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THE ESTIMATION OF CUMULATIVE NOISE EXPOSURE
CAUSED BY AIRCRAFT TRAFFIC

by

DAVID BROWN, B.Sc.

A Master's Thesis

Submitted in partial fulfilment of the requirements for
the award of

Master of Science of the Loughborough University of
Technology
May 1975

Supervisor: J.B. Ollerhead, B.Sc., M.Sc., C.Eng., A.F.R.Ae.S.
Department of Transport Technology

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The work reported herein has been performed as a supplementary study within a research programme on "Public Reaction to Aircraft Noise" under Contract SN/1170/012 for the Civil Aviation Authority, Directorate of Operations Research and Analysis.

The main parts of this report (Sections 3 and 4) evolved from the author's primary responsibility to provide estimates of various noise exposure quantities for correlation with surveyed community-attitude data. While these requirements were achieved by means of predictive techniques based on well-established procedures, there was obvious scope and need for a more fundamental study of noise index characteristics in aircraft exposure applications. This study provided relatively simple relationships for various indices, which can be used to examine their compatibility and to give a predictive estimate of one type of index based on information collected for the estimation of another index type. These uses are developed herein by reference to example exposure conditions.
The author wishes to thank Mr. J.B. Ollerhead, programme supervisor and principal investigator, for his invaluable guidance and support in this and other project tasks of the research programme. Considerable assistance has also been given by Mr. Trevor Ingham and Mr. Tom Aitcheson of CAA (DORA) during their monitoring of the programme.

This project has been based on noise exposure data collected and analysed by the staff engaged on the main research programme and by technician staff of the University's Department of Transport Technology. Particular recognition is due to Dr. R.M. Edwards for his detailed involvement in both data measurement and analysis, to Mr. M. Lanzer and Mr. E. Rodgers for their assistance in preparatory work and participation in the measurement exercise, and to Miss M. Dredge for computer programming.

The author wishes to thank Miss P. Pilkington and Mr. Derek Glenister for their production of the typed text and illustrations contained herein.
Community noise caused by aircraft traffic is examined in relation to its estimation by predictive and measurement methods. The basic properties of the noise exposure at any airport-vicinity site are shown to be mainly defined by the statistics of the peak-level occurrence and noise duration distributions over a given time period. The relationship between these distributions is derived in terms of traffic parameters. This leads to the derivation of an equation for the evaluation of $L_{eq}$, which makes use of information usually acquired for an NNI assessment and which is directly comparable with the NNI formula. An important result of the study is the development of a simple and convenient method for predicting aircraft noise exposures, by which various noise indices ($NNI, L_{eq}, L_{NP}, L_{10}$, etc.) can be directly evaluated.
LIST OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2.0 Airports and Noise Exposure</td>
<td>14</td>
</tr>
<tr>
<td>2.1 Air Traffic and Communities</td>
<td>14</td>
</tr>
<tr>
<td>2.2 Noise Exposure Caused by Air Traffic</td>
<td>21</td>
</tr>
<tr>
<td>2.2.1 Peak Level-based Indices</td>
<td>25</td>
</tr>
<tr>
<td>2.2.2 Indices Based on Noise Duration Statistics</td>
<td>32</td>
</tr>
<tr>
<td>3.0 Relationships Between Noise Indices Based on Peak Level and Duration Statistics</td>
<td>37</td>
</tr>
<tr>
<td>3.1 The Noise Exposure Distributions</td>
<td>37</td>
</tr>
<tr>
<td>3.2 Noise Indices</td>
<td>42</td>
</tr>
<tr>
<td>3.2.1 The Equivalent Continuous Energy Level</td>
<td>42</td>
</tr>
<tr>
<td>3.2.2 The Noise Pollution Level</td>
<td>46</td>
</tr>
<tr>
<td>3.3 Summary</td>
<td>49</td>
</tr>
<tr>
<td>4.0 The Prediction of Aircraft Noise Peak Levels</td>
<td>50</td>
</tr>
<tr>
<td>4.1 Introductory Review</td>
<td>50</td>
</tr>
<tr>
<td>4.2 An Alternative Method</td>
<td>54</td>
</tr>
<tr>
<td>4.3 Aircraft Noise Peak Levels</td>
<td>59</td>
</tr>
<tr>
<td>4.4 Noise Propagation at Low Ground Angles</td>
<td>61</td>
</tr>
</tbody>
</table>
# LIST OF CONTENTS (CONTINUED)

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>NOISE EXPOSURE PREDICTION BY A GRAPHICAL METHOD</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>5.1 The Noise Peak Level Distribution</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>5.2 The Noise Duration Distribution</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>5.3 Noise Indices</td>
<td>71</td>
</tr>
<tr>
<td>6.0</td>
<td>MEASUREMENT AND MONITORING CONSIDERATIONS</td>
<td>74</td>
</tr>
<tr>
<td>7.0</td>
<td>CONCLUSIONS AND RECOMMENDATIONS</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td><strong>TABLES</strong></td>
<td>82</td>
</tr>
<tr>
<td></td>
<td><strong>FIGURES</strong></td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>APPENDIX I AIRCRAFT NOISE MEASUREMENTS AT SITES NEAR HEATHROW AIRPORT</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>APPENDIX II DERIVATION OF NOISE EXPOSURE STATISTICAL DATA FOR A SITE NEAR LIVERPOOL AIRPORT AND A SITE NEAR MANCHESTER AIRPORT</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td>APPENDIX III ERRORS CAUSED BY NEGLECT OF TRUNCATION IN DISTRIBUTIONS OF NOISE EXPOSURE</td>
<td>139</td>
</tr>
<tr>
<td></td>
<td>APPENDIX IV AN EXAMPLE SITE NOISE EXPOSURE PREDICTION</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td>REFERENCED LITERATURE</td>
<td>155</td>
</tr>
</tbody>
</table>
1.0 INTRODUCTION

One of the most significant problems facing airport authorities over the next decade or so, is that of planning for the containment or alleviation of public nuisance attributable to aircraft noise, while, at the same time, allowing for an expected increase in air transport demand. Clearly, there are long-term benefits to be realized with the supersession of the current air transport fleet by the larger-capacity, but quieter, aircraft which are presently in prototype or service introduction stages. For communities in close proximity to the runway thresholds of jet-handling airports, the benefits will be appreciated as a lowering of the peak noise levels and possibly as an end to the growth in aircraft movement activity. Communities in the outer region of the airport route zones will gain an additional benefit of "hearing" fewer aircraft. There will remain, however, established community regions where aircraft noise exposure will be rated as excessive for community comfort. There will be marginal regions where aircraft noise will be part of a wider problem related to the overall noise environment encompassing road traffic and industrial noises. It can also be expected that the development or expansion of smaller regional airports will bring the airport flight patterns closer to as yet unaffected residential sites. The ability to assess such situations, of the present and of the future, and to provide the planning tools by which airport and community developers can reach amicable decisions, are the primary
goals of current studies of environmental noise and its effects.

The intrusion of aircraft noise into what otherwise may have been a satisfactory community environment is a long-established problem; first encountered to the degree of public reaction by complaint in regions around military airfields, and later in areas around civil airports where larger and noisier aircraft, particularly jet-transporters, became regular users of the immediate airspace. Although the problem of community disturbance must have been anticipated by the aircraft manufacturers and operators the retaliation by more active public involvement was really the motive force behind the large-scale inquiry and research devoted to finding methods of defining, quantifying and controlling this disturbance. The more specific objectives of these studies were:

(a) to define viable limits on the noise levels radiated by new and future designs of aircraft during their airport vicinity operation;

(b) to examine and optimise the flight procedures of aircraft in the airport zone, with respect to alleviating their noise burden on exposed communities while maintaining operational safety, and

(c) to derive a measurable scale of cumulative noise exposure that would reliably assess the degree of community disturbance caused by aircraft traffic.
It was intended that the first two of these objectives would lead directly to a containment of the problem, with long-term benefits to be realized from the former and more immediate partial relief from the latter. Being concerned with the noise caused by individual aircraft flights, they could also be dealt with in some isolation from the third objective. The last of the above objectives was equally important in that it would provide a rational planning tool and a method of noise exposure assessment. Its applications would be to give legislative control on,

(i) the restricted development of land areas for residential buildings, where the noise exposures are, or will be in the foreseeable future, unsuited to this purpose;

(ii) the compensation of residents in excessively exposed communities, by improvement of the sound insulation of their homes, and

(iii) the planning of future airports and airport expansions, and the siting of their satellite communities.

It is somewhat ironical that the seemingly most difficult and economically most controversial of these objectives have been more successfully dealt with than the others. Limitations on the noise output by aircraft are now an accepted part of the type-certification process and regulatory methods of aircraft operation in the vicinity of airports are now part of the flight procedures for many civil airports. Although cumulative exposure measures
have been derived for aircraft noise, in the form of the 'Noise and Number Index' for U.K. airports and in other forms in other countries, the reliability of the measures and their applicability to planning decisions of major importance has been disputed on many grounds, not least of which is the apparent lack of predictive accuracy in estimating the variance of community attitude to aircraft noise. These particular problems, and other aspects of the subjective effects of noise on communities, have been recently examined in other Loughborough University studies for the Civil Aviation Authority (Department of Trade). These are listed in the referenced literature at the end of this report.

The present report is confined to an examination of the methods of estimating, by prediction and/or measurement, the noise exposure quantifiers that are presently used, or are proposed for use, for airport noise assessment. An integral part of this examination is the study of the dependency of the noise indices and constituent parameters on the properties of the source and propagation acoustics, and on the statistical properties of the traffic causing the cumulative exposure.

Some insight into the purposes and problems of this particular study is given by briefly reviewing the historical development of noise scales and exposure indices.

The introduction of the decibel unit as a physical scale of sound pressure level was reputedly based on the observation that the human hearing and neurological res-
response to impinging sound is of an approximately logarithmic nature. The subsequent observations of the inadequacy of the sound pressure level in predicting hearing responses at any and all frequencies led to methods of assessing the loudness of sounds by means of frequency-dependent corrections to the sound pressure level spectrum. The better known of these corrective processes are the frequency-weighted networks for Sound Level measurement such as the A, B and C-weighted Sound Level scales. Each of these was found to be preferable for particular types of noises, or noises in particular level ranges. Later investigations of psychometric scales capable of assessing the noisiness of sounds, or their disturbance and annoyance-inducing properties, resulted in many other measurement scales for steady continuous sounds. All of these studies were conducted by subjective laboratory tests, in which the sound stimuli and the subject listening conditions could be carefully controlled. Similar testing procedures provided a means of developing noise scales for short-period noise excursions such as those typical of an aircraft flyover or an automobile pass-by. Through such tests, the Perceived Noise Level unit was developed as being best suited to the definition of aircraft noise levels of any single fly-over event. For the overall effect of the complete noise level excursion, it was found that the peak Perceived Noise Level provides a good correlation with subjective response (Reference 1). A further development was that of "Effective Level" which is basically the average-energy
level of the excursion over a specified time period. A slight improvement in the subjective correlation was obtained (References 2 - 4, for example).

The need for a means of quantifying the subjective effects of long-term, variable, noise exposures has been not so readily satisfied. Whereas the former studies were amenable to controlled laboratory investigations, the cumulative exposure problem is not; at least not without imposing unnatural constraints on the study objectives. Here, the noise exposure is quantified by means of a range of measurable parameters, and the attitudes of residents to their local noise environments are solicited by means of a questionnaire or by analysis of complaints. This has supplied the researcher with a bank of experimental data, from which various empirical noise index forms have emerged through multiple regressions of noise and attitude parameters. The problems of this empirical approach are basically: (a) that the indices have not correlated well with the total bank of individually-expressed opinions on noise, although they have correlated very well with the average, or central tendency, of the opinions in each noise stratum, and (b) that, being empirical, they are suited only to domain of their derivation and hence may not be accurate or appropriate to situations outside that domain. Additionally, it may be argued that some indices derived by such empirical methods can be insensitive to the needs of the planner, mainly because they do not give guidance on how to reduce the noise burden. Thus the problem of
reducing a noise index value, or of diminishing the area within a noise index contour, can be complicated if the index formulation does not contain dependencies on physical traffic parameters. Recourse to iterative planning methods is then necessary.

By tackling each of the different types of noise exposure (such as that of aircraft, road traffic, industrial plant) in some isolation from each other, it is perhaps not surprising that the social survey regression methods have given rise to a number of quite different index forms to suit these different problems. Some characteristic time-histories of various traffic noise exposures are shown in Figure 1. The aircraft noise cases are seen to be a succession of well-spaced (time-wise) discrete noise events with distinguishable and readily measurable peak levels. With the knowledge of this characteristic of airport noise exposure, and with the benefit of the earlier studies of subjective scaling of individual aircraft noise events, the Wilson Committee (Reference 5) and their associate researchers (Reference 6) examined the cumulative exposure index problem by analysis of community attitude data obtained around Heathrow (London) Airport. After consideration of many noise parameters, the final index form was empirically derived by the Wilson Committee from McKennell's data. This index is the Noise and Number Index (NNI). It is based on the peak levels of aircraft traffic noise, measured in Perceived Noise Level units, and is formulated as,
NNI = $\bar{L} + 15\log_{10} N - 80$ (PNdB) \hspace{1cm} (1.1)

where $\bar{L}$ is the average peak-energy level and $N$ is the number of noise peaks 'heard' during an average 12-hour daytime period.

Although seemingly simple at first glance, the NNI is in practice a complicated index to evaluate by measurement. An examination of these complications is contained later in this report (Section 2). However the index form would seem amenable to the planners' needs in that the dependence on noise level and traffic number are separable and directly useful in noise control. Other similar indices have been independently derived in the U.S.A., namely the Composite Noise Rating (CNR) and the Noise Exposure Forecast (NEF) to be discussed later.

Referring again to Figure 1, it is apparent that the use of peak level statistics for road traffic (or for industrial plant noise) exposures would incur severe measurement and analysis problems. Here the noise is of a rapidly fluctuating nature and indices for this more random time history have been derived in terms of levels exceeded for specific percentiles of time. $L_{10}$, $L_{50}$ and $L_{90}$ are the levels exceeded for 10%, 50% and 90%, respectively, of the total period of assessment. These are based on A-weighted Sound Level measurements and were used in the attitude regression studies concerning London traffic noise (Reference 7), the Wilson Committee studies of the same data, and in the subsequent work of the
Building Research Station where new social surveys were performed (Reference 8). Whereas the earlier studies recommended the use of $L_{10}$ for road traffic noise exposure, the Building Research Station study showed that a better correlation with community attitude could be obtained by a more complex index, namely the Traffic Noise Index (TNI), defined as (References 8 and 9),

$$TNI = L_{90} + 4(L_{10} - L_{90}) - 30, \text{ dB(A)} \quad (1.2)$$

For numerous reasons, including those of complexity and the possibility of inherent anomalous properties (e.g. Reference 10), the TNI was not adopted as a legislative index. Instead, the $L_{10}$ over an 18-hour assessment period has become the present legislative measure of road traffic noise (Reference 11) in the United Kingdom. Different indices have been developed in other countries for the road traffic noise problem and for other types of noise exposure. There is consequently an incompatibility between the various noise criteria. This is significant when the noise abatement goals of various countries are compared and when a comparison between aircraft noise and other noise criteria is attempted.

Of probably greater significance is that there is no accepted method (in the U.K.) of assessing a noise exposure situation caused by the simultaneous influence of many different types of sources, including aircraft noise.

Studious attempts to overcome these incompatibilities have been made in recent years, particularly by the
International Standards Organisation. The main recommendation evolving from the ISO work is that the Equivalent Continuous Energy Level ($L_{eq}$) should serve as a compatible and comparable noise exposure index for general noise assessment. The index is definable in its basic form as (Reference 12),

$$L_{eq} = 10 \log_{10} \left[ \frac{1}{T} \int_{0}^{T} \frac{L(t)}{10} \, dt \right]$$

(1.3)

where $L(t)$ is the time history of the A-weighted Sound Level, averaged on a "Slow" signal averaging system, and $T$ is the total period of measurement. It can equally be applied to any other noise scale history, such as PNdB, with appropriate (approximate) corrections being applied for comparison purposes.

The $L_{eq}$, as defined above, is the level of a continuous unchanging noise that would have the same total energy as the actual fluctuating noise over the same time period. Aircraft traffic noise, being intermittent rather than continuous, does not have a sufficient study background in such temporal aspects of noise exposure to allow a ready transformation in assessment applications. The ISO has therefore examined other forms of $L_{eq}$ that could be more readily applied to this particular source. One such form, which is based on the extensive bank of information regarding the Effective Perceived Noise Levels of aircraft flights, is, (Reference 13)

$$L_{PN_{eq}} = L_{E} - 10 \log_{10}(T/To), \text{ PNdB}$$

(1.4)
where $T$ is the total time period under consideration, and $L_E$ is the so-called aircraft exposure level given by,

$$L_E = 10 \log_{10} \left( \sum_{i} 10^{\frac{EPNL_i}{10}} + 10 \log \frac{T_o}{T_o} \right)$$

$T_o = 10$ seconds and $t_o = 1$ second.

When rewritten as

$$L_{NP_{eq}} = 10 \log_{10} \left[ \frac{T_o}{T} \sum_{i} 10^{\frac{EPNL_i}{10}} \right], \text{PNdB}$$

where $T_o = 10$ seconds is the period of the equivalent continuous energy of the highest $\Delta$dB of each noise excursion, represented by the EPNL, then the index is seen to be the long-term average equivalent level of these 10dB range excursions. Although this index form facilitates its prediction by means of established EPNL ratings for the various aircraft types, and obviates the need for detailed noise-duration computations in the prediction of $L_{eq}$, it does not lend itself to monitoring or measurement methods capable of being encapsulated to a single instrumentation 'box', as does the $L_{eq}$.

Another index form, proposed by Robinson (Ref. 14), is the Noise Pollution Level,

$$L_{NP} = L_{eq} + K\sigma_L$$  \hspace{1cm} (1.5)

where $\sigma_L$ is the standard deviation of the noise level fluctuations and $K$ is an empirically derived constant. This index is based on the concept that there are at least two
properties of noise exposure which cause annoyance, the first being the long-term averaged level and the second being the variability of the noise over the exposure period. More recently a third property has been examined, that of the spread of time intervals between noise excursions (Reference 15).

This brief review of the historical development of the noise indices presently in use, or proposed for use, is necessarily incomplete. Many other indices such as the $L_{eq}$ with night-time energy weighting ($L_{dn}$) are being introduced or are in use abroad. The review given in this preamble to the following report sections is intended to illustrate the diverse nature of the various index forms. Although at present the only index applicable to aircraft noise exposure assessments at U.K. airports is the NNI, there is a growing debate on the need for a unified index (e.g. References 16 and 17) and a long-established debate on the need for a modified version of the NNI (e.g. References 18 and 19).

So, while much of the present report is concerned with the estimation of airport noise exposure in terms of the NNI, the apparent need for consideration of the problem in terms of other index forms is also attacked. Primary consideration is given to the problems of obtaining predictive estimates of noise exposure. Although the NNI has been in use for over a decade, there still seems to be some diversity in the basic predictive techniques employed by various consultancy and planning organisations.
Should some new index be introduced, this diversity of approach can be expected to widen and to take some considerable time to be developed into a quasi-confident expertise. With this consequence taken as worthy of study, the present work also examines the possibility of deriving prediction techniques for the other index forms, using the existing bank of knowledge on aircraft peak noise levels as a sufficient reference data set.

