A.1 INTRODUCTION

One of the key elements in the calculation of environmental sound levels is the propagation of sound energy from a given source to a given receiver location.

The past few decades have seen a plethora of research papers and publications devoted to gaining a better understanding of the propagation of sound outdoors. These have varied from highly theoretical approaches to practical, measurement based approaches. Three recent publications, however, have brought together much of this research into a more easily referenced form. These are the texts by E.M. Salomons (2001), K. Attenborough, K. Ming Li and K. Horoshenkov (2006) and the various outcome reports of the EU funded Harmonoise/Imagine projects. Details of all the foregoing documents are listed in the Bibliography section of the main body of this document. The interested reader is strongly recommended to refer to these publications for a more in-depth discussion of the topics that are necessarily discussed only in summary form in the present appendix.

In many practical cases the situation under study requires the calculation of propagation from multiple sources to multiple receiver locations. However, the seeming additional complexity of such multiple path analyses reduces to the problem of analysing for each receiver location the contribution for each source separately, then summing the various source contributions. It is therefore generally valid to limit the present discussion to that of calculating the propagation from a single source to a single receiver. It is only in the final analysis that the consequences of summing multiple source contributions at a single receiver location need be considered.

Given the above, in order to understand the possible factors affecting sound propagation, it is helpful to consider the ‘simple’ case of the propagation of sound from a single point source having a fixed sound power output to a single point receiver location. Despite the apparent physical simplicity of this case, it nevertheless allows the investigation of all the key factors that may affect the propagation of outdoor sound. Adopting the same structured approach adopted by Salomons, it is possible to build up a model that steadily introduces an increasing number of complicating effects into the propagation model. The following images indicate schematically the manner in which these different factors are gradually brought into the discussion throughout the following sections of this appendix.

Figure A.1: Diagrammatic representations of the manner in which the factors affecting the propagation of sound outdoors have been isolated for individual consideration in the present document, and how these factors are gradually combined to build up a complete model of all the key factors required to be accounted for in order to make up a comprehensive sound propagation model.
Reading from left to right, the individual diagrams in Figure A.1 represent the effects on sound propagation of:

1. geometric attenuation and atmospheric absorption in an unbounded homogeneous atmosphere;
2. the additional effect of a bounding flat ground surface;
3. the additional effect of in-homogeneities in the atmosphere through wind and temperature variations that affect sound speed profiles;
4. the additional effect of further in-homogeneities in the atmosphere through turbulence;
5. the additional effect of a non-flat ground surface;
6. the effect of barriers.

Whilst it is useful to understand how each of these effects acting in isolation can modify the propagation of sound, it must always be remembered that in many instances the different effects can interact. Therefore, the cumulative effect under any given set of circumstances may not necessarily be the sum total of each effect considered in isolation. Good examples here include the potential reduction in the attenuation provided by an acoustic barrier when placed downwind of a source of sound, or the effect that an acoustic barrier can have on negating the effect the ground would otherwise have on the propagating sound.

Before looking at each of the situations illustrated in the foregoing diagrams, it is useful to consider what is sought from the exercise of modelling sound propagation. This approach, which involves considering the outcome goal of any exercise in order to better define the exercise from the outset, is fully in accordance with the generally recommended procedure set out in the present guide. In this respect, it must be appreciated that environmental sound fields are inherently variable, and part of this variability results from changes in the propagation paths from source to receiver. Such changes may occur over a wide range of timescales from seconds (due, for example, to local air turbulence or local wind and/or temperature effects) to seasons (due, for example, to changes in ground cover). The question must therefore be asked at the outset of any sound modelling exercise as to what quantity will best inform the desired outcome goal. For example, is the most informative quantity the instantaneous noise level expected under a specific set of conditions, or is it the worst case noise level expected under any foreseeable set of conditions, or is it possibly even the long term average noise level experienced over, say, a whole year? The other key determining factor when considering the appropriate choice of propagation model is the nature of the sound being considered. Is it important, for example, to assess the overall A-weighted noise level due to a source of noise that is broad band in character, or is it some tonal or much narrower band feature of the noise that is of interest. As will be seen from the information contained in this appendix, the accurate modelling of the latter can present significantly greater challenges than the modelling of the former.

**A.2 FACTORS AFFECTING OUTDOOR SOUND PROPAGATION**

The problem of representing in a simple, generalised form the propagation of sound from a source to some receptor location is usually approached by the use of a generic equation of the type shown in equation (1) below:

\[
L_p(r) = L_w + \sum A_i \tag{1}
\]

where:

- \( L_p(r) \) is the sound pressure level at a distance ‘r’ meters from the source;
- \( L_w \) is the sound power level of the source;
- \( A_i \) is a series of modifying factors that either attenuate or enhance the transmission of the sound energy as it propagates from source to receiver.
It is the aim of this appendix to consider what the relevant modifying factors are, and then to identify the physical processes by which each of these factors may affect the propagation of sound energy. Only by developing this level of understanding is it then possible to determine the key physical parameters that each of the modifying factors depends upon and whether or not each factor is dependent on the frequency of the sound.

A.2.1 Geometric attenuation and atmospheric absorption

The propagation of sound away from a simple point source radiating into an unbounded homogeneous atmosphere is subject to two attenuating effects. The first of these, often referred to as geometric attenuation, arises from the spreading of the radiated sound energy over a sphere of increasing area as the wave front propagates away from the source. As the total area of the spherical wave front increases in proportion to the square of the distance, \( r \), from the source, thus the sound intensity and resultant sound pressure level decrease at a rate inversely proportional to \( r^2 \). Equation 2 provides the relationship between the sound power level of the source, \( L_w \), and sound pressure level, \( L_p(r) \), at a distance of \( r \) meters from that source. The effect of this relationship in terms of the attenuation of sound pressure level with increasing distance is provided by equation (3). This equation shows that the sound pressure level, \( L_p \), decreases by a constant 6dB per doubling of distance away from the source. It should be noted that this attenuation arising from geometrical spreading is independent of the frequency of the propagating sound wave.

\[
L_p(r) = L_w + 10 \times \log \left[ \frac{1}{4 \times \pi \times r^2} \right] \quad \text{equation (2)}
\]

\[
L_p(r_2) = L_p(r_1) + 20 \times \log \left[ \frac{r_1}{r_2} \right] \quad \text{equation (3)}
\]

The second attenuating effect that occurs as sound propagates through a homogeneous atmosphere arises from atmospheric absorption. Sound waves comprise the regular and ordered oscillation of air molecules. The higher the frequency of the sound, the greater is the rate of oscillation of the molecules about their equilibrium position. However, this vibration of the air molecules results in a two distinct dissipative mechanisms by which energy can be lost from the propagating sound wave. These mechanisms comprise frictional losses (sometimes termed ‘classical attenuation’, these include losses through viscous action and through heat conduction) and ‘molecular relaxation’ (these involve the interaction of water vapour with the resonance of oxygen and nitrogen molecules). Both of these atmospheric absorption processes are complex but, using the equations of fluid dynamics and statistical mechanics respectively, the overall effects on the attenuation of sound pressure with distance are calculable. As such, standardised techniques have been developed by which the attenuation of sound due to atmospheric absorption effects can be calculated. The most commonly adopted standard for this purpose is ISO9613-1 (1993), which presents both equations for the foregoing calculations and also summary tables of typical atmospheric absorption attenuation rates with distance. What is important to realise here is that the governing equations relating the losses to the propagating waves are frequency dependent. This dependency largely arises from the increasing velocity gradients experienced by the oscillation of air molecules supporting the propagation of sound waves of increasing frequency. The controlling processes are also highly dependent on the temperature and humidity of the air, where again the magnitude of the influence of these parameters is frequency dependent.

Figure A.2 shows the calculated atmospheric attenuations in terms of dB per km for each octave band centre frequency from 63Hz to 4000Hz based on ‘reference’ conditions of an
ambient atmospheric pressure of 101.3 kPa, a temperature of 10 deg C and a relative humidity of 70%. This is representative of the conditions often assumed as being typical for the purpose of noise propagation calculations in the UK. The figure also shows the potential variations about this often assumed ‘reference’ condition based on a range of temperature from -5 to 20 deg C, a range of relative humidity from 10% to 100% and range of ambient atmospheric pressure from 90 to 110kPa. The frequency dependency of the effects is graphically illustrated from the results presented in Figure A.2. Clearly, if one is interested in the propagation of relatively narrow band noise of frequencies of 500Hz or more over even modest distances in environmental sound field terms, the selection of the precise atmospheric parameters relevant to the specific situation under consideration can have a very significant effect on the calculated received sound pressure level.

One of the natural consequences of the increased atmospheric attenuation of higher frequency sounds is that, the further away from a source radiating a relatively flat spectrum of wide band sound a receiver is located, the more the received sound spectrum becomes biased towards the lower frequencies. This effect is illustrated in Figure A.3 which shows the difference between the radiated A-weighted sound power level spectrum from a simple point source and the calculated sound pressure level spectrum at 1km from that source. The calculated sound pressure level has accounted for the effects of geometric attenuation and atmospheric absorption, the latter being based on the aforementioned ‘reference’ conditions. It is noteworthy that the greater attenuation of the higher frequency octave bands results in their contributions to the overall A-weighted sound pressure levels at 1km being insignificant. Thus in this case of a typical broad band source of sound, as may be encountered in many practical situations, the greatly increased sensitivity of the atmospheric attenuation at higher frequencies to specific conditions of temperature, humidity and pressure (as shown graphically in Figure A.2) becomes unimportant.

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**Figure A.2:** Ranges of atmospheric attenuation of sound pressure level in dB per kilometre calculated according to ISO9613-1(1993) for the octave band centre frequencies from 63Hz to 4000Hz. The reference condition is an ambient atmospheric pressure of 101.3 kPa, a temperature of 10 deg C and a relative humidity of 70%. Also shown is the potential range of attenuations based on a range of temperature from -5 to 20 deg C, a range of relative humidity from 10% to 100% and range of ambient atmospheric pressure from 90 to 110kPa.

