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# AN INDEPENDENT COMPARISON AND VALIDATION OF NOISE PREDICTION TECHNIQUES INSIDE FACTORIES

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## 1. INTRODUCTION

A great array of models exist for predicting noise levels in industrial spaces, many of which claim "excellent agreement" with measurements. It is therefore important to independently vet these schemes by comparison to a larger range of factory data. This paper provides a review, critique and evaluation of the most common prediction methods. Both empirical and analytical models were programmed for comparison to fifteen Sound Propagation measurements in nine factories. Models are then graded in terms of accuracy in relation to their complexity, versatility and run time. A much more detailed discussion of the points summarised here is available in [1].

## 2. OVERVIEW OF FACTORS INVOLVED

Noise levels in a factory are characteristically described by the "Sound Propagation" (SP) which is simply the Sound Pressure Level (SPL) normalised to the power level (PWL) of a single sound source and plotted against distance (r) : SP(r) = SPL(r) - PWL dB. Once the SP is known in any particular dimension of a factory it is possible to construct the resultant sound field for any number of sources by assuming them to be incoherent.

It is widely recognised that sound fields in large, disproportionately shaped rooms (such as factories) do not conform to the statistical assumptions of a diffuse sound field as described by the well-known equations of Sabine or Eyring. One must therefore find some other way of predicting the propagation of noise within such buildings. Several researchers have derived empirical equations or corrections to Eyring's equation from observations of Sound Propagation measurements in such enclosures. Others have developed computational methods such as ray-tracing or the image method which make different assumptions, notably that of the occurrence of specular reflections.

These methods give rise to a need for a set of parameters by which to describe the construction, shape and fittings of any industrial building :

(i) **Aspect ratio** Shape of enclosure described as ratio of dimensions.

(ii) **Absorption coefficient**

(iii) **Fitting density** The density of fittings (machines, stores, walkways, etc) within the factory volume must be quantified in order to calculate the proportion of energy which is scattered from them. This is normally described using the "scattering cross-section density" q $m^{-1}$ (or "scattering frequency", "fitting density"). This is described in terms of the surface area per fitting $S_{sl}$ contained within volume V :

$$q = \frac{\sum S_{sl}}{4V} \tag{1}$$

The effect of these parameters on the shape of the SP curve has been well documented; e.g. [2]-[4]. However, it is difficult in practice to obtain fully reliable information for the fitting density and absorption coefficient.

"Typical" information, estimates and assumptions must often be relied upon; e.g. absorption coefficients are diffuse and constant with angle of incidence; the surface area of machines may be taken as the area of an equivalent flat box. Conclusions must therefore consider the effect of variance in these parameters and the validity of using such input.

## 3. REVIEW OF PREDICTION METHODS

### 3.1 Required Facets

Ideally, one requires a method which can account for all possible combinations of parameters. However, the scope is often limited by trade-offs which make the procedure simpler or faster; for example, the prediction model should be capable of distinguishing between different absorbing surfaces as opposed to averaging the absorption coefficient over the entire internal surface area. It should also be capable of taking the source and receiver positions into account, both in respect of one another and in relation to the proximity of highly reflective surfaces. Furthermore, it is desirable to obtain some resolution in frequency; i.e. results in 1:1 or 1:3 octave bands, not simply broadband. It is not generally difficult to incorporate these features, but the simplicity of the approach must be kept in mind. The following review is therefore split into "empirical" (generally based on measurement data or corrections to improper use of theory) and more complex "analytical" methods. For a more detailed review, refer to [1],[3]-[5].

### 3.2 Empirical Models

**3.2.1 Friberg [6]** A very simplistic approach based purely on measurement data. Absorption, fitting and shape characteristics are put in a small number of groups which makes the application very restricted, resulting in an unreferenced SP curve shape.

**3.2.2 Thompson, et al [7]** A modified version of Eyring's equation based on experimental observation which may be written in a single equation :

$$SPL = PWL + 10\log_{10}\left[\frac{Qe^{-mr}}{4\pi r^2} + \frac{\mathcal{L}}{r}\frac{4}{S(\alpha+4Vm/S)}\right] - 10\log_{10}\left[\frac{T+460}{527} + \frac{30}{P_b}\right] \qquad (2)$$

where Q is a directivity factor (=1 for omnidirectional source), m is the air absorption coefficient (Np/m), S is the wall surface area ($m^2$), $\mathcal{L}$ is the mean free path (usually given by $\mathcal{L}$=4V/S), $\alpha$ is the average room absorption coefficient, V is the room volume ($m^3$), T is the Fahrenheit temperature and $P_b$ is the barometric pressure (in of Hg). The factory shape is only indirectly accounted for by the volume and surface area of walls. There is no possibility of modelling variously absorbing surfaces. Fittings and barriers are not accounted for, although some of this error may be offset due to the fact that the empirical corrections were based on measurements in a range of fitted enclosures.

**3.2.3 Ray model** It is possible to calculate a small number of rays by hand : e.g. direct path plus a single reflection from each surface. Shield [8] suggests such a procedure and accounts for the error introduced by using best-fit techniques to alter the power in the inverse square law (i.e. $1/r^2$ becomes $1/r^{1.7}$ ).

**3.2.4 Wilson [9]** The most simple of all models considered : constant dB decays are given for four broad types of "flat" enclosure. For example, an "acoustically hard, empty factory" rates as -3 dB per doubling distance.

**3.2.5 Canadian Standard Z107.52-M1983 [10]** A method applicable only to "flat", empty rooms. Internal surfaces are rated as "poorly", "partly" or "highly" absorptive. A correction curve is given to account for ceiling height, reflection surface absorption ratings and proximity of source and receiver to the walls. The method in which the curve has been determined is not described. The procedure has limited application and is relatively laborious. It is possible to obtain frequency-band information only by re-rating absorbing surfaces.

**3.2.6 Zetterling** [11] A point scoring system for "flat" enclosures. Points are accrued according to the volume, height and width of the space and the average absorption coefficients of the ceiling and side walls. The broadband A-weighted Sound Propagation curve is then read from graphical data (found using Lindqvist's model) according to the "score" and scattering cross-sectional density (for uniformly distributed fittings). Tables only provide information up to 20m. The positioning of source and receiver relative to walls is not considered.

