A Field Study of the Acoustical Insulation of Residential Construction

by

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This thesis is dedicated to my kind parents.

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ABSTRACT

The angle of incidence is a major variable for calculating transmission loss from field data [A.S.T.M. 336-77]. This suggests that the acoustical insulation of residential construction may vary with the relative location of the flight paths and the housing. Alternatively, the Central Mortgage and Housing Corporation assumes in its guideline that the number of reflected paths in normal residential areas is so great as to override any such effect.

The first objective of this study is to investigate the effect of the angle of incidence on the acoustical insulation in residential construction. The second objective is to compare the acoustical insulation as calculated from field transmission loss data with the one estimated in the C.M.H.C. guideline.

Field transmission loss data were collected for each one-third octave band for 30 rooms in the Toronto airport area. The first objective is studied using data from rooms affected by aircraft noise, where the flight path is perpendicular to the plane defined by the element of interest, as well as from rooms affected by road traffic noise. The variation of the acoustical insulation over time is studied. The results suggest that there is a noticeable effect of the angle of incidence for the houses exposed to aircraft noise. The second objective is studied using data from rooms affected by aircraft noise. The acoustical insulation estimated by C.M.H.C. is found to be lower than the one calculated from field transmission loss data.

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CHAPTER 1

INTRODUCTION

The last twenty years have produced an increasing concern for the quality of the environment, and noise has been rightfully included among the pollutants to be controlled. One of the major noise sources is air traffic, which has increased significantly in recent years.

As a result of the increase in air traffic, airports tend to occupy large land areas with multiple runways and extensive airspace involved in landing and take-off procedures. At the same time the trend of urban expansion has resulted in more residential areas close to airports. These two facts make the problem of aircraft noise control an important issue. The fact that the aviation industry is a major sector in the economies of developed countries increases the complexity of the aircraft noise control problem.

All noise control problems involve three parts:

. the noise source;

the recipient of the noise; and

the path between these two.

Protection of the public health and welfare is accomplished most effectively by exercising these three noise control parts combined as a system. In the case of aircraft noise the source control consists of design principles or special hardware for the engine/airframe combination, which will minimize the generation of noise.

The opportunities for noise control at the receiver, residents in the houses close to airports, are extremely limited. The path control consists of either flight procedures or building design procedures for minimizing the propagation of noise.

Normally the permissible noise levels are set for the receiver, and engineering techniques, involving the above mentioned noise control system, must be used in order to reduce excessive outdoor noise levels to levels which are acceptable at least indoors.

One engineering technique, which deals with the path of the noise, is the design of an exterior room envelope that will reduce the given outdoor noise levels to acceptable indoor ones. The Central Mortgage and Housing Corporation (C.M.H.C.), (1), recommends a procedure for the design of an exterior room envelope, so that the indoor noise level will be acceptable. This procedure is based on the acoustical insulation provided by each component of the exterior room envelope. Two assumptions are inherent in this procedure:

- there is no effect of the angle of incidence of the sound waves as the facade on the acoustical insulation of the room; and
- laboratory measurements represent real construction.

In constrast to the first assumption, A.S.T.M. E33 (2) states that the angle of incidence is a major variable on the acoustical insulation. More specifically it is stated that the acoustical insulation decreases for angles up to 70° by the factor

$$+ 10 \text{ Log } (\cos\theta).$$

Thus, for example, in angles of 60° the acoustical insulation decreases by 3 db,as compared to an angle of 0. As regards the second assumption the different outdoor noise sources, as well as the number of reflected paths in normal residential areas may cause different results as measured in real construction rather than in the laboratory.

When the outdoor noise source is road traffic on a highway, with an almost continuous stream of vehicles, a wide range of angles of incidence is incorporated in each measurement. On the contrary when the outdoor noise source is an aircraft, the angle of incidence varies over time. This variation depends on the relative location of the flight path and the housing. Alternatively, the number of reflected paths in normal residential areas may be so great as to override any such effect.

The first objective of this study is to investigate the effect of the angle of incidence on the acoustical insulation of residential construction calculated from field measurements.

The second objective of this study is to compare the acoustical insulation for different rooms calculated from field measurements with the acoustical insulation for the same rooms as calculated from the C.M.H.C. guideline given the number and characteristics of the components of the exterior envelope for each room.

The design procedure as well as the testing at site require an index that can be used for rating the acoustical insulation performance of any room. Due to the fact that the envelope of a room may include many components, such as wall, window, door and ceiling-roof, there is also a need for an index for rating the acoustical insulation performance of each component.

Several indices have been accepted in the literature (3-9), but basically four of them are the most widely used. For reasons that will be explained in the following discussion the C.M.H.C. used the Acoustical Insulation Factor in the guideline for rating the acoustical insulation of each component as well as of each room.

The first index is the Noise Reduction which is expressed as the difference of sound pressure levels (in dB) in front of and behind the element of interest (9), for each one-third octave band.

The second is the Transmission Loss (T.L). It is the corrected Noise Reduction, taking into account the size of the element of interest and the acoustical properties of the receiving room (3,9).

