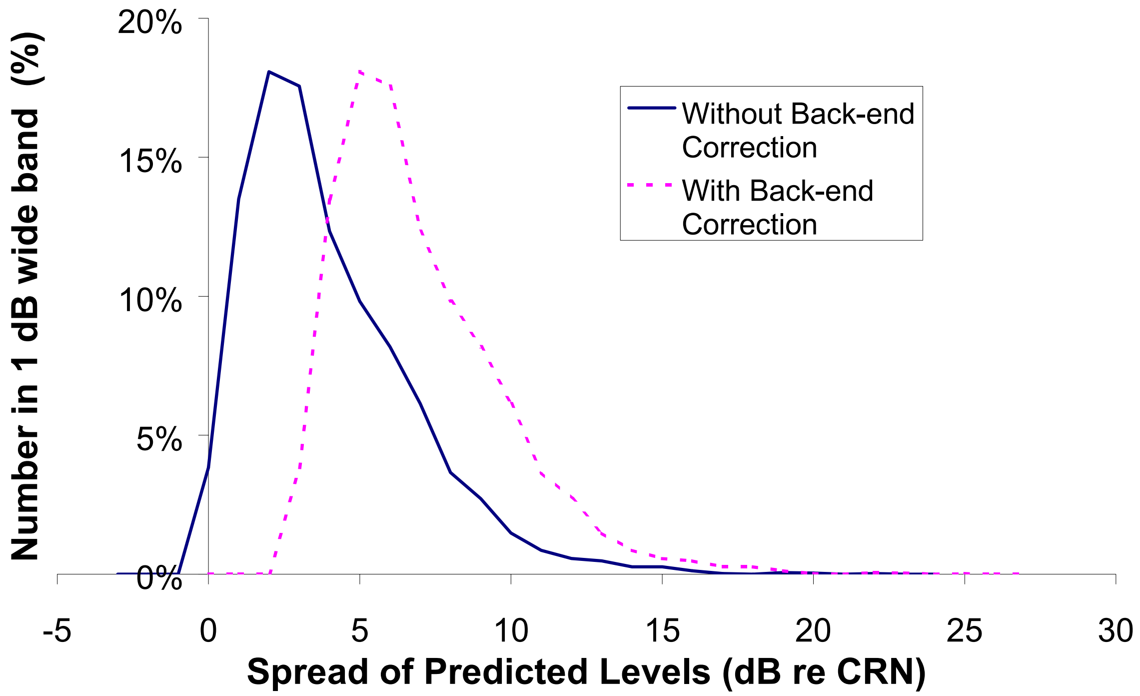

Figure 6-6 Example distributions of the predicted L_{den} for a typical site with and without the back-end correction

However, averaged across a range of sites, the back-end correction reduces the spread of the data and this is shown in Figure 6-7.

It should be noted that the x-axis in Figure 6-7 sets the modes of the distributions to 0 dB so that the distribution shapes can be compared. If this had been done for Figure 6-6 one distribution would simply have lain on top of the other. In Figure 6-6 the x-axis sets the level that CRN would predict as 0 dB. Consequently, the back-end correction has moved the whole distribution 3 dB (the back-end correction at this site) to the right.

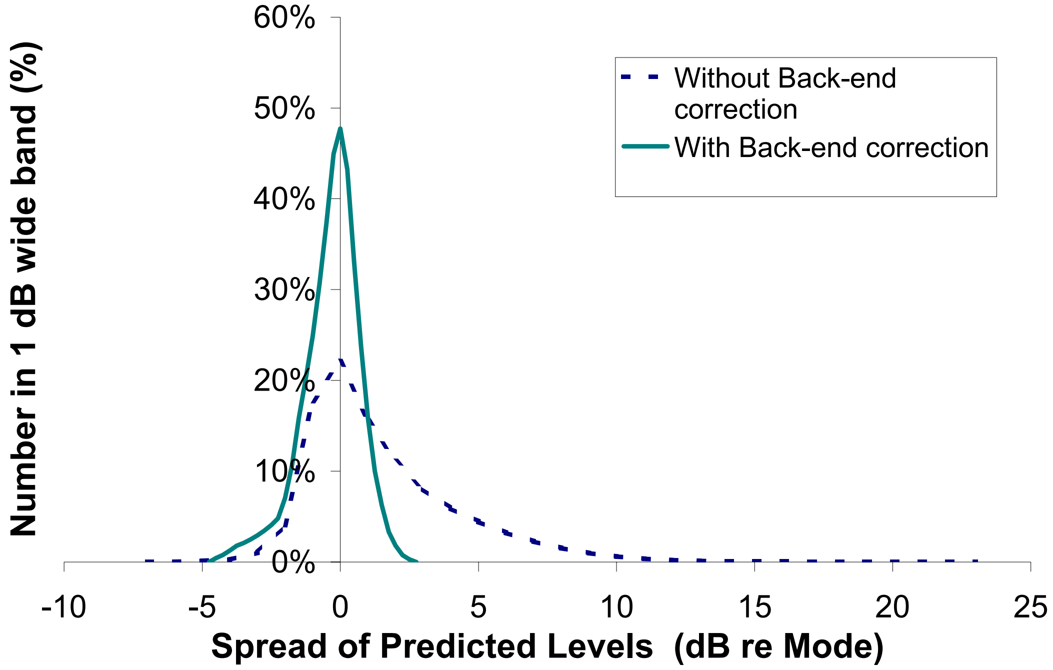

Figure 6-7 Example distribution of the predicted L_{den} for all sites with and without the back-end correction

Figure 6-7 shows that the spread of the data with the back-end correction included is much smaller than that without. It also shows that the back-end correction reduces the chances that the predicted level will be much lower than the actual level. For example, without the back-end correction the 5% level in Figure 6-7 could exceed the mode by 6.6 dB, while with the back-end correction this reduces to 1.1 dB.

The back-end correction provides a global indicator of the effects of typical current UK rail condition on the overall noise emission from the existing fleet under typical operating conditions. L_{den} and L_{night} can therefore be predicted for the entire country using the correction and will provide, on average, a significantly closer representation of the population's noise exposure than CRN would predict in its standard form.

The statistical reliability of the approach can be improved somewhat (depending on the speed distribution at the site) by calculating the CRN values at a receiver position separately for each "speed-group" of trains passing the site and then back-end correcting before combining, rather than defining a single "flow-weighted" speed value at the site.

Figures 6-8, 6-9 and 6.10 show the back-end correction for the rail grinding strategies presented in Section 5.

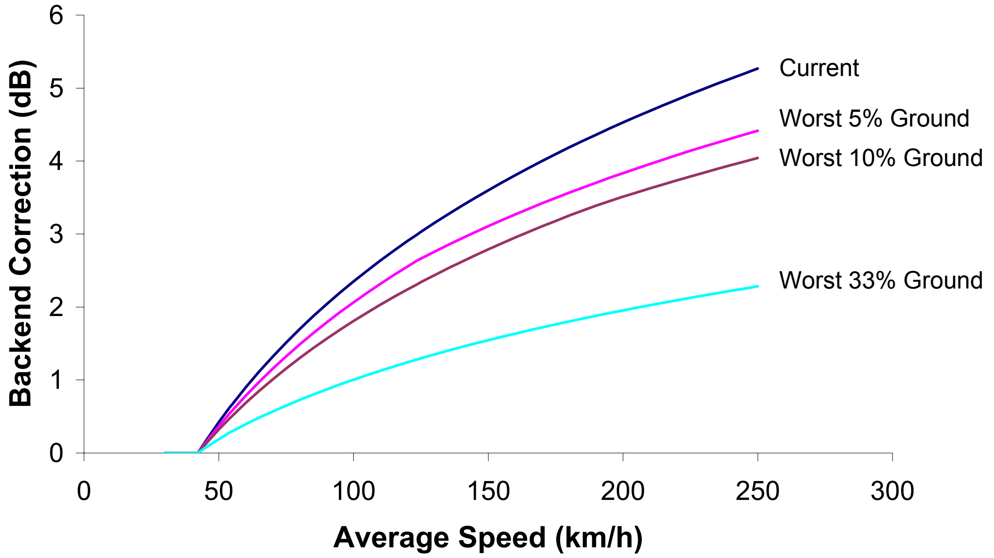

Figure 6-8 Back-end correction to be applied to CRN correction to allow for the different trigger levels of the ATQ and assuming the ground track is distributed evenly throughout the distribution. To allow for a delay between the trigger level being exceeded and the track being ground a maximum of 3 dB above the trigger levels has been assumed