**3.2.7 Sergeyev** [12,13] Based on a large number of scale model and full scale measurements in "typically" fitted factories. A mathematical model is proposed with unknown constants and "Similarity Theory" is used to regressively best-fit the data to the assumed model, hence defining the equation constants. Two types of factory are considered : "flat" and "long". The final equation is the resultant of both of these groups and claimed to be precise in all factory shapes for "large distances" away from the source. The absorption coefficient must be averaged over all internal surfaces. The source and receiver positions are only regarded with respect to one another.

**3.3 Analytical Models**

The following models are based on the image method or ray tracing. The most common algorithms are compared in detail by Stephenson [14] showing that the image method was comparably inefficient. He also suggested that it would not be problematic to adjust ray tracing to account for diffraction. The greatest limitation of simple image methods is that it is extremely difficult to account for non cuboid factory shapes, although Borish [15] has attempted this for auditoria. A large number of such models have been developed, variably describing empty rooms. These have been ignored. The main point on which the methods listed below are selected and compared is their treatment of scattering. The theoretical background is similar in most cases and is carried out on a statistical basis (using the scattering cross-section density, q).

**3.3.1 Jovicic** [16] Two enclosure shapes ("flat" and "duct") were considered based on the image method. Unscattered and scattered energy density contributions are calculated separately and summed; the unscattered element being calculated as for an empty room. Jovicic introduces approximations for the image source array in each case : e.g. when the factory has infinite length and width, the remaining images can be regarded as a series of line sources. The resulting integration is approximated. This makes the calculation time short but results in additional error of approx. 2dB. The model is most limited by its ability to cope with finite factory dimensions and source/receiver positioning.

**3.3.2 Lindqvist** [17] Based on a simple image method approach which may be applied to arbitrarily dimensioned quadrilateral enclosures. The energy density contribution from scattered rays is rigorously derived and summed to the "unscattered" energy density. Fittings must be assumed to be uniform over the floor area and to have an average absorption coefficient, as in most methods. The method involves the longest calculation times of all those considered.

**3.3.3 Lemire and Nicolas** [18] A basic image method is applied, although energy contributions from high-order images are calculated using an empirical expression. Fittings are attributed an average height, with an empty volume above this. The Sound Propagation curve is assumed to decay exponentially such that curve shape is invariable and the method is not truly analytical.

**3.3.4 Kurze [19]** Based on the image method, a rigorous solution is derived for the scattered energy in a flat enclosure (length and width infinite). Only the absorption coefficient of the ceiling can be input as the floor is assumed to be non-absorptive. The fittings are distributed randomly.

**3.3.5 Ondet and Barbry [20]** A ray tracing program specifically designed to model fitted industrial spaces. Fittings are randomly distributed within any number of pre-defined zones. Hence, this is the only model considered which is able to account for varied concentrations of fittings and explicitly describe any shape of room with diverse absorption characteristics. Barriers may also be considered within the building by describing them as finite planes (although this does not include diffraction). The statistical distribution of the distance separating two consecutive obstacles is shown to be exponential with an average value $\lambda$. One may then think of $\lambda$ as the "mean free path" within a particular fitted zone of constant q. The scattering from these obstacles is described by a Poisson process. The Sound Propagation is then predicted over a "plane" of cubic receiving cells at any designated height.

### 3.4 Implementation of Models

Not all of the models reviewed are fully tested. Friberg, Wilson and Zetterling were not selected for many reasons, not least because they do not provide discrete frequency information and allow adequate variation in SP curve shape. Lemire and Nicolas's image method contains the incorrect assumption of exponential attenuation due to fittings and has been said to be "of little application to fitted-room prediction" [5]. The assumptions of factory size and limitation of source/receiver positions and description of absorption introduced by Kurze reduce the applicability of this method. The parameters which each model used is able to take into account is summarised in Table 1.

**Table 1 :** Summary of applicability of prediction methods (● → factors fully taken into account, ⊗ → indirectly/partially accounted for, O → not taken into account).

| | Canadian Standard | Thompson et al | small no. rays | Sergeyev | Ray tracing | Lindqvist | Jovicic "flat" | Jovicic "duct" | Image method (empty) |
|---|---|---|---|---|---|---|---|---|---|
| Factory shape | ⊗ | ⊗ | ⊗ | ⊗ | ● | ⊗ | ⊗ | ⊗ | ⊗ |
| Roof shape | O | O | ⊗ | O | ● | O | O | O | O |
| S-R position | ● | ⊗ | ● | ⊗ | ● | ● | ⊗ | ⊗ | ● |
| Source PWL | ⊗ | ● | ● | ● | ● | ● | ● | ● | ● |
| Surface $\alpha_s$ | ⊗ | ● | ● | ● | ● | ● | ⊗ | ⊗ | ● |
| Different $\alpha_s$ | ● | O | ● | O | ● | ● | O | O | ● |
| Fitting density | O | O | ⊗ | ⊗ | ● | ● | ● | ● | O |
| Fitting $\alpha_f$ | O | O | ● | ⊗ | ● | ● | ● | ● | O |
| Different $\alpha_f$ | O | O | ● | O | ● | O | O | O | O |
| Barriers | O | O | ● | O | ● | O | O | O | O |
| SP curve shape | O | O | ● | ⊗ | ● | ● | ● | ● | ● |
| Freq.variation | ● | ● | ● | ● | ● | ● | ● | ● | ● |

The remaining models have been applied in all measurement cases whether they are strictly applicable or not (although this will be accounted for). For example, only the ray-tracing technique [20] is capable of fully modelling "saw-tooth" roofs. In order to apply other models, a flat roof is assumed such that the enclosure volume remains constant. Adjustments are then made to the value of scattering where appropriate. A similar idea is applied to the occurrence of non-rectangular volumes [1]. For comparison, calculations are also performed using the standard diffuse-field and image source theories where the enclosure must be assumed empty. In the case of Jovicic's methods, both approximate and fully integrated approaches are employed (on modern computers there is not a great difference in processing time). The empirical "ray-tracing" method is undertaken by simply calculating a direct ray path plus a single reflection from each unobstructed surface within the enclosure.