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**Figure A.3:** Attenuating effects of geometric attenuation and atmospheric absorption on the propagation of a typical broad band source spectrum over a distance of 1km. The attenuation due to atmospheric absorption has been calculated according to ISO9613-1(1993) assuming an ambient atmospheric pressure of 101.3 kPa, a temperature of 10 deg C and a relative humidity of 70%.
A.2.2 The effect of a bounding ground plane

The introduction of a ground plane into the situation considered above adds the possibility not only for a sound to propagate directly from the source to the receiver, but additionally for a secondary propagation path resulting from a reflection off the ground plane. This secondary propagation path can result in the occurrence of interference effects at the receiver location between the direct and reflected waves. Depending on the relative amplitudes and phases of the direct and reflected waves this interference effect may be either constructive or destructive: in other words the interference may result in either enhancement or attenuation of the received sound pressure level. The reader is referred to the texts by Salomons and Attenborough for a more detailed discussion of this complex effect, thus restricting the present discussion to the general principles involved and the potential magnitude of effects on received sound pressure levels. Figure A.4 shows the geometry of the simple situation being considered, namely that of a spherical source radiating into a homogeneous atmosphere above a perfectly flat, homogeneous and locally reacting ground surface to a single receiver location which is also located above the same ground surface.

When considering the situation shown in Figure A.4, the first point to recognise is that both the direct and reflected paths are subject to the geometric and atmospheric attenuating effects considered in the preceding section. The only difference between the direct and reflected waves at the receiver location is that the reflected wave has travelled a slightly longer path and, in the process, has been reflected from a surface. The precise relationship between the direct and reflected waves at the receiver critically depends on the following three factors:

- the difference between the direct and reflected path lengths (which is a function of the source and receiver separation distance and the heights of the source and receiver above the ground);
- the wavelength of the sound being considered (which is inversely proportional to its frequency of the sound and proportional to the speed of sound in the atmosphere);
- the effect that the ground reflection has on the amplitude and phase of the reflected sound wave relative to the incident sound wave.

It is useful to consider the extremes of what may occur to gain a basic picture as to the possible effects that the presence of the ground may have on the resultant sound pressure field at the receiver. This will be done in the first instance by considering the specific case of a point source which emits a pure tone at a frequency of 680Hz into a homogeneous atmosphere in which the speed of sound is 340m/s. Thus the wavelength of the sound is 0.5m.

As the first extreme case, the ground is taken to be perfectly acoustically absorptive. In this case all the energy in the incident wave is absorbed by the ground and no reflected wave exists. Therefore there can be no interaction between the direct and reflected waves and
the resultant sound pressure level at the receiver is that which would exist if no ground were present.

At the other extreme the ground becomes perfectly acoustically reflective. In this case all the energy in the incident wave is reflected from the ground.\(^1\)

The consequence of the incident wave being perfectly reflected from the ground is that, at the receiver location, the resultant sound pressure is a combination of that arriving via the direct path and that arriving via the reflected path. The reflected sound pressure is reduced in amplitude relative to the direct pressure wave (by the ratio of the direct path length to the total reflected path length) and it also suffers a time delay (equal to the path length difference between the reflected and direct paths divided by the speed of sound in the atmosphere). It is the relationship between this path length difference and the wavelength of the sound in question that is of critical importance in determining how the direct and reflected waves combine.

For the case of the 680Hz pure tone being considered in the present example, the wavelength is 0.5m. Thus if the path length difference is 0.0m (which can only occur when the receiver lies in the ground plane itself), 0.5m or any other even integer multiple of the sound's half wavelength of 0.25m, then the pressure peaks or troughs of the direct and reflected waves will arrive simultaneously at the receiver location and the waves will interfere constructively. Ignoring any reduction in amplitude of the reflected pressure wave due to the difference in direct and reflected path lengths, for the case of the pure tone being considered this constructive interference will result in a pressure doubling, which equates to an increase in sound pressure level of 6dB. It is also worth noting here that the enhancement of incident sound pressure levels may, under some special circumstances, increase above 6dB. Where this occurs it is due to the presence of so-called ‘surface waves’ which are addressed separately at the end of this section.

In contrast to the above, if the path length difference is 0.25m (i.e. the half wavelength of the sound in question) or any even integer multiple of 0.25m then the arrival of a pressure peak of the direct wave will be matched with the arrival of a pressure trough of the reflected wave, and vice versa. Again ignoring any differences between the amplitudes of the direct and reflected waves, the two waves will destructively interfere. This destructive interference will theoretically result in zero sound pressure, which equates to an infinite reduction in sound pressure level. It should be noted, however, that even in this highly idealised example the difference in amplitudes between the direct and reflected waves, no matter how small, would not allow this perfect cancellation to occur and the reduction in sound pressure level would be limited to a finite level of typically around 30dB to 40dB.

For any situation where the path length difference is not an integer multiple of the half wavelength (an even integer multiple for complete constructive interference, and an odd integer multiple for complete destructive interference) then, depending on the actual path length difference involved compared with the wavelength of the sound of interest, some intermediate degree of partial constructive or destructive interference will occur and the increase or reduction in received sound pressure level will lie somewhere between the extremes just discussed. Note that the important parameter here is the difference between the path length difference and the half wavelength distance of the sound being considered. Thus the theoretical maximum ground effect attenuations may be diminished either because the wavelength of the sound in question doesn’t exactly match in with the path length difference for the particular source/receiver geometry in question, or because the source/receiver geometry of the situation doesn’t match in with the wavelength of the sound of interest.

Figure A.4 illustrates the foregoing effect by showing the calculated ground effect attenuation for propagation over an acoustically perfectly reflective ground across the frequency range from 63Hz to 4000Hz. The figure shows the results for the case of a

\(^1\) note that whilst, for ease of visualisation, the situation is represented here by a single ray path, in reality a point source creates a spherical wave front and therefore the reflection must, for all practical purposes, be determined from equations describing the reflections of a spherical-wave from a surface layer.
source and receiver separated by a distance of 32m, with both being positioned at 2m height above the ground plane. It may be observed that the first attenuation dip occurs at the frequency of 680Hz with a theoretical ground effect of around 40dB attenuation. Thus this geometrical set-up corresponds to the example presented above. What is of interest here is the reduction in attenuation as the frequency of the sound moves away from the 680Hz at which optimal destructive interference occurs. An inspection of Figure A.4 on this basis reveals that the dominant ground effect dip centred around 680Hz is approximately one octave band wide, with a theoretical maximum reduction at 680Hz of around 40dB. It is important to note, however, that this very large attenuation relates to a narrow band analysis, such as may be undertaken if the sound of interest is dominated by a pure tone. Based on a third octave band analysis the maximum reduction of the sound pressure level in any one third octave band is less than 15dB. These quoted ground effect attenuations compare to ground effect enhancement effects of up to 6dB at frequencies between those at which destructive interference occurs.

Figure A.4: Calculated attenuating effects of an acoustically perfectly reflecting ground plane as a function of frequency from 63Hz to 4000Hz for the following conditions: source and receiver height both 2m, source to receiver separation distance 32m, ground plane perfectly acoustically reflecting. Results are shown both for discrete, narrow band frequencies and also for third octave band frequencies.

It remains to place into context the physical situations whereby path length differences large enough to allow significant attenuation of received sound levels may occur. Table A.1 presents a list of path length differences for a number of different source/receiver heights and source/receiver separation distances along with the corresponding sound frequencies whose half wavelength matches the calculated path length differences. All calculations have been based on a sound speed of 340ms⁻¹.

The results of Table A.1 indicate that the typical range of frequencies at which destructive interference may occur are, as expected, very dependent on the exact source/receiver configuration. The stated conditions range from below 100Hz for a source and receiver height of 10m and a separation distance of 100m (i.e. a relatively large propagation path length difference of almost 2m) to above 2000Hz for a source and receiver height of 2m and the same separation distance of 100m (i.e. relatively small propagation path length difference of 0.08m).

The preceding examples have shown the theoretical extremes of what may occur due to the presence of a perfectly reflecting ground compared to the situation that exists in an unbounded atmosphere: namely a potential increase in received sound pressure level of up to 6dB and a potential decrease in sound pressure level of a much greater magnitude for perfectly reflective ground and zero change for perfectly absorbing ground. The examples have also provided a basis for understanding the basic physical mechanism behind the ‘ground effect’; namely that it arises from interference effects between direct and ground reflected waves. The question that must now be addressed is what actually happens between these extremes in practical situations.
### Table A.1: Sample path length differences between direct and reflected waves for various source/receiver height and source/receiver separation distances. The last column also shows the frequency of the sound having the same half wavelength of the path length difference of each source/receiver configuration based on reflection from an acoustically perfectly reflective surface.