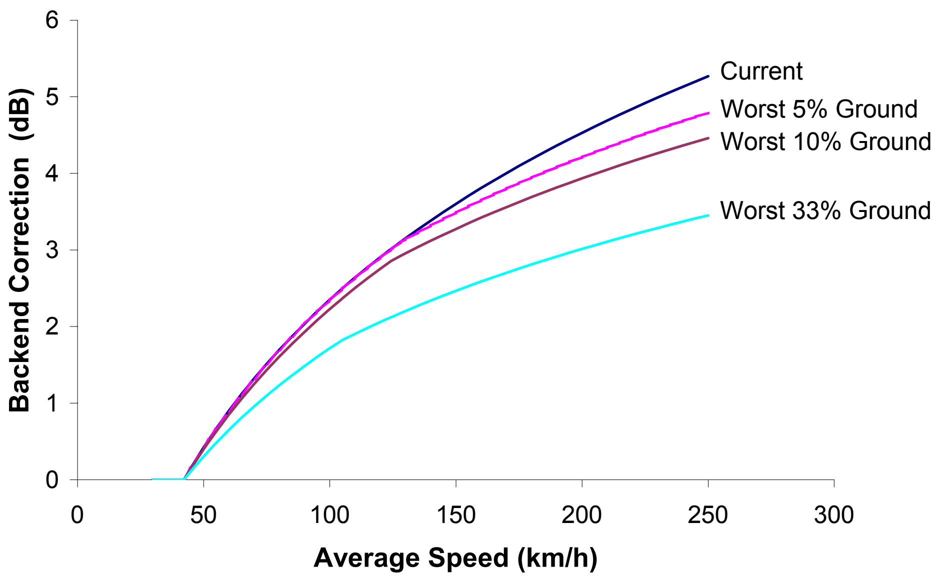

Figure 6-9 Back-end correction to be applied to CRN correction to allow for the different trigger levels of the ATQ and assuming the ground track is distributed evenly throughout the distribution. To allow for a delay between the trigger level being exceeded and the track being ground a maximum of 10 dB above the trigger levels has been assumed

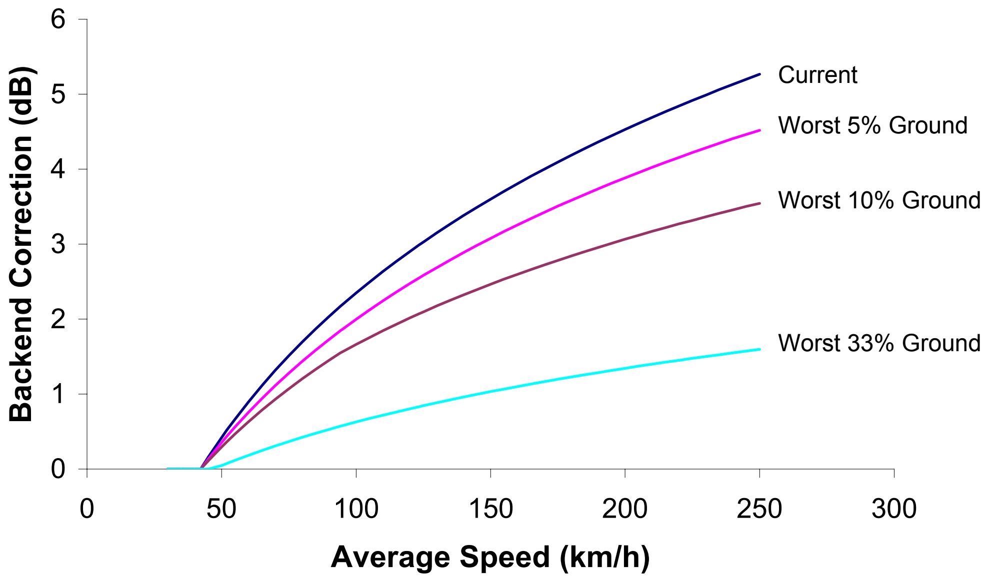

Figure 6-10 Back-end correction to be applied to CRN correction to allow for the different trigger levels of the ATQ and assuming the ground track is distributed within ± 1 dB of an ATQ of 0 dB. To allow for a delay between the trigger level being exceeded and the track being ground a maximum of 3 dB above the trigger levels has been assumed

The curves in Figures 6-8, 6-9 and 6-10 have the general form:
Correction $= a \times \log_{10}(\bar{v} + b) + c$ dB
Where $\bar{v}$ is the average speed of all the individual trains passing the site in km/h and *a*, *b* and *c* are constants for each of the scenarios.

However, because the above equation has been derived empirically it only applies over a limited speed range. The following Table contains the constants *a*, *b* and *c* for each of the curves along with the speed limitations. Because of these speed limits there are two sets of constants for some of the curves.

Figure	**Curve**	***a***	***b***	***c***	**Speed Range (km/h)**	
All	Original	8.33	21	-15	42.2	250.0
6-8	Worst 5%	7.53	23.5	-13.7	42.2	123.5
		6.70	26.1	-11.9	123.5	250.0
	Worst 10%	6.73	25.3	-12.3	42.2	190.1
		6.14	26.8	-11.0	190.1	250.0
	Worst 33.3%	4.22	29.8	-7.8	42.2	54.4
		3.86	31.0	-7.2	54.4	250.0
6-9	Worst 5%	8.31	20.9	-15.0	42.2	128.2
		6.63	24.7	-11.4	128.2	250.0
		7.94	21.5	-14.3	42.2	124.3

	Worst 10%	6.00	23.5	-10.2	124.3	250.0
	Worst 33.3%	6.34	24.7	-11.6	42.2	104.6
		5.09	28.0	-9.0	104.6	250.0
6-10	Worst 5%	7.36	24.4	-13.4	42.2	240.7
		6.76	22.5	-11.9	240.7	250.0
	Worst 10%	6.42	27.7	-11.8	42.2	94.3
		5.53	26.1	-10.0	94.3	250.0
	Worst 33.3%	3.11	42.8	-6.1	42.2	250.0

Below 42.2 km/h the *Correction* = 0 dB.

Section 5 has shown that, in reality, a practical strategy comprising the grinding of the worst 10% of national track miles is likely, at best, to reduce the global exposure from the railway system, when quantified in terms of L_{den} and $L_{night,}$ by around 1 dB. (These figures are for a typical system speed of 160 km/h.) Even grinding the worst 33% of track only increases this to around 2 dB. The largest reductions occur at the highest speeds. This is to be expected as it is at these higher speeds that rolling noise dominates and there will be the greatest benefit in grinding the rail. Of course, local effects can be significantly greater, eg by grinding a severely corrugated site to a low level of rail head roughness, where a 20 dB reduction or more could be achieved. Clearly, the reduction will be lower if there is a high percentage of vehicles with cast iron tread brakes. At the sites considered, reducing the ATQ from 20 dB to 0 dB typically reduces noise levels by between 10 dB and 16 dB. The reduction will always be less than the reduction in the ATQ, even at high speeds, because the CRN corrections for multiple units with disc brakes tend to be slightly higher than Mk 3 and Mk 4 coaches on which the ATQ is based. This is thought to be because the powered wheels have a slightly rougher running surface (and are therefore slightly noisier) than those that are un-powered.

An alternative to using the global approach investigated above would be to produce noise predictions with actual levels of rail head roughness at specific locations, and then to modify this actual roughness by the amount that a targeted grinding would produce. Acoustic Track Quality could be obtained at the specific location using a NoiseMon, or similar, measurement. For prevailing levels, the rolling noise element of the CRN prediction could then be back-end corrected for disc-braked passenger vehicles via the value of ATQ obtained from the NoiseMon approach or by measuring the pass-by noise from known (preferably disc-braked) stock. The correction for the rolling noise from tread-braked passenger vehicles would also be available via Figure 4-5 and Appendix E. The predictions could then be re-run with a reduction in ATQ predicted as resulting from a particular grinding technique.

Across the whole network, the results from applying this discrete approach at all sites and combining the exposures of all the local populations would be the same as those obtained by applying the global correction factor (assuming homogeneous population density).

7 Conclusions

Rail head roughness can have significant effects on levels of rolling noise from trains. This can be a major issue locally, as some trains can be 20 dB or more noisier on very rough, or corrugated, rail than on smooth rail. A back-end correction has been developed that allows predictions made using the Calculation of Railway Noise Procedure (CRN) to reflect typical UK rail conditions rather than conditions of comparatively smooth rail for which the procedure was designed. This approach will enable the global noise exposure in the UK, quantified in terms of L_{den} and L_{night} as required under the Environmental Noise Directive (7), to be more accurately modelled with CRN than would have otherwise been the case.

The study has also considered the effects of rail grinding strategies on overall railway noise exposure. A very large number of simulations of typical UK situations with characteristic traffic levels and mixes, including diesel-powered stock, were carried out, allowing a back-end correction to account for various grinding strategies to be derived.

If local rail head conditions are taken into account rather than national average characteristics however, techniques are available to correct CRN appropriately. The local rail head roughness can be quantified by measuring rolling noise under a disc-braked vehicle passing over the site. The "Acoustic Track Quality" (ATQ) thus derived can be used to correct predicted rolling noise at that site to indicate prevailing environmental levels, either directly for passenger stock with disc-braked wheels, or via derived relationships for other types of braking and classes of stock. Overall, prevailing noise levels, including noise from diesel traction, can then be calculated. The process can be repeated for an assumed reduction in ATQ resulting from a particular grinding exercise.

A "typical" rail roughness growth rate, or a strong relationship between known parameters and that growth rate, has not obviously emerged from the literature studied, except for the fact that the rate of growth appears to increase with roughness level. It has therefore not been possible to predict with certainty the long-term roughness behaviour at sites that have been ground.

It would therefore appear from this study that, if the exposure of the population in general to railway noise is to be quantified in terms of long-term L_{den} and L_{night}, targeted grinding strategies that would be practicable will not show major reductions in the population exposed to particular noise levels. However, if marginal global reductions in exposure are considered to be worthwhile as part of an Action Plan under the Environmental Noise Directive, methods are available as a result of the study that enable CRN to be corrected to account for such strategies.