These practical aspects of the estimation problem are further reviewed and developed in the following sections. Finally, a specific method of predictive estimation of airport noise is presented. It is readily adaptable to be an extension of most other NNI prediction methods for purposes of estimating $L_1$, $L_{10}$, $L_{eq}$, $L_{NP}$ or other noise-duration based indices.
2.0 AIRPORTS AND NOISE EXPOSURE

2.1 Air Traffic and Communities

The main function of civil aviation airports is that of a terminal for the convenient arrival and departure of passenger and freight aircraft which, for the majority of their travelling time, are operated in controlled air corridors consistent with their most economic route and at altitudes which cause negligible noise at ground level. The airspace surrounding an airport serves as a connecting zone between the runway(s) and the "junction" areas of the controlled air corridors and it is while traversing this transitional airspace that aircraft cause noise-induced disturbance to the local communities. Figure 2 is an illustrative overview of the air corridors traversing the U.K., and shows a typical set of traffic control stations near which an aircraft will join or depart from the corridor by changing flight direction, altitude or both. Between the runway(s) and these intersection areas, the aircraft routes and altitude variations are controlled (usually) by the local airport traffic controller and in many cases will be constrained to an established set of explicitly-defined routes such as "Standard Instrument Departure" or "Minimum Noise" routings and flight procedures. Examples of such standard routings are shown in Figure 3 which illustrates their intended avoidance of highly populated zones while aiming towards objective air corridor intersections. Unfortunately, for practical reasons concerned with air traffic control, flight safety
and the avoidance of air space congestion, the routes cannot avoid all communities. Noise assessment is most needed in such regions, which may be close to the runways and thereby exposed to all of the aircraft movements, or distant from the runways but under a departure or landing route and thereby subjected only to the aircraft movements along that route.

The division of the movements into runway-use operations is a pre-requisite for route usage assessments. Many airports have a 'preferred' runway, that is, except in unsuitable wind conditions aircraft will normally take-off and land towards a specific direction of the runway(s) alignment. Two examples of a preferential system are:

".... Unless otherwise required by Air Traffic Control, Runway 24 shall be used for all movements when there is a head wind component and when a tail wind component is not greater than 3kts."

".... In weather conditions when the tail wind component is no greater than 5kts., on the main Runways 28R and 28L, these runways will normally be used in preference to 10R and 10L, provided the runway(s) surface is dry. When an associated cross-wind component on these main runways exceeds 12kts., a runway more nearly into wind will normally be used."

In both examples the preferred movement direction is due-west, into the prevailing wind. Analysis of these systems in relation to long-term (9-year) summaries of
wind vector statistics for the two example airports indicates that the preferred runways would be in use for 79% and 68% of the time, respectively, which compare well with the 80% and 62% usage during August 1972 (obtained from actual runway usage data). This comparison between time-period availability and percentage movement use is rather tenuous since the former is based on all-year, 24-hour, statistics whereas the latter is based on three-month summer season, 12-hour daytime data. However for estimation purposes where more accurate data on runway use is not available, a 70-30% distribution of movements towards the preferred runway is representative of typical U.K. airport conditions.

Route distribution of movements can be treated in a generalised manner, but requires detailed examination of the airport traffic statistics and operational instructions. In many cases sufficient information on defined departure routes is given in Reference 20 for U.K. airports. Where information is not so given, recourse can be made to other publications giving traffic patterns in relation to controlled airspace reporting stations (Reference 21). The more complicated problem is that of distributing the operations among the routes. Here, the most readily applicable approach is to cross-reference the most probable route-used with each flight destination. This form of traffic analysis can be accomplished by reference to detailed airport-runway movement data, or by examination of flight-schedules and assuming the 70-30% division of runway use.
The task of noise exposure prediction is therefore seen to be preceded by the task of estimating the air traffic numbers and fleet-mix which contribute to the exposure characteristics. The influencing factors which must be taken into account for traffic-estimating purposes are, in rank order of importance:

(i) the total numbers of aircraft movements arriving or departing at the airport within a specified period;
(ii) the distribution of these movements with respect to runway alignment, as dictated by wind conditions;
(iii) the distribution of the movements with respect to routings associated with each runway alignment,
(iv) the fleet mix of each route-usage;
and (v) further breakdown of the traffic operating conditions where such factors affect noise output and noise exposure.

Each airport will have unique statistical properties for each of these factors and will require a separate traffic analysis. Some general guidelines as to the expected order of effects can be obtained by review of traffic patterns pertaining at U.K. airports as a whole. Table I is a summary compilation of such information for selected airports and illustrates the individuality of each airport's traffic.

The air transport statistics given in the table include...
landing and take-off events of passenger- and freight aircraft, but do not include events caused by test and training programmes or by movements of empty aircraft between airports. These latter events must obviously contribute to the local noise exposure and in some cases may tend to cause most annoyance because of the concentration of (training) flights into short time periods. Such movements should therefore be included in the definition of the airport traffic matrix for noise estimation purposes, either by retrospective assessment or by projections of airport usage.

So far in this section the discussion of airport traffic has been limited to the spread of aircraft flights across the map of an airport region. It is obvious that the line-routes shown in the Figure 3 examples can only be regarded as a first-order approximation to the dispersal of departing traffic. In reality the aircraft follow these defined routes, but with some degree of lateral scatter about them. Since the noise level caused at a site by an aircraft flyby is dependent on the distance between the site and the aircraft, this lateral scatter must induce some variability into the overall traffic noise exposure, even if all the departing aircraft are of the same type. There are many other causes of variability (in addition to fleet-mix). Atmospheric effects on sound propagation are an obvious example, but are usually neglected in favour of a 'standard-day' atmospheric model. Of greater significance is the vertical spread of the departure flight paths. For any particular departure flight, the height profile of the flight path
will depend on the performance capabilities of the aircraft type under its loading conditions for the trip, on the noise abatement procedures dictated by the airport for the route used and on any height limitations imposed on the route usage for air-traffic control purposes. The last two of these are usually defined in literature governing airport use conditions (e.g. References 21, 22 and 23). The noise abatement procedures are usually defined by reference to the peak noise levels allowable at noise monitoring points (NMP) stationed under and to the side of the routes. The air-traffic control limitations are usually defined as a height at which, or above which in many cases, the aircraft should cross one of the navigational beacons (such as Burnham, Epsom, Ockham, Woodley, etc., in Figure 3(b)).

Considerable study has been made of methods by which this height profile spreading can be modelled for noise prediction purposes, with adequate definition given without detailed and laborious examination of each flight and of the aircraft's performance. The most notable of these models were derived by Bolt, Beranek and Newman Inc. (USA) under contract to the U.S. Federal Aviation Authority (References 24, 25 and 26 for example). The more recent of these is shown in Figure 4 and Table II where the height profiles are categorised and applied to a flight model according to the aircraft type and its destination range (which determines the fuel loading and hence the maximum climb rate capability). The noise abatement climb
rate is often taken as a fixed percentage of the maximum rate, as is the climb-to-cruise level rate. In recent work by Loughborough University on other aspects of noise exposure, these percentage rates have been taken as 40% and 60% respectively. The positions along the flight paths at which these power changes occur will depend on the airport controls. Typical of these is a cutback of power at 5.3km from start of ground run and a resumption of climb power at a height of 910 metres (3000ft.).

With all of the above prerequisite information compiled for a noise exposure prediction exercise, the task of noise level calculations for any particular site or for iso-noise contours around the airport can commence. This is best handled by means of a digital computer with large storage capacity. Various processing logics can be developed for such work. One such programme has been developed by the present author and his associates for the estimation of noise exposure around many U.K. airports (see preliminary referenced literature list). A typical listing of the input traffic data to this programme is shown in Table III. Here, the aircraft types, destination ranges, routes and climb profiles have been categorised and the corresponding average number of events in each category combination is used as the traffic statistic. This method follows closely that of References 24–26, although the programme detail is designed to be very flexible such that many different noise exposure indices and parameters (including NNI, $L_{10}$, $L_{eq}$, $L_{NP}$) can be computed in contour form.
There are clearly many other approaches to the statistical description of airport traffic. The above discussion is mainly of a quasi-deterministic approach with distinct divisions in the event models. A more realistic model would probably be that of a continuous distribution of the traffic (types, heights, lateral distances, etc.) relative to a site or line flight path. It is the author's contention that a much more simple and similarly accurate method is that in which the traffic statistics are basically those of route-usage and fleet mix, all other dispersion effects being incorporated in the technique for noise level calculation. This is developed in the following sections of the present report and in the noise prediction method presented in Section 5. It is still essential, however, to have an in-depth knowledge of the air traffic characteristics and imposed limitations on operations before embarking on a noise exposure assessment of any community environment.

2.2 Noise Exposure caused by Air Traffic

The noise exposure experienced by a community is fundamentally the time history of the noise level fluctuations over a very long period. Noise exposure indices are intended to provide a single-valued rating of this exposure, taking account of the subjective influence of the exposure on the community residents and of as many characteristics of the time history as is necessary (and convenient) to obtain an accurate rating of this influence. The indices must be amenable to measurement,
prediction and noise-abatement interpretation in order to satisfy all of their intended purposes. In the introductory section to this report it was shown that aircraft noise exposure indices, either in present use or being considered for use, fall into two forms. One form is mainly dependent on the statistical distribution of peak noise levels, and the other form depends on the distribution of durations of the noise above various levels. These are now examined with reference to specific examples of statistically analysed data obtained for regions around Heathrow (London) Airport and for Manchester and Liverpool airports. As extensive use of these data is made in this and subsequent sections, a description of the means of acquisition, analysis and compilation is separately given as Appendices to this report. These appendices should be read in order to gain a full understanding of the data-interpretation discussed here and elsewhere in the report.

Figure 5 is a graphical presentation of statistical noise data obtained by analysis of tape recordings of aircraft events, acquired over a 12-hour daytime period at three sites near Heathrow (London) Airport. Two of the sites were close to departure routes and the third site was close to the 3-degree glide slope approach path of one runway. The data for each site are plotted according to the percentile of peak level occurrences and the percentile of the 12-hour time period, respectively, for which specific noise levels were exceeded. These noise
levels were measured in dB(D) units and are presented in units of dB(D) + 7dB, which approximates to PNdB units (but see later comment on this). Step increments of 5dB were used in the analysis.

As a further explanation of the Figure, consider the two sets of data corresponding to the Site 3 exposure. Taking a vertical line through the 10-percentile base scale to intercept the interpolation lines through the upper and lower data sets (for Site 3) we obtain the level which was exceeded by 10% of the noise peaks and the level which was exceeded (by the time history) for 10% of the 12-hour period. In the notation used in this report, these levels are $L_{10}$ and $L_{10}$ respectively. The latter is in common with the noise duration based indices reviewed earlier.

The base scale of Figure 5 is Gaussian incremented about the 50-percentile reference, such that any Gaussian distribution of data would be represented on the graph by a straight line. It is apparent that the noise data measured at the three Heathrow sites can be approximately described by Gaussian distributions of peak levels and of noise durations. These descriptions must be qualified by noting that both distributions (for any site) will be truncated at some upper noise level which is not exceeded by any noise peak. The effect of this truncation on index evaluations is discussed later in the text and in an Appendix.

Before elaborating on these apparent Gaussian prop-
erties of the distributions, it is necessary to examine other noise exposure cases where the total number of flights is typically much less than that at Heathrow. These are presented in Figure 6, the noise data being graphically shown in the same format as those of Figure 5.

The Figure 6 data cases are based on the Site 3 Heathrow noise measurements, which are shown again for reference purposes, but are derived for equivalent sites near Manchester and Liverpool Airports (see Appendix II). The derivations make use of actual runway movement logs from these airports, noise data for each of the flights being extracted from the Heathrow measurements for the identical aircraft type and destination range. They are therefore simulations of noise exposures which would be caused at some sites near the two airports, of identical proximity to flight routes and runways as is Site 3 to the Heathrow Airport routes and runway(s), and assuming identical flight procedures at all three airports. The validity of these assumptions is unimportant to the interpretive use that is made of the data.

Of greatest significance in comparison of the three airport cases is that whereas the peak level distributions apparently retain their approximately Gaussian property, the noise duration distributions do not. This is examined in some detail in Section 3.1 where an analytical expression for the duration distribution is derived. Meanwhile a more general and conceptual interpretation of these data properties is made by considering the various forms of noise
exposure indices and their dependence on the distributions.

2.2.1 Peak Level-Based Indices

Indices based on noise peak level occurrences are the Noise and Number Index (NNI) and the Composite Noise Rating (CNR).

\[
\text{NNI} = L + 15 \log_{10} N - 80, \quad \text{PNdB} \quad (2.1)
\]

\[
\text{CNR} = L + 10 \log_{10} N_f - 12, \quad \text{PNdB} \quad (2.2)
\]

The first is that used in the U.K. for aircraft noise exposure assessment and is based on the number of flights "heard" and on the average peak-energy level of these \(N\) events, \(L\), given by,

\[
L = 10 \log_{10} \left[ \frac{1}{N} \sum_{i=1}^{N} \frac{L_i}{10} \right] \quad (2.3)
\]

In its accepted use, it is applicable to assessment by only considering flight events occurring during the daytime 12-hour period between 0600 and 1800 hours GMT. The CNR is similarly based on \(L\) and \(N\) but is a 24-hour assessment index with higher weighting given to the number of night occurrences of events.

\[
N_f = N_d + 16.7 N_n
\]

where \(N_d\) is the number of exposure-contributing flights within the period 0700 to 2200hrs. and \(N_n\) is the corresponding number within the period 2200 to 0700hrs. (local time).

The CNR was derived (1964) in the U.S.A. for application to regions around military airfields there. Its use for civil airport regions was given extensive study,
but due to the later derivation of the Effective Perceived Noise Level (EPNL) and its adoption as a regulatory measure of individual aircraft noise, the CNR was not formally used for the civil airport problem. Instead the Noise Exposure Forecast (NEF) is used.

\[
\text{NEF} = \overline{EL} + 10\log_{10} N_f - 88, \quad \text{EPNdB}
\]  

(2.4)

where

\[
\overline{EL} = 10\log_{10} \left[ \frac{1}{N} \sum_{i=1}^{N} 10 \frac{EPNL_i}{10} \right].
\]  

(2.5)

Now, noting the form of \( \overline{L} \) in equation (2.3) as containing an average of weighted peak levels, it is clear that it can be evaluated directly from the peak-occurrence distributions of Figures 5 and 6. Thus,

\[
\overline{L} = 10\log_{10} \left[ \int_{0}^{\infty} \frac{\hat{L}/10}{p(\hat{L}).d\hat{L}} \right]
\]  

(2.6)

where \( p(\hat{L}) \) is the probability density function of the 'continuous' peak level distribution.

If a Gaussian distribution is used to describe the peak level statistics, then, by substituting

\[
p(\hat{L}) = \frac{1}{\sqrt{2\pi}\sigma_p} \exp \left[ \frac{-(\hat{L} - \hat{L}_{50})^2}{2\sigma_p^2} \right]
\]

where \( \hat{L}_{50} \) is the 50 percentile level and \( \sigma_p \) is the standard deviation of the peak distribution, the result is obtained,

\[
\overline{L} = \hat{L}_{50} + \frac{\sigma_p^2}{8.68}
\]  

(2.7)
which is (now) well known in its equivalent form for $L_{eq}$ (discussed later). The assumption of the infinite limit in the integration and the potential error incurred by this, is examined in Appendix III. Equation 2.6 can be expressed as,

$$L = 10 \log_{10} \left[ \int_0^{\infty} \frac{\hat{L}}{10} \cdot dP(\hat{L}) \right]$$

(2.8)

which is suited to graphical integration of the Figures 5 and 6 peak occurrence statistics. In the present notation $100xP(\hat{L})$ is the percentile (base scale) of the figures corresponding to any level $\hat{L}$. In summation notation, for increments of 5dB in $\hat{L}$,

$$\bar{L} = 10 \log_{10} \sum_{i} \left[ 10^{\frac{\hat{L}_i}{10}} \cdot \left( P(\hat{L}_i - 2.5dB) - P(\hat{L}_i + 2.5dB) \right) \right]$$

(2.9)

(A correction of approximately 1dB should be added to the result of this estimate, to account for taking the arithmetic centre of the $\hat{L}$ stratum instead of the geometric centre.)

There is, however, a complication involved in using this definition of $\bar{L}$ in the NNI equation 2.1. This arises from the use of term "number heard" in the original derivation of NNI (Reference 5). In the later (1967) survey of Heathrow Airport noise (Reference 18) the NNI evaluations were based on peak levels which exceeded 80PNdB. This lower limit of significance has become adopted as a standard approach for NNI assessments. From the viewpoint of obtaining $\bar{L}$ by graphical means from the peak-occurrence statistics, the
80PNdB limit poses no severe difficulty. In using other methods, such as Equation 2.7, the incurred error can become large depending on the standard deviation of the distribution. Figure 7 shows how \( \overline{L} \) varies with change in the cut-off level of significance (\( \lambda \)) for one of the measured data cases of Figure 5. In this example \( \overline{L}_\lambda \) was evaluated by direct energy averaging of the population of \( \overline{L}_1 \) values, rather than by distribution integrating or other methods. It is seen that in the example case there is little contribution to \( \overline{L} \) made by peaks below 80PNdB. Energy-averaging gives higher weighting to the higher levels. A lower standard deviation (or a lower slope of the Figures 5 and 6 distribution lines) would change the emphasis of the weighting, but this would seem unlikely now in the light of the three airport cases.

Returning now to the air-traffic influence on noise exposure, it might be expected that the peak level distribution is quasi-stationary (in the statistical sense) for any particular site near a particular airport. Hence it would be expected to be independent of the total number of aircraft events and mainly dependent on the typical fleet-mix using the nearby route(s). \( \overline{L} \) would be then expected to be invariant with time, provided of course that a typical route usage occurred.

Figure 8 shows measured cumulative-period values of the average peak-energy level and NNI after each hour of a 12-hour period at 2 sites near Heathrow Airport. As would be expected, the average level approaches its final
(12-hour) value more rapidly than does the NNI, because of the increasing cumulative counting of the number parameter. However, it must be noted that even for a site near a very busy airport route a minimum of 5 hours of continuous monitoring was required to obtain an estimate of the average level within 1dB of the final level. Individual hourly averages over the day were scattered over a range +4, −6.5dB at Site 1, and +3.5, −4.5dB at Site 2. Thus it is clear that abbreviated sampling methods are not suitable as an alternative to the 12-hour averaging process. The NNI is a long-term averaged rating and is required to be estimated for a month or three-month "average" mode of operations. In order to examine the properties of the NNI over such a long period, recourse has been made to a noise prediction method by which the 12-hour values of NNI, average peak level, and the number parameter, have been estimated for the following airport operations cases at Heathrow Airport:

(a) the actual runway utilisation data for different days during August 1972, including the 'worst' cases on total movements and on movements in specific directions and routes;

(b) a runway utilisation case derived by averaging all movements of specific aircraft, by route and a loading factor, over a month of August 1972; and

(c) the actual runway utilisation data for the 12-hour daytime period of April 10, 1973.