<table>
<thead>
<tr>
<th>Source and receiver height, m</th>
<th>Distance between source and receiver, m</th>
<th>Difference between direct and reflected path lengths, m</th>
<th>Frequency of sound with half wavelength equal to the path length difference, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10</td>
<td>0.770</td>
<td>221</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>0.396</td>
<td>429</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>0.265</td>
<td>640</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>0.200</td>
<td>852</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>0.160</td>
<td>1064</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>0.080</td>
<td>2126</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>0.499</td>
<td>341</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>0.250</td>
<td>680</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>0.100</td>
<td>1700</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>1.980</td>
<td>86</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
<td>0.998</td>
<td>170</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
<td>0.400</td>
<td>425</td>
</tr>
</tbody>
</table>

It is true to say that, for virtually all practically encountered ground surfaces, their acoustic properties lie somewhere between the two extremes of being a perfect absorber or a perfect reflector of sound. What this means in practice is that, when an incident sound wave strikes the ground it is able to penetrate the porous surface. In penetrating this porous surface, and in overcoming the frictional energy losses in so doing, a proportion of the sound wave’s energy is converted into heat energy. Thus the amplitude of the reflected wave is reduced relative to amplitude of the incident wave by an amount that is determined by the energy transferred through frictional losses. Furthermore, the reflected sound wave can also experience a time delay, i.e. a phase shift, relative to that which would be expected from a perfectly hard reflective surface. This phase shift is due to the time taken between the sound wave entering and exiting the porous surface. In short, the governing factor is the ‘ease’ with which the sound wave can enter and leave the porous surface, and this is defined by the so called ‘flow resistivity’ of the surface. Flow resistivity represents the ratio of the applied pressure gradient to the induced volume flow rate per unit thickness of material. Surfaces having a high flow resistivity do not easily admit sound waves (e.g. water and concrete, which have a low surface porosity) whilst surfaces having a low flow resistivity more easily admit the incident sound wave (e.g. freshly fallen snow, which has a high surface porosity) [Att].

The manner in which the acoustical properties of the ground may affect received sound levels when considering environmental sound fields has received considerable attention over the past few decades. This is not only from a theoretical point of view but also through experimental validation of the models that have been developed, some of which involve many parameters to describe the acoustic properties of the ground. It is important to realise that not only may the ground’s acoustic properties change as a function of frequency, but they may also vary as a function of angle of incidence of the sound. Furthermore, some investigations not only consider the local acoustical characteristics of the ground surface itself, but also whether or not the ground may exhibit an ‘extended’ reaction to an incident sound wave, i.e. whether a sound wave incident at one particular location can have an

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2 One particular exception to this is water which can act as a nearly perfect reflector of airborne sound. For this reason the calculation of sound propagation over water using models that have been derived empirically based on measurements made over land can lead to significant errors.
effect at another location due to the extended response of sound wave/surface interaction. These and other developments in the understanding of ground effects are covered in considerable detail in the recent publication by Attenborough, 2006, who has been one of the key researchers in this area. The interested reader is therefore strongly urged to refer to that publication for a more detailed discussion of this very detailed subject, which is necessarily only dealt with on a summary basis in this appendix. This is in line with the intent of the document which is to make the reader aware of the factors that may modify the propagation of sound outdoors and to give some indication as to the typical magnitudes of changes in received sound pressure levels that may result from these factors.

It needs, therefore, to now be considered how the foregoing factors associated with practically encountered ground surfaces may affect the situations considered earlier, where the principles of the ground effect were discussed by reference to the extreme example of an acoustically perfectly reflecting ground surface.

The results listed in the foregoing Table A.1 confirm the expected trend that the greater the path length difference between the direct and reflected propagation paths, the lower the minimum frequency at which destructive interference may occur. It is important to note here that an increase in propagation path length difference equates to an increase in the time delay between the arrival of the direct and reflected paths. One of the points already made about porous ground surfaces is that they introduce an additional time delay in the reflected propagation path due to the phase lag between the incident wave entering the porous surface of the ground and the reflected wave leaving the porous surface layer. This additional delay therefore makes the effective path length difference between the direct and reflected paths even greater than would be the case for the same geometrical configuration of source and receiver over a perfectly reflecting ground surface. For this reason it may reasonably be expected that the minimum frequency at which destructive interference occurs will be reduced for propagation over a porous ground compared to that predicted over a perfectly reflecting ground for the same source/receiver configuration. This reduction in frequency will be directly related to the effective increase in path length difference between the direct and reflected paths, taking into account the additional time delay introduced at the surface of the porous ground itself. This additional delay is related to the acoustic impedance of the ground surface relative to the acoustic impedance of the air, and in particular to the flow resistivity of the ground.

Several models have been developed for the derivation of ground surface acoustic impedance characteristics. Again it is not proposed to go into any detail on these models in this appendix. Instead the interested reader is directed to the recent text by Attenborough, 2006, for more detailed information on this matter. However, for reference purposes, Figure A.5 shows the calculated ground effect attenuations for the same physical configuration of source and receiver as detailed in Figure A.4, but now with a non-acoustically 'hard' ground surface having a flow resistivity corresponding to that of typical grassland, or 200kPa.s.m⁻².

The results of Figure A.5 confirm that the additional time delay between direct and reflected waves introduced by the porous surface results in an increase in the effective path length differences between the direct and reflected waves and thus a decrease in the frequency of the main ground effect dips. However, not only have the frequencies of these dips been lowered, but their maximum depths have also been reduced. This is due to the fact that the reflected wave is of significantly lower amplitude when compared to the direct wave as a result of losses incurred on reflection from the ground surface. Thus the destructive interference between the direct and reflected waves is much less complete than for the case where the reflected wave was reflected from an acoustically perfectly reflective surface, even for the case when the phase match between the two waves is perfect. Conversely, the potentially significant enhancements in received sound levels due to the ground effect shown for the acoustically perfectly reflective surface are also reduced greatly in magnitude, to the point where this enhancement effect is only now a potentially significant factor at frequencies below the first ground attenuation dip.
Figure A.5: Calculated attenuating effects of an acoustically partially absorbing ground plane as a function of frequency from 63Hz to 4000Hz for the following conditions: source and receiver height both 2m, source to receiver separation distance 32m, ground plane flow resistivity 200 kPa.s.m⁻². Results are shown both for discrete, narrow band frequencies and also for third octave band frequencies. The results obtained from Figure A.4 based on an acoustically perfectly reflecting ground surface are also shown as the thinner lines for comparison.

One final effect of spherical propagation of sound over a porous ground surface is the possible existence of a 'surface wave' in addition to the direct and reflected waves thus far considered. This facet of sound propagation is dealt with in some detail by Attenborough, 2006, who concludes that the surface wave can only propagate effectively if the ground possesses certain special impedance characteristics.

Physically, the surface wave comprises the motion of air particles in an elliptical pattern close to the surface region. The wave is separate from the main body of the propagating sound wave and moves at a different (slower) speed than it. It can only exist if the acoustic impedance characteristics of the ground surface are such that its reactance is considerably larger than its resistance. This condition means that the induced sound field will suffer relatively little dissipative energy loss as a result of its interaction with the surface. The satisfaction of this condition relies on a combination of the ground surface’s material properties, and the frequency and angle of incidence of the sound. It is the presence of this special impedance condition that allows the elliptical particle motion to be supported, owing to the combination of particle motion parallel to the surface with particle motion in and out of the surface pores in a direction that is normal to the surface. Given the requirements for this interaction condition to exist to support the surface wave, it is self-evident that it will only exist close to the surface. The term ‘close’ here is defined relative to the wavelength of the sound being considered.

As pointed out by Attenborough, 2006, the resistive component of most practically encountered ground surfaces is such that any surface waves decay rapidly as they propagate along the surface. However, for certain special conditions surface waves have been positively identified and measured in practical outdoor experiments. One example of this was in the experiments reported by Albert, 1992, which involved the use of a pistol shot as the source to investigate the propagation of impulses over newly fallen snow on frozen ground. This particular scenario, of a thin porous surface layer over an effectively hard backing, is precisely that which is required to support particle motion in and out of the pores normal to the surface whilst also offering the low resistive losses required to allow the surface wave to propagate over larger distances with a low rate of attenuation. Due to the slower propagation of the surface wave relative to the direct and reflected propagation paths, Albert was able to positively identify sound energy arriving at the receiver location via the surface wave separately from the energy arriving via the direct and reflected paths.

The consequence of the above is that the surface wave is a real effect and its presence can, under certain special circumstances and at low frequencies, result in an enhancement of sound pressure level measured close to the ground surface. This means that the theoretical maximum limit of +6dB enhancement of sound pressure level above a ground surface resulting from the constructive interference of direct and reflected waves alone may, under these special set of circumstances, be exceeded.
A.2.3 The effects of wind and temperature on sound speed

The discussions of sections A2.1 and A2.2 have accounted for the attenuating effects of the atmosphere in terms of atmospheric absorption, but they have somewhat simplistically assumed that the atmosphere is acoustically homogeneous. In virtually all practically encountered situations this isn't the case. The wind, for instance, is slowed down by friction as it passes over the ground surface thereby resulting in lower wind speeds at lower heights above ground level. Also, convection within the atmosphere and the radiative heating/cooling effects of the mass of the ground often result in quite different air temperatures close to the earth’s surface than at heights even a few meters or tens of meters above the surface. It is therefore true to say that, during most weather conditions, both the temperature and wind vary with height above the ground.

As both wind and temperature affect the speed of sound in air, these variations result in an acoustically non-homogenous atmosphere with sound speeds either decreasing or increasing with height above the earth's surface. Also, not only is the atmosphere non-homogeneous with regards height, but the presence of a wind direction also affects the directional propagation of sound. This section discusses these in-homogeneities and their effects on the propagation of sound.

In the presence of a vertical gradient of sound speed, sound waves are refracted in the direction from higher sound speeds to lower sound speeds. Depending on the particular circumstances, there are two possible curving trends, downwards or upwards.

**Downward refraction**

The downward propagation of acoustical paths usually occurs under a temperature inversion (stable atmospheric conditions) or under a downwind propagation. The resulting propagation of sound under these two atmospheric phenomena is essentially very similar, but could differ if the shapes of the wind and temperature vertical profiles are different. Any sound speed function which increases with increasing height will generate a downward sound propagation, as shown by Figure A.6.