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Appendix A
Terminology

Acoustic Track Quality (ATQ)	The difference between the measured speed-normalised A-weighted sound pressure level from a wheel running on a section of track and the A-weighted sound pressure level that would be produced if the wheel was running on track with a surface roughness at the level that is implicit within CRN
A-weighting network	An electronic filter that approximates, under defined conditions, to the frequency response of the human ear.
Cast iron tread brakes	A tread braking system where the brake block is made from cast iron. These systems provide very effective braking but roughen the surface of the wheel.
Composition tread brakes	A tread braking system where the brake block is a composition material (much the same as the materials used in road vehicles). These systems do not roughen the surface of the wheel in the same way as cast iron but can impose higher thermal loads on the wheel under severe braking conditions.
Corrugation	Periodic wear pattern on the rail head
Creepage	In normal running the wheel and rail profiles are designed to compensate for the fact that on corners the outer wheel has to roll further than the inner wheel. However, on very tight curves, or when the wheels are worn, it is possible for the profiles to be unable to compensate fully for the differences in distance that the wheels need to roll. When this happens there is initially a residual twisting force in the axle. Eventually this twisting force is large enough to overcome the friction between the wheel and the rail and the wheel moves relative to the rail without rolling, ie it 'creeps'.
Decibel scale	A linear numbering scale used to define a logarithmic amplitude scale.
Diesel Multiple Unit	One or more permanently coupled vehicles that carry passengers or goods, with their own dedicated diesel traction equipment. In some cases, not all the vehicles

	in a diesel multiple unit are powered.
Diesel Traction	Motive power provided by an on-board diesel engine.
Disc brakes	A braking system where the braking is provided by a disc mounted either on the wheel or on the axle. Disc brakes are usually essential for stopping fast trains.
DMU	See Diesel Multiple Unit
Electric Multiple Unit	One or more permanently coupled vehicles that carry passengers or goods, with their own dedicated electric traction equipment. In some cases, not all the vehicles in an electric multiple unit are powered.
Electric Traction	Motive power provided by either an overhead AC supply or by DC conductor rails
Electrified Line	A line equipped to supply vehicles with electric traction. Diesel trains can also run on electrified lines.
EMU	See Electric Multiple Unit
Equivalent continuous sound pressure level	The equivalent continuous sound level which has the same sound energy over the stated period of time as a time varying sound.
Fourier Analysis	A method for breaking down any time varying signal into a series of sine waves
Frequency	1/(time taken for a sine wave to complete 1 cycle). (See figure A-2)
Hertz (Hz)	The unit of frequency measurement.
High Speed Train	A train comprising typically 7 or 8 Mk 3 coaches (actually trailer cars) with a Class 43 locomotive at each end. Sometimes called IC125 because the maximum speed is 125 mph.
HST	See High Speed Train
L_{Aeq}	The A-weighted equivalent continuous sound pressure level.
L_{den}	The energy sum of the L_{Aeq} from the trains for a 12 hour day, a 4 hour evening and an 8 hour night adjusted by adding 5 dB to the evening L_{Aeq} and 10 dB to the night. $L_{den} = 10 \times \log_{10}\left[(12 \times 10^{Lday/10} + 4 \times 10^{(Levening+5)/10} + 8 \times 10^{(Lnight+10)/10}) / 24 \right]$
L_{night}	The L_{Aeq} from the railway over the 8 hour night time.
Line	One or more tracks.
Locomotive	A vehicle that provides the traction power for a train and does not carry passengers or goods

Maximum train speed	The maximum speed permitted for a particular type of train.
Mk 1 coach	A standard BR passenger coach built between 1951 and 1963. Now largely withdrawn from passenger trains but still used to carry parcels, etc.
Mk 2 coach	A standard BR passenger coach built between 1963 and 1975.
Mk 3 coach	A standard BR passenger coach built between 1975 and 1985. The High Speed Train (HST) trailer cars are essentially Mk 3 coaches.
Mk 4 coach	A BR passenger coach built between 1989 and 1991 for use on the East Coast Mainline between London Kings Cross, Leeds and Edinburgh.
Network	All the routes in the UK.
Passenger coach	A railway vehicle designed to carry passengers and intended to be hauled by a locomotive.
Permissible speed	The maximum speed permitted on a section of line.
Pinned - Pinned frequency	The fundamental frequency at which a beam vibrates when pinned at two points. The pinning allows rotation around the point but not vertical or lateral displacement. See figure A-3
Polygonisation	Multiple small wheel flats around a wheel.
Route	The line or lines between two major points on the railway network.
SEL	See Sound Exposure Level
Sound Exposure Level (SEL)	The A-weighted sound pressure level which, if it lasted for 1 second, would produce the same A-weighted sound energy as the actual event.
Sound pressure level (SPL)	A fundamental measure of sound pressure. Defined as: $SPL = 10 \times \log_{10}\left(\frac{p^2}{p_0^2}\right)$ Where p is the sound pressure and p_0 is the reference pressure level of 20 microPascals (μPa)
TEL	See Transit Exposure Level
Track	A pair of rails normally supported by sleepers, along which a train runs.
Train	One or more vehicles running along the track as a single entity.

Train consist	The vehicles that make up the train.
Transit exposure level	The A-weighted sound pressure level which, if it lasted for the time taken for the train to pass, would produce the same A-weighted sound energy as the actual complete train passage.
Tread brakes	A braking system where the brake block acts on the running surface of the wheel.
Virgin Voyager	A high speed dmu designed to replace the Cross Country HSTs.
(Roughness) Wavelength	The distance between identical points on a sine wave forming one component of the overall roughness spectrum. (See figure A-1)
Wheel flat	When a train brakes the braking forces are transferred to the rail and the rail/wheel contact patch. If these forces exceed the adhesion limit, the wheel will slide on the rail. In some circumstances, this sliding can be sufficient to 'grind' away a small part of the wheel. This is known as a wheel flat and results in the wheels producing a characteristic banging sound as the train passes at low speeds.
Wheelset	Two wheels and an axle.