Although both indices can provide some information about the acoustical insulation performance of an element, neither can be easily used for design purposes, because of the following two major disadvantages:

they depend on frequency; and

they can not be combined over all elements of a room to provide a single figure describing the acoustical insulation of the room.

The third index is the Sound Transmission Class, which was introduced in order to provide a single figure rating that can be used for comparing different elements of interest for general building design purposes (10). To determine the Sound Transmission Class of an element, the curve representing its transmission loss as a function of frequency is compared with a standardized reference frequency curve, the so-called Sound Transmission Class contour. The Sound Transmission Class contour is shifted vertically relative to the test curve until the sum of deviations of the test curve from the contour is not more than 32 dB and is shifted vertically relative to the test curve until the sum of deviations of the test curve from the contour is not more than 32 dB and none of those deviations exceeds 8 dB. When the test curve is so adjusted, the Sound Transmission Class value is read as the Transmission Loss value corresponding to the intersection of the Sound Transmission Class contour and the 500 Hz frequency line.

A.S.T.M. E 413-73 (10, section 1) states that the Sound Transmission Class procedure is designed for typical indoor sounds such as speech, radio, music and similar sources of noise in offices and buildings, and is not applicable for sources with spectra that differ markedly from those described above. Thus the noise produced by road or aircraft traffic is excluded from the scope of this rating procedure.

The fourth index, the Acoustical Insulation Factor (A.I.F.), was introduced in 1973 by R.J. Donato (11). The objectives were to establish an index for rating the acoustical insulation of different elements that will not depend on frequency, and which will be used for outdoor noise sources such as road, rail and aircraft.

A revised version was issued in 1978 as a supplement to the Central Mortgage and Housing Corporation Site Planning Handbook where tables with Acoustical Insulation Factors for various elements of a building were presented (1). In Appendix 1 of the same publication the procedure for determining the appropriate building components given the design of the building and the outdoor aircraft noise level is illustrated as well. In this guideline several problems can be identified. First of all there is no single figure for rating the typical roof-attic-ceiling systems.

In 1978 the results of extensive research, undertaken for the Central Mortgage and Housing Corporation, were presented in the Journal of the Acoustical Society of America (12). Although the reported results do not include all window and wall construction, they do cover a sufficient range to permit reasonable estimates of the performance of most constructions of interest in typical residential buildings. In the same study the procedure for combining the A.I.F. of all elements of a room into the A.I.F. for the room is presented as well.

In 1979 two reports were published by Northwood et al. (13), and Quirt (14) and the procedure for calculating the A.I.F. for any element of a room from field transmission loss data was presented.

The A.I.F. is based on a standard outdoor source spectrum which is similar to spectra produced by aircraft, road traffic and railroad sources. The standard spectrum used for the outdoor noise source is presented in Figure 1.1. By subtracting the field transmission loss values from the standard sound source levels, the corresponding transmitted sound levels in each 1/3 octave band are obtained. Combining these 1/3 octave band levels yields the A-weighted sound level that would be measured in a room if only that component were transmitting sound. The difference between the standard sound level and the calculated transmitted A-weighted level is the A.I.F. for the component (14, page 11).