However, depending on the relationship between sound speed and height (i.e. linear, logarithmic, etc. ...), the downward propagation will have specific properties. A linear sound speed variation with height will make sound rays travel from source to receiver along circular arcs with centres of curvature lying on a horizontal line at a distance $1/\gamma_T$ from the surface ($\gamma_T$ being the rate of increase in sound speed with height). In contrast to the linear case, logarithmic sound speed profiles do not generate a homogeneous sound path throughout the atmospheric boundary layer. Sound rays are almost circular arcs at high altitudes, where the logarithmic sound speed function is nearly linear, but at heights close to the ground it becomes much more difficult to assign an analytic description of their
behaviour as the logarithmic dependency demonstrates a less linear behaviour. Other, less common, profiles may also be considered such as power or exponential relations.

The main effect of downward sound propagation is the possible generation of multiple reflected rays from source to receiver. Whilst it is not the purpose of the present sections to establish preferred modelling techniques for representing the features being discussed, it is nevertheless useful to use one of the techniques, ray tracing, to demonstrate what the typical magnitude of effects on received sound levels may be as a result of the downward refraction of sound waves as they propagate through a non-homogeneous atmosphere.

Using ray tracing it is possible to evaluate the trajectory through the atmosphere of the sound waves as they propagate from source to receiver. It is also possible to account for the effects of reflection of these waves from the ground of known, finite impedance. Finally, it is possible to evaluate the cumulative sound intensity of waves at the receiver. The method works for the case considered here of a linear sound speed profile with positive slope (downwind conditions or temperature inversion). Under these conditions, the ray paths are circular concave arcs with centres of curvature lying all on a horizontal line at a distance $1/\gamma$ below the surface. Making use of this geometrical property it is possible to establish all possible ray paths from source to receiver. For the general case of finite height for source and receiver, $h_s$ and $h_r$, there are a total of four reflected ray paths for each number of reflections per ray, $n$, greater than one. Figure A.7 shows the case of $n = 1$, where the ray group consists of 3 ray paths instead of 4. Figure A.8 shows a set of ray paths for $n = 2$, where now the four rays per group are evident.

![Figure A.7: The grouping of individual rays according to ray theory. In particular, 3 ray paths form the group of rays that reaches the receiver when only one reflection from the ground (n=1) occurs. With n≥2 each group is formed by 4 rays instead of 3.](image)

More detailed analysis of the problem indicates that if the height reached by a predicted ray, $H$, is smaller than the minimum height of either the source or receiver, then the ray cannot exist. As the zenith height of rays is a function of $n$, this fundamental requirement therefore defines an upper limit to the number of possible reflections that may exist under any given set of conditions. The relevant controlling parameters are the source and receiver heights and their separation distance, together with the vertical sound speed gradient.

![Figure A.8: The grouping of individual rays according to ray theory. In particular these 4 ray paths form the group that reaches the maximum height at zenith.](image)
Once the number of possible ray paths and reflections are known, it is possible to calculate the intensity and excess of sound pressure level over neutral conditions at the receiver through the summation of the contributions of each ray. This approach was first developed by Embleton. For the case of a reflecting hard ground surface and an infinite sound ray path situation \(h_s=h_r=0\) it can be determined that the maximum correction to be added in an inversion/downwind situation over a neutral one is approximately +2.2 dB. A lower increase than 2.2 dB is obtained with soft ground by assuming a reflection coefficient less than unity for the intermediate reflections at the ground surface.

There are clearly limitations to the foregoing conclusions, such as the simplifying assumption of a linear sound speed profile and the assumption that this same profile exists along the whole propagation path from source to receiver. However, the analysis places into context the typical upper range of the increase in overall sound pressure level that may be expected to occur as a result of propagation under downwind or temperature inversion conditions when compared to propagation between the same source and receiver under neutral conditions.

It is frequently observed that downwind propagation increases received sound levels significantly, whereas the foregoing analysis would suggest otherwise. In addition, dedicated measurements have repeatedly confirmed that the effect of downwind propagation results in only a marginal increase in overall noise levels of typically less than 3 dB when compared to propagation under acoustically neutral conditions. The question must therefore be raised as to the cause of this apparent discrepancy between observed and measured/predicted scenarios. The details contained in the following section will show that received noise levels under upwind propagation conditions can be 15 dB or more lower than the received noise levels under neutral conditions. It is thus highly probable that, when claims of very significant increases in received noise levels under downwind conditions are made, the comparison is actually being made with the greatly reduced received noise levels under upwind conditions rather than those experienced under neutral propagation conditions.

One point that should be appreciated when considering the foregoing conclusions is that they relate only to broadband overall noise levels. For pure tones or much narrower bandwidth noise the underlying principles of constructive and destructive interference are just the same as already discussed in some detail in section A2.1 in relation to interference between direct and ground reflected waves. Therefore, whilst the increase in the number of sound ray paths between source and receiver generally results in the moderate amplification of the received overall noise levels, the varying lengths of the reflected rays and their several interactions with the ground can also cause more significant constructive and destructive interference effects at some frequencies.

**Upward refraction**

When the sound speed decreases with height, the sound rays are bent upwards away from the ground, as depicted by Figure A.9. For typical sound speed profiles there is a limiting ray leaving the source which grazes the ground. Above this limiting ray the sound field is composed of direct and ground-reflected waves, whereas below the limiting ray there is an acoustical shadow in which sound waves do not exist, at least in theory, as shown in Figure A.10. In practice, however, some sound energy does penetrate these shadow zones.
A number of different studies have considered in greater detail the process of sound penetration into shadow areas. Salomons, 2001, considers that sound waves are mainly scattered into shadow regions by the refraction of sound waves caused by small random changes of the propagation direction as a result of local air turbulence, whilst a diffractive penetration mechanism also causes some transfer of sound energy into the zones. This diffractive mechanism is described as being analogous to the diffraction of sound waves at the top of an acoustic barrier, beyond which a shadow zone where no sound energy penetrates should theoretically exist, at least based on simple ray theory, whereas practical attenuations are limited to no more than around 15dB to 20dB.

It is difficult to accurately quantify the potential magnitude of the various effects referred to above from measurements. This is due to the difficulties associated with separating out the different effects and also in quantifying the controlling parameter (sound speed) along the entire sound propagation path.

An alternative approach is to model the effects theoretically. In practice it is known that any measurement of environmental sound over time will yield a spread of sound levels distributed in some manner about a central tendency. To be useful in establishing sensitivity to meteorological parameters, any theoretical model must be capable of adequately deriving both this central tendency and the scatter of sound levels about this central value. Using such a model enables a parametric sensitivity analysis to be performed to quantify the effects of changes in each meteorological parameter on received sound levels. Measurements of the statistical distributions of controlling meteorological parameters can then be input to the model to estimate the potential variability in received sound levels under practically encountered conditions.

In conclusion to this section, refraction in the atmosphere caused by vertical sound speed gradients (be these caused by vertical wind speed or temperature gradients, or some combination of the two) may result in increases in overall sound pressure levels of typically +2dB for the case of positive vertical sound speed gradients when compared with acoustically neutral propagation conditions, but decreases in overall sound pressure levels of 10dB to 15dB or more in the case of negative vertical sound speed gradients.

A.2.4 The effects of turbulence

Whilst the discussion of section A2.3 has accounted for the effects of sound speed gradients, it has assumed that these gradients are constant, both in time and space. In reality air turbulence introduces perturbations in local sound speed, and therefore the assumed sound speed profiles may only be considered as spatial averages over typical periods of 10 minutes or more. Turbulence arises from atmospheric instability of which there are two responsible types: shear and buoyancy [Attenborough, 2006]. Shear instabilities arise primarily from the disturbance of
the air by the wind and are therefore prevalent in higher wind conditions. Buoyancy effects arise due to the presence of larger temperature differences between the ground and the air such that convective air circulation occurs. Thus convective turbulence tends to be most prevalent when the ground is much warmer than the air immediately above it such as on a hot sunny day.

The effect of turbulence on the propagation of sound is that, as a wave front passes through a turbulent region, it sees a local change in the sound speed. As already discussed in the previous section, any change of sound speed will result in local refraction, i.e. a local change in direction, of the wave. By its very nature, however, turbulent effects are quite random. Therefore, unlike the systematic upwards or downwards refraction discussed in Section A2.3 that occurs under conditions of a steady change in temperature with height, turbulence induces random small scale changes in direction of the propagating wave. This effect is generally termed 'wave scattering' as it scatters the wave energy about its mean direction propagation.

The extent to which any wave is scattered by turbulence depends very much on the relationship between the wavelength of the wave and the length scale of the turbulence, taken together with the turbulence intensity. As a guide, the typical length scales involved range from around 20m for frequencies of 100Hz to 0.2m for frequencies of 10kHz.

One of the features of turbulent scattering is that it is a two way process: just as energy is scattered out of the direction of propagation, so too is energy scattered back. Thus one of the effects of turbulence is that it results in short term fluctuations about the mean received sound pressure level. It is sometimes assumed that the further away the receptor point is from the source, the greater the amplitude of these short term fluctuations will become. However, the full effects of turbulent scattering of sound energy are realised relatively close to the source and then do not increase above this with distance.

![Figure A.11](image)

Figure A.11: Short term variations in sound levels due to the effects of turbulent scattering plotted as a function of distance from a pure tone sound source. Both measured and predicted results are shown for frequencies of 63Hz, 250Hz and 1000Hz [Alberola, 2005]

Figure A.11 demonstrates this feature by showing the a comparison of measured and calculated variations in received sound pressure level as a function of distance up to around 1km away from the source. Results for three discrete frequencies are shown, 63Hz, 250Hz and 1000Hz. The results of both the measurements and the predictions (based on a Parabolic Equation model incorporating the effects of turbulence) show two significant features. First, once the effects of turbulent scattering have developed with distance, which in this example is at about 200m for the 250Hz sound and 100m for the 1000Hz sound, the magnitude of the effect thereafter remains relatively constant. Second, the standard deviation of the received sound pressure level is typically no greater than around 15dB,
even for the 1000Hz pure tone at 1km. For overall levels of broadband sound these variations will be significantly less, with the standard deviation of short term variations in received sound levels being more likely to be around 5dB.