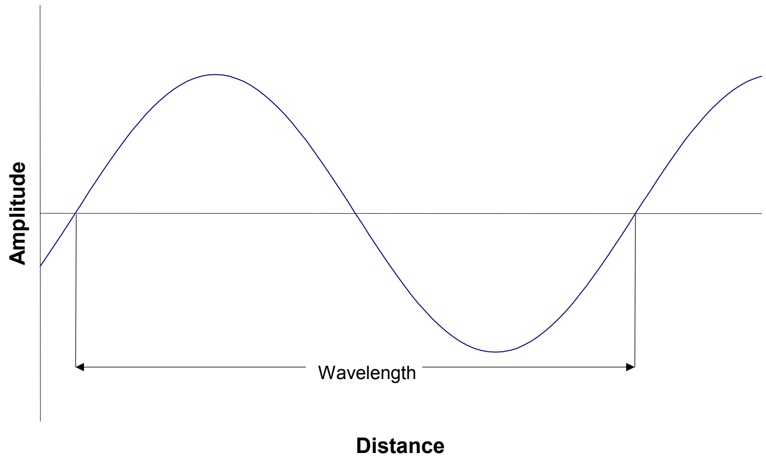


Figure A-1 Wavelength

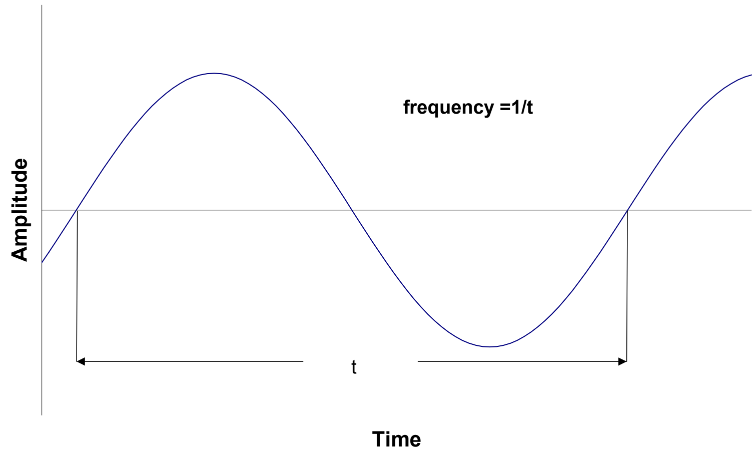


Figure A-2 Frequency

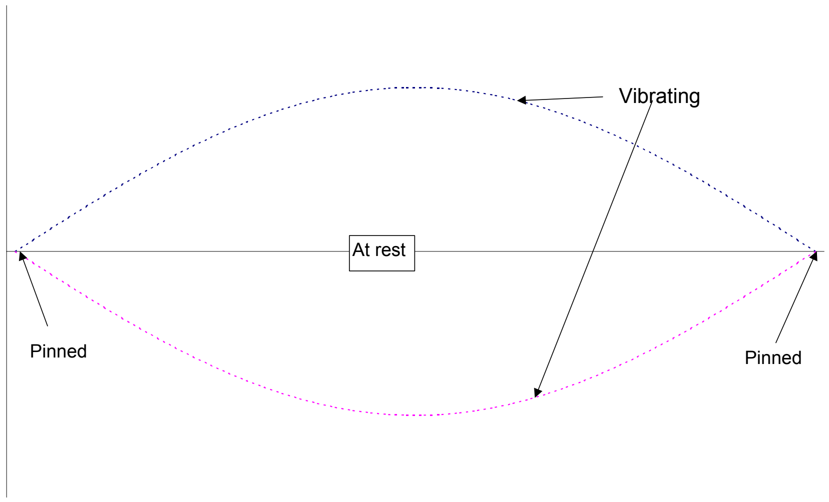


Figure A-3 Pinned-Pinned frequency

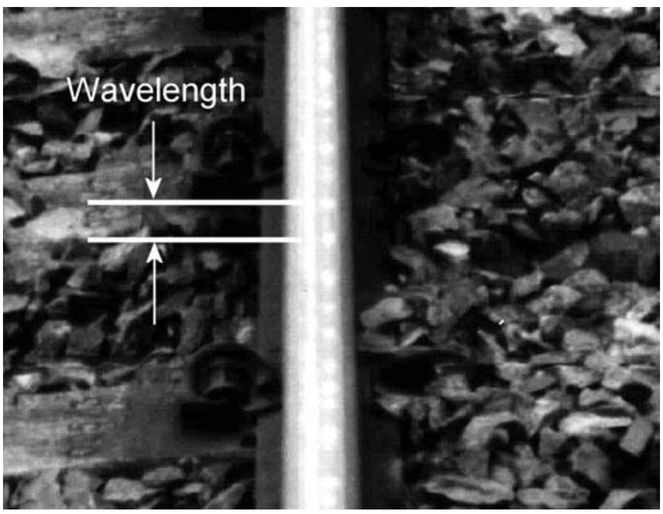


Figure A-4 Corrugation wavelength

Appendix B
Details of selected sites

The sites for the simulations were selected on the basis of available data on the numbers, types and speeds of trains observed passing known locations. These trains were then supplemented by trains known to run on the route but not seen during the observation period.

As the observations were made during the day, the evening and night time trains were obtained by using timetable information and, unless there was evidence to the contrary, assuming that the train "consist" and speeds remained the same. When there was evidence that the evening and night flows included some additional trains not observed during the day, the consists and train speeds were obtained from observations made at other similar locations.

It was found that the number of trains predicted for each year using this approach was higher than those predicted using a more detailed approach. This is because the data used in these predictions were taken during a busy part of the day, no account was taken of weekend and holiday working, and because of the normal sampling errors that will occur when obtaining data in this way. Because the output of these predictions are differences and not absolute levels the difference in the total number of trains will have made no difference to the findings presented in this report.

Site 1

Between Tamworth and Stafford on the West Coast Main Line.

Number of tracks	2		
Total number of trains/year	57000		
Average speed of trains for L_{den}	135 km/h		
Average speed of trains for L_{night}	113 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	70.4%	13.3%	16.3%
Percentage Diesel Passenger	4.3%	7.7%	0.0%
Percentage Electric Passenger	65.2%	53.8%	37.5%
Percentage Diesel Multiple Units	13.0%	7.7%	12.5%
Percentage Electric Multiple Units	4.3%	7.7%	12.5%
Percentage Diesel Freight	4.3%	7.7%	12.5%
Percentage Electric Freight	8.7%	15.4%	25.0%
Percentage of axles with cast iron tread brakes	38.9%	47.9%	57.2%

Site 2

Between Bletchley and Milton Keynes on the West Coast Main Line.

Number of tracks	4		
Total number of trains/year	116000		
Average speed of trains for L_{den}	132 km/h		
Average speed of trains for L_{night}	107 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	77.5%	11.9%	10.6%
Percentage Diesel Passenger	2.5%	5.3%	11.1%
Percentage Electric Passenger	38.8%	34.2%	22.2%
Percentage Diesel Multiple Units	0.0%	0.0%	0.0%
Percentage Electric Multiple Units	48.8%	42.1%	27.8%
Percentage Diesel Freight	6.3%	13.2%	27.8%
Percentage Electric Freight	3.8%	5.3%	11.1%
Percentage of axles with cast iron tread brakes	31.0%	33.7%	37.0%

Site 3

Trans Pennine route between Sheffield and Manchester. Near to a local station where 1 train an hour in each direction stops during the day. Throughout the night there is a through service to Manchester Airport.

Number of tracks	2		
Total number of trains/year	49000		
Average speed of trains for L_{den}	88 km/h		
Average speed of trains for L_{night}	94 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	76.6%	10.6%	12.8%
Percentage Diesel Passenger	0.0%	0.0%	0.0%
Percentage Electric Passenger	0.0%	0.0%	0.0%
Percentage Diesel Multiple Units	83.3%	80.0%	66.7%
Percentage Electric Multiple Units	0.0%	0.0%	0.0%
Percentage Diesel Freight	16.7%	20.0%	33.3%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	17.4%	0.0%	0.0%

Site 4

As Site 3 but with the additional trains that have started to operate along the route since the original data were collected.

Number of tracks	2		
Total number of trains/year	71000		
Average speed of trains for L_{den}	98 km/h		
Average speed of trains for L_{night}	101 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	78.3%	10.1%	11.6%
Percentage Diesel Passenger	0.0%	0.0%	0.0%

Percentage Electric Passenger	0.0%	0.0%	0.0%
Percentage Diesel Multiple Units	83.3%	71.4%	50.0%
Percentage Electric Multiple Units	0.0%	0.0%	0.0%
Percentage Diesel Freight	16.7%	28.6%	50.0%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	8.6%	0.0%	0.0%

Site 5

On the Midland Mainline between Derby and Chesterfield. This location has a mixture of traffic on the Cross Country route from Bristol to Newcastle and on the Midland Mainline between London and Sheffield.

Number of tracks	2		
Total number of trains/year	73000		
Average speed of trains for L_{den}	121 km/h		
Average speed of trains for L_{night}	103 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	81.8%	10.1%	8.1%
Percentage Diesel Passenger	72.2%	60.0%	25.0%
Percentage Electric Passenger	0.0%	0.0%	0.0%
Percentage Diesel Multiple Units	18.5%	20.0%	25.0%
Percentage Electric Multiple Units	0.0%	0.0%	0.0%
Percentage Diesel Freight	9.3%	20.0%	50.0%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	41.9%	60.1%	86.1%

Site 6

As Site 5 but with the cross-country HST sets replaced by the Virgin Voyager DMUs. As there are twice as many Voyagers than the HSTs they replaced, the number of trains has increased. In addition, there has been an increase in the amount of freight traffic.

Number of tracks	2		
Total number of trains/year	103000		
Average speed of trains for L_{den}	124 km/h		
Average speed of trains for L_{night}	111 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	75.2%	12.2%	12.5%
Percentage Diesel Passenger	28.8%	0.0%	0.0%
Percentage Electric Passenger	0.0%	0.0%	0.0%
Percentage Diesel Multiple Units	52.5%	53.3%	22.2%
Percentage Electric Multiple Units	0.0%	0.0%	0.0%
Percentage Diesel Freight	18.8%	46.7%	77.8%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	17.9%	18.3%	20.1%

Site 7

On the East Coast Mainline between Newark and Retford.

Number of tracks	2		
Total number of trains/year	79000		
Average speed of trains for L_{den}	87 km/h		
Average speed of trains for L_{night}	74 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	68.9%	11.4%	19.7%
Percentage Diesel Passenger	7.1%	0.0%	0.0%
Percentage Electric Passenger	57.1%	66.7%	33.3%
Percentage Diesel Multiple Units	14.3%	0.0%	0.0%
Percentage Electric Multiple Units	0.0%	0.0%	0.0%
Percentage Diesel Freight	21.4%	33.3%	66.7%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	23.3%	29.3%	41.8%

Site 8

On the East Coast Mainline between Newark and Retford. Although this site is on the same section of line as Site 7 the data were collected at a different time with more trains travelling at higher speeds.

Number of tracks	2		
Total number of trains/year	103000		
Average speed of trains for L_{den}	104 km/h		
Average speed of trains for L_{night}	84 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	67.2%	11.9%	20.9%
Percentage Diesel Passenger	13.3%	0.0%	0.0%
Percentage Electric Passenger	53.3%	57.1%	33.3%
Percentage Diesel Multiple Units	13.3%	0.0%	0.0%
Percentage Electric Multiple Units	0.0%	0.0%	0.0%
Percentage Diesel Freight	20.0%	42.9%	66.7%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	35.7%	48.4%	45.6%

Site 9

Between Gatwick Airport and London. The trains at this site are predominately multiple units and, at the time the data were collected, the Gatwick Express was operated by a locomotive hauling Mk 2 coaches.

Number of tracks	2		
Total number of trains/year	37000		
Average speed of trains for L_{den}	104 km/h		
Average speed of trains for L_{night}	84 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	79.5%	13.3%	7.2%
Percentage Diesel Passenger	0.0%	0.0%	0.0%

Percentage Electric Passenger	22.7%	36.4%	66.7%
Percentage Diesel Multiple Units	0.0%	0.0%	0.0%
Percentage Electric Multiple Units	77.3%	63.6%	33.3%
Percentage Diesel Freight	0.0%	0.0%	0.0%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	62.9%	75.0%	77.8%

Site 10

As Site 9 but with the Gatwick Express trains operated by modern emus with the result that all the trains are disc braked.