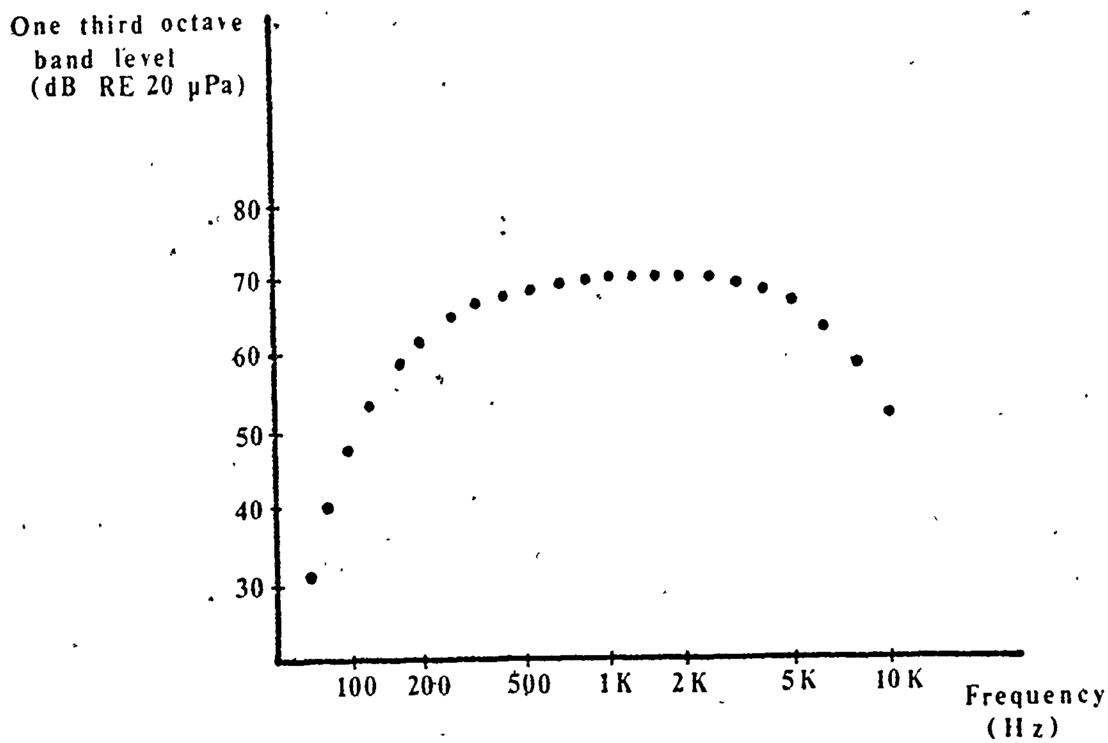

FIGURE 1.1. A-weighted source standard spectrum used for A.I.F. calculation.

Source: J.D. Quirt 1979, (14, Figure 1.).

In summary three points about the A.I.F. need emphasis.

1. It can be used for rating the acoustical insulation provided by an element as well as a room envelope.
2. It is a single number for each case.
3. It is designed for outdoor noise sources, such as rail, road and aircraft.

Quirt (12, page 827) states that the room A.I.F. depends strongly on aircraft position. He also states that the A.I.F. reaches a maximum when the angle of incidence is nearest normal, and a minimum when the angle is in the range of 70°-80° from the normal to the facade. In the same report (12, page 827) the construction studied was not located in a representative residential location, as regards reflected paths from other houses.

The possible effect of the angle of incidence is investigated in this study using both aircraft and road traffic sites. In the aircraft sites used in this investigation the flight path is perpendicular to the plane defined by the element of interest. Thus, as the aircraft is approaching the house, the angle of incidence increases as measured from the normal. For these sites the variation of the A.I.F. is studied over time. As was previously mentioned, in the road traffic sites a wide range of angles of incidence is incorporated in each time measurement.

The results will indicate if the reflected paths are so great that they can override any effect of the angle of incidence on the acoustical insulation of residential construction. If such an effect does exist, then the C.M.H.C. guideline has to be improved to incorporate this effect.

The second objective is studied by using three more aircraft sites, where the flight path is parallel to the plane defined by the element of interest. The results of the comparison between the A.I.F. calculated from field transmission loss data and the A.I.F. as calculated from the C.M.H.C. guideline, given the structural characteristics of the exterior envelope of the room, will provide useful information on the variation of the estimated insulation based on the characteristics of the room's elements in actual construction. If such a variation exists, then the estimated acoustical insulation using the C.M.H.C. guideline will not represent the actual insulation of the room.

This thesis is divided into six chapters. The next chapter deals with the data acquisition. The procedures used for collecting all the necessary data for each room are presented. In this chapter the equipment used is also described.

The third chapter deals with the data reduction. The procedure is presented which was used to reduce the data to the sections that satisfy the assumptions inherent in the concept of acoustical insulation. In the same chapter a table with all the original and reduced data is also presented.

The fourth chapter deals with the analysis of the reduced data. The equations and procedures used for calculating the room A.I.F. are presented. Some comments as regards the accuracy of the analysis are made in the last section of this chapter.

The fifth chapter discusses the results for both objectives of this study.

In the final chapter a summary of the results is presented, and some suggestions for further research are made.

CHAPTER 2

DATA COLLECTION

This chapter describes the procedures followed for collecting the data required for this study. The data were acquired during the summer of 1980. Two objectives were introduced in chapter 1:

to study the effect of the angle of incidence on the acoustical insulation of residential construction; and

to study the variation between the A.I.F. calculated from field transmission loss data and the one suggested by C.M.H.C. given the structural characteristics of each room.

Two types of data are required so that these objectives can be accomplished:

field transmission loss data for each site; and

structural and dimensional characteristics of each site.

Collection of the first set of data entails three tasks:

selection of the indoor microphone's location;

simultaneous measurement of indoor and outdoor sound pressure levels for each one third octave band; and

reverberation time measurement.

The first step in the data collection was the selection of the sites. The procedures and criteria used for this selection of the houses to be tested are described in the first section of this chapter.

The equipment used affects the data collection procedures, so a description of the equipment is contained in the second section of the chapter. The third section describes the procedures used to obtain field transmission loss data, under the three measurement headings identified above. Acquisition of information on structural characteristics is discussed in the fourth section. The two final sections deal with the difficulties of and constraints on the data collection, and their effect on the quality of the collected data. Some recommendations are made as regards future data collection procedures, including criteria used in the selection of sites.

2.1 Selection of sites

The selection of the sites was completed in four steps.

1. Identification of the sites to be used in Toronto area.
2. A letter was mailed to all residents of the identified sites.
3. The availability of the residents for the following working days was examined by calling them over the phone.
4. Information was obtained daily from the Air Traffic Control Tower as regards the runways used for take-off and landing at Toronto Airport.

The first step was based on previous studies conducted in the same areas. Thus most of the addresses of the sites were known. The second step was made to restore a contact with the residents and to inform them of the study and that we would call them in the near future.