A major impediment to absolute comparison between measurement and prediction is the difficulty in determining accurate absorption coefficients. It is noted that many papers simply employ "best fit" techniques : not a valid approach in this case! This is of special consequence in the case of machines. Orlowski and Hodgson [21] measured the absorption of a lathe and a sheeting machine and concluded that a Sabine absorption of approx. $1m^2$ could be used for metal machines "with major dimensions of approximately 1-2m". Hodgson [22] stated that this could be translated into an absorption coefficient of 0.1 for the frequency range considered (100Hz to 5KHz). In all cases considered here, this is the value employed for all machines and other metal fittings (e.g. walkways, girders).

## 4. FACTORY MEASUREMENTS

The Sound Propagation data described are measurements carried out by the University of Salford; except one from existing literature [20]. Clearly, there is a certain amount of reliance on "typical" values for some of the computational parameters, especially the absorption coefficient and surface area of fittings (required to obtain the scattering cross section density, q). Nine factories have been measured, varying in volume from 912 to 24,444 $m^3$ and with values of q between 0.0082 (~empty) to 0.134 (very densely fitted) as summarised in Table 2. The value of scattering cross section density given is the average estimated over the whole enclosure.

Table 2 : summary of factories measured.

| factory number | aspect ratio | volume ($m^3$) | q |
|---|---|---|---|
| 1 | 7.8 : 2.1 | 912 | 0.134 |
| 2 | 7.8 : 6.8 | 17,512 | 0.043 |
| 3 | 11.8 : 7.6 | 15,015 | 0.055 |
| 4 | 5.2 : 2.6 | 1,190 | 0.071 |
| 5 | 1.7 : 1.2 | 2,223 | 0.008 |
| 6 | 2.0 : 1.8 | 2,768 | 0.016 |
| 7 | 4.4 : 2.0 | 6,624 | 0.009 |
| 8 | 5.1 : 2.8 | 1,466 | 0.010 |
| 9 | "L" (~8.4 : 2.8) | 24,444 | 0.063 |

## 5. COMPARISON OF RESULTS

Figures 1 and 2 demonstrate typical comparisons between SP measurements and predictions (diagonally and along the length of factory 2 respectively). The figures represent only the 1KHz 1:3 octave band. However, it was not found that great discrepancies in accuracy occurred for different frequencies.

The mean amplitude error (dB.) for each prediction may be calculated from :

$$e_{av} = \frac{\sum_{n=1}^{N} |L_{M_n} - L_{P_n}|}{N} \tag{3}$$

where $L_{M_n}$ is the measured value of SP at a point, $L_{P_n}$ is its predicted value, and N is the number of measurement points. A comparison is also made of the curve shapes using the "correlation coefficient" :

$$r = \frac{1}{N} \sum \frac{(x-\bar{x})}{\sigma_x} \frac{(y-\bar{y})}{\sigma_y} \tag{4}$$

where x and y represent the measured and predicted data sets, with standard deviations given by $\sigma_x$ and $\sigma_y$ respectively. The correlation coefficient may vary from -1 (negative correlation, i.e. reflection in x-axis), through 0 (no correlation) to 1 (perfect match).

Table 3 provides a summary of the errors and correlations averaged over all 15 SP measurements. Where a factory configuration is out of the stated applicable bounds of a particular model, comparisons are still made by "forcing" the use of the method. It is recognised that this may cause large errors, but may be instructive in the search for a good generalised prediction technique. Hence, the mean amplitude error and correlation coefficient are calculated for each model (i) over all enclosures, and (ii) over applicable cases only.

Clearly, the Ondet and Barbry ray-tracing program [20] provides the most consistent predictions over all factory sizes and shapes and can be recommended, particularly because the user-input is very straightforward. It is also interesting to note that the modified version of Eyring's equation by Thompson, et al [7] also exhibits good accuracy (generally better than the other more complicated analytical approaches). This is surprising because fitting density is not accounted for, other than that the model is based on measurements in "typically fitted" enclosures; i.e. large errors will occur in the same enclosure where the fittings are altered because the prediction will remain the same. The method also generally works better in larger volumes [1].

Considering each model in turn : the standard diffuse field theory is inapplicable except for small, proportionately shaped, empty rooms (e.g. factories 5 and 7) which is as expected. The Canadian standard [10] provided the most disappointing results, generally underestimating SPL and producing an "exponential" curve shape. Using a simplistic ray model generally underestimated levels, although correlation with the SP curve shape is good. Employing Shield's alteration to the inverse-square law [8] will therefore improve accuracy. Sergeyev's equation [12,13] is also disappointing considering the number of measurements on which it is based. He suggested it be used with measured Reverberation Time data as opposed to using "text book" absorption figures. However, even this does not seem to help much [1]. The Jovicic models [16] only work well when the real factory approximates infinite ducts or "flat" spaces. His assumptions generally add several dB to the prediction. The results produced by Lindqvist's program [17] should generally be about the same as ray-tracing for simple, rectilinear enclosures [17]. However, it is more complicated, inflexible and computer run-times are approximately 10 times longer. The standard image model overestimates levels as fittings are ignored. However, it is reasonable accurate for smaller, empty, proportionately shaped enclosures (but then so are easier empirical models!).