Number of tracks	2		
Total number of trains/year	37000		
Average speed of trains for L_{den}	104 km/h		
Average speed of trains for L_{night}	84 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	79.5%	13.3%	7.2%
Percentage Diesel Passenger	0.0%	0.0%	0.0%
Percentage Electric Passenger	0.0%	0.0%	0.0%
Percentage Diesel Multiple Units	0.0%	0.0%	0.0%
Percentage Electric Multiple Units	100.0%	100.0%	100.0%
Percentage Diesel Freight	0.0%	0.0%	0.0%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	0.0%	0.0%	0.0%

Site 11

North of St Pancras station on the Midland Main Line. This site includes the Thameslink services.

Number of tracks	4		
Total number of trains/year	172000		
Average speed of trains for L_{den}	101 km/h		
Average speed of trains for L_{night}	92 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	78.9%	12.9%	8.2%
Percentage Diesel Passenger	17.6%	0.0%	0.0%
Percentage Electric Passenger	0.0%	0.0%	0.0%
Percentage Diesel Multiple Units	7.8%	10.5%	20.0%
Percentage Electric Multiple Units	70.6%	78.9%	60.0%
Percentage Diesel Freight	3.9%	10.5%	20.0%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	13.4%	21.6%	41.8%

Site 12

On the West Coast Main Line between Tamworth and Stafford a short distance north of Tamworth station. Although this is on the same section of line as Site 1 changes to the timetable and a different speed profile means that the mixture of trains is different.

Number of tracks	2		
Total number of trains/year	85000		
Average speed of trains for L_{den}	124 km/h		
Average speed of trains for L_{night}	96 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	75.0%	12.9%	12.1%
Percentage Diesel Passenger	3.0%	0.0%	0.0%
Percentage Electric Passenger	75.8%	68.8%	42.9%
Percentage Diesel Multiple Units	9.1%	12.5%	0.0%
Percentage Electric Multiple Units	3.0%	0.0%	0.0%
Percentage Diesel Freight	6.1%	18.8%	57.1%
Percentage Electric Freight	3.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	24.0%	33.1%	37.3%

Site 13

As Site 4 but with additional trains that are projected to operate on this route.

Number of tracks	2		
Total number of trains/year	89000		
Average speed of trains for L_{den}	99 km/h		
Average speed of trains for L_{night}	101 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	77.5%	10.1%	12.4%
Percentage Diesel Passenger	0.0%	0.0%	0.0%
Percentage Electric Passenger	0.0%	0.0%	0.0%
Percentage Diesel Multiple Units	80.4%	66.7%	45.5%
Percentage Electric Multiple Units	0.0%	0.0%	0.0%
Percentage Diesel Freight	19.6%	33.3%	54.5%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	8.4%	0.0%	0.0%

Site 14

As Site 3 but with additional trains that are projected to operate on this route.

Number of tracks	2		
Total number of trains/year	56000		
Average speed of trains for L_{den}	88 km/h		
Average speed of trains for L_{night}	93 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	76.1%	10.8%	13.1%

Percentage Diesel Passenger	0.0%	0.0%	0.0%
Percentage Electric Passenger	0.0%	0.0%	0.0%
Percentage Diesel Multiple Units	81.8%	78.6%	64.7%
Percentage Electric Multiple Units	0.0%	0.0%	0.0%
Percentage Diesel Freight	18.2%	21.4%	35.3%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	17.1%	0.0%	0.0%

Site 15

As Site 14 but with alternative possible trains and speeds.

Number of tracks	2		
Total number of trains/year	41000		
Average speed of trains for L_{den}	114 km/h		
Average speed of trains for L_{night}	112 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	79.6%	13.0%	7.4%
Percentage Diesel Passenger	0.0%	0.0%	0.0%
Percentage Electric Passenger	23.0%	36.7%	64.7%
Percentage Diesel Multiple Units	0.0%	0.0%	0.0%
Percentage Electric Multiple Units	77.0%	63.3%	35.3%
Percentage Diesel Freight	0.0%	0.0%	0.0%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	64.9%	76.8%	77.8%

Site 16

As Site 3 but with all the vehicles having cast iron tread brakes.

Number of tracks	2		
Total number of trains/year	49000		
Average speed of trains for L_{den}	88 km/h		
Average speed of trains for L_{night}	94 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	76.6%	10.6%	12.8%
Percentage Diesel Passenger	0.0%	0.0%	0.0%
Percentage Electric Passenger	0.0%	0.0%	0.0%
Percentage Diesel Multiple Units	83.3%	80.0%	66.7%
Percentage Electric Multiple Units	0.0%	0.0%	0.0%
Percentage Diesel Freight	16.7%	20.0%	33.3%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	100.0%	100.0%	100.0%

Site 17

As Site 16 but with the additional trains that have started to operate along the route since the original data were collected.

Number of tracks	2		
Total number of trains/year	54000		
Average speed of trains for L_{den}	87 km/h		
Average speed of trains for L_{night}	88 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	76.2%	10.7%	13.1%
Percentage Diesel Passenger	0.0%	0.0%	0.0%
Percentage Electric Passenger	0.0%	0.0%	0.0%
Percentage Diesel Multiple Units	81.8%	78.6%	64.7%
Percentage Electric Multiple Units	0.0%	0.0%	0.0%
Percentage Diesel Freight	18.2%	21.4%	35.3%
Percentage Electric Freight	0.0%	0.0%	0.0%
Percentage of axles with cast iron tread brakes	100.0%	100.0%	100.0%

Site 18

Projected traffic on the West Coast Main Line following the future upgrade of the line. The site is typical for the section of line between Tring and Milton Keynes. The speed data for this prediction are taken from a detailed simulation of the performance of the trains along this section of track. The main difference between Site 18 and Site 2 is the replacement of many of the locomotive hauled passenger trains with high speed multiple units.

Number of tracks	4		
Total number of trains/year	142000		
Average speed of trains for L_{den}	150 km/h		
Average speed of trains for L_{night}	111 km/h		
	Day	**Evening**	**Night**
Percentage of trains in a period	78.8%	11.8%	9.4%
Percentage Diesel Passenger	4.0%	0.0%	0.0%
Percentage Electric Passenger	1.6%	0.0%	0.0%
Percentage Diesel Multiple Units	2.4%	1.9%	0.0%
Percentage Electric Multiple Units	72.2%	67.9%	40.9%
Percentage Diesel Freight	10.3%	7.5%	4.5%
Percentage Electric Freight	9.5%	22.6%	54.5%
Percentage of axles with cast iron tread brakes	20.1%	27.0%	32.8%

Appendix C
Analysis of Pass-by Noise

Trains often comprise a number of different types of vehicle. This can create a problem when trying to measure the amount of noise produced by a particular type of vehicle that can only run as part of a train. The problem becomes particularly difficult when the train has a mixture of wheels with cast iron tread brakes and disc brakes. An example of a time history for an HST is shown in Figure C-1.

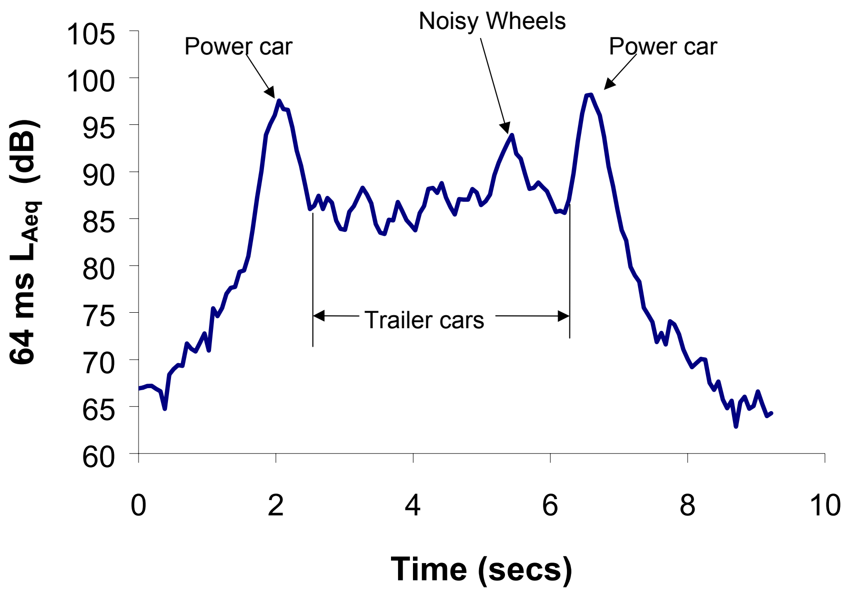


Figure C-1 A typical pass-by time history for an HST travelling at 155 km/h, measured 7.9 m from track centre line.

In this figure, the importance of the cast iron tread brakes on the power cars can be seen. Furthermore, the effect of some noisy wheels can also be seen. The reason these wheels are noisy is likely to be the result of tread damage.

In the early 1970s Peters developed a way of predicting the time-histories of passing trains (C1). This method treats each wheel as a simple dipole and by defining the sound power radiated by each wheel it is possible to predict the time-history. Clearly, using the same approach it should be possible to predict the sound powers of the sources given a measured time history. In practice, because the noise at any moment in time is a combination of the noise from all the wheels in the train, there are some limitations to this approach. The main limitation is that the combined length of the 'quiet' vehicles is less than 1.5 times the distance from the measurement point to the track. It can be seen that this is not a problem in Figure C-1 as the individual trailer cars are 23 metres long.