The third step was a contact by phone, with all residents in the identified sites. The purpose of this step was to obtain their agreement to participate and to examine their availability for the following working days.

Due to the fact that the runways used at Toronto International Airport were changed every 4 hours during the day, a contact with the Air Traffic Control Tower was established as well. Thus the fourth step was repeated daily and the runways used and planned to be used were identified.

The final selection of the sites to be studied each day was based on the availability of the residents and the runways used for take-off and landing at Toronto International Airport. In order to increase the productivity during the data collection, sites affected by road traffic noise were studied when there was no aircraft site available.

By the end of the data collection, measurements had been completed for eight (8) aircraft sites and twenty-two (22) road traffic sites.

2.2 Equipment used

The equipment used meets the ASTM E-33 (2, section 9) requirements for collecting field transmission loss data. Two GEN-RAD 1995 integrating real-time analyzers were used for the sound analysis into 30 one-third octave bands covering the range of 25 Hz to 20 KHz as well as the A-weighted and flat-weighted level. The overall measurement range of these analyzers is from 20 dB to 140 dB, although only 53.5 dB range can be used for each setting. The GEN-RAD 1995 analyzer is also capable of analyzing a specific one-third octave band vs time.

Three GEN-RAD microphones were used. Two of them were 1" (25.4 mm) ceramic and the other was 1/2" (12.7 mm) electret condenser. The two 1" microphones were used for the selection of the indoor microphone's location. One 1/2" microphone was used for the outdoor measurements on the facade and one of the two 1" microphones was used for the indoor measurements. Due to the fact that no more than two microphones were used at the same time, only two GEN-RAD pre-amplifiers were used. A HEWLETT-PACKARD 9825A mini-computer with 23228 bytes of Random Access Memory was connected through the IEEE-488 digital interface with the analyzers. Thus, the sound pressure level for each one-third octave band as well as the A-weighted and flat-weighted levels were transferred to the minicomputer and stored on a cassette. The software used is presented in Appendix A.

A starter's pistol was used in the first 10 sites for recording on a UHER 4200 Tape Recorder the reverberation times in the room of interest. For the remaining sites a Tracoustics noise source (Model NS-100) was used. A GEN-RAD 1567 Sound level Calibrator was used for calibrating the analyzers and the tape recorder. The calibrator had an output of 114 dB in the frequency of 1KHz.

2.3 Field transmission loss data

2.3.1 Location of indoor microphone

Due to the fact that only one microphone was available for indoor measurements a representative location had to be found. A preliminary survey was made using a stationary and a moving microphone. The stationary microphone was located approximately at the middle of the room while the second one was moved to six different locations such that the following conditions specified by ASTM E-33 (2, section 7.3) were satisfied:

no microphone position was closer than 1 meter to the inside surface of the exterior wall; and

no microphone position was closer than 0.5 meters to any other extended surface.

If the A-weighted sound pressure level measured by the moving microphone did not differ more than 2 dB from the same level measured by the stationary microphone, the location of the stationary microphone was assumed to be representative of the room. Otherwise a new location of the stationary microphone was selected and the above mentioned survey was repeated until the limit was satisfied. The integration period used at eaoh location of the moving microphone was 10 seconds.

2.3.2 Indoor-outdoor noise measurements

The indoor-outdoor noise measurements were made using two microphones. The indoor microphone (1" ceramic) was located as identified in 2.3.1. The outdoor microphone was mounted on the center of the outside surface of the element of interest. A 1/2" electret condenser microphone was used so that the microphone diaphragm was within 20 mm of the facade, as is suggested by ASTM E-33 (2 section 7.3 Note 7). A wind screen was also used to eliminate the effect of wind on the outdoor measurements. Three samples were taken in each site.

In road traffic sites, when there is a continuous stream of vehicles, the averaging interval was 1 second, while each sample had 60 seconds of information.

In the aircraft sites, some fluctuations were expected, because of the moving source, and a shorter averaging interval of 0.5 second was used.

The analyzer connected with the outdoor microphone was set for a maximum level of 100 dB, while the analyzer connected with the indoor microphone was set at a maximum level of 80 dB. The range was selected so that the analyzers were not overloaded during the data collection.

The sound pressure levels were measured with flat response. In the aircraft sites an attempt was made to record three angles of incidence during each flyover, as well as the respective time for each of them. When the flight path was parallel to the plane defined by the element of interest, the initial angle, the angle at the time of the shortest distance from the element of interest and one before the end of the sample were to be recorded. When the flight path was perpendicular to the plane defined by the element of interest, the initial angle, one more before the grazing incidence and the one at grazing incidence were to be recorded. Unfortunately this task was not always feasible because of other existing structures, other obstacles, or other tasks occupying the crew.

During the simultaneous indoor-outdoor measurements all indoor noise sources had to be off, so that the data would not be contaminated.

2.3.3 Reverberation time measurements

The reverberation time of the room of interest was measured in each site. The indoor microphone was used at the same location as for the indoor-outdoor measurements.

For the first ten sites the impulse sound was produced by a starter's pistol. Due to the fact that the starter's pistol could not reproduce sound in a wide spectrum, the noise source described in 2.2 was used for the remaining sites.