**Figure 1** : predictions compared to measured SP diagonally across factory 2 at 1KHz.

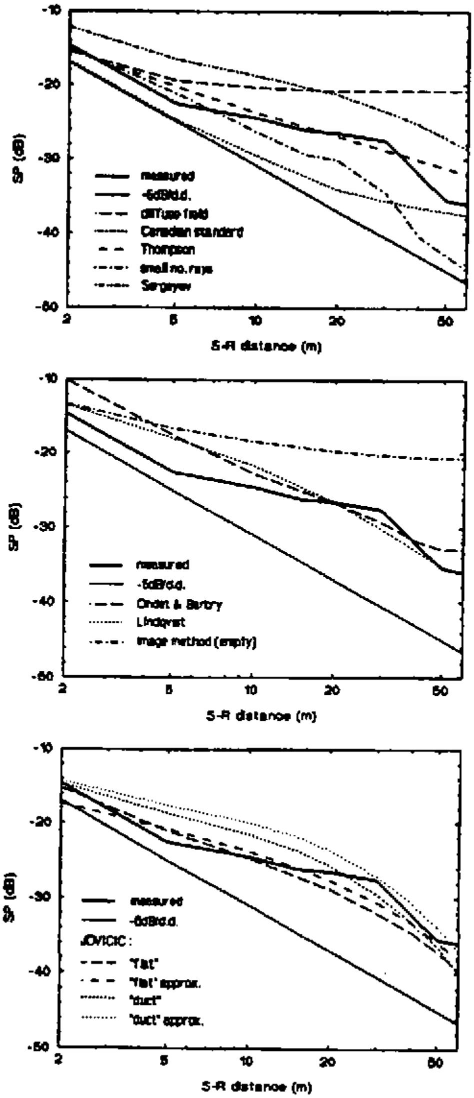

**Figure 2** : predictions compared to measured SP along length of factory 2 at 1KHz.

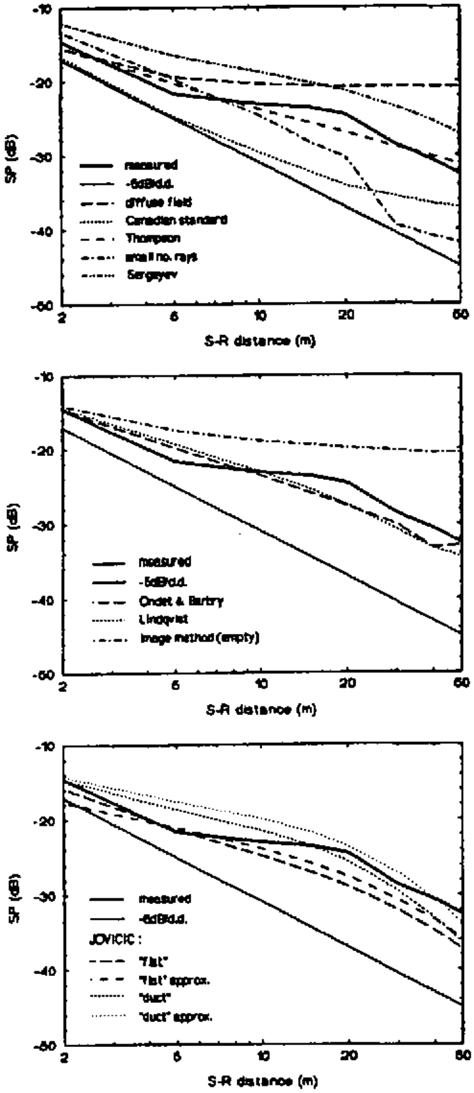

Table 3 : Summary of average mean amplitude errors and correlation coefficients.

A average error for all cases (dB)
B average error for applicable cases only (dB)
C average correlation coefficient for all cases
D average correlation coefficient for applicable cases only

| model | A | B | C | D |
|---|---|---|---|---|
| diffuse field | 5.082 | 2.669 | 0.87 | 0.93 |
| Canadian Standard | 6.026 | 3.850 | 0.95 | 0.93 |
| Thompson, et al. | 1.738 | | 0.98 | |
| small no. rays | 4.418 | | 0.98 | |
| Sergeyev | 3.457 | | 0.99 | |
| Ray tracing | 1.548 | | 0.97 | |
| Lindqvist | 1.742 | | 0.98 | |
| Jovicic "flat" | 3.959 | 1.629 | 0.99 | 0.99 |
| Jov. "flat" approx. | 4.218 | 1.877 | 0.98 | 0.98 |
| Jovicic "duct" | 3.170 | 2.849 | 0.98 | 0.98 |
| Jov. "duct" approx. | 2.950 | 2.542 | 0.98 | 0.98 |
| Image (empty) | 5.095 | | 0.95 | |

It is accepted that this analysis is dependant on absorption data which may not be wholly accurate. However, one is rarely (if ever) in the situation where such information is available. It could easily be debated that the huge amount of energy currently spent on small improvements to existing methods (particularly that of Ondet and Barbry) could be better employed finding a way to account for *in situ* absorption coefficients. Curve-fitting could have been employed for all of the techniques considered - but then any method could give favourable results when the input data is adjusted to do so! Nevertheless, it is noted that employing $\alpha=0.1$ for metal fittings does seem reasonable. Including the internal surfaces of the building as scattering objects (e.g. for profiled walls such as steel cladding) will also improve the accuracy of ray-tracing [1].

## 6. CONCLUSION

It has been shown that the ray tracing model developed by Ondet and Barbry is the most accurate Sound Propagation prediction tool currently available and provides adequate results for present noise control problems. Lindqvist's method is similarly accurate but less attractive because of its limited applicability and long run times. One empirical method was also found to attain surprising accuracy : Thompson, et al's model may be used successfully when applied to large factories with a normal and uniform amount of fittings.

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## ACOUSTICS OF UNDERGROUND PLATFORMS

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## ACOUSTICS OF UNDERGROUND PLATFORMS

This Paper is in three parts. Firstly a presentation of results obtained from measurements taken at the Aldywch Station as part of a speech intelligibility investigation, secondly from measurements made at Old Street and St. Johns Wood as part of a measurement exercise and finally the application of the results obtained in a speech intelligibility prediction model.

The measurements in this Paper all relate to reverberation time, propagation and Speech Transmission Index.

## ALDWYCH PROJECT

During the early part of 1993 we were commissioned by London Underground Ltd. to carry out a speech intelligibility investigation with the prime objective of rank-ordering the factors which affect speech intelligibility as relayed by the present London Underground public address system.

A small part of this investigation was to examine the acoustic properties of platforms.

The Aldwych platform was unique and of considerable acoustic interest. Work was halted during a refurbishment programme at a point when half of the ceramic tiles had been stripped-off.

This left one-half of the platform acoustically live and the other acoustically dead.

The acoustically live end had a mid-frequency $RT_{500Hz}$ of around 2.5 sec. whereas the acoustically dead end was nearer 1.0 sec.

The transition was abrupt. Over a distance of less than 2m there was a subjectively noticeable transition from live to dead.

Although the investigation was conducted in a spirit of open-mindedness we were sure that the findings would cite both the system design and reverberation time as the primary causes of reduced intelligibility. As such we were also surprised that even in the live end the RT was as low as 2.5 sec.

In sound system design terms, a reverberation time of 2.5 secs. whilst not routine is a relatively pedestrian matter in that it is comparatively easy to design a system to provide the prescribed speech intelligibility. Sound system design starts to become difficult with RT's measurements of 3.5 secs.

The results of the RT measurements provided the first and most significant clue.

Measurements were made at 5m intervals along the platform with the source firstly in the centre of the live end and secondly with the source in the centre of the dead end.