The latter corresponds to the measured data cases.
which were acquired on that date at the three sites around Heathrow Airport.

The data obtained by these prediction and measurement exercises is compiled in Table IV. It is seen that good agreement has been obtained between the measured and predicted values of average peak-energy level for the three sites, and that very little variability has been predicted in the values of this noise parameter at each site over the fairly wide range of operations numbers. Based on these results, which do not allow for variations caused by extreme atmospheric effects such as high wind velocities and large-scale temperature inversions, it can be reasonably concluded that the Noise and Number Index contains a fairly stable parameter, the average peak-energy level, which is amenable to both measurement and prediction. From the measurement viewpoint, a single day measurement exercise would suffice to provide an estimate of $\bar{L}$ in a long-term NNI assessment.

Of greatest significance is the typical fleet mix using the route(s). Similarly, the peak level distribution can be regarded as stable and amenable to both measurement and prediction. One point of note to the measurement aspect, however, is the complexity of measuring in the Perceived Noise Level scale. The computational complexity of this scale requires a very laborious processing of the continuously changing sound pressure spectrum, in $\frac{1}{3}$-octave or octave band levels. This demands the convenience of digital computing facilities either on-site, or for later
processing of accurately recorded data. For peak level data it has been found that a good approximation to the peak Perceived Noise Level is given by the peak D-weighted Sound Level plus 7dB. In an extensive study of community noise (reference 27) this approximation was tested for over 4000 samples of aircraft noise events. The standard deviation of the error was 1.8dB over the total sample population. For NNI monitoring purposes this much simpler measurement process is now widely accepted as adequate.

From the noise exposure prediction viewpoint, the stability of the peak level distribution can be used to some considerable advantage in estimating $\bar{L}$, NNI and other indices such as $L_1$, $L_{10}$, $L_{eq}$ and $L_{NP}$. This is developed in sections 3, 4 and 5 of the present work.

The number parameter in the NNI, $15\log_{10}N$, can present more difficult problems in the measurement or prediction process, because of the 80PNdB cut-off. In the Figure 7 example a consistent error of 2dB, say, in the measurement of the peak levels would have introduced a 2dB error in $\bar{L}$ and about 1dB in $15\log_{10}N$, giving a total error of 3dB in NNI. However, reference to the statistical distributions of Figures 5 and 6, and consideration of these at lower levels (by a downward translation of the data), illustrates that the 2dB error could introduce an error on $15\log_{10}N$ of 4 to 5dB. This would give an error of 6 to 7dB on NNI. Clearly such cases would only occur where the NNI was of low magnitude, less than 20 say. This error potential should always be carefully examined when it is necessary to
predict or measure low order NNI values. Recourse to the
distribution analysis provides a clear method of such exam-
ination.

2.2.2 **Indices based on Noise Duration Statistics**

Level exceedence statistics are obtainable from noise
histories by means of analogue or digital processing equip-
ment. The most common form of output from such analysis is
of cumulative time counts, giving the time over which the
noise history exceeded pre-set levels (most often in 5dB
level increments). From these, the percentile duration
above each level can be calculated and presented graphically
as shown in the examples of Figure 5. The statistical
levels $L_{10}$, $L_{50}$, etc., can be interpolated from the graphs.

The main application of level-exceedence statistics has
been to assess road traffic noise. In a study of the
relationships between this type of noise and the attitudes of
communities to it, it was found that the correlation coef-
ficients of the regressions were 0.6, 0.45 and 0.26 for $L_{10}$,
$L_{50}$ and $L_{90}$ respectively. Multiple regression of these
levels with the attitude data indicated a significant prefer-
ence to an index based on $L_{10} - 0.75L_{90}$, from which the
Traffic Noise Index was derived. The correlation coefficient
for the TNI was 0.88.

In the U.K., the $L_{10}$ (18-hour) has been recently form-
ally adopted as the regulatory measure of noise exposure due
to road traffic noise. In the U.S.A., the noise assessment
guidelines used by the Department of Housing and Urban
Development for general noise environments (excluding air-
craft) are based on the level exceedence criteria (refs. 28, 29) as follows:

Unacceptable:

Exceeds 80dB(A) for 60 minutes per 24 hours, or
Exceeds 75dB(A) for 8 hours per 24 hours.

Discretionary (Normally Unacceptable):

Exceeds 65dB(A) for 8 hours per 24 hours.

Discretionary (Normally Acceptable):

Does not Exceed 65dB(A) for 8 hours per 24 hours.

Acceptable:

Does not Exceed 45dB(A) for more than 30 minutes per 24 hours.

As it is difficult to meet the last criterion even in remote rural countryside (see Reference 30), the usual distinction between acceptable and unacceptable (as applied in the U.S.A.) is that of 65dB(A) for 33% of a 24-hour period. If it is assumed that night-time noise is of a lower level, then for the eighteen-hour period of assessment used in the U.K. (for road traffic noise) this would correspond to a limit of $L_{44}$ equal to 54dB(A). The U.K. limit is $L_{10}$ equal to 68dB(A).

Another way of examining or comparing the various noise duration criteria is to consider them all as elements of a limiting distribution. This is shown in Figure 9 where a Gaussian distribution line criterion has been drawn through the $L_{10}, L_{50}$ and $L_{90}$ limits (between acceptable and unacceptable.
for each) given in Reference 8 work for 24-hour exposures. The U.S. HUD limit, and an aircraft limit of 92PNdB at L_{05}, have also been included. Also shown is a similar criterion line derived and proposed by Schultz (Reference 31). The interpretation and use of the line-distribution criterion is that if any actual (measured) distribution of noise level exceedences breaks through the limiting line, then the exposure would be assessed as unacceptable. It is interesting to note that if the limiting line is taken as an actual exposure distribution, the values of TNI, L_{eq} and L_{NP} for the exposure agree very closely with the centroids of regression obtained by re-analysis of the road traffic survey data. This re-analysis is reproduced as Figure 10 of the present report and is contained in Reference 30 based on Reference 8 results. It may be postulated that such a limiting distribution criterion provides both necessary and sufficient conditions of acceptability. The constituent elements, such as L_{10} or L_{50}, are only necessary conditions. From a practical viewpoint it would be desirable to place some constraints on the extent to which the distribution should be extrapolated. The L_{1} level, which would be the level exceeded for about 7 minutes of a 12-hour period, would include the worst cases of aircraft noise. Without such constraint, the criterion would apply also to impulsive (transient) noises such as quarry-blast explosions and sonic booms.
Consideration of the $L_{10}$ or higher-percentile levels in relation to the aircraft noise data of Figure 6 clearly indicates the inappropriateness of such indices for the airport exposure case. A lower percentile level, such as $L_1$, might be useful but there is no real evidence to support this contention. The use of the limiting distribution (Figure 9) or a family of such distributions each with a rating value for assessment purposes, would appear to be viable. Of the noise duration distributions presented in Figures 5 and 6, those which violated the Figure 9 criterion had NNI values in excess of 35NNI. Other sources of noise (road traffic, industrial plant, etc.) could easily be assessed in isolation from each other or as a total combined environment (including aircraft contributions).

Of greater interest, at present, is the potential use of the Equivalent Continuous Energy Level, $L_{eq}$, for individual and combined noise source fields. One of the benefits of such an approach is that $L_{eq}$ values for individual source fields (measured over the same time period and in the same units) can be energy added to give the overall $L_{eq}$. Thus a measured or predicted value of $L_{eq}$ for aircraft noise over a 12-hour period can be compared with $L_{eq}$ values for other sources operating in the same period, or energy added to them to obtain the overall value.

The basic definition of $L_{eq}$ was given in Section 1, Equation 1.3. In the same way as the average peak-energy level is obtainable from the peak-occurrence distribution.
(Equations 2.6 and 2.8), so also is $L_{eq}$ obtainable from the noise duration distributions. Thus,

$$L_{eq} = 10 \log_{10} \left[ \int_{0}^{\infty} \frac{L}{10} p(L) dL \right]$$

where $p(L)$ is the probability density function of the noise duration distribution. The graphical integration methods discussed in Section 2.2.1 are equally applicable to $L_{eq}$. Recourse to the Gaussian approximation form of Equation 2.7 cannot be confidently made in all the Figures 5 and 6 cases. Unacceptable errors would be incurred in the Manchester and Liverpool cases for example.

The difficulties associated with the prediction or noise abatement interpretive use of $L_{eq}$ are:

(i) its estimation requires detailed knowledge of the noise duration distribution;
(ii) this distribution is sensitive to the number of aircraft involved in the noise exposure, but this is not explicit in the index formulae;
(iii) there is no clear method of interpreting how to reduce a level of $L_{eq}$.

These difficulties are resolved in the next section, with specific consideration of aircraft noise exposures.
3.0 RELATIONSHIPS BETWEEN NOISE INDICES BASED ON PEAK LEVEL AND DURATION STATISTICS

In the preceding sections a review has been made of some of the basic characteristics of noise exposure due to aircraft traffic sources and of the noise indices currently used (or proposed) for assessment of noise exposures. It has been shown that many of the noise indices can be evaluated by reference to the statistical distribution of either the peak level occurrences or the level-exceedence durations. In this section the relationship between these distributions is examined for aircraft noise exposures, and the corresponding dependencies between noise indices are developed.

3.1 The Noise Exposure Distributions

The aircraft traffic noise environment is considered as a succession of individual and separable noise events, in which the overlap of the noise level excursions can be neglected. Further, the statistical distribution of peak level occurrences is considered to be known (or readily predictable by existing estimation methods*) and to be adequately approximated as Gaussian. It is also worth noting again that the peak occurrence distribution is relatively stable (invariant) with respect to time (in the day-to-day sense) and the total number of daily movements at the airport. The main dependency (other than distance to the flight route) is that of fleet mix.

*See Section 4.0 for examples.
The problem to be tackled here is to derive a definition of the statistical properties of the level exceedence durations, based on knowledge of the peak level distribution and other parameters. The inverse problem is well known in other topics such as cumulative fatigue damage of structures, but is based on the existence of Gaussian properties of higher order than can be assumed for the present work. Instead, a much simpler model of each noise level excursion is used here to obtain a solution.

Consider a single noise level excursion caused by an aircraft travelling along a straight line path with a minimum slant range distance $h$ from the (noise-exposed) site (Figure 11(a)). The peak sound level at the site is $L$, caused by the aircraft at its closest approach point. The directivity of the sound level radiated from the aircraft is assumed to be spherically uniform when measured in dB(D) or PNdB (as shown in Reference 32).

The time history model to be used is a symmetrically triangular sound level excursion, by which the duration of the sound above a level $\lambda$ is given by,

$$t_\lambda = \frac{2(L - \lambda)}{\frac{dL}{dt}}$$

(3.1)

as shown in Figure 11(b).

Now the sound level caused by the aircraft at some other radius $r$ is:

$$L(r) = L(h) - 10\log(r/h)^k$$
where \( k \) is the propagation exponent, usually taken as equal to 2.67 (for 8PNdB attenuation per distance doubling) for air-to-ground propagation. Neglecting retarded time effects, we have for the time history,

\[
L(t) = L - 10 \log_{10} \left( 1 + a^2 t^2 \right) \quad \text{for the time history,}
\]

where \( a = U/h \), \( U \) is the aircraft speed. Hence,

\[
\left| \frac{dL}{dt} \right| = \frac{10 \, ka}{2.31} \left( \frac{at}{1 + (at)^2} \right)
\tag{3.2}
\]

Figure 11(c) shows the manner in which the bracketed term varies with \( at \). Of particular interest is the average value between the peak (\( at = 0 \)) and various \( at \). It is seen that

\[
10 \left( \frac{at}{1 + (at)^2} \right) = 3.0
\]

will give a reasonable approximation. Substituting this in (3.2), equation (3.1) becomes,

\[
\lambda = \frac{2(L - \lambda)}{\left| \frac{dL}{dt} \right|} = \frac{(L - \lambda)}{0.65ka}
\tag{3.3}
\]

Now, for \( N \) aircraft events whose peak levels are continuously distributed with probability density \( p(L) \), the total time for which the level \( \lambda \) is exceeded can be expressed as,

\[
T_\lambda = N \int_{\lambda}^{\infty} \frac{(L - \lambda)}{0.65ka} \cdot p(L) \cdot dL
\tag{3.4}
\]

The use of an infinite upper limit in this equation is of course questionable, because we know that there is always a finite truncation of the peak level distribution. This point, and its consequences on the developed results, are
examined in Appendix III. The infinite limit is retained here for simplicity of integration. It is also worth noting that the development of the model can be further simplified by taking the average value of $ka$ as applicable to all events on a particular route.

Hence the fraction of time for which $\lambda$ is exceeded, when the $N$ events occur within the total time period $T$, is,

$$ P(\lambda) = \frac{T\lambda}{T} = \frac{N}{T} \int_{0.65ka}^{\infty} \frac{(L - \lambda)}{0.65ka} \cdot \exp(-0.65ka) \cdot dL $$

(3.6)

Substituting the Gaussian distribution model of the peak level occurrences this becomes,

$$ 0.65ka P(\lambda) = \frac{N}{T} \cdot \frac{1}{\sqrt{2\pi} \sigma_p} \int_{\lambda}^{\infty} \left( \frac{L - \lambda}{\sigma_p} \right) \exp\left( \frac{(L - L_{50})^2}{2 \sigma_p^2} \right) dL $$

(3.7)

where $L_{50}$ is the average peak level and $\sigma_p$ is the standard deviation of the peak level distribution. With $u = (L - L_{50})/\sigma_p$ equation 3.7 becomes

$$ 0.65ka P(\lambda) = \frac{N}{T} \cdot \frac{1}{\sqrt{2\pi} \sigma_p} \int_{u}^{\infty} \left[ \sigma_p u + (L_{50} - \lambda) \right] e^{-\frac{u^2}{2}} \cdot du $$

(3.8)

with the resultant expression for $P(\lambda)$ as:

$$ 0.65ka P(\lambda) = \frac{N}{T} \cdot \frac{\hat{L}_{50} - \lambda}{2} \left[ 1 + \text{erf} \left( \frac{\hat{L}_{50} - \lambda}{\sqrt{2} \sigma_p} \right) \right] $$

$$ + \frac{\sigma_p}{\sqrt{2\pi}} \exp \left( \frac{(\hat{L}_{50} - \lambda)^2}{2 \sigma_p^2} \right) $$

(3.9)

This equation can now be used to give an estimate of $P(\lambda) \times 100\%$, which is the percentage of the total time period $T$ for which the level $\lambda$ is exceeded. The distribut-
bution of \( P(\lambda) \) can be drawn, or by inserting a percentile value the corresponding level of \( \lambda \) can be estimated. Thus by inserting \( P(\lambda) = 0.5 \), the resultant \( \lambda \) is \( L_{50} \), etc. The information required for such evaluation is:

(i) \( L_{50} \) and \( \sigma_p \) for the peak level occurrences;
(ii) the number of events occurring in the time period;
(iii) the average value of \( a = U/h \) for the aircraft route, and
(iv) the propagation exponent, \( k \), appropriate to the site position relative to the flight path.

Taking \( k = 2.67 \) (8dB per distance doubling) and \( T = 3.6 \times 10^3 \) seconds, \( N \) becomes the average number of flights per hour. The expression (3.9) becomes,

\[
6.25\left(\frac{\sigma}{n}\right)^2 \times 10^3 \times P(\lambda) = \frac{\left(L_{50} - \lambda\right)^{-2}}{2 \sqrt{\pi} \sigma_p} \left[ 1 + \text{erf}\left(\frac{L_{50} - \lambda}{\sqrt{2} \sigma_p}\right) \right] + \frac{\sigma_p}{2 \sigma_p^2}
\]

where \( n \) is the average number of flights per hour and \( a = U/h \) in units of 1/seconds.

An obvious and available test on the validity of equation 3.10 is in its application to the Figure 6 data cases for sites near Heathrow, Manchester and Liverpool Airports. For all three test cases a slant range distance (h) of 610 metres (2000ft.) is taken as this was the average estimate when the original data was measured. An average aircraft speed of 91.4 metres per second (300f.p.s.) is taken giving a equal to 0.15. Table V is a compilation of
calculated results from equation 3.10, using $\sigma$ from the
Figure 6 peak-occurrence distributions and the appropriate
average number of flights per hour for each of the cases.
These are further presented in graphical form in Figure 12,
being superimposed as continuous line distributions on the
data from Figure 6. It is seen that very close agreement
is obtained for the Liverpool and Manchester cases. The
distribution given for the Heathrow case is about 3dB too
high. This could be due to the overlap of noise events
that was noted to occur during the measurements and is inc-
luded in the analysed data. The theoretical model does not
account for such overlap and would therefore be adding
components of time histories that in fact occur simultaneously.
This overlap problem will only typically occur at sites
close to Heathrow Airport, which has very high numbers of
operations per hour, and should be negligible when the estimate
is for an averaged condition over a month or three month
period.

Equation 3.10 is therefore considered to be a novel and
very useful method for predicting noise durations. Its
application to noise exposure index estimation is now
examined.