The short term variability in received sound pressure levels due to local changes in propagation paths is just one of the effects of turbulent scattering. It is also possibly the effect that can be most easily appreciated from a subjective point of view. One manifestation of the effects of turbulent scattering is that of standing some distance from a source that varies in audibility over periods of a few seconds, with certain frequencies bands of the sound appearing to be enhanced more than others. The effect is particularly evident with amplified music which, when heard at large distances from the source, can vary between being clearly audible and even intelligible to being barely audible, with these changes occurring over periods of just a few seconds.

Whilst the foregoing discussion has focussed on the effects of scattering along the propagation path and the resultant variability induced in received sound pressure levels, turbulence effects also impact on other facets of sound propagation. All the effects thus far considered in this appendix have relied on idealised descriptions that make assumptions concerning the geometry and temporal stability of the situation. The discussion of the ground effect, for instance, has assumed perfectly spherical wave fronts when considering the combination of direct and reflected waves. This has resulted in conclusions of very significant ground dip excess attenuations of up to around 40dB for pure tone sources. The introduction of turbulence to the analysis means that, even though the physical geometry of the source and receiver may provide the effective path length difference between direct and reflected waves required to maximise the effects of destructive interference at the receiver, turbulent effects may change local sound speeds and also cause local angles of incidence on the ground surface to vary, thereby causing short term variability in the effective path length. The resultant effect of this variability is that the precise conditions required to produce extreme excess attenuations (i.e. the exact phase matching of direct and reflected waves) will never be maintained, and the excess attenuation at the ground dip will always in practice be limited to lower levels.

Another area where turbulence plays a major role in modifying the conclusions presented in the earlier sections is in the propagation of sound under upwind and/or temperature lapse conditions. This scenario has already been shown in Figures A.9 and A.10. Under these conditions the sound waves are refracted upwards such that, in theory at least, beyond some limiting ray there is a ‘shadow’ region where no sound energy from the source can enter, thereby resulting in an infinite excess attenuation due to the effects of the refracting atmosphere. What happens in practice is that turbulence causes scattering of sound energy into the shadow zone. Whilst this scattering may only result in a small fraction of the sound energy leaking in to the shadow zone, its effects in limiting the excess attenuation to more realistic levels is very significant. The effect may be likened to the effect of opening a sound insulating window or door by a tiny amount: the reduction in sound insulation performance is quite dramatic. The magnitude of the effect of scattering sound energy into shadow zones is both frequency and situation specific. However, in practical terms it will typically limit the excess attenuation of overall sound levels due to an upward refracting atmosphere to no more than around 20dB.

![Figure A.12: Sound curvature under temperature lapse and/or upwind conditions, with the additional effects of turbulence shown which scatter sound energy into the 'shadow' zone.](image-url)
In conclusion to this section, the effects of turbulence potentially impact on all areas of sound propagation. All the foregoing analyses have assumed that the sound speed profile remains constant between the source and receiver, both in time and space, also ignoring any localised changes in sound speed. However, the propagation of sound from a source to a receiver separated by, say, 1000m, will take a total of approximately 3 seconds in air. Given the relatively large times and distances involved, it is highly improbable that atmospheric conditions would remain constant during the course of the propagation of the sound waves, there will always be some perturbations. Thus turbulent effects will always limit the extreme excess attenuations predicted to arise from idealised models (be these due to ground effects, barrier effects, refraction effects, or whatever other effects may be considered) if those models do not take any account of turbulence and other local variations in sound speed. Of course the consequence of this conclusion is that, in order to model any scenario accurately, the atmospheric factors affecting local sound speed variations must be known precisely at every moment and at every point along the propagation path(s). Clearly this is an onerous requirement that is outside the capabilities of any existing measurement schemes. It is therefore inevitable that any sound propagation modelling exercise must include some degree of averaging in its approach, certainly temporally and possibly also spatially, coupled with a statistical estimate as to the degree of variation that may be expected to occur around the calculated central tendency.

A.2.5 The effects of barriers

A barrier is any solid object located between a source and receiver. The presence of the barrier interrupts the sound propagation path between source and receiver such that the received sound pressure level at the receiver is reduced compared to the level that would otherwise have resulted from the same source.

Barriers may be introduced purposefully for the attenuation of sound, or they may occur as natural features such as terrain. The purpose of any introduced barrier is generally to interrupt the direct sound propagation path. In order to achieve this the barrier will normally be designed such that it wholly interrupts the direct line of sight between the source and receiver.

Methodologies for calculating barrier insertion losses are well developed and available in numerous published texts. For this reason they will not be discussed in any greater detail here. Instead, this section will concentrate on the interaction of barrier effects with the other sound propagation effects already considered, as it is often the case that calculated excess attenuations due to barriers in a neutral atmosphere can be significantly reduced under conditions commonly encountered in outdoor sound propagation. It is also the case that the introduction of an acoustic barrier into a propagation path may have an influence on other excess attenuations. Most notably, the removal of a ground reflected path from the situation can result in the total loss of any ground effect.

The excess attenuation provided by a simple, infinitely long, acoustic barrier under neutral propagation conditions, as shown schematically in Figure A.13, is a function of the following variables:

- the distance from the source to the barrier
- the distance from the barrier to the receiver
- the heights of the source, receiver and barrier
  (all the above combine to make up the path length difference between the direct path in the absence of the barrier and the shortest path over the top of the barrier)
- the frequency (wavelength) of the propagating sound
As sound travels in straight lines, then theoretically no sound energy should be able to transmit to any point on the far side of the barrier that has no direct line of sight with the source. However, through the process of diffraction, the interaction of the sound wave with the barrier effectively creates a series of virtual sources along the top of the barrier. These virtual sources then allow sound energy to be radiated into what would otherwise be the shadow region. This diffraction effect is, however, frequency dependent with low frequency sounds being re-radiated deeper into the shadow region than high frequency sounds, as indicated in Figure A.13. It is for this reason that excess attenuations calculated for barriers in neutral atmospheres increase with increasing frequency. Typical overall excess attenuations for an effective, purpose built acoustic barriers installed relatively close to, say, a busy road can be anything up to 20dB(A) or more. The actual attenuation achieved will depend on the exact configuration of the barrier relative to the source and receiver geometries and also on the source spectrum. However, in achieving this overall reduction in sound level of 20dB(A), the excess attenuation at 63Hz will only be around 5dB whereas the attenuation at 8kHz will be around 30dB.

When considering the installation of a barrier as a possible outdoor noise control solution, there are two important considerations to account for when estimating by calculation the performance of that barrier under practical circumstances:

- the impact of non-neutral sound propagation conditions and the refraction of sound waves.
- the impact of the barrier on the excess attenuation already provided by the ground effect;

Considering the issue of the non-neutral sound propagation first, reference to section A2.3 shows that under temperature inversion or downwind conditions the positive vertical sound speed gradient causes the downwards refraction of sound waves. The resultant effects are shown in Figures A.7 and A.8, which indicate that sound waves no longer travel in a straight line between source and receiver but instead via curved paths, either directly or via reflections off the ground. The curvature of these paths is dependent on the prevailing atmospheric conditions, but it is easy to see how a barrier that provides significant excess attenuation under neutral propagation conditions may provide virtually no excess attenuation when downwards refraction causes the curved sound propagation path to pass over the top of it. Whether or not this reduction in excess attenuation will occur in practice in any given situation depends largely on the relative separation distances between the source, receiver and barrier. Where all three are located relatively close together (i.e. within a few metres of each other) then there will be insufficient distance for the curvature of the sound propagation path to refract downwards into the shadow region. However, where separation distances extend to tens of metres or more it is possible that the reductions in excess attenuation experienced under conditions of temperature inversion, and particularly under downwind conditions when the curvature of the sound waves can be more tighter, may be very significant to the extent of possibly being totally negated.

Now considering the issue of the ground effect, reference to section A2.2 shows that excess attenuation arising from this effect arises from constructive and destructive interference between the direct and reflected propagation paths (in other words the
‘attenuation’ can be both positive and negative, depending on the geometrical configuration of the source, ground, receiver layout and the frequency of the propagating sound. If the presence of a barrier removes this ground reflected path, but a direct path still exists through downward refraction, then it is possible that in those frequency regions where a ground effect dip would otherwise have existed, the barrier may result in the noise level actually increasing above that which would exist in the absence of the barrier. It is for this reason that schemes for predicting outdoor sound propagation that rely on the additive effects of each attenuation mechanism calculated separately can significantly overestimate the actual performance of barriers.

A.3 OUTDOOR SOUND PROPAGATION MODELS

A.3.1 Introduction
The complexity of atmospheric conditions makes it impractical to accurately define all relevant environmental parameters that may influence local sound speed along all possible sound propagation paths between a source and receiver. Any practical model therefore requires that at least some assumptions and simplifications be adopted. This has led to the existence of a variety of sound propagation models, of which some are inter-related, others are hybrids and others unique, but all are limited in capability in some respect or another. Generally, all these models can be classified by the three categories listed below. The models are sorted here by increasing complexity and potentially increased accuracy. However, it should be appreciated that the more complex the model, the more demanding the requirements for the accurate specification of more input parameters. The promise of greater accuracy of more complex models can only be realised if the values of all input parameters adequately represent the situation being modelled.

Practical engineering methods: The technique adopted by these models involves the calculation of noise levels by adding the separate contributions that each sound attenuation factor has on noise propagation. The common factor in all these models is that they are mainly based on empirical results. In general, they are simple and easy-to-use, but at the same time their considerable amount of assumptions and simplifications make them be much less accurate than other models.