Figs. 1, 2 and 3 show the results obtained in the 500Hz, 1kHz and 2kHz bands. Clearly in classical terms each end should be cognisant of the influence of the other since by definition there is an equal probability of sound arriving or passing from any particular direction.

In the case of the source in the dead end, the RT measured in the dead end appears to be independent of the acoustics of the live end.

This clearly demonstrates that the propagation is bi-directional. Examination of the impulse responses indicate relatively small reflections from the head walls. In almost all cases the decay process was monotonic with little or no evidence of coupled spaces.

The results are not surprising when considered in light of our subjective experience which was that the transition from dead to live or live to dead was abrupt. In a classical or semi-classical space this would not be true.

We also carried out propagation measurements using a B & K artificial mouth. In this experiment the attenuation with distance was determined at measured distances from the source. We measured both in front of and behind the source. The results are shown in figs. 4 and 5.

It can be seen that the sound pressure level continued to fall with increasing distance and further that the decrease in level was greater for the dead end than the live. It can be seen that the difference is considerable and that the attenuation under tunnel acoustics is much reduced which would decrease the effective direct-to-reverberant ratio. Figs. 6 and 7 show the comparison between the live and dead end at 500Hz and 2kHz.

Fig. 8 shows the predicted resultant field if the source was placed in a classical space with the same volume and reverberation time.

OLD STREET AND ST. JOHNS WOOD

The problem with the Aldwych Station was that only half of the length was available for comparison since the acoustics of each half was quite different. We were afforded the opportunity at Old Street and St. Johns Wood to utilise most of the platform length. The two stations differed in that Old Street had been acoustically treated and had a reverberation time of around 1.4 sec. (500Hz) and St. Johns Wood was around 4.0 sec. (500Hz).

In this experiment we used a self-powered loudspeaker as the source mounted at a height of 1.8m facing down the length of the platform.

The results are shown in figs. 9 and 10.

It can be seen that the attenuation is frequency dependent and further that no reverberant level is reached.

Conclusions

From the foregoing we can suggest that the acoustic properties of underground stations do not conform to our expectation based on a classical treatment. In a sense this should not be unexpected. Fig. 11 shows the results obtained for all stations.

Calculation or prediction of RT therefore cannot be on a classical basis. The expression:

$$RT = \frac{0.163V}{S\bar{\alpha}}$$

does not hold true since this relies on an equal probability of sound arriving from any particular direction. From a consideration of path differences, velocity of sound and surface absorption coefficient it is possible to deduce that the RT of a tube may be approximated by:

$$RT = \frac{D}{55Lg(1-\alpha)}$$

where: D = mean tube diameter
$\alpha$ = surface absorption.

The results obtained are quite good and much closer to the measured values than would be produced by a classical approach.

## INTELLIGIBILITY PREDICTION MODEL

The attenuation along a tunnel may be approximated by the empirical expression:

$$Attn_{500} = \frac{0.38}{RT}(d+8)+2.5$$

$$Attn_{2k} = \frac{0.31}{RT}(d+16.5)+3$$

where: RT = Reverberation of the space (sec.)
d = distance from the source (m).

The general Modulation Transfer Function m(F) is given by:

$$m(F) = \frac{\left|\int_0^\infty g^2(t)e^{-i2\pi Ft}dt\right|}{\int_0^\infty g^2(t)dt} \cdot \left[1 + 10^{\frac{S/N}{10}}\right]^{-1}$$

where: $g^2(t)$ = square of the impulse response
S/N = Signal-to-Noise ratio.

It can be shown that the solution may be given by:

$$m(F) = \frac{\left(A^2+B^2\right)^{1/2}}{C} \cdot \frac{1}{1 + 10^{\frac{-S/N}{10}}}$$

where: $$A = \frac{Q}{r^2} + \frac{1}{r_c^2}\left[1 + \left(\frac{2\pi FT}{13.8}\right)^2\right]^{-1}$$

$$B = \frac{2\pi FT}{13.8} \cdot \frac{1}{r^2}\left[1 + \left(\frac{2\pi FT}{13.8}\right)^2\right]^{-1}$$

$$C = \frac{Q}{r^2} + \frac{1}{r_c^2}$$

By utilising the Attenuation results and mimicking the RASTI computations we were able to obtain the following predictions for STI measured in the following stations:

| | | RASTI | |
|---|---|---|---|
| Station | | Measured | Predicted |
| Aldwych (dead) | ON | 0.51 | 0.65 |
| | OFF | 0.45 | 0.58 |
| Aldwych (live) | ON | 0.43 | 0.47 |
| | OFF | 0.39 | 0.43 |
| Old Street | ON | 0.58 | 0.62 |
| | OFF | 0.54 | 0.55 |
| St. Johns Wood | ON | 0.38 | 0.40 |
| | OFF | 0.32 | 0.35 |

It can be seen from the above table that the agreement is generally good especially in the Old Street and St. Johns' platforms. The Aldwych live end also gives reasonable agreement. The Aldwych dead end results however give poor agreement. We believe this results from the fact that our prediction model is not cognisant of the contribution to the dead end acoustics made by the live end. This is consistent with the live end results since the contribution to the live from the dead end is relatively insignificant.

Finally we are able to conclude that the acoustics of tube platforms do not conform to accepted classical computations.

References:

[1] Aldwych Project - AMS Acoustics Research Project
[2] Houtgast et al. (various Papers)
[3] Tube Propagation - AMS Acoustics - Internal Research Paper
[4] Tube Acoustics - AMS Acoustics - Internal Research Paper.

RT DISTRIBUTION ALONG PLATFORM @ 500Hz.

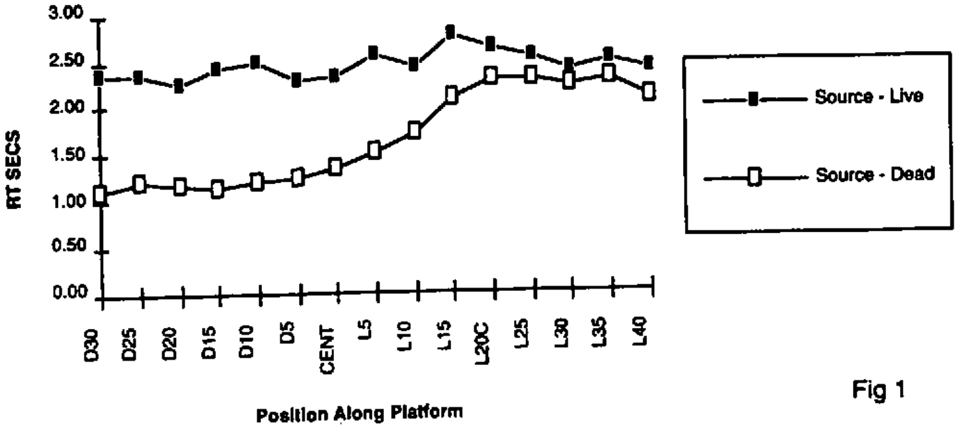



Fig 1

RT DISTRIBUTION ALONG PLATFORM @ 1KHz.