3.2 Noise Indices

3.2.1 The equivalent continuous energy level ($L_{eq}$)

In section 2.2 the definition of $L_{eq}$ was given in
alternative form as

$$L_{eq} = 10\log_{10} \int_{0}^{\infty} \frac{L}{10} \cdot p(L) \cdot dL.$$
where \( p(L) \) is the probability density function of the time distribution of level \( L \). Using the \( \lambda \) and \( P(\lambda) \) notation of the preceding subsection (3.1), the form of \( L_{eq} \) can be rewritten as

\[
L_{eq} = 10 \log_{10} \int_{0}^{\infty} 10 \lambda_{10}^{10} p(\lambda) \, d\lambda
\]

\[
= 10 \log_{10} \int_{0}^{\infty} 10 \lambda_{10}^{10} \frac{dp(\lambda)}{d\lambda} \, d\lambda
\]

From equation 3.10, with \( k_{i} = 6.25(a/n) \times 10^{3} \), we obtain

\[
k_{i} \frac{dp(\lambda)}{d\lambda} = - \frac{1}{2} \left[ 1 + \text{erf} \frac{z}{\sqrt{2} \sigma_{p}} \right]
\]

where \( z = \frac{L_{50} - \lambda}{\sqrt{2} \sigma_{p}} \)

Equation 3.11 therefore becomes,

\[
L_{eq} = 10 \log \left[ \frac{\sigma_{p}}{\sqrt{2} k_{i} 10} \int_{0}^{\infty} 10^{-\frac{z}{\sqrt{2} \sigma_{p}}} (1 + \text{erf}z) \, dz \right]
\]

This can be expanded to,

\[
L_{eq} = L_{50} + 10 \log_{10} \left( \frac{\sigma_{p}}{\sqrt{2}} \right) - 10 \log_{10} k_{i} + 10 \log_{10} \int_{0}^{\infty} 10^{-\frac{d}{\sigma_{p}}} (1 + \text{erf}z) \, dz
\]

where \( \sigma = \frac{\sqrt{2} \sigma_{p}}{10} \)

The last term in the above equation has been numerically evaluated for various levels of \( \sigma_{p} \) in the range

\[
3 \leq \sigma_{p} \leq 16 \quad \text{(dB)}
\]
and the results graphically presented in Figure 13. So

$L_{eq}$ can now be estimated by means of equation 3.13 and

Figure 13. An approximation to the last term is also shown

in the Figure. This has been restrained to a single $\sigma_p^2$

term for the following purpose:

With the last term approximated by $\sigma_p^2/10$, (which is

within ±1dB over the range $6 \leq \sigma_p \leq 15$, and underestimates

at lower $\sigma_p$) equation 3.13 becomes,

\[
L_{eq} = L_{50} + \frac{\sigma_p^2}{10} + 10\log_{10}\left(\frac{\sigma_p}{\sqrt{2}}\right) - 10\log_{10} K_i
\]

\[
= L_{50} + \frac{\sigma_p^2}{8.68} + 10\log\left(\frac{\sigma_p}{\sqrt{2}}\right) - 10\log_{10} K_i - \frac{\sigma_p^2}{65.76}
\]

\[\cdots (3.14)\]

Using again the assumption of a Gaussian distribution of

peak level occurrences, then the average peak-energy level

is,

\[
\bar{L} = L_{50} + \frac{\sigma_p^2}{8.68} \quad \text{(from equation 2.7)}.
\]

Also, we have

\[
10\log_{10} K_i = 10\log_{10}\left(\frac{6.25 \times 10^3 \times U}{h \times n}\right)
\]

Equation 3.4 therefore becomes,

\[
L_{eq} = \bar{L} + 10\log_{10} h + 10\log_{10}(h/10U) + 10\log_{10}(\sigma_p)
\]

\[\cdots - \frac{\sigma_p^2}{65.8} - 29.5, \text{ dB} \quad (3.15)\]

This can be compared with the Noise and Number Index and Com­

posite Noise Rating when these are written in terms of the

average hourly number of events; thus,
NNI = $\bar{L} + 15\log_{10} n - 63.8$, \quad \text{PNdB} \quad (3.16)

CNR = $\bar{L} + 10\log_{10} n_f + 1.8$, \quad \text{PNdB} \quad (3.17)

where the NNI is a 12-hour index and CNR a 24-hour index.

If \( \sigma_p \) equal to between 6PNdB and 7PNdB is taken as typical and a site is considered where \( h \) is typically 915 metres (3000ft.) slant range, \( U \) is typically 91.5 metres per second (300f.p.s., 190 kts), then the \( L_{eq} \) formula becomes,

$$\text{Leq} = \bar{L} + 10\log_{10} n - 22, \quad \text{PNdB} \quad (3.18)$$

The apparent differences among these index forms must be resolved by their correlation to attitude survey data. However, if a very wide range of uncorrelated noise and number conditions were included in the survey then it must be expected that only one of these index forms would emerge as most suitable.

Calculated values of \( L_{eq} \) and NNI, using equations 3.15 and 3.16 are given in Table V for the Heathrow, Manchester and Liverpool site conditions. These are plotted in Figure 14 and suggest the co-relationship

$$\text{Leq} = 0.80\text{NNI} + 44.5 \quad \text{(PNdB)}$$

While this agrees with other empirically derived relationships for converting NNI to \( L_{eq} \), a comparison of Equations 3.15 and 3.16 would suggest that a more accurate expression is,

$$\text{Leq} = \text{NNI} - 5\log_{10} n + 34.3$$
$$+ 10\log_{10} \left(\frac{h}{1000}\right) - 10\log(U/100)$$
$$- 10\log_{10} \left(\frac{\sigma_p}{65.8}\right) \quad (3.19)$$
Average values of speed \( (U) \) and altitude as functions of distance along route (from start of roll) are derived in Section 5 for application to the noise prediction method.

Referring back to the discussion in Section 2.2.2 of the difficulties associated with the application of \( L_{eq} \) to aircraft noise exposures, it can be seen that the foregoing analytical work has helped to resolve these. A detailed knowledge of the noise duration distribution can be obtained from available information on the peak level occurrences. The dependence of \( L_{eq} \) on traffic and other parameters can be more readily appraised and various trade-off approaches to reducing an \( L_{eq} \) assessment can be derived by means of equation 3.15.

### 3.2.2 The Noise Pollution Level \( (L_{NP}) \)

The \( L_{NP} \) was conceived by Robinson of the National Physical Laboratory as being of the form,

\[
L_{NP} = L_{eq} + K\sigma_L
\]

where \( \sigma_L \) can now be regarded as the standard deviation of the noise duration distribution. When applied in a regression analysis of Griffiths and Langdon's road traffic survey data (Reference 8) the form of \( L_{NP} \) was found to be,

\[
L_{NP} = L_{eq} + (L_{10} - L_{90})
\]

which for a Normal (Gaussian) distribution of noise durations gives \( K = 2.56 \). That is,

\[
L_{NP} = L_{eq} + 2.56 \sigma_L
\]

which is now the known form of \( L_{NP} \).
So, to estimate \( L_{NP} \) by measurement or predictive methods, there is again the need to develop the noise duration distribution. This time it is not only for an evaluation of \( L_{eq} \) but also for \( \sigma_L \). No attempt is made here to derive a simple equation for \( \sigma_L \) in terms of the peak-occurrence and traffic statistics. The obvious available approach, using the results of the earlier sections, is to evaluate both \( L_{eq} \), \( \sigma_L \) and subsequently \( L_{NP} \) by development and analysis of the duration distribution. For a single site assessment, this can be done quite quickly by manual computation. For a large number of sites recourse can be made to a fairly simple digital computer programming task.

Before leaving the \( L_{NP} \) as a discussion topic, an interesting point can be made regarding its formulation. It has been shown in Figures 5 and 6 that for aircraft noise exposures the peak-occurrence and noise duration distributions are well separated in their significant level range (as indicated by \( L_{1-1} \), \( L_{10-10} \), etc.). The standard deviations of the distributions, \( \sigma_P \) and \( \sigma_L \) respectively, are also quite different for any particular site, but this difference decreases as the average number of flights per hour is increased. Now reference to Figure 15 and equation 3.10 provides an interesting comparison for road traffic noise. The Figure contains analysed data for peak distributions and noise duration distributions obtained from tape recordings of noise exposures near the M6 motorway. The measurement site was 36.5 metres (120ft.) from the motorway and the traffic flow rate was 1100 vehicles per hour.
(The actual sample time was 15 minutes). Taking the average vehicle speed as 100km/hr. (60m.p.h. or 88f.p.s.) and observing that \( \sigma_p \) is about 7dB, Equation 3.10 gives for 
\[ \hat{L}_{50} - L_{50} \]
which agrees with the measured data despite the obvious question of overlap error. Further examination of equation 3.10 and change of the propagation exponent from 2.67 (8dB/distance doubling) for the road traffic case, gives the inequality,
\[ \hat{L}_{50} - L_{50} < 4.5 \times 10^3 \frac{\sigma}{\bar{n}} \]
So, at distances of about 20 metres from a very busy city road the separation between \( \hat{L}_{50} \) and \( L_{50} \) would be expected to be very small. This closeness of the peak and noise duration statistics has apparently been observed in measured \( L_{10} \) data, as use is sometimes made of a method of measuring \( L_{10} \) by reference to the peak needle fluctuations of a sound Level Meter.

With this point made, regarding the near coincidence of the peak and duration distributions for road traffic noise, some inference can be made about noise indices.

For the coincidence case,
\[ \bar{L} = L_{eq}, \quad \sigma_p = \sigma_L \]
and \( L_{NP} = \bar{L} + K \sigma_p \)
With the addition of a number term this would look very
much like a Noise and Number Index for road traffic. The \( \sigma_p \) term would be an additional accounting of the traffic mix condition and hence of the variability of the noise that Robinson suggests should be included.

3.3 Summary

In this section an analytical noise model has been developed which allows the distribution of noise excursion durations to be predicted from knowledge of the more stable peak statistics and other parameters. It has been shown to give good agreement with measured data and to provide a simple means of predicting \( L_{eq} \) and \( L_{NP} \).

It uses as a predictive tool is of course dependent on the availability of a separate method for predicting the peak-level distribution for air traffic. Many predictive methods capable of satisfying this latter requirement are currently being used for NNI assessment purposes although their usage is usually restricted to estimating \( \bar{L} \) and \( 15 \log N \) directly. The basic form of these methods is discussed in the next section and an alternative method is derived from further study of the Heathrow site noise measurements.
4.0 THE PREDICTION OF AIRCRAFT NOISE PEAK LEVELS

4.1 Introductory Review

The noise radiated outwards from an aircraft to a distant site is a complex mixture of frequency spectrum components emitted from various stages of the aircraft engines. The components may be tonal, such as the whine of the engine compressor or fan, or may be broadband random such as the roar of the jet efflux noise. They may be predominant in a particular frequency region of the auditory spectrum range, or extend over a wide spectral domain. From a noise exposure prediction viewpoint, the contributory sources are of little interest because their individual contributions are difficult to estimate even when detailed information on the engine operating parameters is known. Of greater significance is the influence that the spectrum shape and content plays in controlling the behaviour of the subjective aspects of the noise, as summarized by the PNdB level or other noise scales. Many studies of these spectral properties have been performed (References 2,3,4,32,33,34 for example) with various purposes in mind. Some of these have led to well-developed empirical methods for the prediction of aircraft noise levels (References 24 to 26 for example). Such results are used here, in conjunction with other data, to derive a peak level prediction method suited to estimating noise exposure statistics.

The flight path of an aircraft using an airport can be partially defined by the ground trace of its allocated arrival or departure routeing. In following this routeing the aircraft will be operated at different engine-power settings to pro-
vide the necessary climb rate or descent-rate commensurate with performance and safety requirements. As the noise output from the aircraft varies with engine power setting, so also does the height profile of the flight path, thereby causing a double influence on the noise level reaching the exposure site. The prediction of the noise peak level due to an aircraft event must therefore be based on an adequate modelling of the power-setting profile of the aircraft flight path. This is commonly achieved by defining the operation as a segmented history of power-setting modes, comprising the appropriate of the following settings:

(i) maximum take-off power
(ii) noise-abatement climb power
(iii) climb-to-cruise-level power
(iv) 3-degree glide approach power

Other settings, such as reverse thrust after touch-down and level flight to intersect the glide slope, can be included in the noise model.

A typical take-off procedure from airports where noise-abatement procedures are mandatory will consist of a maximum power take-off from the runway "to a height of at least 1000ft., at which power will be reduced to a setting which provides a reducing level of noise at ground level while maintaining a minimum climb rate of 500ft. per minute." This cut-back power condition is usually maintained to a height of at least 3000ft. (or 1000metres) and is followed by an increase of power setting to give an increased climb-
rate to achieve cruise level, or to give increased flight speed. Local airport traffic controls may dictate other procedures, such as level flight at 2500ft., when crossing navigational beacons.

For noise prediction purposes, when account must be taken of flights by different aircraft on different routes, the most common approach used is to categorise these events. For each event category a model of the flight path profile and aircraft noise emission is compiled. Figure 16 shows a straight-line-segmented representation of a flight path travelled by an aircraft in its departure from an airport. For digital computing purposes this flight path can be represented by a system of ground plane co-ordinates, two co-ordinate values being used to specify the extremity of each segment of the projected ground trace. The height profile is initially defined by the ground run distance and maximum climb rate. The model is further segmented to include subsequent changes of aircraft power setting, giving changes in the climb rate and in the noise output from the aircraft. Thus the noise output is constant along a segment, but may differ from segment to segment.

The noise exposure at any site in the vicinity of the airport can, in general terms, be defined by the peak noise level caused at the site by each aircraft and by the durations of the noise above specified levels. For the flight trajectory shown in Figure 16 it is therefore necessary to estimate the maximum radiated noise level at the site.
and the duration of the noise excursion above the specified levels. In a computerised method this can be accomplished for each segment of the flight path, the peak level for the overall event being the highest of the segment maxima and the total durations being summated over the segments. This approach is repeated for other aircraft using the route and for other conditions of climb rates and power settings along the route and subsequently for all other routes and route users which contribute to the site noise exposure. From the resultant set of peak noise levels, the average peak energy level and the number of events above various specified levels can be computed, leading to an NNI estimate and to the peak distribution. The total noise durations above preset levels (e.g. 80, 85, 90, 95PNdB, etc.) can be used to give estimates of $L_{10}, L_{50}, L_{eq}, L_{NP}$, etc., for each site. By continuing this computation process for a grid-matrix of site co-ordinates and using an interpolative subroutine on the results, iso-noise contours can be plotted for the airport region in any of the estimated exposure parameters or indices.

This computational method is essentially similar to those used in the U.K. and U.S.A. for NNI and NEF predictions. The particular form described above and developed for noise duration estimates is reported in Reference 35. One of the limitations of the method is that of adequately describing the variability of the noise peak levels at a site, particularly when most of the flights have a common route and height profile. The method also requires a very elab-
orate and detailed analysis of the airport traffic in terms of destination range, which indicates the climb-rate capability of each aircraft. These problems could be overcome by a less rigorous breakdown of the climb-rate dependency than that given in Table II and by incorporating a lateral spread of the aircraft routes about their defined (Figure 3) traces.

An alternative approach is pursued in the present study. This leads to a simpler method of predicting the peak level distribution for a site, which can then be used in conjunction with the Section 3 results to give estimates of other noise exposure properties. It is based on measured distributions of noise peak levels, rather than on elaborate distribution of the climb profiles of aircraft flights along a route. From a practical viewpoint, the former is more readily measurable and in the earlier discussions was considered to be stable such that a measured distribution of peaks can be taken as a long-term characteristic of a site exposure.

4.2 An Alternative Method

Figure 17 shows a breakdown of the noise peak data for each of a number of aircraft groups which contributed to the total peak level distribution at two sites near Heathrow. The total peak distributions are taken from Figure 5 and were measured at the two sites shown in the insert, one being subjected only to aircraft landing movements and the other only to take-off events. The noise peak data for individual aircraft and aircraft groupings were compiled
by cross-reference of the measured event peaks with the actual runway utilization logs for the measurement period. In the take-off data, only aircraft using Clacton/Daventry departure routes have been extracted from the overall compilations.

The landing case data are of special significance because the aircraft flights are constrained to two well-defined approach paths, the 3-degree 'glide-slopes' for each runway. No obvious deviation from the nearer of these paths was observed for the runway 28R landings during the test period. Although the mean peak levels of the aircraft group data are well spaced discrete values, the dispersion of the peaks about these mean values is sufficient to transform the total distribution into a continuous form. A more detailed presentation of these data is given in Table VII which shows that breakdown of the noise peaks by aircraft type, rather than by grouping, provides very little reduction of the dispersion. The typical standard deviation of the data is about 3.5dB for an aircraft type or grouping.

The departure case data of Figure 17 are similarly dispersed in each aircraft grouping, the typical standard deviation being of the order of 5dB. Again, breakdown by aircraft type provides little benefit (Table VIII). In these cases there are explanations for the noise dispersion, other than that of a variation in engine power settings, which have been described as lateral and vertical flight path spreads. Horonjeff and Soroka (Reference 36) attempted an analysis of these spreads by reference to histograms.
of take-off weights, but the latter could not be found to follow any established probability law.

The alternative approach to predicting noise peak distributions is based on the observations of the peak level dispersion. It is assumed that the air traffic along a known approach or departure route can be described by a categorised breakdown of the traffic mix, namely:

- Jumbo (B747)
- 4-engined Turbofan (B707, DC8, VC10, etc.)
- 3-engined Turbofan (B727, HS21, etc.)
- 2-engined Turbofan (DC9, B737, BAC1-11, etc.)
- 4-engined Turboprop (VC8, VC9, etc.)

Other categories, such as wide-body, 3-engined aircraft (DC10, L1011) or 2-engine turbopropellor aircraft can be included when necessary.

Now rather than account for the noise distribution by further subdivision of the traffic mix, as is required for use of Figure 4 via Table II, we can associate the mean peak level caused by each aircraft category with the mean flight profile for that category. The dispersion of these peaks about their respective mean values can be subsequently made in the statistical development of the noise distribution.

To predict the mean peak level caused by each aircraft category it is necessary to know the slant range distance of the (average) flight path relative to the exposed site. The horizontal component of this distance can be taken as the minimum distance between the site and the defined ground trace of the intended route (Figure 3).
The vertical component (height) can be obtained by constructing an average climb profile for the particular aircraft category. An example of this is now developed.

From tables of "Aircraft Type and Utilization" published in the Civil Aviation Authority Monthly Statistics (Reference 37) the average stage destination range of each of about thirty different aircraft types used as U.K. airports can be calculated. Taking summer season statistics and calculating these averages for the type-categories mentioned earlier, the typical stage distances are,

- B747 3900 miles
- 4eng.TF 3200 miles
- 3eng.TF 700 miles
- 2eng.TF 600 miles

These values can be used in conjunction with Figure 4 and Table II to define the average initial take-off profile of each aircraft category. The subsequent profile characteristics are dependent on the power cut-back climb rates and where these commence. For the Reference 35 computer programme, the present author used a cut-back rate given by 40% of the initial climb-rate, and a cut-back point of 5.3 kilometres from start of ground run (provided the aircraft height exceeded 1000ft.). Comparison of the profiles given by these procedures, with radar-tracked height data provided by the Civil Aviation Authority, is shown in Figure 18. It is seen that the profiles would agree slightly better if a cut-back commencement criterion of 1500ft. height was used. It is also evident that there is no
noticeable change in climb rate at the 3000ft. height point.

Figure 19 shows the developed average height profiles for the five aircraft categories, based on the preceding arguments and observations. These can be used to develop the peak level distributions of noise for any site and for the noise duration computations of Section 3 (by calculation of the slant range distances). The landing path height profiles are simply given by a 3-degree glide slope extending from a runway point that gives 50ft. clearance height at the runway threshold, to a height of 2000ft. which is the usual intersection from a level flight approach condition.

The remainder of the peak distribution development is fairly straight forward. The mean peak level caused by each of these aircraft categories and its flight profile is estimated by means of any preferred method (e.g. References 24 - 26). One method is given in the next subsection. These are inserted in Column 2 of Table IX. The percentage fleet mix of the aircraft using the route is inserted in Column 3 of the Table. These route-usage percentages are now distributed over the 5dB incremented (peak) noise level bands as follows:

- Band containing $PL_2$ 0.38P%
- Bands containing $PL_2 - 5dB$ and $PL_2 + 5dB$ 0.24P%, each
- Bands containing $PL_2 - 10dB$ and $PL_2 + 10dB$ 0.07P%, each
These are derived from standard deviations of aircraft noise in take-off conditions. For aircraft on approach routes the corresponding criteria are:

- $PL_2$ Band: 0.60P%
- $PL_2-5\text{dB}$ and $PL_2+5\text{dB}$ Bands: 0.19P%, each
- $PL_2-10\text{dB}$ and $PL_2+10\text{dB}$ Bands: 0.01P%, each

With the appropriate percentage occurrence values inserted in the Table, the cumulative distribution can be obtained by column summations. The probability of peaks exceeding each 5dB incremented level is then obtained by right-to-left cumulative summation of the column sums.