The impulse sound and its decay were recorded in a UHER tape recorder using the highest available speed of 19 cm/sec covering all frequencies from 40 Hz to 20 KHz.

The tape recorder was calibrated in each site using the calibrator described in 2.2. An attenuation of 10 dB was enforced before the recording so that the dynamic range of the tape recorder was not exceeded.

In order to increase the precision of the estimate of the reverberation time three samples were recorded for each site.

2.4 Structural characteristics and dimensions

A sketch of each site was drawn and the following dimensions were measured:

- dimensions of the room of interest;
- dimensions of the element of interest;
- thickness of panes; and
- distance between panes.

For the last two mentioned dimensions the manufacturer's label was used, or if that was not possible an estimate was made. These dimensions as well as the following structural characteristics were needed for providing information on the A.I.F. as calculated by the C.M.H.C. procedures for the room of interest:

number of windows in the room of interest;

sealed or unsealed panes on each window;

material of external facade; and

number of lites for each window.

2.5 Constraints and difficulties identified during the data collection

One constraint and two difficulties were identified during the data collection. The constraint was the time the group was allowed to spend in each site. A self-imposed maximum limit of 90 minutes was set, to minimize the imposition on the residents. This constraint was satisfied in almost all road sites, although there were a few cases of delay caused by faulty equipment. The data collection phase of this study was interrrupted three times, because of one malfunctioning analyzer. In many aircraft sites the time constraint was extremely difficult to meet. The major reason was the irregular frequency of the aircraft movements. Although there was communication with the Air Traffic Control Tower, the frequency of the taking-off and landing aircrafts could not be identified or predicted.

The first difficulty was identified in many aircraft sites, when the angles of incidence had to be recorded. The existence of other houses or physical obstacles made the recording of these angles impossible.

The second difficulty was in ensuring that the indoor background levels were sufficiently low for the outdoor measurements. At some specific sites which have been marked, the indoor background noise was too high, especially in low frequencies. In some of these cases either the refrigerator was on, or some children were trying to enter the room of interest. These measurements were ignored and new measurements were collected.

Three recommendations are suggested to minimize the effect of these difficulties during the data collection.

1. Better communication with the Air Traffic Control Tower should be established, so that information on the frequency of taking off-landing aircraft as well as the expected traffic and the runways to be used could be provided. Thus excessive delay at aircraft sites can be avoided.
2. The fact that the angle of incidence has to be recorded should be a criterion on the site selection. Thus all information about the angle of incidence can be recorded.
3. During the indoor-outdoor measurement all indoor noise sources have to be off and no one should be in the house. Explanations can be provided by a member of the group to the residents, on the importance of this factor. Thus the contamination of the data will be minimized.

2.6 Comments on the quantity and quality of the data

The constraint and difficulties just discussed have an effect on the quantity and quality of the collected data.

The excessive delay caused by inadequate information from the Air Traffic Control Tower was the major variable on the quantity of the data.

The lack of information as regards the angles of incidence in aircraft sites has an effect on the proposed analysis for the first objective, because it does not always permit a direct comparison between the acoustical insulation provided by the same site at different angles.

The high indoor background levels at a site are extremely important because their effect on the quality of the data can be tremendous. If an indoor noise source is identified at a site, some more time will have to be spent in the specific site and consequently the quantity of the data is reduced. In some cases such a source is not easy to be identified at site, simply because it is not loud enough. In these cases the data collected at the beginning and/or at the end of the samples, when the outdoor noise is not loud enough, can be contaminated. For this reason and for some more that will be discussed in the next chapter, the collected data were reduced and in most of the cases only a segment of each collected sample was used in the analysis.

CHAPTER 3

DATA REDUCTION

The analysis of the indoor-outdoor noise measurements is based on the assumption that the indoor noise measurements are dominated by the outdoor source as measured at the surface of the element of interest. If this assumption is not satisfied by a sample, then that sample is not valid for calculation and study of the acoustical insulation of the room of interest. There are three conditions that need to be met by the sample for this assumption to be satisfied.

1. The outdoor noise measurements taken at the element of interest are representative of the dominant outdoor noise incident on the room envelope.
2. The outdoor noise source is loud enough so that when transmitted indoors, it is above the indoor background noise.
3. There is no noise source that contaminates the indoor measurements.

These conditions are tested by the data reduction procedures described in this chapter. These procedures will possibly reduce some samples to shorter segments that meet the above conditions. These shorter segments will be used in the analysis.

This chapter describes the procedures used for screening each collected sample to ensure that it meets each of these three conditions. The first section describes the computer program on which screening was based. Eaoh condition is then described in a separate section. One example is also illustrated for each condition. A summary of the collected as well as the reduced data is presented in Table 3.1. In the last section of this chapter one recommendation is made for an efficient use of the data reduction procedures during the data collection.

3.1 Screening the data

A program was written for the mini-computer to read each sample and print some of the sound pressure levels. (A listing of this program is presented in Appendix B). The sound pressure levels were printed for four (4) one-third octave bands: the 24th, 27th, 30th and 33rd corresponding to 250 Hz, 500 Hz, 1000 Hz and 2000 Hz, in the middle frequency ranges most important for interference in human speech. The duration of the time interval used for calculating the average indoor and outdoor sound pressure level for these bands, was a parameter in the program, which was set to different values for different purposes.