Approximate semi-analytical methods: These methods retain the same practical structure as engineering methods, but are based on simplified analytical solutions of the wave equation rather than empirical results. While the practical engineering methods only take into account averaged meteorological effects, these methods allow a better tracking of the influence of specific meteorological conditions on noise levels, such as upwind or downwind situations. Simple ray tracing models are the most popular methods within this category.

Numerical methods: This group includes a range of methods such as the Fast Field Program (FFP), the Parabolic Equation (PE) and other models based on the direct solution of the wave equation. In general, all these methods allow the calculation of sound propagation over non-complex level terrain with any user-specified atmospheric conditions. They are extremely useful for analysing sound propagation under specific meteorological conditions. The problem is that they yield results for only those specific conditions and give little indication of statistical mean values of sound levels. Also, the user must provide substantially more information which can be difficult to generate, such as complete profiles of wind and temperature.

A.3.2 Overview of engineering methods
There are numerous practical engineering (empirical) methods which have become available over the years which are applicable for industrial sound propagation modelling. Commercial software packages which implement standard and other well established non-standard engineering methods are common place. The following provides a listing of available and commonly used methods, and implementation in commercial software.
The HARMONOISE and IMAGINE projects have reviewed engineering methods extensively, rendering it unnecessary to repeat the exercise here. The interested reader is therefore recommended to consult the outcome reports of these projects for further information. It is, however, useful to consider the outcome in brief here.

IMAGINE notes that the calculation methods are generally equal, based on the same principle. We would suggest however, that each deals with particular components slightly differently, requiring differing amounts of effort. The IMAGINE review indicates that most methods are valid for downwind conditions; only CONCAWE and NORD 2000 are able to deal with different type of meteorology. It concludes that all the prediction methods have shortcomings, most commonly relating to the account for screening by several buildings. It suggests that the NORD 2000 method is by far the most sophisticated, and this being the case, has been the one of the starting points for developing an engineering propagation model under HARMONOISE. The accuracy of the various methods over different distances is discussed, indicating levels of generally less than 3 dB for downwind conditions, although it acknowledges that deviations of more than 5 dB have been measured at 500 metres. It does not, however, explain how these accuracy values have been derived for each.

It is suggested that achievement of these accuracy levels is very much dependent on the definition of the situation in terms of the algorithms used to compute the propagation between source and receiver, which will inevitably include some assumptions about the intervening environment. Even where the same method is adopted by two different modellers there is potential for a degree of variation in construction of the predictive models, where the definition of the inputs is open to interpretation. This is more a consequence of the assessment requirements in the UK, and points to the need for improved definition in assessment policy, effectively fixing a window with minimum requirements for predictive models. The need for assumptions is also commonly the result of limited available data, particularly precise geometry of noise mitigation, and meteorological data. It would seem helpful that the user of these methods be offered guidance on the implications of the decisions made in defining the inputs, effectively instructing them on the depth of effort to be afforded to obtaining input information to construct the model so as to achieve an acceptable level of accuracy for the case to be assessed.

Notably, the IMAGINE review does not offer technical comment on the implementation of the various engineering methods in commercial software. DEFRA are understood to have assessed accuracy of implementation in software prior to letting contracts for noise mapping of England, although we are not aware of any published results or comments. It is taken that there were no major concerns about the software to be used for strategic noise mapping and as such, it was unnecessary to dwell on the issue. It is, however, our view based on experience that with the commercial implementation of the algorithms by different software developers there is risk of minor variations in computational process. It may not be that the methods have been implemented incorrectly in the code but perhaps allow for computational efficiencies. It is, for example, understood that the default mode of some software is to run a cut-down version, and of others to run the full version. Some software packages do not specify what factors are ignored to make efficiencies in runtimes, and it is not necessarily common for software to warn against abnormal input data. The variation in
output from different software may only be small and it is thus understandable that the issue is not of great concern for strategic noise mapping. However, for situation specific noise assessment the consequence of slight differences could potentially lead to problems, for example where the output indicates a slight excess over a critical absolute criterion, which then triggers action. Awareness of this potential pitfall would clearly be of benefit users and those impacted by the output results.

Separate to the IMAGINE review efforts, there have been a number of independent studies comparing different methods. The Witte studies have been referenced by IMAGINE. Richards also produced some interesting results from an objective comparison of ISO 9613-2, CONCAWE, and the Nord 2000 method. The work was done on the acknowledgement that there are a variety of propagation models available which are implemented in commercial software. It suggested that software tools were invaluable for large new industrial plants. However, the point was raised that selection poses a problem for the practitioner as it is unknown which will give the right answer. The importance of the issue was demonstrated by the high costs that can result form an invalid prediction due to over engineering noise control. Differences between overall A-weighted measured and predicted levels were calculated. All three prediction methods were found to show relatively good consistency, predicting around 4 to 5 dB higher then the measured levels. More interesting, however, were the apparent differences between different predicted frequency bands. At 100m the difference between the Nordic method and CONCAWE was typically around 10 dB at 250 Hz. The ISO 9613 method was 5 dB different from both of the other methods. Such significant differences could have serious implications were the intention is develop noise control system to avoid noise nuisance. The differences between octave band predictions were apparent at all distance and frequencies.

In summary, it is clear that there are limitations with practical engineering methods and that such differences in output can result not only between calculation methods but also when compared against measured data. There are a variety of possible causes including, varied limitations of methods to mathematically represent the real world, interpretation allowed by current assessment policy, assumptions due to limited available information, and the possibility of differences that may occur from using different software packages.

### A.3.3 Technical review of hybrid methods

Alternative to the use of the well established but relatively simplistic engineering methods, a group of hybrid numerically derived methods are available for evaluating propagation of noise from industrial operations. The use of such methods is undoubtedly limited in practice to relatively complex situations. The general principle of these methods is to solve the wave equation or Helmholtz equation such as to deduce the sound field generated by an acoustic source.

Although simply stated above, the procedure for solving the wave equation is generally difficult to implement due to the complexity of the atmospheric-acoustic environment. In fact, except for the very simplest boundary conditions and uniform media (which rarely occur in reality), it is not possible to obtain a complete analytical solution for either the wave or Helmholtz equation, therefore it is necessary to use numerical methods to solve these equations. Several different types of solution for the sound field have evolved over the past thirty years or more: ray tracing provides a very graphic picture of the field, the Fast Field Program (FFP) is accurate but computationally intensive and the parabolic-equation is an approximation to the wave equation that has been solved using explicit and implicit finite different schemes.

To demonstrate the potential use of these various methods, the following provides an overview of how they work, along with a brief review of the potential advantages and limitations. This includes an indication of situations where their use may or may not be appropriate. Consideration has been given to the most popular numerical methods including: ray-tracing, FFP and PE. It is noted that the review only examines the accuracy of the better known 2D models (as per the HARMONOISE Reference method) and does not include for the limited number of three-dimensional numerical propagation models which have been developed. The implicit assumption in such models is that a sound ray
launched into a particular vertical plane remains in that plane over the entire transmission path. In the atmosphere, where variations of the sound speed profile in the horizontal may be negligibly small as compared to the vertical variations, this assumption is often reasonable, in which case a 2D model provides a satisfactory description of the acoustic environment.

A.3.3.1 Ray-tracing models

Ray-tracing models are fast to compute, providing a pictorial representation, in the form of ray diagrams, of the sound field. Further advantages of ray tracing are that the directionality of the source and receiver can be fairly easily accommodated, by introducing appropriate launch- and arrival-angle weighting factors; and rays can be traced through range-dependent sound speed profiles.

Briefly, the basis of the ray tracing technique is as follows. The Helmholtz equation for the complex sound pressure $p$:

$$
\nabla^2 p + \frac{\omega^2}{c^2} p = \nabla^2 p + k^2 p = 0
$$

where $c$ is the speed of sound and $k$ the wavenumber, can be solved by expressing $p$ in polar form:

$$
p = Ae^{ik_0\varphi}
$$

where $A$ is the modulus (amplitude) of $p$, $\varphi$ is the argument (phase) and $k_0$ is a reference wavenumber. After (2) is substituted into equation (1) and the real and imaginary parts separated, the following two equations are obtained:

Real: $$\nabla^2 A - Ak_0^2 \nabla \varphi \varphi + k^2 A = 0$$

(3a)

Imaginary: $$2A \nabla \varphi + A \nabla^2 \varphi = 0$$

(3b)

On introducing the geometrical optics approximation, whereby the first term in equation (3a) is assumed to be negligible compared with $k^2$, we arrive at the eikonal equation:

$$
\nabla \varphi \cdot \nabla \varphi = \left(\frac{k}{k_0}\right)^2 = n^2
$$

whose solution gives the surfaces of constant phase (wavefronts) and where $n$ denotes the “refractive index”. The direction of the energy flow is along the ray trajectories, which are orthogonal to these surfaces. The amplitude of the field is proportional to the density of the rays, and can be determined formally by solving equation (3b).

Ray-tracing models are limited in capability only as a consequence of the approximation leading to the eikonal equation, since no other approximations appear in the ray-theoretic development. This assumption imposes several restrictions on the physics, which in turn limit the applicability of ray theory. Firstly, the amplitude must not vary significantly over a wavelength; i.e. the theory would be invalid when diffraction takes place about a solid object, because in the shadow of the object the pressure field has regions which exhibit large spatial variations. Secondly, the speed of sound must not vary significantly over a wavelength. This implies that the above theory may not be valid with abrupt changes in the sound speed.

These two limitations infer that the ray solution of the wave equation is a high frequency approximation, and that low frequencies will be poorly performed by this model. The two main anomalies derived from these limitations are caustics and shadow areas. Caustics occur when a family of rays turn and cause a line along which the intensity, as predicted by this theory, is infinite. Conditions of infinite intensity never occur in reality. These caustics arise, not because of the underlying physics, but are purely a consequence
of the approximations used in the model. In practice these curves of infinite intensity would
normally be missed unless a receiver is situated precisely on a caustic. Nevertheless, the
problem can be significant, because the intensity is high not just at the caustic but in a zone
surrounding the caustic. Here exists a clear risk of an invalid prediction if the user is
unaware of the effect of the approximations.