The description given above applies only to the traffic on a single route. This can be extended to apply to traffic on a number of routes, provided the Column 3 summation total is 100%. However if noise durations are to be estimated it is essential that the different routes be treated separately.

4.3 Aircraft Noise Peak Levels

The modelling of the noise of an aircraft is most readily accomplished by definition of a noise level at a specified reference radius from the aircraft, together with a propagation law for the estimation of levels at other radii. Since such modelling is, of necessity, empirical in derivation then the precaution must be taken that the reference level and propagation law are compatible over a wide range of radii, thereby providing minimised error over the range rather than at one radius only. Thus the reference value must be derived in conjunction with
the propagation law. The model can be expressed as:

\[ L_{ij}(r) = L_{ij}(R) - A_{ij}(r,R) \]  

(4.1)

where \( L_{ij}(R) \) is the noise level produced by aircraft type \( i \) at power setting \( j \), at the reference radius \( R \); \( L_{ij} \) is the corresponding level at some other radius \( r \); and \( A_{ij}(r,R) \) is the atmospheric propagation loss over the radius difference between \( r \) and \( R \). For peak noise levels it is the common practise to base the model on the minimum slant range distance between the site and the flight path (segment). The model is therefore of cylindrical radiation form, as opposed to a spherical form and the expression required is

\[ \hat{L}_{ij}(r) = \hat{L}_{ij}(R) - \hat{A}_{ij}(r,R) \]  

(4.2)

In order to use, and compare, reference data from other literature, the reference sideline distance \( R' \) is taken here as 1000ft. (304 metres).

The propagation law can be expressed in many different forms; as a constant attenuation per doubling of distance, or as an attenuation per unit distance, or as a combination of these. The last is probably the most accurate as the attenuation has a spherical divergence content (6dB per distance doubling) and atmospheric losses (dispersion and dissipation) which are usually expressed as per unit distance. However, for extrapolation of noise levels in PNdB units the use of a distance doubling law has become the most common approach. With this, the value of 8PNdB per distance doubling can be taken for air-to-ground propagation (that is, for propagation paths at high incidence angles to the ground plane) without much controversy. Lanzer's peak
level data (Reference 32) suggests that attenuations of the order of 10 or 11 dB(D) per distance doubling are more accurate for the maximum power take-off condition. De Witt's limited data (Reference 38) also suggests this and that the 8 dB/distance doubling occurs at cut-back power condition. However, without extensive substantiation that these results apply to peak PN dB levels over a wide range of distance, there seems little justification (at present) for use of these higher attenuation rates. Equation 4.2 therefore becomes, for air-to-ground propa-
gation,

$$\hat{L}_{ij}(r) = \hat{L}_{ij}(R) - 26.67 \log_{10}(r/304)$$  \hspace{1cm} (4.3)

where \( r \) is in metres. (\( R = 304 \) metres).

Application of this propagation law to available published data on noise peak levels allows a comparison to be made of the reference levels suggested by these data. These are compiled in Table X for the landing, level flight, and take-off modes of aircraft operation. The set of reference peak levels to be used in the following sections is also given in the Table.

4.4 Noise Propagation at Low Ground Angles

Equation 4.3 must not be used for the prediction of noise level at sites where the propagation path is at low angles to the ground plane (less than 15 degrees, say). For such cases the extra attenuation caused by ground effect dispersion and dissipation can be very significant. This excess (relative to the air-to-ground attenuation) is very much frequency-dependent and will of course vary
according to the nature of the ground coverage (grass, woodland, residential area, etc.). Figure 20 shows some published data on the form of the ground effect. In Figures 20(a) and (b) it is presented as an attenuation per 1000 ft., whereas in Figures 20(c) it neither conforms to a constant value per unit distance nor a constant value per distance doubling. This latter point is also true of atmospheric effects, but when these are applied to the frequency spectra of aircraft noise, and the result evaluated in PNdB units, the 8PNdB per distance doubling law gives a reasonable approximation to the total loss. (The law was actually derived from measured PNdB data). A similar simple law for ground effects on aircraft noise propagation is therefore expected. Discussions with other agencies who work on aircraft noise predictions reveals that there is some disparity in the laws used and in the derivative basis of these laws. The subject is therefore examined here to provide a reasonable basis for the adoption of some law that can be used in the present work.

First, an examination of Table XI gives a direct comparison of some simple attenuation laws that could be used for the total losses (including the air-to-ground term). It is seen that the logarithmic forms (constant attenuation per distance doubling) approximate closely to the combined logarithmic and linear forms over a range of distance. The following points should also be noted:
(i) It is well known that the application of a linear attenuation law to the overall level of a complex frequency spectrum noise gives a gross underestimate of the level expected at large distances. (This is due to the continuous change in frequency component significance that occurs in reality.)

(ii) For airport noise exposures there is no need to predict very low noise level values. For NNI assessments $80\text{PNdB}$ is the limit of interest. However, taking $70\text{PNdB}$ as a more general limit of interest, the maximum attenuation range is of the order of $50\text{PNdB}$ (re. the 1000ft. range levels).

(iii) If the need was to predict mapped contours of iso-noise level, then the various models in Table XI would give considerably different spreadings of these contours.

Now taking these points into account, Table XI can be used to assess two particular propagation laws that have been used for noise exposure estimation purposes. These are,

- $10\text{PNdB}$ per distance doubling, and
- $15\text{PNdB}$ per distance doubling,

for ground-to-ground radiated aircraft noise. The first corresponds to an average ground excess attenuation of $1\text{PNdB}$ per 1000ft. up to a range of about 8000ft. (2.4km) and a lower attenuation thereafter. This does not compare well with the Figure 20(c) aircraft noise data, which were
measured under the more favourable propagation conditions of a "down-wind" greater than 5 metres per second. On the other hand, the 15PNdB per distance doubling corresponds to an attenuation of 3.5PNdB per 1000ft. to a range of 4000ft. to 8000ft. (2.4km), and 1PNdB/1000ft. from 8000ft. to 16000ft. (4.88km). While this might seem to be conservative in the light of the Figures 20(a) and (b) data, and possibly reasonable in consideration of the downwind effects on the Figure 20(c) data, there is obviously a need for some experimental justification of such a high attenuation rate. A limited attempt at such justification has been included in the present work, by the inclusion of two other measurement sites in the Heathrow noise survey (Appendix I). These sites were located at Hanworth Park and Kempton Park Race Course, to the south-east of Heathrow Airport runways. The distances to the (approximate) start-of-run point of Runway 28L are about 4.5km (14,800ft.) and 6km (19,700ft.) respectively. Analysis of the recorded data has yielded useful noise level data from the 4.5km site measurements, but none such from the 6km site. The problem in the latter case was that of distinguishing the take-off ground run noise events from other noise events in the background.

The 4.5km site data have been analysed in dB(D) units, and the peak levels for the ground run portion of the noise histories are given in Table XII. The mean peak level and the standard deviation of the peaks is also given in the Table, for each aircraft category. A comparison of
these mean values with the reference levels (for 1000ft. range) of Table X, allowing dB(D) equal to PNdB minus 7dB, gives an average attenuation of 48dB(D). This corresponds to an attenuation rate of,

12.3dB(D) per distance doubling

over the 4.5km (14,800 ft.) range and for peak noise levels of the order of 60 to 70 "PNdB" at this range.

With this attenuation rate the peak levels at the 6km distant site would be expected to be 5dB lower, but this could not be verified because of the inability to separately identify the aircraft ground run noise excursions from other excursions of the expected magnitude.

This 12.3dB per distance doubling rate cannot be readily applied to the estimation of PNdB levels without some check on the relationship between dB(D) and PNdB in these near-ground propagation conditions. Rather than analyse all of the data for their peak PNdB levels, a sample of BAC 1-11 and DC-8 aircraft recordings was selected for this more detailed analysis. It was found that the difference between PNdB and dB(D) unit levels for the noise peaks was typically of the order of 5dB. Using this in the comparison with the reference data gives an attenuation rate of,

12.8PNdB per distance doubling

for ground-to-ground propagation.

Without further derivation or justification, this rate is taken here to be appropriate to the zero ground
incidence attenuation of aircraft peak noise levels. A smooth continuous reduction of this rate for ground angles increasing to 15 degrees (at and above which the 8PNdB per distance doubling law is used) is given by:

\[ \hat{L}_{ij}(r) = \hat{L}_{ij}(R) - (26.67 + 16 \exp(-(10 \sin \theta)^2)) \log_{10}(r/304) \]

\[ \ldots \ldots \ldots (4.4) \]

where \( r \) is in metres, and \( \theta \) is the propagation grazing angle relative to the ground plane.

This is shown graphically in Figure 21.
5.0 NOISE EXPOSURE PREDICTION BY A GRAPHICAL METHOD

The methods developed in Sections 3 and 4 are amenable to a simple chart-form presentation. These are summarised in the following two-phase analysis description. The distribution of noise peak levels is developed first and from this the noise duration statistics are evaluated. An example of method's application is given in Appendix IV.

The information required is as follows:

(1) the distance along the route (ground trace) from the usual start-of-run position on the runway to the nearest point of approach to the noise-exposed site;

(2) the side-line distance from the site to this closest point on the ground trace;

(3) the typical percentage fleet-mix of the aircraft using the route, defined in categories
   - Jumbo-jet (B747)
   - 4-engined turbofan
   - 3-engined turbofan
   - 2-engined turbofan
   - 4-engined turbopropeller.
   (2-engined turboprop and 4-engined piston aircraft can be included as a separate combined category.)

(4) the average hourly number of flights using the route. This number should include only those aircraft that fall into the item (3) categories. The average should be for the specific period of the day that is required for an index evaluation,
(e.g. between 0600 and 1800hrs. GMT for an NNI estimate.) It should also be the average for any specified long-term period required in the index definition (e.g. for a 3-month summer period NNI).

5.1 The Noise Peak Level Distribution

The peak-level distribution is developed as follows:

(a) From Figure 22 or 23 obtain for each aircraft category the mean peak level, PL₁, by reference to the distance along the route to the nearest point of approach (item 1).

(Figure 22 has been derived by direct combined use of the Figure 19 height profiles, the Table X reference peak levels and the Figure 21 attenuation rate for very large angles.)

(b) From Figure 24 or 25 obtain the corrections (ΔL₁) for side-line distance, applicable to each aircraft category.

(c) Calculate the mean peak levels caused at the site by each aircraft category,

\[ PL₂ = PL₁ - ΔL₁ \]

and insert these in Column 2 of Table IX.

(d) Insert in Table IX, Column 3, the percentage usage of the route by each aircraft category.

(e) Distribute the percentage route-usage values over columns 4 to 11 according to the procedure described in Section 4.2. That is,
Departure Routes

Band containing PL₂ 0.38P%
PL₂ -SdB and PL₂ +SdB bands 0.24P%
PL₂ -10dB and PL₂ +10dB bands 0.07P%

Approach Routes

Band containing PL₂ 0.60P%
PL₂ -5dB and PL₂ +5dB bands 0.19P%
PL₂ -10dB and PL₂ +10dB bands 0.01P%

(f) Calculate column totals, which are the percentage number of peaks occurring in each 5dB band. Calculate right-to-left cumulative totals. These are the percentage of peak levels exceeding each noise band lower limit.

(g) The percentage exceedence values should be plotted on a Normal Distribution Probability chart as shown in the Figure 5 and 6 examples. The best fit straight line should be drawn through these data points, and the upper (truncation) limit of the highest-occurring noise band should be marked on the line.

This procedure gives the level-exceedence distribution of the peak noise level occurrences.

5.2 The Noise Duration Distribution

The level-exceedence distribution of noise durations is obtained by means of equation 3.10 (of Section 3.1), with allowance for a different noise propagation exponent. A step-by-step procedure for applying this equation is as
follows:

(a) Prepare a tabular form similar to that shown in Table XIII. It is seen that the objective is to obtain values of $P(\lambda)$ corresponding to levels $\lambda$ at 5dB increments above and below $L_{50}$. ($L_{50}$ is the level obtained by interpolation of the peak distribution line.)

(b) By reference to the height profiles shown in Figure 19, and the percentage usage of these as inserted in Column 3 of Table IX, find the average height of the aircraft passing over the route point closest to the site. Using this value $(H)$ and the sideline distance of the site to the route ground trace, $(s)$, calculate

- the slant range $h = (H^2 + s^2)^{1/2}$
- the propagation angle $\theta = \tan^{-1}(H/s)$ degrees.

(c) Find the propagation exponent $k$, for the $\theta$ value, from Figure 26. Insert the value of $k$ and $h$ in Table XIII.

(d) Find the average speed $(U)$ of departing aircraft at the closest route point by reference to Figure 27. (This figure has been derived from radar-tracking information supplied by the CAA.) For landing aircraft, take $U = 86$m/sec. (280fps).

(e) Insert the value of $U$ and of $n$ (item 4) in the table and calculate,

$$\alpha = 2.34 \times 10^3 \cdot k \cdot a/n.$$
(f) From the developed peak level distribution obtain a value for \( \sigma_p \), by,
\[
\sigma_p = \frac{\hat{L}_{10} - \hat{L}_{50}}{1.28}.
\]
(g) From Figure 28, obtain values of Equation 10 right-hand-side (RHS) corresponding to the calculated \( \sigma_p \) and each value of \( \hat{L}_{50} - \lambda \) shown in the Table XIII. Insert these in the Table and calculate each \( P(\lambda) \) given by
\[
P(\lambda) = \frac{\text{RHS}}{\lambda}.
\]
(h) Plot these \( P(\lambda) \) values on the chart used for the peak-distribution. In each case the level \( \lambda \) dB is given by its increment relative to \( \hat{L}_{50} \). The level exceedence distribution of noise durations is thereby obtained. This corresponds to the distributions shown in Figures 5 and 6.

5.3 Noise Indices

The Noise and Number Index (NNI) can be evaluated by means of the peak-level distribution, and equation 3.16. That is,
\[
\text{NNI} = \bar{L}_{80} + 15 \log_{10} n_{80} - 63.8 \text{, PNdB}
\]
where \( n_{80} \) is the number of events exceeding 80PNdB (per hour) and \( \bar{L}_{80} \) is the average peak-energy level of these events.

The percentage of peaks exceeding 80PNdB is read directly from the developed peak distribution. The product of this and the total number of flights (n, item 4) gives \( n_{80} \) as an average hourly value. The value of \( \bar{L}_{80} \) can be obtained by graphical integration of the peak distribution between the limits of 80PNdB and the upper truncation level. This is
described in Section 2.2, Equation 2.9. Alternatively, the expression

\[ L = \hat{L}_{50} + \frac{\sigma_p^2}{8.68} \]

can be used provided account is taken of the limits (see Appendix III).

The Equivalent Continuous Energy Level \( (L_{eq}) \) is obtained from Equation 3.14 by use of the peak-level distribution, or from Equation 2.9 which is an integration of the noise duration distribution. An example of both methods is presented in Appendix IV. Use of the approximation for a Gaussian distribution is not recommended.

Other Noise Exposure Parameters, such as \( L_1 \), \( L_{10} \), \( L_{50} \), etc., can be obtained directly by interpolation of the developed distribution. The standard deviation of the noise level excursions (\( \sigma_L \)) can be easily obtained for a Gaussian distribution. For non-Gaussian data recourse must be made to statistical analysis of the variance about the \( L_{50} \) level. This can be performed by use of the plotted distribution. With \( L_{eq} \) and \( \sigma_L \) known, the Noise Pollution Level \( (L_{NP}) \) can be obtained.

Note that, whereas \( L_{eq} \) values for different routes can be energy-added to give a total exposure \( L_{eq} \), other indices cannot be so treated.

The overall average peak energy level \( (\bar{L}_T) \) caused by
operations on two traffic routes can be obtained from the individual route $\bar{L}_1$ and $\bar{L}_2$ levels as follows:

$$\bar{L}_T = 10 \log_{10} \left[ \frac{1}{n_1 + n_2} \left( n_1 \frac{\bar{L}_1}{10} + n_2 \frac{\bar{L}_2}{10} \right) \right]$$

where $n_1$ and $n_2$ are the respective route usage numbers (exceeding 80PNdB).

The NNI becomes

$$\text{NNI} = \bar{L}_T + 15 \log(n_1 + n_2) - 63.8, \quad \text{PNdB}$$

Finally, it must be remembered that the graphical representations of the mean peak levels (Figures 22 and 23) and the sideline correction terms (Figures 24 and 25) are based on specific models of height profile. These were derived from destination range estimates averaged over U.K. airports. For any particular airport it would be preferable to rederive the charts for the aircraft operating out of that airport. Account should also be taken of any height restrictions imposed on flights along any route.
6.0 MEASUREMENT AND MONITORING CONSIDERATIONS

In the preceding sections attention has been given almost exclusively to the problems of estimation by predictive techniques. An equally essential aspect of noise assessment is that of noise measurement and monitoring, which may take the form of intermittent sampling, occasional precision measurements over a single day or period, or long-term, continuous recording and analysis. It is clear that long-term measurement exercises are more of a research tool than an assessment approach and that noise contours based on three-month averaged estimates are more readily obtained by the predictive techniques. The need for measured data will persist however, especially for specific site assessments and for verification of predictive methods and results. Some guideline suggestions have arisen in the preceding sections as to methods by which data should be acquired for such purposes. The present section is a brief summary of these guidelines.

First consideration must be given to the objectives of a measurement task. For an estimate of NNI or other peak-level based exposure index it is recommended that the peak-level data be acquired and stored in a manner that will allow the statistical distribution of maxima to be developed. Where there is a possible need, or future requirement, for evaluation of duration-based exposure measures such as $L_{10}$ or $L_{eq}$ then it is recommended that data be acquired on both peak and level-exceedence distribution statistics, simultaneously.

The use of D or N-weighted sound level, with appropriate
correlations, is considered to be an acceptable measurement alternative to PNL measurement for purposes of cumulative noise exposure assessment. This allows great simplification of the noise measurement and analysis tasks, particularly as on-line monitoring of the data can be accomplished with relatively uncomplicated instrumentation. The corrections for near-ground propagated noise need to be studied in some detail, however.

The measurement task should employ "precision-grade" instrumentation. Careful consideration should be given to the selection of the measurement transducer (microphone), particularly to the directional characteristics of the unit when noise duration estimates are required. In the field exercises reported here, the transducers were free-field response units. A preferable system is a pressure-response unit, mounted in a grazing-incidence orientation with respect to the flight path. Recording of the noise signal history on magnetic tape was found to be easily practised with a recording "switch-on" trigger at 65dB(D) for each event. The termination of each event-recording was not so readily definable in terms of a fixed level because of sudden drops and resurgences of the level after aircraft pass.