3.2 Outdoor measurements

The objective of this step is to identify the portion of each sample during which the measured outdoor noise is representative of the noise source dominating the exterior envelope of the room. This condition can only be satisfied if the major outdoor noise source and the outdoor microphone are located at the same side of the house.

In four aircraft sites, where the flight paths were perpendicular to the plane defined by the element of interst, each collected sample had to be limited to a smaller segment which meets the condition. More specifically after the aircraft passes over the house the outdoor noise measurements taken at the element of interest are no longer representative of the dominant outdoor noise incident on the room envelope. Thus the time at which the aircraft passes over the house had to be identified and all the data after this time were not used in the analysis as they do not meet the first condition.

An example should help to clarify the procedure, and the need for it. The average outdoor sound pressure level for band 24 (250 HZ), was calculating using a 4 second interval in the above mentioned program. The results are illustrated in Figure 3.1. After the 12th second, the sound pressure level drops and in the interval 16-20 seconds it drops dramatically by 10 dB. This behaviour of the outdoor sound pressure level is expected, because the aircraft passes over the house and therefore the measured outdoor noise is no longer representative of the outdoor noise source. In order to identify the exact time at which the aircraft passes over the house, a smaller time interval was used and the results are illustrated in Figure 3.2. On the basis of the 1 second interval analysis, it can be assumed that at the end of the 12th second the aircraft passes over the house. Thus the segment of this sample that meets the first condition, and therefore can be used in the analysis, ends at the 12th second of the sample.

This step was completed for all 4 bands mentioned in section 3.1 and the segment finally used in the analysis satisfied this condition for all 4 bands.

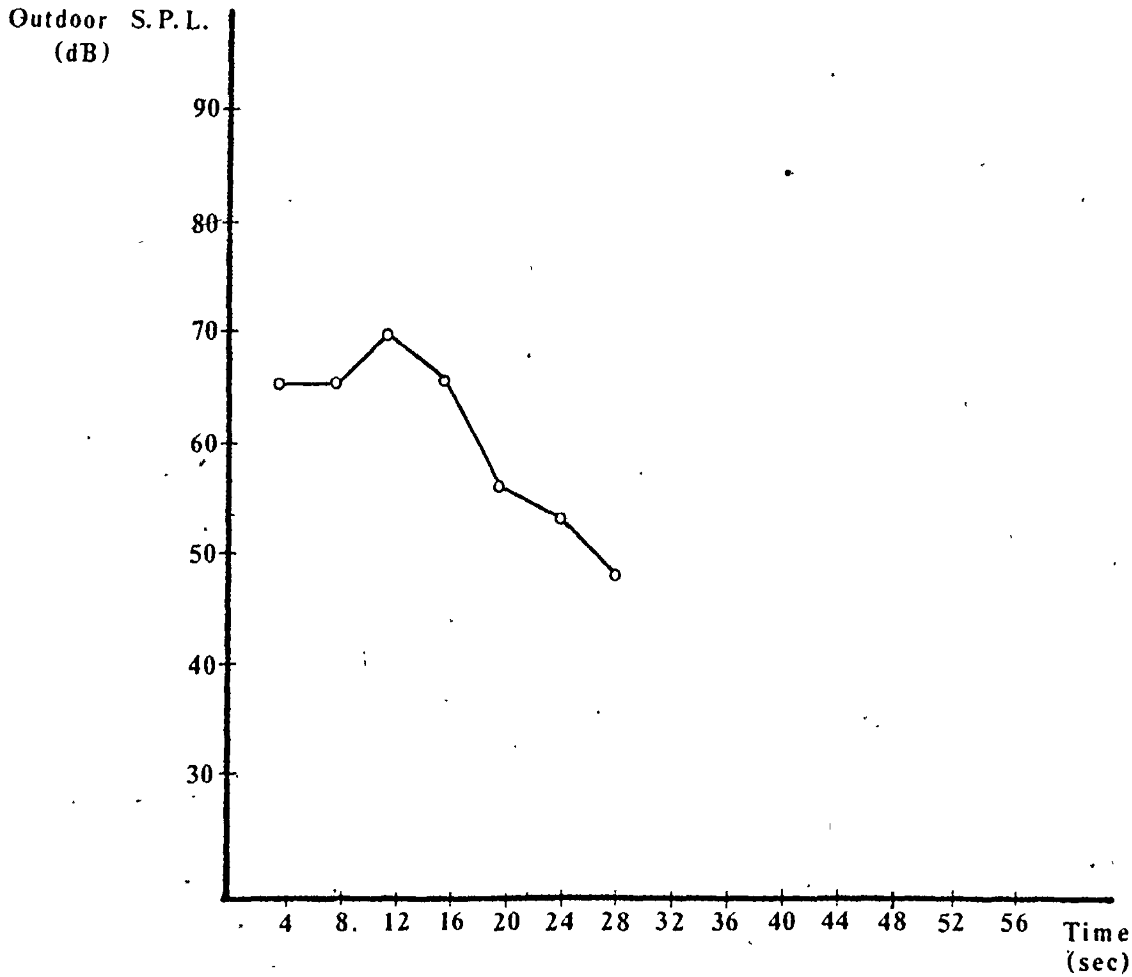

FIGURE 3.1. Outdoor S.P.L. over time for band #24 (250 HZ). Perpendicular aircraft case. Site #18. Four seconds interval.