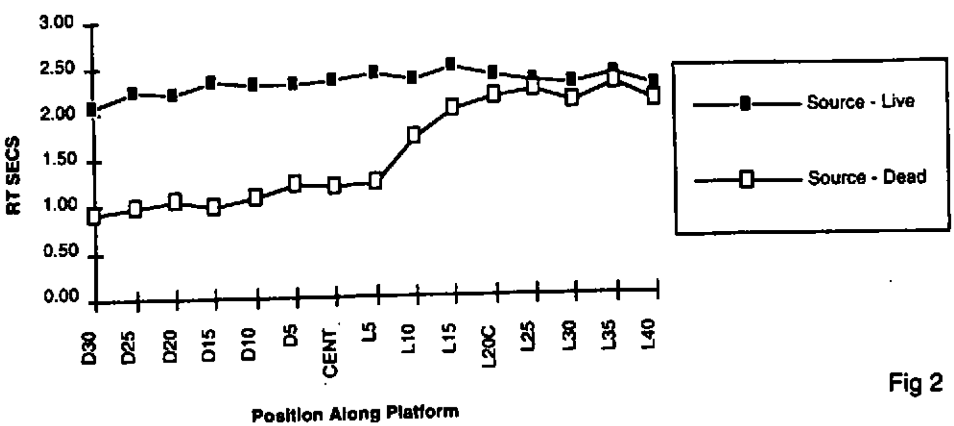
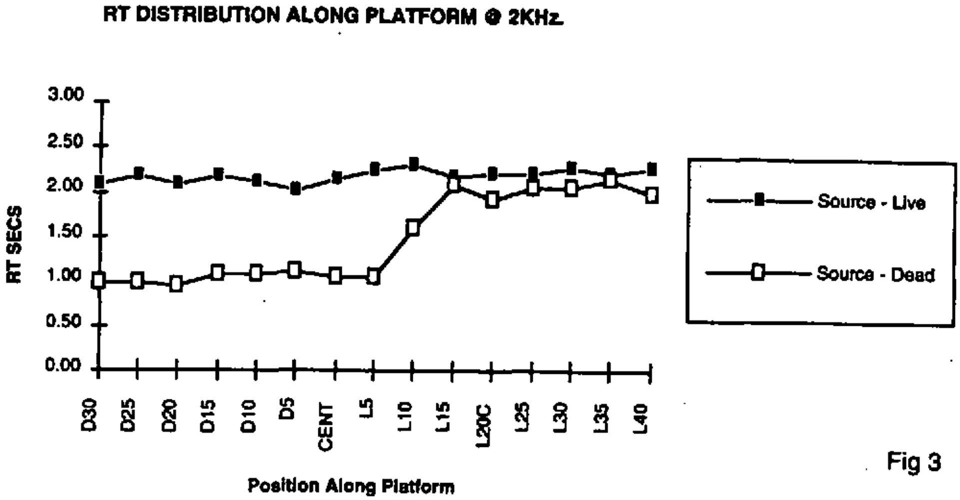
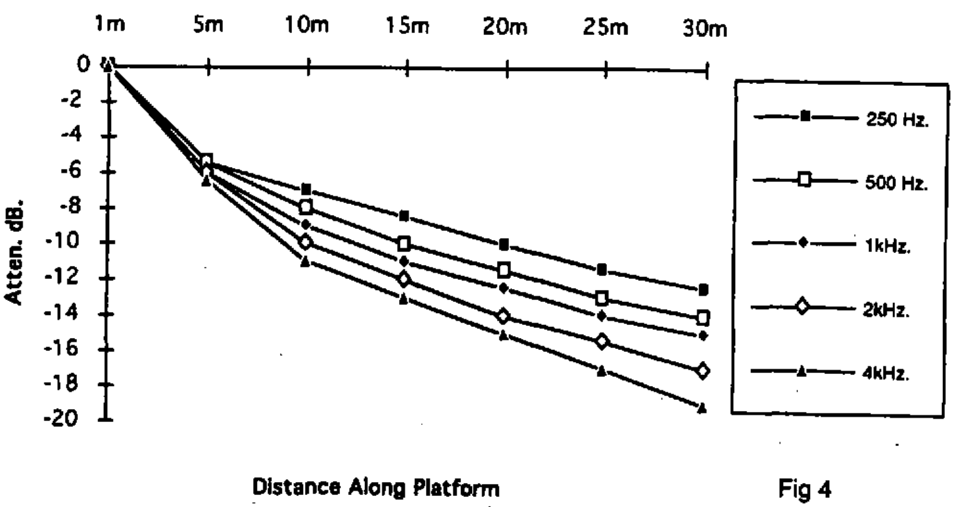



Fig 2



RT DISTRIBUTION ALONG PLATFORM @ 2KHz
RT SECS
3.00
2.50
2.00
1.50
1.00
0.50
0.00
D30
D25
D20
D15
D10
D5
CENT
L5
L10
L15
L20C
L25
L30
L35
L40
Source - Live
Source - Dead
Position Along Platform


Fig 3



1m
5m
10m
15m
20m
25m
30m
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
Atten. dB.
250 Hz.
500 Hz.
1kHz.
2kHz.
4kHz.
Distance Along Platform