Estimates of the traffic parameters n, h and r should be recorded with the stored data, where n is the average hourly traffic count for the period of measurement, h is average height of the aircraft and r is the average slant range distance.
The selection of a noise-measurement period must depend on the characteristic airport or route usage. A continuous attendance period at a site should preferably be 12 hours for a Noise distribution assessment. Noise sampling methods over a number of days or weeks should attempt to construct the distribution of noise expected in a single day period, whether worst case or averaged, and it is here that much of the difficulty will arise. Particular attention should be given to (a) the variability of aircraft movement numbers on a day-to-day basis, (b) whether runway usage is shared on a preferential system or, for multiple runway airports, whether the sharing of runway usage is based on a consistent, time-period, allocation, and (c) the hourly characteristics of the movement schedules.

Finally, it can be claimed that one of the greatest problems is knowing just how elaborate a measurement technique should be to satisfy the requirements of the noise assessment exercise, or in other words, "what price should be paid for accuracy?" Are digital computer facilities and highly-expensive measurement equipment really necessary for the purpose of estimating a noise index which, in itself, is criticized as being inadequate? The answers to these questions must depend on the immediate application of the estimate. For compensatory purposes an erroneous estimate may be much more expensive than the equipment costs needed for an accurate measurement. As a planning guideline, however, a relaxed accuracy may be quite acceptable. In many noise exposure situations, the measurement of an index value is not a practical proposition because
of the variability of the noise from day to day and over longer periods. To obtain estimates for sufficient conditions to establish long-term averages or contours around an airport would be an unacceptably expensive task, particularly when this variability is considered. So, as predictive techniques become more necessary for the assessment of new or extended airports, it is much more desirable that they are validated by application and test in existing, measurable, airport sites.
7.0 **CONCLUSIONS AND RECOMMENDATIONS**

The work reported herein has been an examination of methods by which aircraft noise exposure can be estimated; emphasis has been given to predictive methods.

Although the Noise and Number Index (NNI) is the only cumulative noise exposure measure formally adopted in the U.K. for aircraft noise assessments, the consideration currently being given by national and international advisory bodies to the introduction of a more generally applicable index has suggested that a useful study of predictive methods should include a capability to derive basic information from which other measures can be evaluated. The study has therefore commenced with a review of various forms of cumulative exposure measures with some attention being given to their basic properties and inter-relationships in terms of traffic parameters.

It has been shown that, by means of a fairly simple representation of traffic along a route, useful expressions can be derived for the inter-relationship of peak-level and noise duration based exposure statistics. It has been further shown that these relationships can be employed in a predictive methodology which aims, first, at estimating the statistical characteristics of the peak level occurrences and, second, at estimating the noise duration statistics. From these, most of the noise indices can be evaluated.

A comparison of the dependencies of the Equivalent Continuous Energy Level, $L_{eq}$, and the NNI has been made by relating the former to an expression which includes the
average peak-energy level as a constituent. The index forms are, respectively,

\[ L_{eq} = \overline{L} + 10 \log_{10} n + 10 \log_{10} (\sigma_p^2) + 10 \log_{10} (h/10U) \]

\[ - \sigma_p^2/66 - 29.5, \quad \text{PNdB} \]

\[ \text{NNI} = \overline{L} + 15 \log_{10} n - 63.8, \quad \text{PNdB} \]

where \( n \) is the hourly traffic count averaged over 12 hours, \( U \) is the average traffic speed along its route and \( h \) is the minimum slant range between site and the route. \( \overline{L} \) is the average peak-energy level as used in the NNI formulation. For regions where the slant range is of the order of 915 metres (3000ft.) and \( \sigma_p \) is about 6PNdB, \( L_{eq} \) becomes

\[ L_{eq} = \overline{L} + 10 \log_{10} n - 22, \quad \text{PNdB} \]

Any debate on the relative merits of these indices must be by reference to their respective attributes in predicting community annoyance. However, the derived forms of \( L_{eq} \), given here, clarify some aspects of its applicability to aircraft noise exposures. It is recommended that future studies of index derivation by means of attitude-regression empiricism should be accompanied by studies of the physical-acoustic properties of the contender index forms.

An examination of the dependency of noise indices on traffic patterns and route usage has illustrated some of the basic problems of measurement and prediction. It is apparent that most indices can be considered to comprise a relatively
invariant term and a term which is greatly influenced by the variability of day-to-day route (or airport) movement numbers. Thus the estimation problem can be partially alleviated by separate consideration of these terms. The noise peak level distribution and the average peak-energy level ($L$) can be regarded as being relatively stable quantifiers of aircraft noise. They are thereby amenable to short-term measurement for purposes of evaluating a long-term averaged (3-month for example) index or of validating a prediction method. Noise duration, or other event-number based, constituents of a noise index are not so amenable to short-term measurements for purposes of obtaining long-term averaged values. These latter terms account for the accumulative effects of noise exposure and are therefore essential to the composition of an index. It is concluded that expression of these terms as functions of meaningful planning parameters (such as is already included in the NNI and as has been derived for $L_{eq}$) is best suited to the aircraft noise assessment problem. Account for the variability of the exposure over a daytime or three-month period (as suggested by Robinson's $L_{NP}$) could be readily represented by inclusion in the index of a maximum-to-average event number ratio ($n_{max}/n_{ave}$) or some similar subjectively meaningful parameter.

A noise-exposure prediction method has been developed in this report. This is founded on a well-established and documented methodology originally designed for Composite Noise Rating evaluations of airport environments. Its
adaptation to the present work is extended to provide estimates of duration-based exposure measures such as $L_1$, $L_{10}$, $L_{eq}$. In its original form, the method requires a laborious breakdown of airport and route traffic into categories of aircraft type, mode of operation and destination range. The definition of an aircraft movement in terms of these categories can be accomplished for retrospective assessments by reference to detailed airport movement data, if available, or by a complicated cross-referencing system employing runway movement logs and flight schedules. This task is circumvented by the noise-prediction method given herein, which is based on a modelling of the dispersion of noise peak levels about an expected average for a given category of aircraft on a well-defined flight path. It is shown that this approach is amenable to simple chart and tabular computation. The estimation of duration-based noise exposure parameters is obtained by means of the relationships between peak and duration statistics as developed in Section 3.1. It is recommended that further detailed study and testing of the statistical predictive approach be initiated. The flexibility of the method in providing compatible estimates of noise exposure, in various index forms, would appear to satisfy a much needed requirement in predictive noise assessment capability.
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<th>ALL U.K. AIRPORTS</th>
<th>HEATHROW</th>
<th>GATWICK</th>
<th>MANCHESTER</th>
<th>BIRMINGHAM</th>
<th>PRESTWICK</th>
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+From data of August-1972 (0600 - 1800 GMT)
Table II

See Figure 4
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<td>3</td>
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<td>0.83</td>
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<td>0.10</td>
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<td>7</td>
<td>3</td>
<td>1</td>
<td>0.27</td>
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<tr>
<td>4</td>
<td>8</td>
<td>3</td>
<td>1</td>
<td>0.03</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>0.04</td>
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<tr>
<td>6</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>0.35</td>
</tr>
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<td>8</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>0.01</td>
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<tr>
<td>8</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>0.35</td>
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<tr>
<td>1</td>
<td>2</td>
<td>9</td>
<td>1</td>
<td>0.01</td>
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<td>3</td>
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<td>9</td>
<td>1</td>
<td>0.14</td>
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<tr>
<td>4</td>
<td>1</td>
<td>9</td>
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<td>0.37</td>
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<tr>
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<td>9</td>
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<td>0.15</td>
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<tr>
<td>4</td>
<td>3</td>
<td>9</td>
<td>1</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Table IV  Noise and Number Parameter Estimates for Five Sites on Various Days

<table>
<thead>
<tr>
<th>Date of Exposure</th>
<th>Total No. of Operations</th>
<th>$L_{\text{av}}$ Peak-Energy Level</th>
<th>$15\log N_{k}$</th>
<th>NNI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Site No. 1 2 3 4 5</td>
<td>Site No. 1 2 3 4 5</td>
<td>Site No. 1 2 3 4 5</td>
</tr>
<tr>
<td>8.8.72</td>
<td>841 (652)</td>
<td>90 91 95 93 88</td>
<td>4 32 35 35 15</td>
<td>14 43 50 48 23</td>
</tr>
<tr>
<td>10.8.72</td>
<td>879 (661)</td>
<td>93 91 95 94 88</td>
<td>43 35 33 32 41</td>
<td>56 46 48 45 49</td>
</tr>
<tr>
<td>23.8.72</td>
<td>893 (672)</td>
<td>93 92 94 95 89</td>
<td>23 35 37 33 40</td>
<td>36 47 51 48 49</td>
</tr>
<tr>
<td>25.8.72</td>
<td>932 (689)</td>
<td>92 91 95 93 87</td>
<td>31 29 26 24 40</td>
<td>43 40 51 47 47</td>
</tr>
<tr>
<td>31.8.72</td>
<td>914 (702)</td>
<td>92 90 94 93 87</td>
<td>32 24 35 31 17</td>
<td>44 34 49 34 24</td>
</tr>
<tr>
<td>'Av. Day' Aug. 1972</td>
<td>868</td>
<td>92 92 95 93 89</td>
<td>35 32 35 33 35</td>
<td>47 44 50 46 44</td>
</tr>
<tr>
<td>10.4.73</td>
<td></td>
<td>93 93 94 -- --</td>
<td>33 32 36 -- --</td>
<td>46 45 50 -- --</td>
</tr>
<tr>
<td>&quot;(measured)&quot;</td>
<td></td>
<td>91 92 95 -- --</td>
<td>31 33 36 -- --</td>
<td>42 45 51 -- --</td>
</tr>
</tbody>
</table>

* in PNdB units

**Total No. of airport movements, including arrivals and departures, "24hr. total (12hr. daytime)".
### Table V: Calculated $P(\lambda)$ Values for Heathrow, Manchester, and Liverpool Airport Site Examples (Using Equation 3.10)

Heathrow Airport Case; $\sigma_p = 7.3$dB, $n = 252/12$

<table>
<thead>
<tr>
<th>$\hat{L}_{50} - \lambda$</th>
<th>-10</th>
<th>-5</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(\lambda)$ %</td>
<td>.65</td>
<td>2.4</td>
<td>6.5</td>
<td>13.6</td>
<td>23.0</td>
<td>33.6</td>
</tr>
</tbody>
</table>

Manchester Airport Case; $\sigma_p = 5.5$dB, $n = 41/12$

<table>
<thead>
<tr>
<th>$\hat{L}_{50} - \lambda$</th>
<th>-5</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(\lambda)$ %</td>
<td>.19</td>
<td>.8</td>
<td>2.0</td>
<td>3.7</td>
<td>5.7</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Liverpool Airport Case; $\sigma_p = 5.5$dB, $n = 18/12$

<table>
<thead>
<tr>
<th>$\hat{L}_{50} - \lambda$</th>
<th>-5</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(\lambda)$ %</td>
<td>.08</td>
<td>.35</td>
<td>.88</td>
<td>1.67</td>
<td>2.4</td>
<td>3.2</td>
</tr>
</tbody>
</table>
### Table VI  Comparison of Measured and Calculated Noise Index Values for Figure 6 Sites

<table>
<thead>
<tr>
<th>Airport</th>
<th>Noise Exposure Site</th>
<th>Measured Data</th>
<th>NNI* Eqn. 3.16</th>
<th>L_eq* Eqn. 3.15</th>
<th>L_eq* Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\hat{L}_{50}$</td>
<td>$\sigma_P$</td>
<td>$\bar{L}$</td>
<td>n/hr.</td>
</tr>
<tr>
<td>Heathrow</td>
<td></td>
<td>82.2</td>
<td>7.8</td>
<td>89.2</td>
<td>21.0</td>
</tr>
<tr>
<td>Manchester</td>
<td></td>
<td>83.8</td>
<td>5.5</td>
<td>87.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Liverpool</td>
<td></td>
<td>80.5</td>
<td>5.5</td>
<td>84.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

**Units:**
- $db(D)$
- $dB(D)$
- $PNdB$

*7dB has been added to convert the values from $db(D)$ to $PNdB*
### Table VII: Statistical Summary of Aircraft Type and Grouped Noise Levels Measured at Site Near Landing Paths

<table>
<thead>
<tr>
<th>Aircraft Type(s)</th>
<th>NEAR PATH (28R)</th>
<th>FAR PATH (28L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>Ave. Pk. Level</td>
</tr>
<tr>
<td>747</td>
<td>9</td>
<td>81.8 dB(D)</td>
</tr>
<tr>
<td>707</td>
<td>14</td>
<td>83.1 dB(D)</td>
</tr>
<tr>
<td>VC10</td>
<td>6</td>
<td>84.2 dB(D)</td>
</tr>
<tr>
<td>HS21</td>
<td>35</td>
<td>84.7 dB(D)</td>
</tr>
<tr>
<td>727</td>
<td>6</td>
<td>78.8 dB(D)</td>
</tr>
<tr>
<td>1-11</td>
<td>6</td>
<td>82.2 dB(D)</td>
</tr>
<tr>
<td>707, DC8</td>
<td>18</td>
<td>83.5 dB(D)</td>
</tr>
<tr>
<td>707, DC8, VC10</td>
<td>24</td>
<td>83.7 dB(D)</td>
</tr>
<tr>
<td>DC9, 737</td>
<td>15</td>
<td>78.3 dB(D)</td>
</tr>
<tr>
<td>DC9, 737, 1-11</td>
<td>21</td>
<td>79.4 dB(D)</td>
</tr>
<tr>
<td>VC8, VC9</td>
<td>16</td>
<td>76.3 dB(D)</td>
</tr>
</tbody>
</table>

### Table VIII: Statistical Summary of Aircraft Type and Grouped Noise Levels Measured at Site Near Departure Routes

<table>
<thead>
<tr>
<th>Aircraft Type(s)</th>
<th>RUNWAY 28L</th>
<th>RUNWAY 28R</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>Ave. Pk. Level</td>
</tr>
<tr>
<td>747</td>
<td>2</td>
<td>87.0 dB(D)</td>
</tr>
<tr>
<td>707</td>
<td>6</td>
<td>91.0 dB(D)</td>
</tr>
<tr>
<td>VC10</td>
<td>3</td>
<td>87.7 dB(D)</td>
</tr>
<tr>
<td>HS21</td>
<td>19</td>
<td>91.3 dB(D)</td>
</tr>
<tr>
<td>727</td>
<td>1</td>
<td>94.0 dB(D)</td>
</tr>
<tr>
<td>1-11</td>
<td>3</td>
<td>95.0 dB(D)</td>
</tr>
<tr>
<td>707, DC8</td>
<td>7</td>
<td>91.6 dB(D)</td>
</tr>
<tr>
<td>707, DC8, VC10</td>
<td>10</td>
<td>90.4 dB(D)</td>
</tr>
<tr>
<td>DC9, 737</td>
<td>4</td>
<td>87.7 dB(D)</td>
</tr>
<tr>
<td>DC9, 737, 1-11</td>
<td>7</td>
<td>90.0 dB(D)</td>
</tr>
<tr>
<td>VC8, VC9</td>
<td>6</td>
<td>82.7 dB(D)</td>
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Table IX  Noise Maxima Distribution (Example values inserted)

<table>
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<tr>
<th>A/c Cat.</th>
<th>PL₂ PNdB</th>
<th>p%</th>
<th>76-80</th>
<th>81-85</th>
<th>86-90</th>
<th>91-95</th>
<th>96-100</th>
<th>100-105</th>
<th>106-110</th>
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</thead>
<tbody>
<tr>
<td>Jumbo</td>
<td>89.5</td>
<td>7</td>
<td>0.5</td>
<td>1.7</td>
<td>2.6</td>
<td>1.7</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4TF</td>
<td>93.5</td>
<td>15</td>
<td>1.1</td>
<td>3.6</td>
<td>5.6</td>
<td>3.6</td>
<td>1.1</td>
<td></td>
<td></td>
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<tr>
<td>3TF</td>
<td>88.5</td>
<td>24</td>
<td>1.7</td>
<td>5.8</td>
<td>9.0</td>
<td>5.8</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2TF</td>
<td>88</td>
<td>32</td>
<td>2.2</td>
<td>7.7</td>
<td>12.2</td>
<td>7.7</td>
<td>2.2</td>
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<td></td>
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<tr>
<td>2TP</td>
<td>83</td>
<td>22</td>
<td>5.3</td>
<td>8.4</td>
<td>5.3</td>
<td>1.5</td>
<td></td>
<td></td>
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<tr>
<td>Column Totals</td>
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<td>9.7</td>
<td>24.7</td>
<td>32.7</td>
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<td>1.1</td>
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</tr>
<tr>
<td>Probability of Exceedence</td>
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<td>98.5</td>
<td>88.8</td>
<td>64.1</td>
<td>31.4</td>
<td>9.1</td>
<td>1.1 %</td>
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Table X  Noise Peak Levels (PNdB) of Aircraft at 304 metres (1000ft.) Distance

<table>
<thead>
<tr>
<th>Operation Mode</th>
<th>Data Source (Ref.)</th>
<th>Aircraft Type or Category</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Jumbo</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B747</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>32</td>
<td>114</td>
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<tr>
<td>Take-off</td>
<td>38</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>115</td>
</tr>
<tr>
<td>Approach (Landing)</td>
<td>24</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>97</td>
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<tr>
<td></td>
<td>39</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>101</td>
</tr>
<tr>
<td>Level Flight</td>
<td>39</td>
<td>108</td>
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<tr>
<td>Climb to Cruise</td>
<td>39</td>
<td>112</td>
</tr>
<tr>
<td>Max. T/O</td>
<td></td>
<td>113</td>
</tr>
<tr>
<td>Approach</td>
<td></td>
<td>100</td>
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</tbody>
</table>
Table XI  Total Attenuations Given by Various Laws (dB re. 1000ft. Reference)

<table>
<thead>
<tr>
<th>Dist. from Source (ft.)</th>
<th>Air to Ground 8dB/d.d</th>
<th>8dB/d.d +1dB/1000'</th>
<th>8dB/d.d +2dB/1000'</th>
<th>8dB/d.d +3dB/1000'</th>
<th>WithGround Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10dB/d.d</td>
<td>12dB/d.d</td>
<td>14dB/d.d</td>
<td>16dB/d.d</td>
</tr>
<tr>
<td>1000</td>
<td>.3</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>.61</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>4000</td>
<td>1.22</td>
<td>16</td>
<td>20</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>8000</td>
<td>2.44</td>
<td>24</td>
<td>32</td>
<td>40</td>
<td>36</td>
</tr>
<tr>
<td>16000</td>
<td>4.88</td>
<td>32</td>
<td>48</td>
<td>64</td>
<td>48</td>
</tr>
</tbody>
</table>

dB/dd is dB per doubling of distance.
<table>
<thead>
<tr>
<th>Aircraft Category</th>
<th>Mean Level dB(D)</th>
<th>Standard Deviation dB(D)</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>B747</td>
<td>54</td>
<td>2.8</td>
<td>4</td>
</tr>
<tr>
<td>4eng.TF</td>
<td>64</td>
<td>4.8</td>
<td>5</td>
</tr>
<tr>
<td>3eng.TF</td>
<td>60</td>
<td>3.2</td>
<td>17</td>
</tr>
<tr>
<td>2eng. TF</td>
<td>60</td>
<td>3.2</td>
<td>8</td>
</tr>
</tbody>
</table>

Table XII
Ground to Ground Propagated Noise Peak Levels
(Measured at 4.5km from Runway)