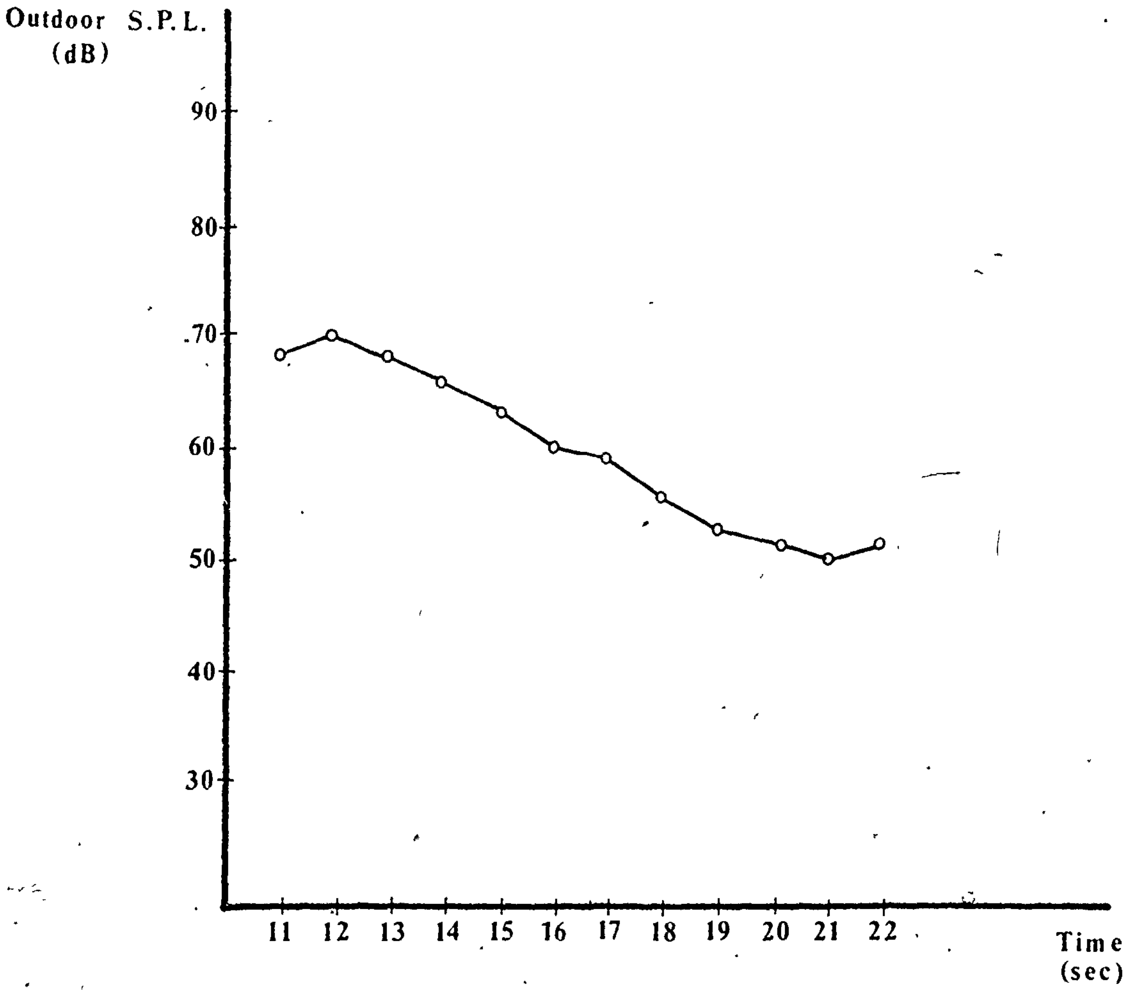

FIGURE 3.2. Outoor S.P.L. over time for band #24 (250 HZ). Perpendicular aircraft case. Site #18. One second interval.

3.3 Indoor background noise

The objective of this step is to identify and reject all parts of each sample for which the outdoor noise is not loud enough to produce indoor noise above the indoor background level. In some aircraft samples a part in the beginning and the end of the sample did not satisfy this condition, because the aircraft was far from the house and the outdoor noise was not so loud.

The first task was the identification of the indoor background noise level. Then the time at which the indoor noise level was higher than the background one had to be identified. For field measurements it is suggested by A.S.T.M. E33 (2, page 4) that the indoor noise level has to be at least 10 dB higher than the background indoor level, otherwise the measured indoor level is not produced by the outdoor noise source only but by a combination of outdoor source and indoor background level. Due to the fact that in most of the samples the indoor level was never 10 dB higher than the background indoor one, the value of 5 dB was used as it is recommended by A.S.T.M. for laboratory measurements (15, section 9.5).