When a vehicle is noisier than the adjacent vehicles the situation is much simpler. This is because louder noises will dominate quieter noises when combined on the decibel scale and is illustrated in Figure C-1 by the peak caused by 'Noisy' wheels.

Assuming that all the wheels on the power cars are the same and, except for the 'noisy' wheels, all wheels on the trailer cars are the same, the average sound powers for the power car wheels, the trailer car wheels and the 'noisy' wheels can be calculated. Figure C-2 shows the predicted train time history using these calculated average sound powers.

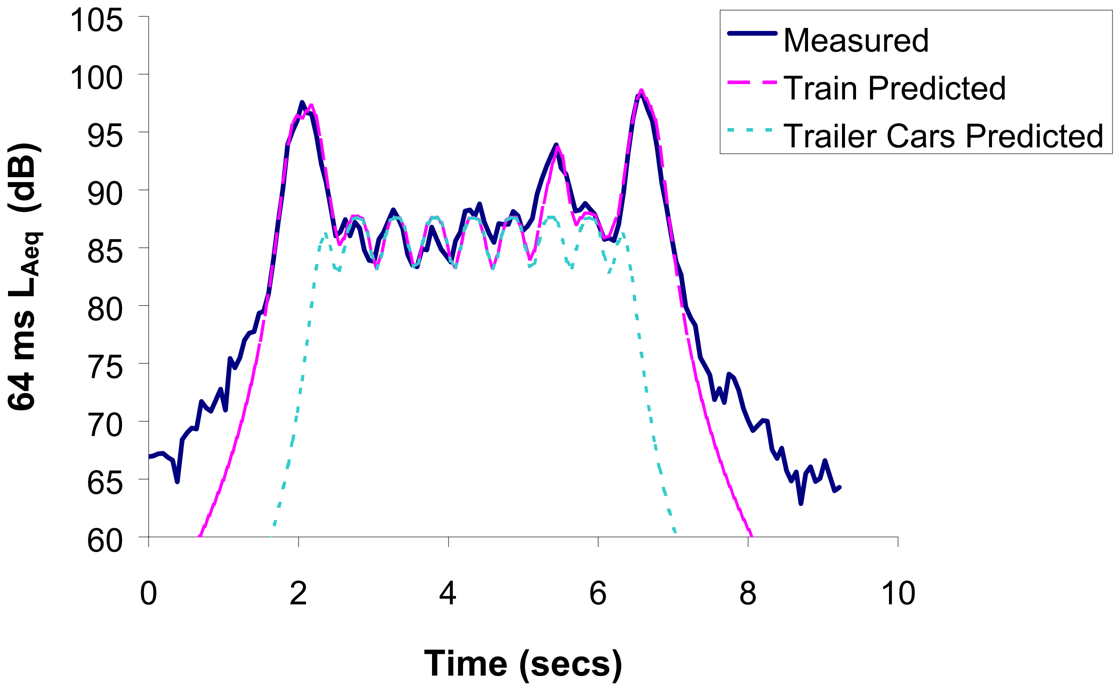


Figure C-2 The measured and predicted pass-by time histories for an HST

Figure C-2 also includes the time history for the trailer cars without the 'noisy' wheel. Using this time history for the trailer cars it is possible to calculate the pass-by L_{Aeq}, SEL, TEL and L_{Amax}.

This approach has the advantage that it produces a result that uses the maximum amount of available data and so improves the statistical reliability of the result.

Reference

C1 S Peters, 'The prediction of railway noise profiles'; Journal of Sound and Vibration, Volume 32, No. 1, pages 87-99, 1974

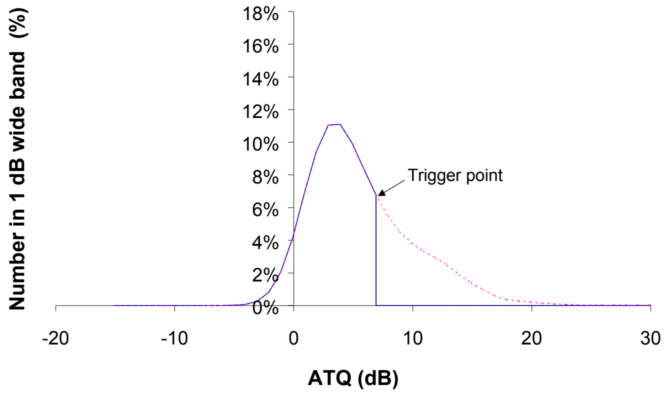
Appendix D
Rail Grinding Strategy

The changes in the distribution of the ATQ for the different rail grinding strategies were calculated for the two cases as follows:

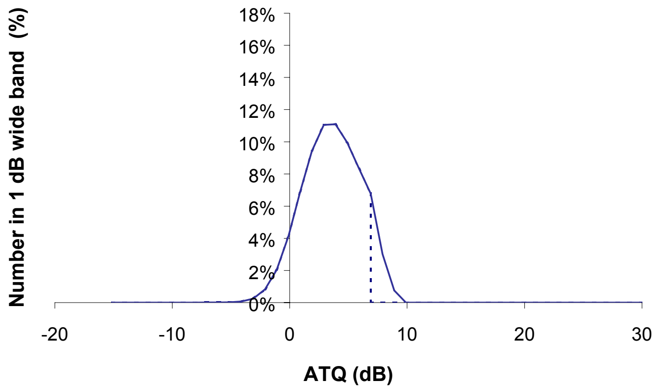
Case 1

For this case it was assumed that all the track that was ground would have a distribution of ATQs that was the same as occurred on all the other track.

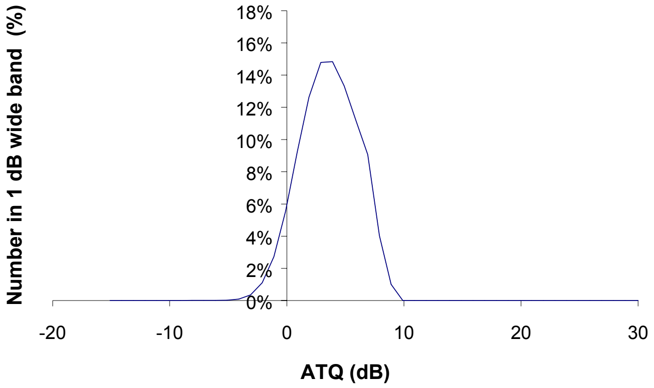
First, the distribution is truncated at the trigger point. The cumulative sum of the distribution is now less than 100%.



The sharp ending is smoothed and shifted to take into account the delay (eg “3dB” or “10dB” deterioration) between the decision to grind and the actual grinding. Although this increases the cumulative sum, it is still less than 100%.



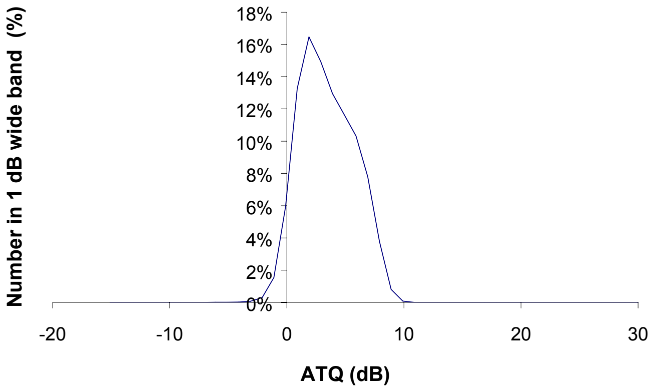
The remaining track that was in the truncated part of the distribution is distributed throughout the curve as if it had the same distribution. This returns the cumulative sum to 100%.



Case 2

For this case it was assumed that all the track that was ground would retain an ATQ in the range of -2 dB to + 2dB of ATQ= 0dB.

The first two stages of this process are the same as for Case 1. However, to return the cumulative sum of the distribution to 100% the values in each distribution between -2 dB and +2 dB are multiplied by a constant to return the cumulative sum to 100%.



What is noticeable about this distribution is that the peak is higher and it occurs at a lower ATQ than for Case 1.

Appendix E
Adjusted CRN Rolling Noise

The rolling noise source terms given in the ‘Calculation of Railway Noise 1995’ are for ‘good’ track (ATQ = 0 dB). The following figures give the source terms corrected for the Acoustic Track Quality for a range of vehicles.