<table>
<thead>
<tr>
<th>B747</th>
<th>HS21/B727</th>
<th>S210/DC9/1-11</th>
<th>707/DC8</th>
</tr>
</thead>
<tbody>
<tr>
<td>51 dB(D)</td>
<td>57 dB(D)</td>
<td>64 dB(D)</td>
<td>62 dB(D)</td>
</tr>
<tr>
<td>58</td>
<td>57</td>
<td>63</td>
<td>57</td>
</tr>
<tr>
<td>56</td>
<td>63</td>
<td>60</td>
<td>68</td>
</tr>
<tr>
<td>52</td>
<td>65</td>
<td>57</td>
<td>70</td>
</tr>
<tr>
<td>60</td>
<td>56</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>66</td>
<td>61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>62</td>
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<td></td>
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<tr>
<td>57</td>
<td>55</td>
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<tr>
<td>65</td>
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<td>58</td>
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<td>59</td>
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<td>57</td>
<td></td>
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<td>59</td>
<td>58</td>
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<tr>
<td>58</td>
<td>58</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>57</td>
<td>58</td>
<td></td>
</tr>
</tbody>
</table>
Table XIII  Method for the Evaluation of $P(\lambda)$

Equation 3.10, for variable $k$, is

$$2.34 \frac{k a}{n} \times 10^3 x P(\lambda) = \frac{(L_{50} - \lambda)}{2} \left[ 1 + \text{erf} \left( \frac{L_{50} - \lambda}{\sqrt{2} \sigma_p} \right) \right] + \frac{\sigma_p}{\sqrt{2\pi}} \exp \left( -\frac{(L_{50} - \lambda)^2}{2 \sigma_p^2} \right)$$

- $k$ = (from Figure 26)
- $h$ =
- $n$ =
- $U$ = (from Figure 27)  \[ a = U/h = \]
- $\alpha = 2.34 \times 10^3 \cdot \frac{ka}{n}$

<table>
<thead>
<tr>
<th>$L_{50} - \lambda$, dB</th>
<th>-15</th>
<th>-10</th>
<th>-5</th>
<th>0</th>
<th>+5</th>
<th>+10</th>
<th>+15</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHS (From Figure 28)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$P(\lambda) = \frac{\text{RHS}}{\alpha}$
FIGURE 1. EXAMPLES OF NOISE TIME HISTORIES
FIGURE 2  CONTROLLED AIRSPACE
Minimum Noise Routings - LUTON AIRPORT
FIGURE 3b; Minimum Noise Routeings—LONDON (Heathrow) AIRPORT
FIGURE 4 GENERALISED CLIMB RATES (REF 25)

Table II Climb Profiles for Departing Aircraft

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>Destination Range (miles)</th>
<th>&lt;500</th>
<th>500-1000</th>
<th>1000-1500</th>
<th>1500-2500</th>
<th>2500-3500</th>
<th>3500-4500</th>
<th>&gt;4500</th>
</tr>
</thead>
<tbody>
<tr>
<td>B747 1 1 1 1 2 3 4</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>4 eng. TF 1 1 1 1 2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3 eng. TF 1 2 3 4 4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
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<tr>
<td>2 eng. TF 1 1 1 1</td>
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<td>1</td>
<td>1</td>
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</tr>
<tr>
<td>4 eng. TP 5 5 5 5 5 5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
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</tr>
<tr>
<td>Wide Body (3TF) 1 2 2 3 3</td>
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<td>2</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 4 GENERALISED CLIMB RATES (REF 25)
Percentage of peaks exceeding each noise level.

Percentage of time for which each noise level is exceeded.

FIGURE 5 NOISE STATISTICS FOR THREE SITES NEAR HEATHROW AIRPORT
FIGURE 6 NOISE STATISTICS FOR SITES NEAR HEATHROW, MANCHESTER AND LIVERPOOL AIRPORTS.
FIGURE 7. AVERAGE PEAK-ENERGY LEVEL AND NUMBER OF PEAK LEVELS, FOR AIRCRAFT NOISE MAXIMA IN EXCESS OF LEVEL $\lambda$. (HEATHROW MEASURED DATA)
Figure 8 Cumulative Noise Exposure Levels Measured for Periods from 0700 GMT

(a) Site 1 Near Heathrow Airport

(b) Site 2 Near Heathrow Airport
△ ROAD TRAFFIC NOISE $L_{10}, L_{50}, L_{90}$ (REF. 8)
◊ LIMIT BETWEEN NORMALLY ACCEPTABLE AND UNACCEPTABLE, U.S. HUD (REF. 28)
□ AIRCRAFT NOISE (REF. 5)
----- B.B.N. (U.S.A.) DERIVED LIMIT (REF. 31)

FIGURE 9 ACCEPTABILITY CRITERIA AT DIFFERENT PERCENTILE TIME EXPOSURES
FIG. 10 REGRESSION OF TNI, $L_{eq}$ AND $L_{NP}$ ON DISSATISFACTION FROM REF. 30 BASED ON REF. 8 DATA
Figure 11 Aircraft Noise Event Model
FIGURE 12 COMPARISON OF MEASURED NOISE STATISTICS WITH EQUATION 3 THEORY ($P(\lambda)$)
FIGURE 13 INTEGRAL TERM OF EQUATION 3.13 versus $\sigma_P$
\( L_{eq} = 0.8 \text{NNI} + 44.5 \text{PN dB} \)

**FIGURE 14: CROSS PLOT OF \( L_{eq} \) & NNI VALUES**
FIGURE 15 MEASURED DISTRIBUTIONS OF PEAK LEVEL AND NOISE DURATION DATA FOR MOTORWAY NOISE EXPOSURES
FIGURE 16  REPRESENTATION OF AN AIRCRAFT FLIGHT PATH
Level-Exceedance Distribution of all Peaks

(A) LANDING AIRCRAFT

(B) DEPARTING AIRCRAFT

FIGURE 17 DISTRIBUTION OF VARIOUS AIRCRAFT TO OVERALL PEAK NOISE LEVEL DISTRIBUTIONS
FIGURE 18 COMPARISON OF GENERALISED CLIMB PROFILES WITH RADAR TRACKED DATA
FIGURE 19  AVERAGE CLimb PROFILE FOR EACH AIRCRAFT CATEGORY
(a) Effect of Terrain and Elevation Angle (150 - 300Hz) (Reference 41 & 42)

(b) Ground Attenuation over High Grass, Source and Receiver 6ft above ground level (Reference 42)

(c) Downwind Ground to Ground Excess Attenuation (Reference 43)

**FIGURE 20** EXCESS ATTENUATION DUE TO GROUND EFFECTS
**FIGURE 21** AIRCRAFT NOISE PROPAGATION LAW
(EQUATION 4.4)
FIGURE 22 MEAN PEAK LEVEL (PL₁) vs DISTANCE FROM START OF RUN (DEPARTURE ROUTES)
Figure 23: Mean Peak Level (PL₁) vs Distance from Runway Threshold (Approach Routes)
(a) 2-engined Turbo-fan Aircraft

FIGURE 24  CORRECTION ($\Delta L_z$) FOR SIDELINE DISTANCE FROM ROUTE (DEPARTURE ROUTES)
(b) 3 and 4-engined Turbo-fan Aircraft

Distance from start of run (km)

Sideline distance (km)
FIGURE 24 CONTINUED

(c) B747 AIRCRAFT

Sideline distance (km)

Distance from start of run (km)
FIGURE 24 CONCLUDED

4-engined Turbo-propeller Aircraft
FIGURE 25 CORRECTION ($\Delta L_1$) FOR SIDELINE DISTANCES FROM ROUTE (APPROACH ROUTES)
FIGURE 26 PROPAGATION EXPONENT, k, FOR GROUND INCIDENCE ANGLE θ.
FIGURE 27 AIRCRAFT AVERAGE SPEED ($u$) vs DISTANCE FROM START OF RUN (DEPARTING AIRCRAFT)
FIGURE 28  RHS. OF EQUATION 3.10 vs \( \sigma_p \) FOR \( \hat{L}_{50} - \lambda \) IN 5 dB STEPS.
APPENDIX I

AIRCRAFT NOISE MEASUREMENTS AT SITES NEAR HEATHROW AIRPORT

1. Measurement Procedures

The objective of this exercise was to obtain a large sample of aircraft noise data corresponding to various modes of aircraft operation in the near-airport vicinity. To suit this purpose five sites were selected in the region around Heathrow (London) Airport. These are shown in Figure I.1 in relation to the aircraft routes used on the measurement day. Two sites are within a departure-route region where the noise would normally be attributable to aircraft in a noise-abatement climb. One site is near the three-degree approach path to Runway 28R and also allows measurement of the approach flights to the more distant 28L runway. The two other sites are in a region where it was hoped to measure "ground-to-ground" propagated noise from aircraft in their maximum-power take-off ground run. The condition of maximum-power overflight was not included as it was receiving a separate and concentrated study effort by Lanzer (Reference 32).

The period of measurement was from 07.00 to 19.00 hours (BST) on Tuesday, April 10, 1973. During this period all arriving and departing aircraft used Runways 28R and 28L. Interchange of runway use (from landing to take-off and vice-versa) occurred at 10.04, 12.30 and 16.14 hours (BST). At all but one of the sites the noise data recording procedure was to commence tape recording when a flight
could be positively identified as relevant to the programme and to terminate recording when the sound had diminished to an insignificant level. At one of the "ground-to-ground propagation" sites the procedure was to continuously record noise exposure with minimum interruption.

Runway logs for the noise measurement period were supplied by the Civil Aviation Authority. These originate at Heathrow Air Traffic Control and comprise a listing of each flight; with flight number, aircraft type, time of event (GMT), runway used and route used. Meteorological data for the period were obtained from the airport meteorological office and are reproduced here as Table I.I.

The measuring and recording equipment at each site comprised a sound level meter, acoustic calibrator, microphone windscreen, tripod, Scotch 220 magnetic tapes, and a Nagra IV-S magnetic tape recorder. The sound level meters available for the exercise were Brul and Kjaer types 2203 (one), 2204 (two) and 2205 (two). These were deployed according to the expected requirements of each site noise condition. The B&K 2205 system is not a precision sound level meter within the requirements of References 44 and 45 specifications. However, this limitation is due only to the characteristics of its installed microphone and can be disregarded when the system is used to meet restricted measurement requirements. Calibration charts for the available 2205 systems show the sensitivity to frontal-incidence (0°) plane waves to be within 0.5dB.
(from nominal) over the frequency range 20Hz to 8kHz. The systems were therefore considered adequate for measurements at the "ground-to-ground-propagated" noise sites, where the higher frequency sound content is of low magnitude compared with the 20Hz to 8kHz range content. A single direction of propagation at these sites was also suited to the use of the 2205 systems. A disadvantage is that of lower nominal sensitivity than other systems which accommodate condenser-type microphones. Again, consideration of the expected level range of interest, down to about 55PNdB (42dB(A) approx.) suggested the adequacy of the type 2205 systems in this particular application. (These have an inherent noise 'floor' of about 27dB(A)).

The B&K 2203 and 2204 sound level meters were used at the flyover (or flyby) noise sites. While the author's preference is to use B&K 4134 type, pressure-response, microphones (in a grazing incidence orientation to the flight path) for flyover noise measurements, this could not be accommodated by the available range of equipment. The SLM systems were therefore used with B&K 4133 (one) and B&K 4145 (two) free field microphones installed. In each application the microphone was oriented such that the normal (0°) incidence line was pointed towards the closest point of flight approach (or the closest predictable approximation to the CPA).

All recordings at all sites were made with a tape-transport speed of 7½ips. A calibration signal was recorded at the beginning of each tape by means of an
acoustical signal imposed at the microphone. Pistonphone
types B&K 4220 and 4230 were used. Windscreens (B&K type
UA 0207 or UA 0237 according to microphone diameter) were
applied to the microphones, and these measurement units
were tripod-mounted at a height of 1.2 metres (about
4ft.) above ground level. Detailed logs of the data
acquisition history and signal-conditioning processes
imposed on the recordings, were compiled throughout the
measurement programme.

2. Data Analysis

The tape-recorded data acquired at the flyover-noise
sites were analysed by means of a Brüel and Kjaer equip-
ment comprising (see Figure 1.2);

(a) Measuring Amplifier Type 2607

(b) Level Recorder Type 2305

(c) Statistical Distribution Analyser Type 4420

The recorded data on each tape were processed through the analysis system twice. After calibration of the output by means of the recorded reference signal, each tape was played-back in a continuous (non-stop) mode to provide a first-look time history trace of the D-weighted sound level. While this was being produced on the Graphic level recorder, the statistical distribution analyser was processing the trace fluctuations to give a total cumulative count of level exceedence data. Here, the distribution analyser was set to sample the trace level at 1/10 second intervals. The twelve counter indicators of the analyser were set to provide a total cumulative count of the number of "instances" at which the D-weighted
trace level exceeded 5dB incremented levels of 60dB(D) to 115dB(D). This procedure was applied to all of the recorded tapes for each flyover site. The total level-exceedence counts for each site exposure were obtained by summation of the respective indicator values for the site-tapes. These data correspond to the aircraft noise duration statistics shown in Figure 5 of this report, where they are presented as a percentile of the total measurement period. The lower sound level percentiles are omitted where they were obviously influenced by non-aircraft noises and tape-gaps between event recordings.

The tapes were subsequently re-analysed through the same equipment, but in this second analysis each flight event was individually processed to provide the noise duration statistics of its contribution to the exposure. Guidance on analysis start and stop times was obtained from the first-run time history traces. These individual event analyses data were tabulated on computer-punching data sheets as shown in Figure 1.3. The tabulation included, for each event: the tape number, event number, event time (BST), aircraft type (coded), approximate distance (coded), sound level meter range setting, total count of 1/10 second instances at which trace exceeded 60dB(D), 65dB(D), ... to 100dB(D) in 5dB steps, minimum level (dB(D)), of data validity, measurement operator identity (coded), aircraft type (operator guess), coded key to causes of possible error, peak sound level of event (dB(D)). With these data punched on computer cards,
various forms of digital processing were then available. Examples of these have been presented in this report and include the breakdown of peak levels by aircraft type, numbers of peak levels above various sound levels, average peak-energy levels and equivalent continuous energy levels.

The ground-to-ground propagated noise data acquired at the two other sites were first processed by the same analysis method to provide time-history traces of the D-weighted sound level, but not the statistical breakdown of the temporal characteristics. Comparison of these traces with the runway-logs provided an identification of the aircraft events causing the noise excursions at the nearer of the two sites. The traces obtained at the further (from airport) site consisted of many sound level excursions of similar magnitude to each other. These could not be separated into aircraft and non-aircraft events and further analysis of these particular records was abandoned.

Peak D-weighted sound levels were then obtained from the nearer-site data traces and compiled into sets for each aircraft type operating from Runway 28L. These have been presented in the report. Frequency analysis of some selected records (for BAC 1-11 and DC8 aircraft) was performed by repeating the time-history trace production with the input signal to the level recorder limited to octave-bandwidths. Synchronisation of these traces with the D-weighted sound level traces allowed an octave-band frequency spectrum to be compiled for each case of an event noise peak (i.e. the peak D-weighted level). From
these spectra the corresponding values of Perceived Noise Level and D-weighted Sound Level were computed and compared. Since it is known that the peak PNL and D-weighted sound level do not necessarily coincide (in time) for an aircraft event, octave band spectra were developed for instances 1 and 2 seconds prior to and after the peak D-sound level occurrence, and PNL values computed from these. These have been discussed in Section 4.4.
Table I.1  Meteorological Data for Heathrow Airport on April 10, 1973

<table>
<thead>
<tr>
<th>Time GMT</th>
<th>Temperature °C</th>
<th>Airfield Barometric Pressure m.bar</th>
<th>Wind Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Bulb</td>
<td>Wet Bulb</td>
<td></td>
</tr>
<tr>
<td>0600</td>
<td>0.5</td>
<td>-0.4</td>
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<td>0700</td>
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</tr>
<tr>
<td>0800</td>
<td>3.5</td>
<td>1.4</td>
<td>1015.4</td>
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<tr>
<td>1800</td>
<td>10.4</td>
<td>4.9</td>
<td>1012.4</td>
</tr>
</tbody>
</table>
FIGURE I-1  MEASUREMENT SITE LOCATIONS
FIGURE 1.2 ANALYSIS EQUIPMENT

Nagra IV Tape Recorder

Linear Record, Playback 7½ips tape transport.

Measuring Amplifier B&K 2607

Direct Input D-weighting Filter

Level Recorder B&K 2305

50dB logarithmic potentiometer
Pot. range 50dB
Lower Limiting Frequency 20Hz
Rectifier Response, RMS
Writing Speed 63mm/sec.
Paper Speed 1mm/sec.

Statistical Distribution Analyser B&K 4420

Cumulative Distribution 0.1 second sampling
FIGURE I.3 Data Input for Digital Processing
APPENDIX II

DERIVATION OF NOISE EXPOSURE STATISTICAL DATA FOR A SITE NEAR LIVERPOOL AIRPORT AND A SITE NEAR MANCHESTER AIRPORT

The objective was to simulate the aircraft noise exposures that would be experienced at the Heathrow site #3 if the operations were restricted to those of smaller regional airports. The noise exposure statistics resulting from these simulations have been presented as Figure 6 of this report.

As was described in the preceding Appendix, the Heathrow noise data were compiled as computer input and identified by site number, time and aircraft type, etc. For the present purpose, runway logs for Liverpool and Manchester Airport operations were obtained and from these the air-transport movements were extracted for the 12-hour period between 0600 and 1800hrs. GMT on October 4, 1974. These movements were identified by aircraft type and time of departure. Noise data, including peak level and duration counts, were then compiled for these particular successions of events by extracting the corresponding event data from the measured Heathrow Site 3 storage. In this procedure, the aircraft type identity was rigorously maintained in the data extraction. The event time (GMT) was also followed as closely as possible, although this was not always feasible for some aircraft types. Avoidance of using the same data in repetitive aircraft events was also intended, but could not be maintained
for the VC8 type aircraft due to their more frequent usage at the regional airports (than at Heathrow). Finally, the data extraction process was limited to only those aircraft events that operated on the departure routes closest to the Heathrow measurement site.

The Figure 6 presentation of peak level occurrence and noise duration statistics was simply developed from these simulated compilations. The peak level statistics were expressed as a percentile of occurrence, above 5dB incremented levels. The duration statistics were similarly expressed as a percentile of the 12-hour period for which each level was exceeded.
APPENDIX III

ERRORS CAUSED BY NEGLECT OF TRUNCATION IN DISTRIBUTIONS OF NOISE EXPOSURE

The Equivalent Continuous Energy Level, \( L_{eq} \), is of current interest as a possible means of assessing a noise exposure. Its fundamental definition is,

\[
L_{eq} = 10 \log_{10} \left[ \frac{1}{T} \int_{0}^{T} \frac{L(t)}{10} \, dt \right] \tag{1}
\]

but it is equally expressable as

\[
L_{eq} = 10 \log_{10} \left[ \int_{0}^{L_{max}} \frac{L/10}{10} \cdot p(L) \, dL \right] \tag{2}
\]

where \( p(L) \) is the probability density of the statistical distribution of the noise exposure (time-history) and \( L_{max} \) is the highest level reached by the time-history.