Fig 4

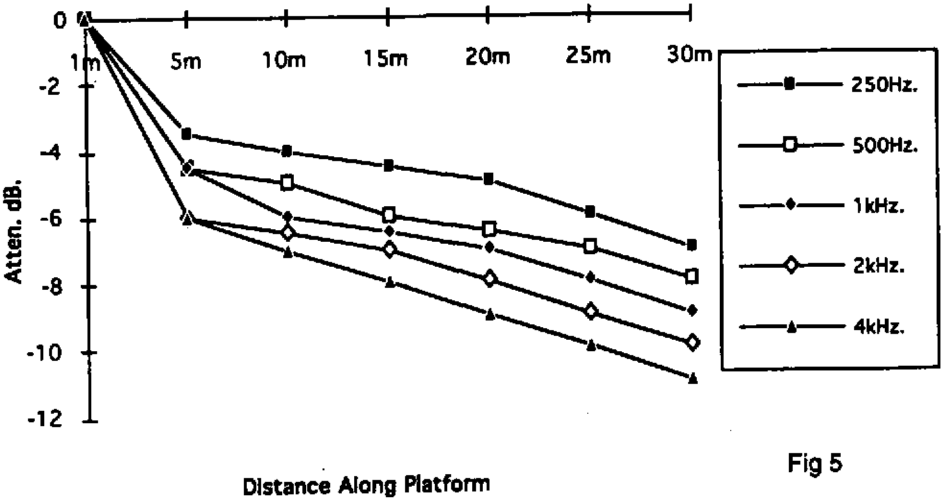

0
-2
-4
-6
-8
-10
-12
Atten. dB.
1m
5m
10m
15m
20m
25m
30m
250Hz.
500Hz.
1kHz.
2kHz.
4kHz.
Distance Along Platform

Fig 5

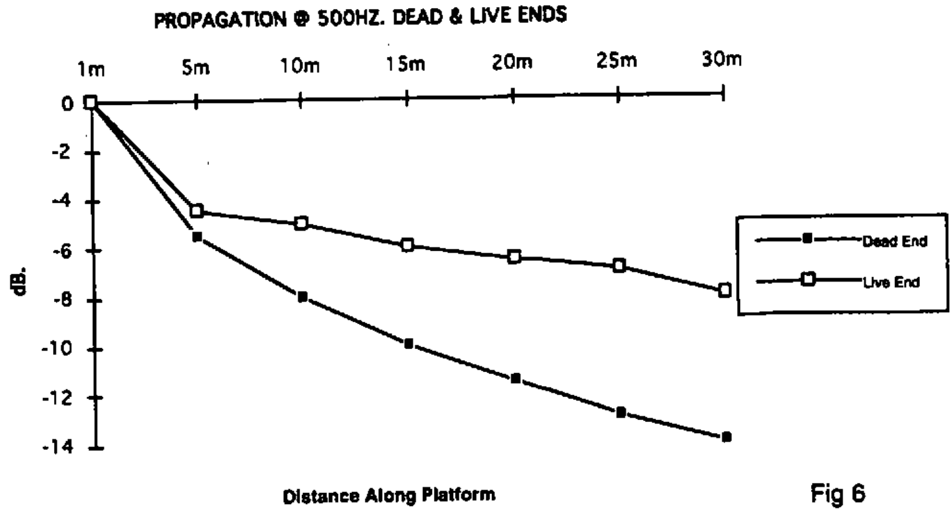

PROPAGATION @ 500HZ. DEAD & LIVE ENDS
1m
5m
10m
15m
20m
25m
30m
0
-2
-4
-6
-8
-10
-12
-14
dB.
Dead End
Live End
Distance Along Platform

Fig 6

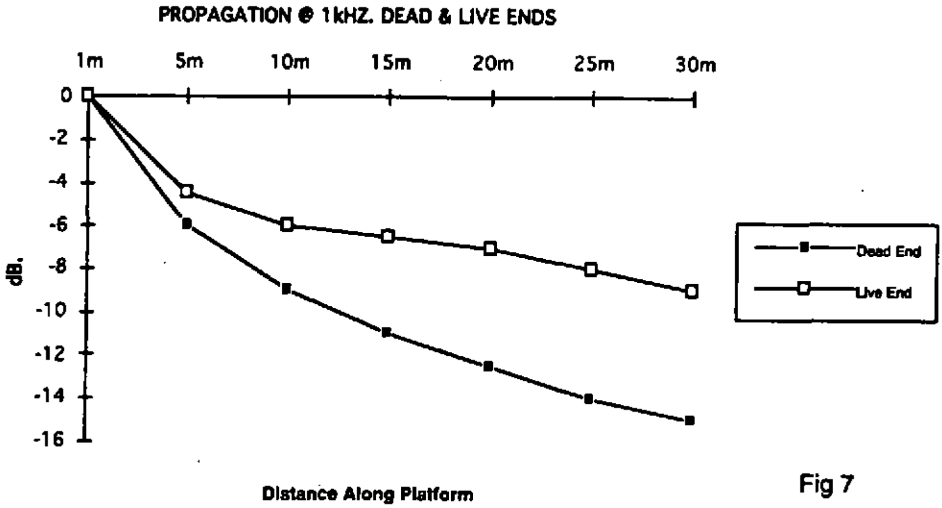

PROPAGATION @ 1kHZ. DEAD & LIVE ENDS
1m
5m
10m
15m
20m
25m
30m
0
-2
-4
-6
-8
-10
-12
-14
-16
dB.
Dead End
Live End
Distance Along Platform

Fig 7

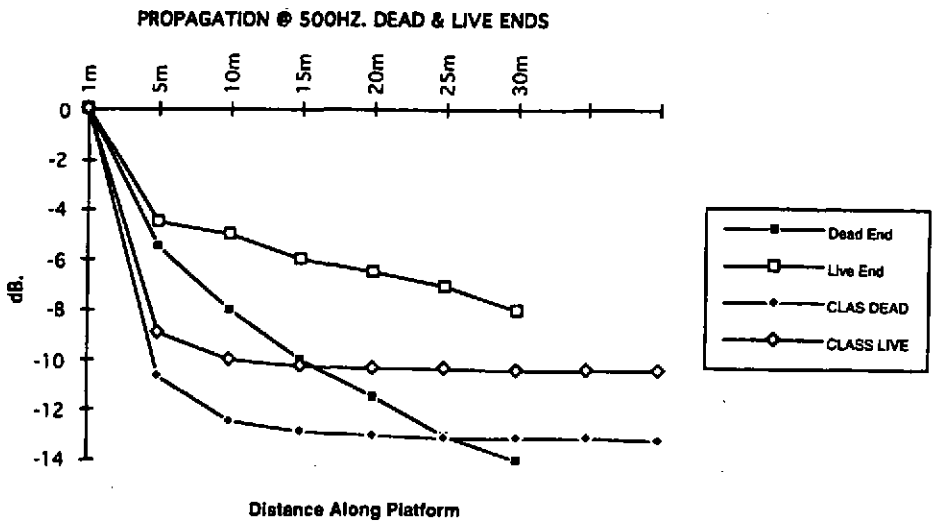

PROPAGATION @ 500HZ. DEAD & LIVE ENDS
1m
5m
10m
15m
20m
25m
30m
0
-2
-4
-6
-8
-10
-12
-14
dB.
Dead End
Live End
CLAS DEAD
CLASS LIVE
Distance Along Platform