Figure A.14: Example ray tracing plot showing the development of a caustic
where theoretically infinite sound pressure results.

Shadow areas are the other common flaw of ray-based models where no rays pass and
therefore the pressure field is identically zero. To illustrate this point, we consider a simpler
upwind sound-speed profile in which the sound speed decreases linearly with height. The
sound speed profile and resulting ray trace are shown in Error! Reference source not found.A.15 for a source height of 27.65m. Over distances up to 500m, the pressure field is
composed of contributions from a direct ray (blue solid lines) and a surface-reflected ray
(discontinuous black lines). Beyond about 600m we can see clearly from the ray trace that
we are entering a shadow region where there are no rays. The ray (black solid line) that
forms the border between the shadow zone and the two-ray region is called the limiting ray.
Since no rays get into this shadow area, the sound pressure field predicted by the ray
theory becomes ~ dB, while in reality some sound energy enters the shadow region via
diffraction and scattering of the sound waves.

Figure A.15: Example ray tracing plot showing the development of a shadow
region where theoretically zero sound pressure results.

Such difficulties can be overcome by introducing different modifications, allowing the ray
tracing to be extended to lower frequencies, accounting to some extent for caustics and
diffraction. For instance, using a caustic correction and dealing with shadow areas based
on considering complex take-off angles. However, in practical applications, such
modifications are almost never used because they introduce an increased complexity in the
calculation. Variants of ray tracing have also been developed, notably a technique for
tracing Gaussian beams (“fuzzy rays”).
A.3.3.2 Fast Field Program (FFP)

A class of propagation model exists which give the full wave solution for the field in a horizontally stratified medium. Such a model is known either as the “fast field program” or the “wave number integration method”. The method provides an exact solution of the Helmholtz equation, except within a wavelength or so of the source.

As provided for the ray tracing method above, it is useful to consider the basic theory to help demonstrate both complexity and practicability. It also helps to identify limitations. The FFP method is based on a Fourier transformation of the wave equation from the horizontal spatial domain to the horizontal wave number domain. The transformed wave equation is solved numerically, and the solution is transformed back to the spatial domain by an inverse Fourier transformation. Thus, the solution in the spatial domain is an inverse Fourier integral over horizontal wave numbers.

The mathematical development of the above theoretical description is rather long and complex to be included here, but has been well reported by others.

No approximations appear in the theoretical development that could possibly constrain the accuracy of the FFP method. However, probably the most significant limitation is the use of the Fourier transformation to the horizontal wave number domain restricts the method to systems with a layered atmosphere and a homogeneous ground surface. Therefore, systems with a range-dependent terrain (either in terms of ground impedance or terrain shape), or with a range-dependent atmospheric environment (variable sound speed profile with range) cannot be modelled with the FFP method. This would clearly limit practicality over long distances with mixed ground conditions. Furthermore, the computation of a complete spectrum requires separate computations for all frequencies of the spectrum. In general, the computing time increases with increasing frequency, and the computing time for a complete spectrum is often considerable.

A.3.3.3 Parabolic Equation (PE)

In contrast to the FFP method, the Parabolic Equation (PE) method is not restricted to systems with a layered atmosphere and a homogeneous ground surface. In fact, the PE method is the only current technique that can handle environmental range-dependent variations.

As with the other methods it is useful to gain an understanding the basic theory. Essentially, the PE method is based on an approximate form of the wave equation. Depending on the approximation made to the wave equation, one can obtain either a wide-angle parabolic equation or a standard (narrow-angle) form as the one shown below:

\[
2i k_0 \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial z^2} + k_0^2 \left( n^2(r,z) - 1 \right) u = 0 \tag{4}
\]

where \( u \) is a variable proportional to the sound field. For more details about the derivation of this standard PE or other wide-angle PEs, the reader could consult Salomons, 2001.

Different solution techniques exist to cope with the parabolic equation. Amongst them, the most popular are: The Crack-Nicholson PE (CNPE) method and the Green’s Function PE (GFPE) method. Both methods make use of a rectangular grid in the rz plane. The source is represented by a starting function \( p_c(r=0,z) \) of the complex pressure amplitude at range \( r = 0 \). This starting function is extrapolated step-wise on the grid, in the positive r direction. An extrapolation step from range \( r \) to range \( r + \Delta r \) can be expressed as

\[
p_c(r,z) \rightarrow p_c(r + \Delta r,z) \tag{5}
\]

By repeating this extrapolation step many times, the complete field \( p_c(r,z) \) of the complex pressure amplitude is computed.
The CNPE method was the first PE solution scheme introduced in atmospheric acoustics and essentially involves a finite-difference solution of a wide-angle parabolic equation. The horizontal and vertical grid spacings $\Delta r$ and $\Delta z$ in the CNPE method are limited to a maximum value of about $\lambda/10$, where $\lambda$ is an average wavelength. Consequently, the number of grid points, and hence the computing time, increases with increasing frequency.

The GFPE method, described in a less accurate than the CNPE method in situations with wide-angle propagation and large sound speed gradients; however, for most applications and particularly for many ground-to-ground propagation configurations, the GFPE method is sufficiently accurate. In the GFPE, the vertical grid spacing is also limited to about $\lambda/10$, but the horizontal grid spacing (or range step) may be chosen considerably larger, up to about 50$\lambda$. Consequently, the advantage of the GFPE over the CNPE method is that can take considerably larger extrapolation steps (i.e. range steps), resulting in a more efficient and faster computation.

There are three distinct limitations to the various forms of the PE method. Firstly, PE algorithms have an unfortunate disadvantage in that they only give accurate results in a region limited by a maximum elevation angle $\alpha_{\text{max}}$, as demonstrated in Figure A.16. The value of this angle oscillates from 10° to 70° or higher (Salomons, 2001), depending on the angle approximation used in the derivation of the parabolic equation. Figure A.17 goes on to show an example of a PE prediction attenuation for a downwind condition indicating the effect of the angle limitation.

![Figure A.16: Elevation angle limits for the PE model $-\alpha_{\text{max}} < \theta < +\alpha_{\text{max}}$.](image)

Secondly, the computation of a full frequency spectrum is not a straightforward process. As it occurred with the FFP, the PE methods compute one frequency at a time. Therefore, the computing time for a complete spectrum is often considerable, particularly for the calculation of frequencies above 600 Hz.

Finally, scattering by sound speed gradients in the direction back to the source is neglected by a parabolic equation. In other words, a parabolic equation is a one-way wave equation, taking into account only sound waves travelling in the direction from the source to the receiver. As the sound speed is usually a smooth function of position in the atmosphere, the one-way wave propagation approximation is usually a good approximation. However, when turbulence is taken into account, the backscattering limitation might be an effect to be considered.

When differentiating the GFPE and the CNPE, the main factors affecting appropriateness are that the CNPE offer a wider angle solution (70°) than the GFPE (20°), but requires much more computational time.
A.3.3.4 Concluding remarks on hybrid methods

The hybrid methods are generally based on solutions of the wave equation, ranging from simplified analytical solutions (simple ray tracing) through to direct solutions such as the Parabolic Equation. They possess the ability to provide highly accurate representations of propagation effects for individual frequencies in certain conditions. Such methods have provided the basis for the ‘reference model’ used to validate the engineering method produced by HARMONOISE.

On the downside, the techniques are generally computationally intense, and most commonly only employed only for 2D prediction. Furthermore, the methods are not widely available within common commercial software, and involve fairly complex computational procedures. There are different ranges of accuracy, relating to limited source radiation angle, optimum frequency ranges, non-homogenous ground conditions, and topographical complexity.

Clearly the brief review indicates that numerical methods have many strengths, mainly in accuracy, but also some weakness, mainly in practical application. It is reasonable to conclude that none of the examined methods is capable on its own of handling ALL possible environmental conditions, frequencies and transmission ranges of interest in practical applications. One method will be more appropriate than another for a particular problem scenario, and thus selection of the best method must be situation specific.

As a rough preliminary guide to demonstrate how the most appropriate method might be selected, an attempt has been made to compare in relative terms how well the properties of the various modelling methods would deal with important procedural characteristics. For comparison purposes the practical engineering method ISO 9613 has also been included. A summary has been provided in Table A.2.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Engineering</th>
<th>Hybrid modelling methods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Approximate semi-analytical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ISO 9613</td>
</tr>
<tr>
<td>Computing time (Present)</td>
<td>Fast</td>
<td>Fast</td>
</tr>
<tr>
<td>Accuracy (Relative)</td>
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<tr>
<td>Ideal frequency range</td>
<td>All freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td>Range-dependent conditions</td>
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<td>NO</td>
</tr>
<tr>
<td>Shadows and caustics</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Elevated sources</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>

Table A.2: Comparative guide to properties of different sound propagation prediction models

A.4 PROBLEMS WITH CURRENT PRACTICE OF USING PREDICTION FOR NOISE ASSESSMENT

Having established where, when and how the modelling approach is used, identifying strengths and weaknesses in the process, we can begin to focus in on why problems may arise due to the use of prediction methods for assessment of industrial noise immission. It is considered that the potential for dispute and risk of incorrect assessment from prediction can be summarised into three categories;
1. Current prediction algorithms are limited in their ability to represent real world sources, particularly complex environments acoustic features and variable propagation effects, all of which must be considered for the outcome of an assessment of nuisance to be valid. Commonly, engineering methods which are depended upon are widely accepted for having shortcomings.

2. There is an absence of nationally standardised requirements for the verification and quality assurance of commercial software which implement engineering methods.