It has become quite common in recent literature on the subject to quote the approximation for \( L_{eq} \) that arises from the assumption of a Normal (Gaussian) probability distribution with infinite upper limit. This is derivable from (2) as

\[
L_{eq} = L_{50} + \frac{\sigma_{L}^2}{8.68} \tag{3}
\]

where \( L_{50} \) is the level exceeded for 50% of the time and

\*Level and Sound Level are used here to mean some appropriately short-time averaged and weighted measure of noise exposure level.
\( \sigma_L^2 \) is the variance of the sound level fluctuations.

The errors associated with this approximation can be large, even when the exposure statistics appear to be Normally distributed over most of the level range. Of greatest significance is the effect of an abrupt truncation of the distribution at some level,

\[
L_T = L_{50} + k\sigma_L
\]

as is shown in Figure III.1. Because of this truncation there will also be a departure from Normalcy at the lower levels of exposures. The effect of this on \( L_{eq} \) is usually insignificant due to the much lower order of energy contribution.

Now, for the truncated distribution, \( L_{eq} \) can be approximated as,

\[
L_{eq} = 10 \log_{10} \int_{L_{50} - \infty}^{L_{50} + k\sigma_L} \frac{10}{10} \log_{10} p(L) \cdot dL
\]

where

\[
p(L) = \frac{1}{\sigma_L \sqrt{2\pi}} \cdot \exp \left( \frac{-(L - L_{50})^2}{2 \sigma_L^2} \right)
\]

Substituting (5) into (4) with \( \tilde{L} = (L - L_{50}) / \sigma_L \),

\[
L_{eq} = L_{50} + 10 \log_{10} \left[ \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{10} \left( \frac{\sigma_L}{10} \right) \cdot \exp(-\frac{\tilde{L}^2}{2}) \cdot d\tilde{L} \right]
\]

which reduces to
\[ L_{eq} = L_{50} + \frac{\sigma_L^2}{8.58} + 10\log_{10} \left[ \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{k'-b} e^{-z^2/2} \, dz \right] \]

\[ \sigma_L/10 \]

where \( b = 2.31\sigma_L/10 \) (i.e. \( b = \log e_{10} \))

and \( z = \tilde{L} - b \)

This gives equation (3) when \( k' = \infty \).

For finite \( k' \) (that is, a truncated distribution),

\[ L_{eq} = L_{50} + \frac{\sigma_L^2}{8.58} - 3 + 10\log_{10} \left[ 1 + \text{erf} \left( \frac{k'-b}{\sqrt{2}} \right) \right] \]

\[ \sigma_L/10 \]

where \( \text{erf} \) is the well-known error function.

Comparing equations (3) and (7) it is immediately obvious that the difference will be less than 3dB when the \( \text{erf} \) argument is greater than zero. This means that for equation (3) to give \( L_{eq} \) within 3dB, the distribution of noise exposure must be Normal up to a level of at least,

\[ L_T = L_{50} + \frac{\sigma_L^2}{4.34}, \text{ dB}. \]

The error caused by using equation (3) for other truncated distributions, which are Normal between the truncation limit and some very low level, can be evaluated from equation (7). Table III.I gives approximate values of these errors for various combinations of \( \sigma_L \) and \( \Delta \), where \( \Delta \) (equal to \( k\sigma_L \)) is the interval in dB above \( L_{50} \) at which
truncation occurs. This table should be used as a guide to the potential error, not as a compilation of correction factors. Where unacceptable error is indicated by the table, $L_{eq}$ should be evaluated by means of equations (1) or (2). The average peak-energy level ($\overline{L}$) of the peak distribution can be similarly expressed as

$$\overline{L} = \hat{L}_{50} + \frac{\sigma_p^2}{8.68} - 3 + 10\log_{10}\left[1 + \text{erf}\left(\frac{k-b}{\sqrt{2}}\right)\right]$$

\hspace{10cm} (8)

where the truncation limit is $L_{50} + k\sigma_p$, and $b = 2.31\sigma_p/10$.

Table III.1 can be used to assess the potential error caused by using,

$$\overline{L} = \hat{L}_{50} + \frac{\sigma_p^2}{8.68}$$

on the peak level distribution.

The effect of an 80PNdB cut-off on the range of significance is not so readily estimated. This effect is introduced in the NNI formula, where $\overline{L}$ is evaluated for peaks in excess of 80PNdB. If this cut-off is expressed in similar form to the truncation level, that is,

$$80\text{PNdB} = \hat{L}_{50} + \varepsilon \sigma_p$$

then an equation similar to (6) can be developed. In the peak distribution notation, equation (6) becomes

$$\overline{L} = \hat{L}_{50} + \frac{\sigma_p^2}{8.68} + 10\log_{10}\left[\frac{1}{\sqrt{2\pi}} \int_{\varepsilon-b}^{\infty} e^{-z^2/2} \, dz \right]$$

(9)
where $b = 2.310\sigma_p / 10$

$$z = \left( L - L^*_{50} - b \sigma_p \right) / \sigma_p$$

In this case the equivalent of equation (7) is,

$$\overline{L} = L^*_{50} + \frac{\sigma_p^2}{8.68} - 3 + 10 \log_{10} \left[ \text{erf} \left( \frac{k-b}{\sqrt{2}} \right) - \text{erf} \left( \frac{E-b}{\sqrt{2}} \right) \right]$$

\[ \cdots \cdots \cdots \cdot (10) \]

So, if $k$ is very large and positive (indicating an upper truncation limit well in excess of $L^*_{50} + \sigma_p^2 / 4.34$), and $E$ is very large and negative (indicating that the 80PNdB level is well below $L^*_{50} + \sigma_p^2 / 4.34$) then the approximation

$$\overline{L} = L^*_{50} + \frac{\sigma_p^2}{8.68}$$

is again given.

The correction to this approximation, allowing for both cut-off and truncation, is best evaluated by means of equation (10). Tables of error function values are given in many text-books on statistics and standard functions. One such source is Reference 46.
TABLE III.1  

<table>
<thead>
<tr>
<th>$\Delta$ (dB)</th>
<th>Standard Deviation $\sigma_L$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>35</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Less than 1dB</td>
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<td></td>
</tr>
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<td>15</td>
<td></td>
</tr>
<tr>
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<td></td>
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<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

*see Figure III.1

$\Delta$ = interval, above $L_{50}$ where abrupt truncation occurs.

$\sigma_L$ is the standard deviation calculated by $(L_{10} - L_{50})/1.28.$
FIGURE III.1 ILLUSTRATION OF TRUNCATION LIMIT
APPENDIX IV

AN EXAMPLE SITE NOISE EXPOSURE PREDICTION

The case to be considered is that of a site which is 1.3km to the side of an airport departure route ground trace. The distance along this route trace, from the start of run point on the runway to the nearest approach point relative to the site, is 15km. The aircraft fleet mix using the route, averaged for a 12-hour daytime period (0600 to 1800hrs. GMT) over a three-month summer season is:

<table>
<thead>
<tr>
<th>A.C.</th>
<th>PL₁</th>
<th>ΔL₁</th>
<th>PL₂</th>
</tr>
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<tbody>
<tr>
<td>B747</td>
<td>98.5</td>
<td>9</td>
<td>89.5</td>
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<tr>
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<td>2 TF</td>
<td>93</td>
<td>5</td>
<td>88</td>
</tr>
<tr>
<td>4 TP</td>
<td>89.5</td>
<td>6.5</td>
<td>83</td>
</tr>
<tr>
<td>PNdB</td>
<td>PNdB</td>
<td>PNdB</td>
<td></td>
</tr>
</tbody>
</table>

and the average number of flights on the route is 48 per 12-hour day.

From Figures 22 and 24, the following values of PL₁ and ΔL₁ are obtained and PL₂ = PL₁ - ΔL₁ calculated:
The PL\textsubscript{2} values are inserted in Table IX (page 89) and the percentages of peaks in each noise level band are calculated according to the definitions in Section 5.1. The column totals are calculated and the probabilities of exceedence obtained by right-to-left cumulative summation of these. Figure IV.1 shows a graphical plot of the level-exceedence percentages using Normal Distribution graph paper. An interpolative distribution line has been superimposed.

An estimate of the Noise and Number Index (NNI) can be obtained by means of this graph. First, the number of flights exceeding 80PNdB is given as 89% of the average daily total. That is,

\[ N_{80} = 0.89 \times 48 = 42.7, \quad \text{and} \]
\[ 15\log_{10}N_{80} = 24.4 \]

Next, the average peak-energy level, \( \overline{L}_{80} \), of these flights is required. This can be obtained by three different methods discussed in this report.

(a) Equation 2.9 can be used as a graphical integration method. This is worked out in Table IV.I, with the result \( \overline{L}_{80} = 90.5\text{PNdB} \).

(b) Equation 2.7 can be used provided the effects of distribution truncation at 80PNdB and 105PNdB are small. From the graph it is observed that \( \hat{L}_{50} = 87\text{PNdB} \) and that \( \hat{L}_{10} - \hat{L}_{50} = 7.2\text{PNdB} \).

Taking
\[
\frac{\hat{L}_{10} - \hat{L}_{50}}{\sigma_p} = \frac{7.2}{1.28} = 5.6\text{PNdB}.
\]
Equation (2.7) gives

\[ L = \hat{L}_{50} + \frac{\sigma_p^2}{8.68} = 90.6 \text{PNdB}. \]

The effect of truncation is included in the following method:

(c) Equation (10) of Appendix III can be used. The upper truncation limit is expressed by

\[ k' = \frac{105 - \hat{L}_{50}}{\sigma_p} = 3.22 \]

The lower truncation limit is expressed by

\[ \varepsilon = \frac{80 - \hat{L}_{50}}{\sigma_p} = -1.24 \]

The value of \( b \) is also required.

\[ b = 2.31 \sigma_p / 10 = 1.29 \]

Now,

\[ L_{80} = L \text{ (from the previous method)} - 3 \text{PNdB} \]

\[ + 10 \log_{10} \left[ \text{erf} \left( \frac{k'-b}{\sqrt{2}} \right) - \text{erf} \left( \frac{\varepsilon-b}{\sqrt{2}} \right) \right] \]

where \( \frac{k'-b}{\sqrt{2}} = 1.36, \text{erf} = 0.946 \)

\( \frac{\varepsilon-b}{\sqrt{2}} = -2.53, \text{erf} = -1.0 \)

Therefore,

\[ L_{80} = 90.6 - 3 + 10 \log_{10} \left[ 1.946 \right] = 90.5 \text{PNdB}. \]
The value of NNI is therefore,

\[ \text{NNI} = 90.5' + 24.4 - 80 = 34.9 \]

An estimate of \( L_{eq} \) can be obtained by means of Equations 3.14 or 3.15. The latter gives

\[ L_{eq} = \frac{L}{10} + 10\log_{10} n + 10\log_{10} \frac{\sigma}{\sigma_p} - \frac{\sigma^2}{65.8} - 29.5 \]

\[ + 10\log_{10} \left( \frac{h}{10U} \right) \]

Substituting \( \frac{L}{10} = 90.6 \text{PNdB} \), \( n = 48/12 = 4 \text{ per hr.} \),

and \( \frac{\sigma}{\sigma_p} = 5.6 \text{PNdB} \),

\[ L_{eq} = 74.1 \text{PNdB} + 10\log(h/10U) \]

From Figure 19 and the percentage usage of the route, the average height of the aircraft at the closest approach point is 970 metres (3190ft.). With the sideline distance of 1300 metres, the average slant range is 1620 metres.

i.e. \( h = 1620 \text{ metres} \)

From Figure 27, the average aircraft speed at the closest approach point is 103 metres/second,

i.e. \( U = 103 \text{ metres/sec.} \)

Therefore, \( L_{eq} = 76.1 \text{PNdB} \).

Other noise duration characteristics can be obtained by development of the level-exceedence time distribution, as described in Section 5.2. For this, a facsimile of Table XIII is used (Table IV.II of this Appendix).

Following the steps given in Section 5.2, the values to be inserted in the table are,
\[ r = 1620 \text{ metres} \]
\[ k = 2.67 \]
\[ U = 103 \text{ metres/second} \]
\[ \alpha = 99.4 \]

Figure 28 is now used to obtain values for the right-hand-side (RHS) of equation 3.10. These are shown in the Table and correspond to \( \sigma_P = 5.6 \text{PNdB} \). \( P(\lambda) \) is calculated and inserted in the table.

The final step in developing the level-exceedence distribution of noise durations is to plot these values (in percentage units) on Figure IV.1. The \( L_{50} \) level is used as a reference.

Indices such as \( L_1 \), \( L_{10} \), etc., can be directly obtained by interpolation.

\( L_{eq} \) can be obtained by means of Equation 2.9, with change of notation from peak levels to level exceedences. A working chart of this graphical integration procedure is given as Table IV.III. The value obtained by this method is,

\[ L_{eq} = 76.7 \text{PNdB} \]

which compares well with the previous estimate.
Table IV.1  Evaluation of $\bar{L}_{80}$ by Means of Equation 2.9

<table>
<thead>
<tr>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{L}_1$</td>
<td>$10^{L_1/10}$</td>
<td>$P(\hat{L}_1-2.5\text{dB})$</td>
<td>$P(\hat{L}_1+2.5\text{dB})$</td>
<td>$(3)-(4)$</td>
<td>$(5) \times (2)/100%$</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>100</td>
<td>$10 \times 10^9$</td>
<td>3.0%</td>
<td>0.3%</td>
<td>2.7%</td>
<td>$27 \times 10^7$</td>
</tr>
<tr>
<td>95</td>
<td>$3.16 \times 10^9$</td>
<td>16.5%</td>
<td>3.0%</td>
<td>13.5%</td>
<td>$42.6 \times 10^7$</td>
</tr>
<tr>
<td>90</td>
<td>$1 \times 10^9$</td>
<td>46.0%</td>
<td>16.5%</td>
<td>29.5%</td>
<td>$29.5 \times 10^7$</td>
</tr>
<tr>
<td>85</td>
<td>$0.32 \times 10^9$</td>
<td>79.0%</td>
<td>46.0%</td>
<td>33.0%</td>
<td>$10.5 \times 10^7$</td>
</tr>
<tr>
<td>80*</td>
<td>$0.13 \times 10^9$</td>
<td>89.0%*</td>
<td>79.0%</td>
<td>10.0%</td>
<td>$1.3 \times 10^7$</td>
</tr>
</tbody>
</table>

\[ \sum \text{column (6)} = 110.9 \times 10^7 \]

$\bar{L}_{80} = 10 \log_{10}(110.9 \times 10^7) = 90.5\text{PNdB}$

*The 80PNdB limit is applied to this stratum.
Table IV.II Method for the Evaluation of $P(\lambda)$

Equation 3.10, for variable $k$, is

$$2.34 \frac{k \cdot a}{n} \cdot 10^3 \cdot P(\lambda) = \frac{(L_{50} - \lambda)}{2} \left[ 1 + \text{erf} \left( \frac{L_{50} - \lambda}{\sqrt{2} \frac{\sigma_p}{\sigma}} \right) \right] + \frac{\sigma_p}{\sqrt{2\pi}} \exp \left( \frac{-(L_{50} - \lambda)^2}{2 \sigma_p^2} \right).$$

$k = (\text{from Figure 26}) = 2.67 \quad h = 1620m \quad n = 4 \text{ per hour}$

$U = (\text{from Figure 27}) = 103m/\text{sec.} \quad a = U/h = .064 \quad \lambda = 2.34 \times 10^3 \frac{ka}{n} = 99.4$

<table>
<thead>
<tr>
<th>$L_{50} - \lambda, \text{dB}$</th>
<th>$-15$</th>
<th>$-10$</th>
<th>$-5$</th>
<th>$0$</th>
<th>$+5$</th>
<th>$+10$</th>
<th>$+15$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHS (From Figure 28)</td>
<td>15</td>
<td>10</td>
<td>5.6</td>
<td>2.2</td>
<td>.54</td>
<td>.09</td>
<td></td>
</tr>
<tr>
<td>$P(\lambda) = \frac{RHS}{\lambda}$</td>
<td>.15</td>
<td>.1</td>
<td>.056</td>
<td>.022</td>
<td>.0054</td>
<td>.0009</td>
<td></td>
</tr>
</tbody>
</table>
### Table IV.III  Evaluation of $L_{eq}$ by Means of Equation 2.9

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>$10^{L_1/10}$</td>
<td>$P(L_1-2.5dB)$</td>
<td>$P(L_1+2.5dB)$</td>
<td>$(3)-(4)$</td>
<td>$(5)(2)/100%$</td>
</tr>
<tr>
<td>97</td>
<td>$.5 \times 10^9$</td>
<td>.25%</td>
<td>.03%</td>
<td>.22%</td>
<td>$1.10 \times 10^7$</td>
</tr>
<tr>
<td>92</td>
<td>$1.58 \times 10^9$</td>
<td>1.1%</td>
<td>.25%</td>
<td>.85%</td>
<td>$1.34 \times 10^7$</td>
</tr>
<tr>
<td>87</td>
<td>$.5 \times 10^9$</td>
<td>3.6%</td>
<td>1.1%</td>
<td>2.5%</td>
<td>$1.25 \times 10^7$</td>
</tr>
<tr>
<td>82</td>
<td>$.16 \times 10^9$</td>
<td>8.0%</td>
<td>3.6%</td>
<td>4.4%</td>
<td>$.70 \times 10^7$</td>
</tr>
<tr>
<td>77</td>
<td>$.05 \times 10^9$</td>
<td>12.5%</td>
<td>8.0%</td>
<td>4.5%</td>
<td>$.22 \times 10^7$</td>
</tr>
<tr>
<td>72</td>
<td>$.016 \times 10^9$</td>
<td>17.5%</td>
<td>12.5%</td>
<td>5.0%</td>
<td>$.08 \times 10^7$</td>
</tr>
</tbody>
</table>

$\sum_{column \ (6)} = 4.69 \times 10^7$

$L_{eq} = 10 \log_{10}(4.69 \times 10^7) = 76.7\text{PNdB}$
Figure IV.1 Noise Exposure Example Case.
(a) Loughborough University Reports


N. Deva-Aditya and J.B. Ollerhead "Criteria for Assessing the Acceptability of Airport Noise Nuisance
Volume 1 The Role of Social Justice
Volume 2 Applications of Social Justice Principles"
LUT TT *, 1975.


(b) Text References


* Reports presently under review - not yet assigned numbers.


20. Civil Aviation Authority "The General Aviation Flight Guide" HMSO.


29. U.S. Department of Housing and Urban Development (HUD), "Noise Assessment Guidelines".

31. Schultz, T.J. "Noise Assessment Guide Line, Technical Background for Noise Assessment in HUD's Operating Programs" U.S. HUD TE/MA 172 (1971). This report has not been reviewed. The criteria have been reproduced in other reports.


38. de Wit, G.A.M. "On the Noise in the Vicinity of the Brussels National Airport" Proceedings of the 5th and

39. Loughborough Consultants Ltd. "Aircraft Noise Datum Levels Used for Airport Assessments".