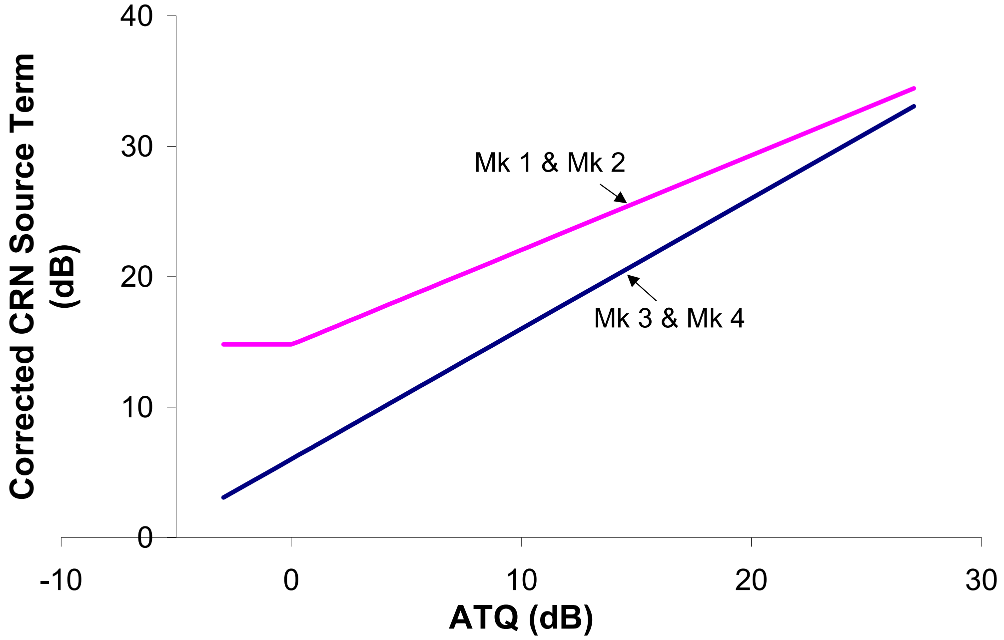


Figure E-1 ATQ-Corrected Source Terms for Passenger Coaches

The data for both curves in Figure E-1 have been derived from measurements. The equation for the Mk 3 and 4 data is:

$$CRN = ATQ + 6 \quad \text{(dB)}$$

For the Mk 1 and Mk2 data the equations are:

ATQ≤ 0 dB	$CRN = 14.8$	(dB)
ATQ> 0 dB	$CRN = 0.726 \times ATQ + 14.8$	(dB)

For vehicles with CRN corrections that fall between these values the Corrected CRN Source Terms have been derived from knowledge of braking arrangements and with reference to AEA Technology’s database.