3. There are variable approaches to the use of algorithms/methods and/or the commercial implementations in software. There are three sub-components which lead to variable approaches;
   - Absence of clearly defined assessment requirements, and therefore conditions that should be included for in prediction models.
   - Availability of quality input data suitable to give the appropriate level of accuracy.
   - Absence of defined system for generating traceable accounts of a model output’s development/construction.

These problems and risks are then compounded by other factors. Firstly, there is varied industry understanding of modelling limitations. Secondly, there is an absence of guidance on how to deal with the limitations and uncertainties of predictions. Finally, competitive tendering pressures play a part where the scope of any prediction exercise may be limited without recognising the risks involved, or considering the merits of alternative assessment options.

A.5 RECENT DEVELOPMENTS & SYNERGIES

Part of the preliminary study to inform the development of the guidance has been to assess the current state of knowledge on industrial noise modelling by reviewing related research and development work.

A.5.1 Harmonoise

The following points have been observed from the HARMONOISE Final Technical Report as being relevant to this project.

- De-coupling the description of source from the description of propagation has provided the basis for two general noise propagation methods:
  - Reference (Calibration of engineering method)
  - Engineering Point 2 Point (General use)

- Methods have been developed to be suitable for both noise mapping and for detailed computations for noise assessment studies. The accuracy will depend mainly on the chosen input parameters.

- It is the conviction of the HARMONOISE team that guidelines must be developed both on a European and National level on what accuracy is required at every application of the methods.

- HARMONOISE has acknowledged the importance of the need for the methods to be transparent. It has been stated that it is essential that every part of the engineering method can be checked by using the original formulas and algorithms. This would help to avoid dispute between models, where all factors can be clearly accounted for.

- A process of standardisation is needed to enhance rapid introduction of methods. CEN standardisation of these improved propagation prediction methods is recommended for the long term. They state that this would allow maintenance and revision by the scientific and technical communities.

- A standardised database is available for extension of the work by other researchers.
In summary, HARMONOISE has produced an improved engineering propagation prediction method, but it has been developed and validated only for road and rail sources under limited long term conditions. IMAGINE, the follow on project, proposes to improve further on the techniques, tailoring the methods for both aircraft and industry sources. Subsequently in this appendix projections are offered on how these developments along with other academic works are likely to impact on the problems currently faced by the UK noise modelling practitioner. Notably the HARMONOISE team have expressed the importance of developing guidance to direct accuracy requirements for different applications, which is in close synergy with the NMS project objective. It will be important to keep abreast of the IMAGINE project and any other related works carrying on from HARMONOISE.

A.5.2 WG-AEN Good practice guide to strategic noise mapping


It is understood that the purpose of this Position Paper is to assist Member States and their competent authorities to undertake noise mapping and produce the associated data required by Directive 2002/49/EC relating to the assessment and management of environmental noise.

The paper guides the user on the implications of defining the inputs in terms of complexity, accuracy, and cost. For example it will aid the user decide the effort to be afforded to defining the necessary traffic flow input required to produce a noise map, indicating the relative difference in complexity and cost of constructing and running calculations for the map, and the output accuracy expected with respect to the detail of the traffic data.

Although the format of the guidance is considered somewhat difficult to interpret, it undoubtedly offers a useful reference for the development of the NMS guidance.

A.5.3 NMS 2001 – 2004 Environmental Noise

Under the NMS 2001 – 2004 Acoustical Metrology Programme, guidance has been prepared to raise awareness of the risks associated with the use of environmental sound measurements to inform decision making processes. This is achieved through the promotion of a general procedural framework that actively encourages all users of environmental measurements to consider the scale and extent of measurement strategies required to inform a decision to the degree of risk deemed to be acceptable.

The guidance comprises two main sections.

• Environmental sound variability and other related factors affecting risk.

• General guidance and considerations for environmental sound measurements including reference to strategy design, the execution of measurements and post-measurement analysis and evaluation.

This will be an important reference for the development of guidance relating to industrial noise immission modelling. There are direct synergies between this guidance on environmental noise measurements and the expected outcome of the current project which addresses risks associated the use of invalid model predictions.

A.5.4 DEFRA report on adverse effects of industrial noise

As briefly mentioned earlier in the discussion of the complexities of industrial noise, DEFRA recently commissioned a study to gain a better understanding of potential disturbance and impact on amenity by industrial noise and the reported relationship between industrial noise and people’s response.

It was reported that the core of the project was to review and analyse relevant literature. Notably it was indicated that limited knowledge of the industrial noise dose response
relationship had been published with relatively few surveys carried out in comparison to transportation sources. It was recommended that an extensive survey of industrial noise situations be carried out. Reference was also made to laboratory studies of subjective response to industrial type noise sources. This indicated that cases involving impulsive noise, the A-weighted level may need to be corrected by as much as 10 dB, which is significantly higher than is currently accounted for in the BS 4142 assessment methodology. It was made clear that in order to both assess and then control industrial noise, good descriptors of the physical magnitude of various features such as tonality and impulsivity which relate closely with the subjective characteristics were needed. It was recommended that funding should be provided to research and develop improved descriptors. There is an important synergy here with the NMS project. If new descriptors, which are apparently needed, were to be developed, the predictive methodologies would clearly need to be brought into line. This would drive the revision of engineering methods, and may call upon the use of the hybrid methods. The NMS project can help to inform where the weaknesses exist in the current techniques and outline potential capabilities for future development. It would be of benefit to all funders to collaborate, or at least be aware of each of the related works. DEFRA should be consulted directly on the possibility of joining forces to drive forward the improvement of policy and methods to minimise industrial noise impacts.

A.5.5 SSFM Guidance on mathematical modelling uncertainty analysis

Development of guidance to aid industry is conducted throughout the NMS. In April 2004, NPL published under the Software Support for Metrology (SSFM) programme, a Best Practice Guide relating to mathematical model building covering aspects such as construction, parameterisation, uncertainty, choice of parameter estimation algorithms and their implementation in software. The concepts have been illustrated by case studies. This provides a comprehensive insight into the development of mathematical models of physical systems. It addresses the need to assess the risks associated with an invalid model and more importantly the significance of designing and implementing processes to limit the risks to an acceptable level. Various approaches for validating models are detailed. This document will be a useful reference for development of the guidance relating to industrial noise immission modelling.

A.5.6 Projected developments in near future

The previous sub sections have essentially set out the current state of knowledge, highlighting some of the problems with current practice, particularly with engineering methods and there implementation in commercial software packages but also indicated from a review of more sophisticated modelling methods, and related development works, that there is potential for future technical improvements to the existing methods. It is therefore worthwhile, at least in brief, considering how both the output of related development work such as IMAGINE and DEFRA effects studies and the ongoing academic research of more sophisticated techniques into outdoor sound propagation is likely to impact upon current modelling practice.

A.5.6.1 IMAGINE development of HARMONOISE methods

Imagine is seeking to advance the work conducted under HARMONOISE and, relevantly, it will focus efforts on developing an engineering standard method modelling emission from industrial noise sources. Aligned within this, the reference method (based on numerical computations) will also be tailored for industrial sources. As with the HARMONOISE project, the development of engineering methods will be declared as for both strategic mapping and situation specific modelling. The validation of the methods are, however, only likely to be based on long term impacts, which allows for smoothing of temporal variations. Situation specific assessments need to consider short-term impacts for which the methods will not be proven. Another unfortunate downside of the IMAGINE work is that it is likely to focus further development of the method to predict the overall A-weighted value. The
outcome of the DEFRA study into industrial noise effects eluded to the need for methods to be improved to account for acoustic features such as tonality and impulsivity.

There is some suggestion that the IMAGINE work will feed into the improvement of the current international standard for outdoor propagation calculation, ISO 9613-2. This being the case, there may be scope to enhance the methods to be reliable beyond the A-weighted result, prior to standardisation. The output of this NMS project should actively encourage improvements.

IMAGINE will also aim to develop in collaboration, guidance on input requirements for the construction of models. However it is unlikely, considering the remit of the project which focuses on strategic mapping, that this guidance would specifically indicate appropriate input definition where the output is to be used for situation specific noise assessment.

Thus, whilst the development of methods under the IMAGINE project may improve on current methods, it will not solve the problems discussed above with current practice in the UK. There will continue to be a need for improved methods and clarification on the risks associated with decision on specific methods and the costing of the model.

A.5.7 On-going academic developments

There has been intense research into calculation of outdoor sound propagation, and by all accounts the work is set to continue with vigour. The review of the most popular sophisticated methods which have derived from academic research over the years highlighted many of the technical benefits increased accuracy from the methods. Unfortunately, the limitations also had to be pointed out. Although the numerical methods can theoretically give a near to true representation of the real physical propagation system, and thus offer an accurate output, there are practical limitations. One of the key factors here is the fact the techniques can only ever produce results that are as good as the input data describing the physical system being modelled, yet in most cases this is a highly complex system for which it is impossible to precisely specify the controlling parameters, especially as many of these parameters are subject to short term temporal and spatial variability. The ‘accurate’ output of these models is, therefore, only accurate with reference to the input conditions. If these input conditions are inadequately or incorrectly specified then the output results may be quite misleading, and in some cases less accurate with reference to the real world situation being modelled than the output of much simpler engineering models that adopt certain simplifying assumptions that ‘average out’ the effects of some of these variable parameters. Further to this, the running of calculations with the computation of complete frequency spectra is a lengthy process, although this may change with advancement of computer technology.

Projections are, that availability of sophisticated techniques will be beneficial particularly where the situation to be assessed has complex characteristics such as impulsive signals or discrete tones or where there is a need, perhaps as a result of seasonal noise complaints, to evaluate the effect of propagation factors such as variable temperature gradients.

The output of the academic work provides a useful insight into the potential capability of modelling and an important foundation to reference engineering methods against. However, the development of a harmonised hybrid method for use in assessing common industrial and commercial noise problems would still appear to be some way off.