Fig 8

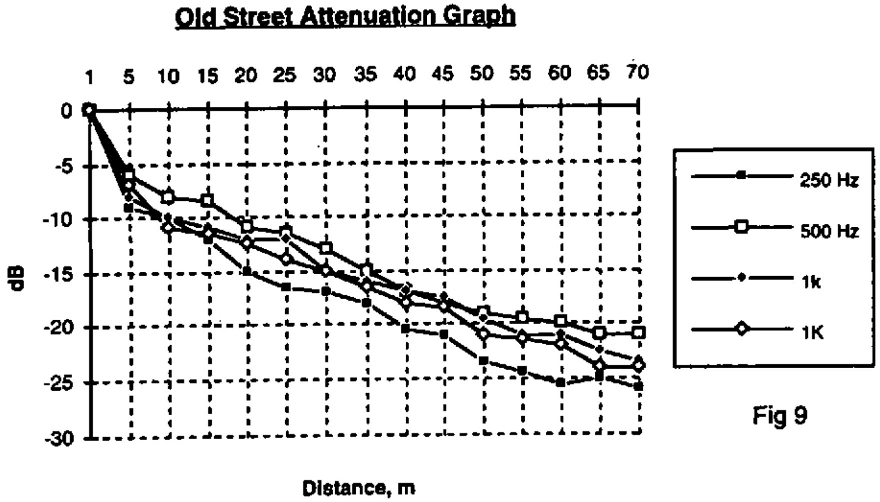

Old Street Attenuation Graph
1
5
10
15
20
25
30
35
40
45
50
55
60
65
70
0
-5
-10
-15
-20
-25
-30
dB
250 Hz
500 Hz
1k
1K
Distance, m

Fig 9

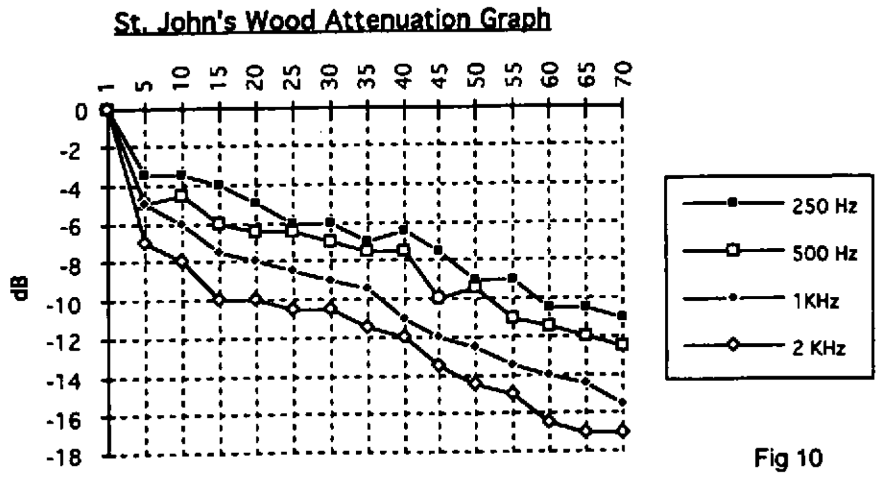

St. John's Wood Attenuation Graph
1
5
10
15
20
25
30
35
40
45
50
55
60
65
70
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
dB
250 Hz
500 Hz
1KHz
2 KHz
Distance,m

Fig 10

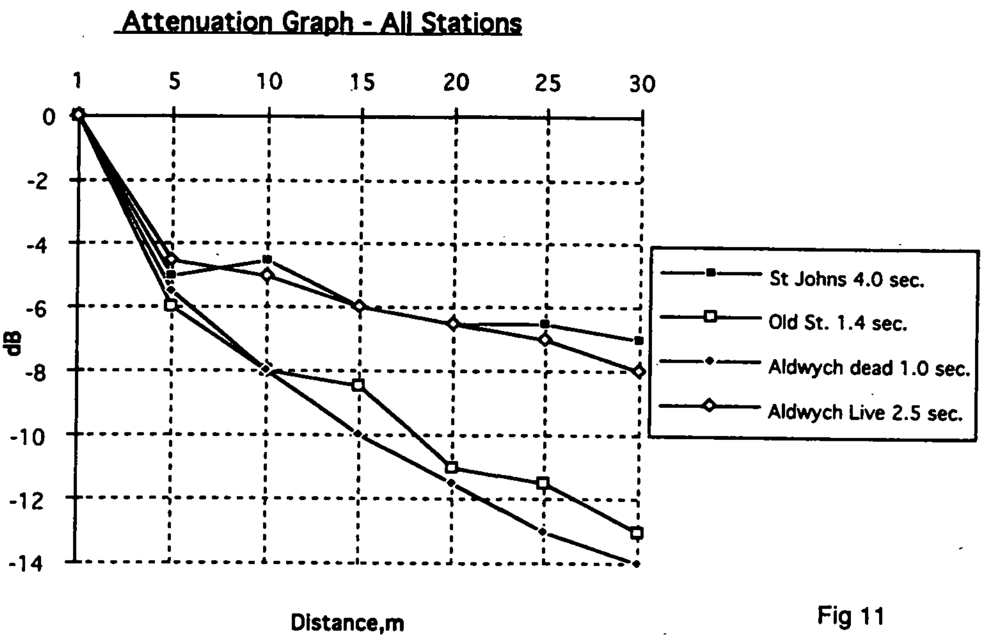

Attenuation Graph - All Stations
1
5
10
15
20
25
30
0
-2
-4
-6
-8
-10
-12
-14
dB
St Johns 4.0 sec.
Old St. 1.4 sec.
Aldwych dead 1.0 sec.
Aldwych Live 2.5 sec.
Distance,m

Fig 11