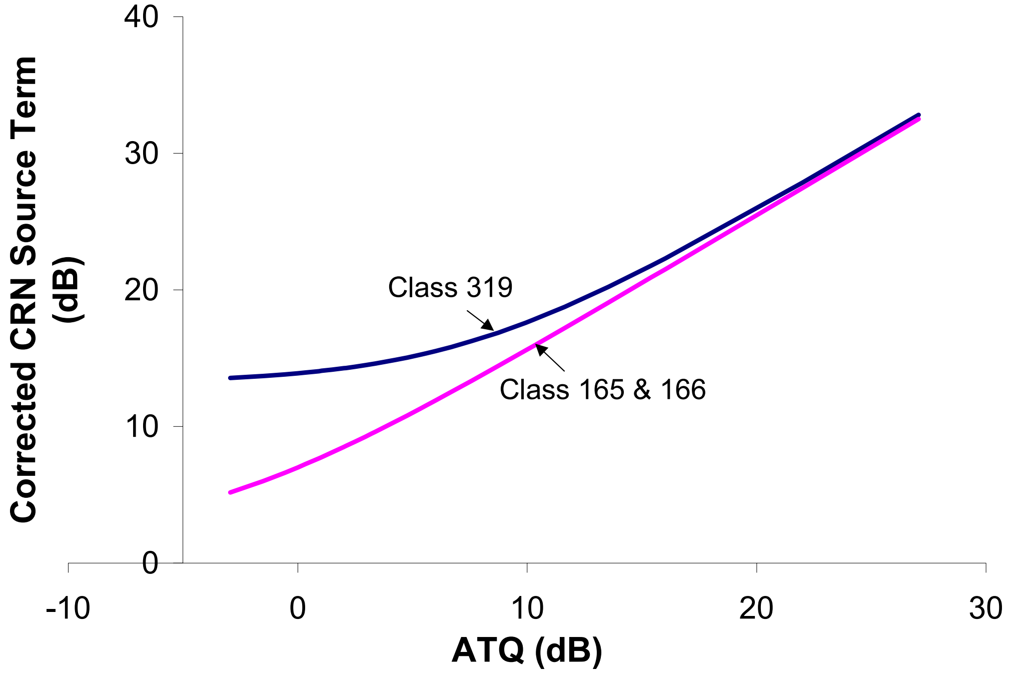


Figure E-2 ATQ-Corrected Source Terms - Multiple Unit Examples

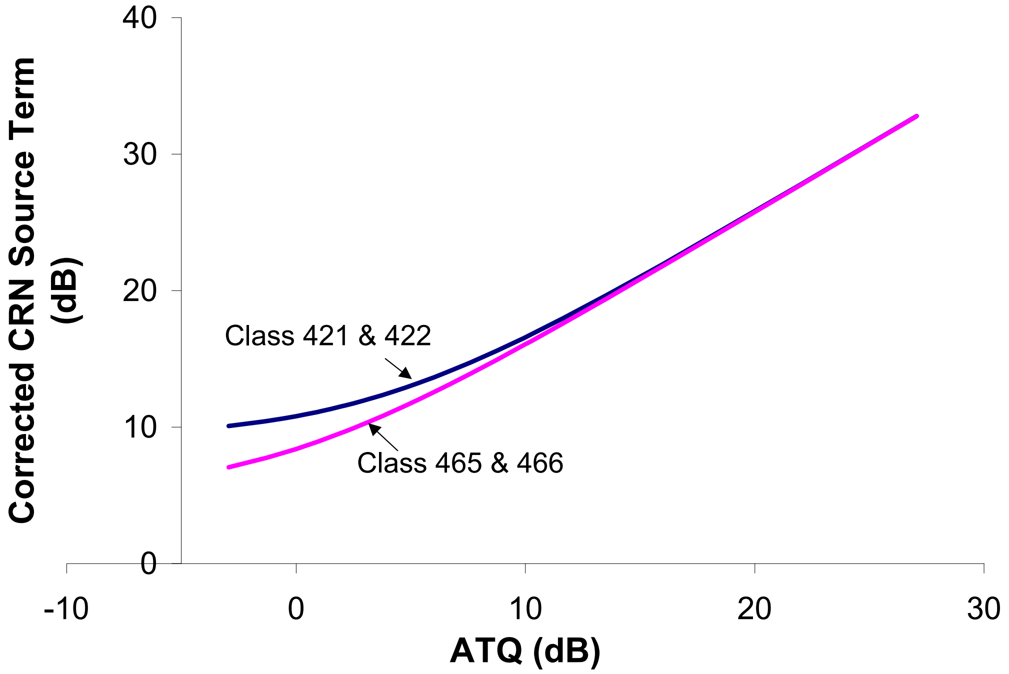


Figure E-3 ATQ-Corrected Source Terms - Electric Multiple Unit Examples

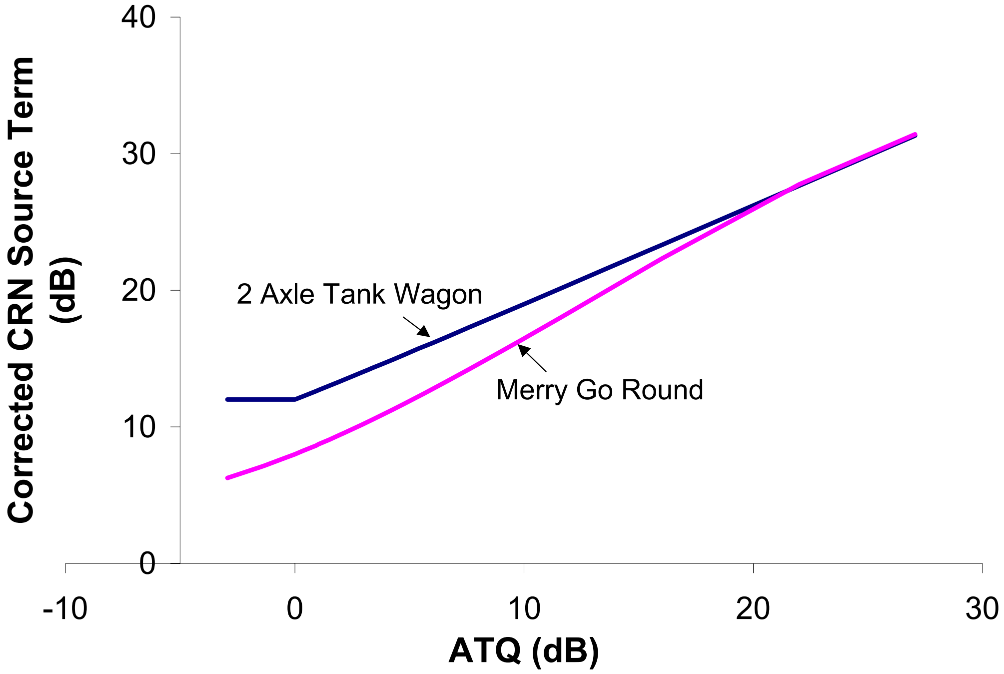


Figure E-4 ATQ-Corrected Source Terms – example Freight Vehicles with 2 axles

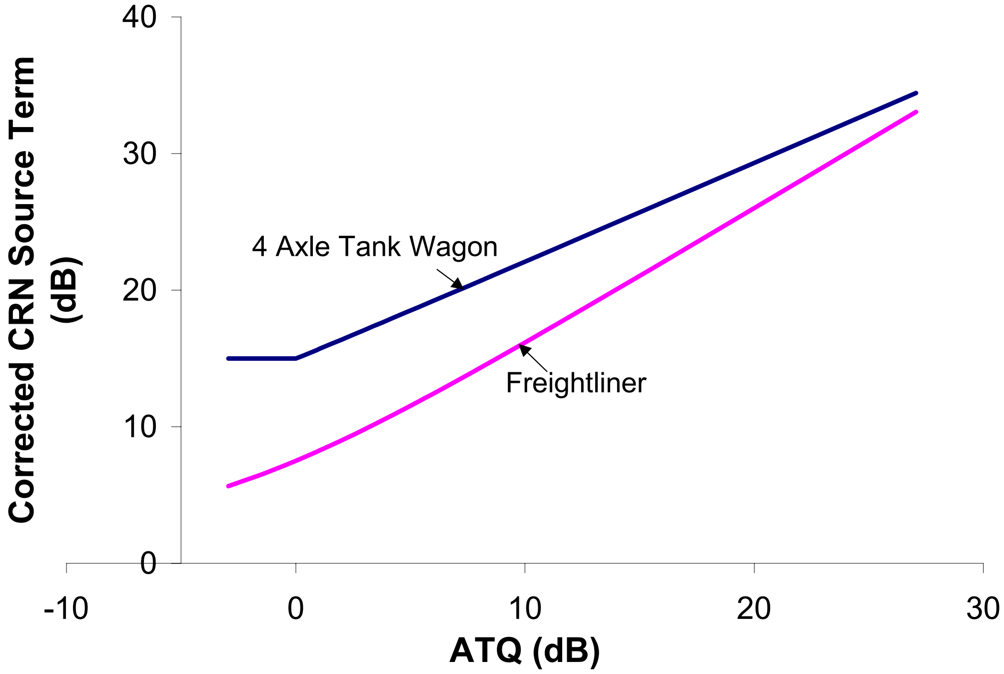


Figure E-5 ATQ-Corrected Source Terms – example Freight Vehicles with 4 axles

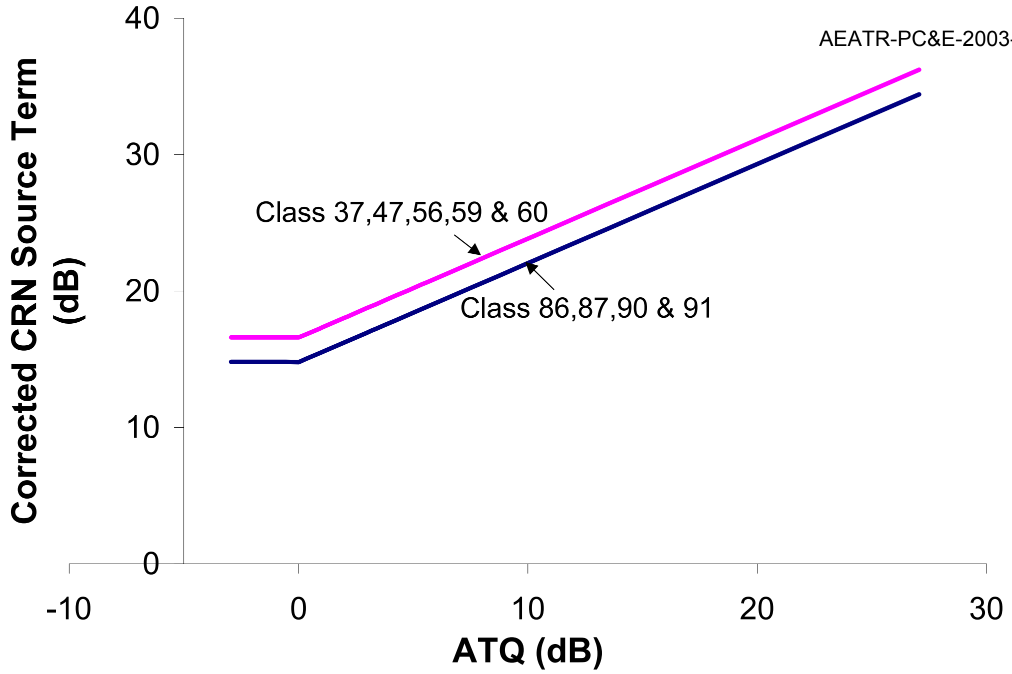


Figure E-6 ATQ-Corrected Source Terms - Locomotive Examples

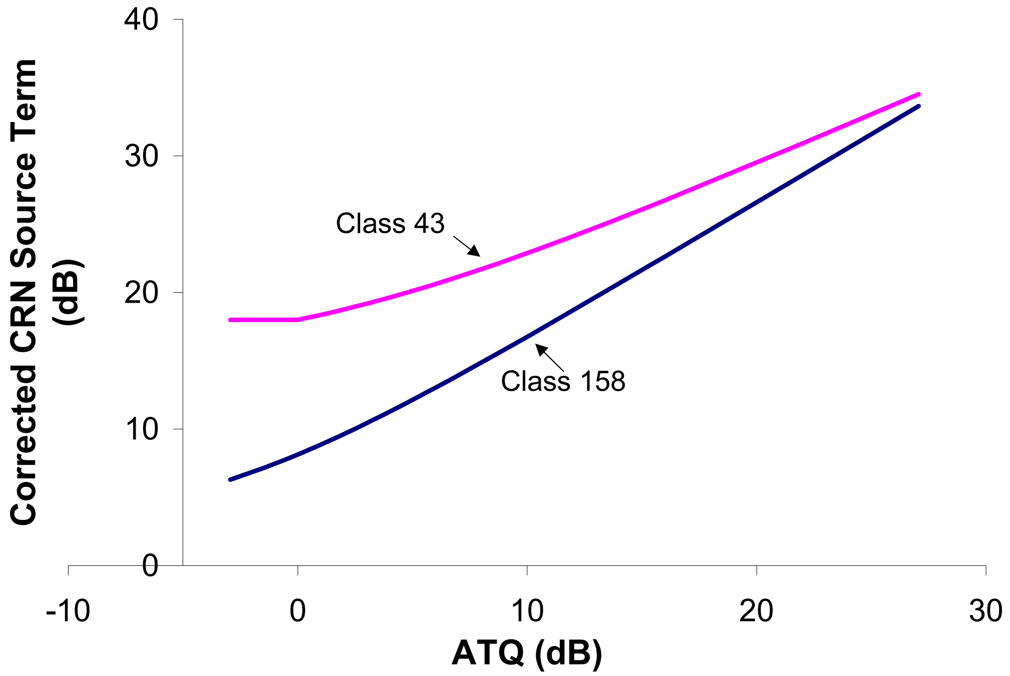


Figure E-7 ATQ-Corrected Source Terms for the Class 43 locomotive and Class 158 DMU

Supplement 1 of the Calculation of Railway Noise 1995 contains the rolling noise source terms for the complete Eurostar (Class 373) train. To enable these data to be compared with other data in CRN directly, Figure E-8 gives the source terms for Eurostar and a complete "IC225" train, ie a Class 91 locomotive hauling 9 Mk 4 coaches and a Driving Van Trailer (DVT).

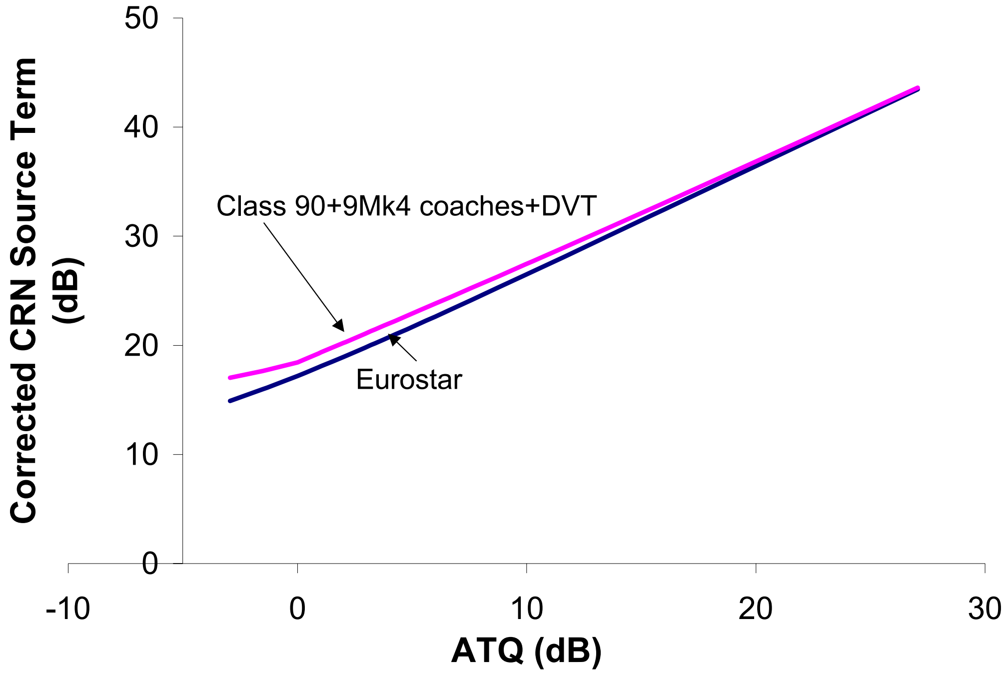


Figure E-8 ATQ-Corrected Source Terms for a complete Eurostar and a Class 91 locomotive hauling 9 Mk 4 coaches and a DVT