An example of another aircraft sample is presented in Figure 3.3 for band 24 using a 4 second averaging interval. A background indoor noise level of approximately 39 dB can be identified, as well as the fact that two parts of the sample do not meet this condition. The first part is from the beginning of the sample up to almost the 20th second, while the second part is from almost the 32nd second up to the end of the sample.

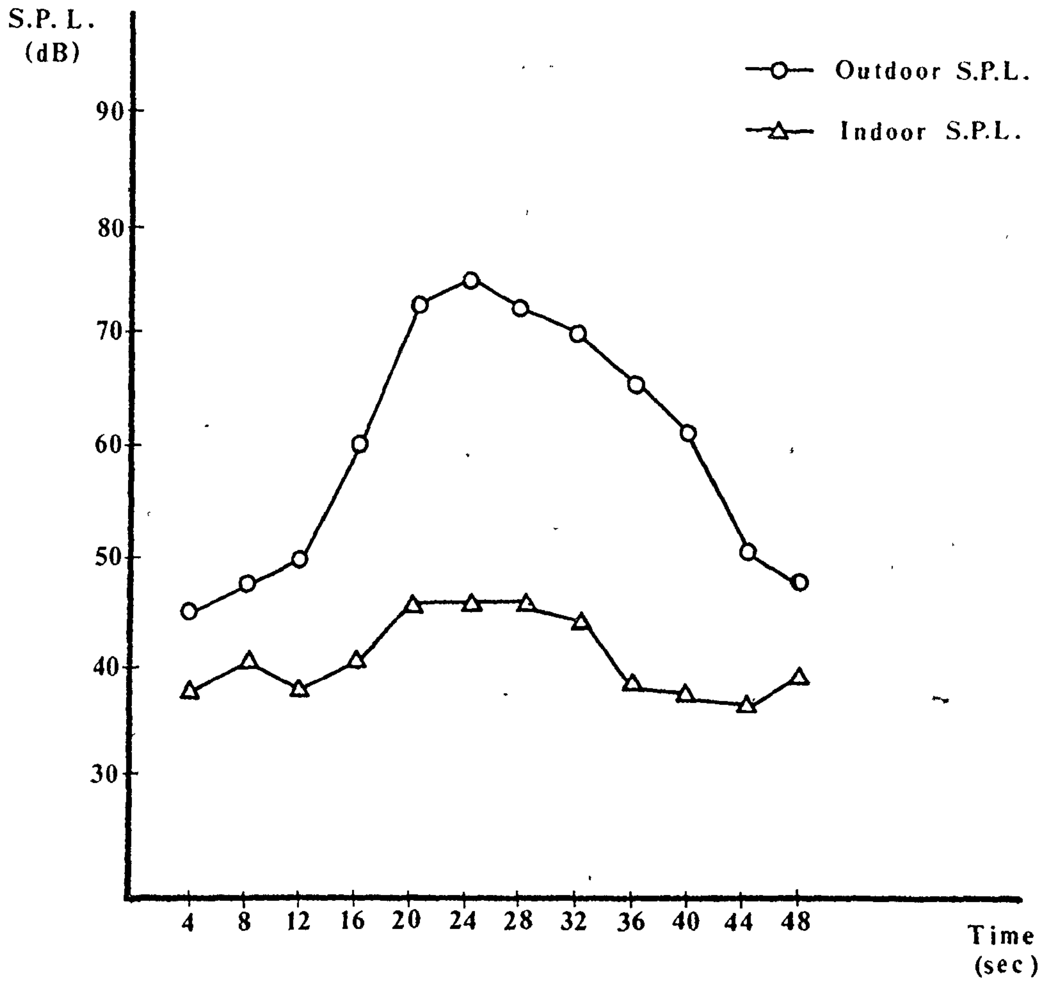

FIGURE 3.3. Indoor-outdoor S.P.L. over time for band #24 (250 HZ). Parallel aircraft case. Site #14. Four seconds interval.

A smaller averaging time interval of 1 second was used to identify the exact times for those two parts. These results are presented in figures 3.4 and 3.5. In Figure 3.4 it can be observed that only after the 17th second is the indoor level more than 5 dB higher than the previously identified background indoor level. From Figure 3.5 it can be observed that only up to the 30th second is the indoor level more than 5 dB higher than the previously identified background indoor level.

Thus only the segment between the 17th second and the 30th second meets the second condition and can be used in the analysis. This step was also completed for all 4 bands mentioned in section 3.1 and the segment finally used in the analysis satisfied this condition for all the 4 bands.

3.4 Possible contamination of indoor measurements

The objective of this final step of the data reduction was to test if there is any indoor noise source that contaminates the collected samples.

An example is presented in Figure 3.6 for a road traffic site. The outdoor as well as the indoor sound pressure levels are plotted using 4 second averaging interval for band 24 (250 Hz). It can be observed that for four intervals corresponding to 12, 16, 52 and 56 seconds the indoor sound pressure level is higher than the outdoor one. Thus an indoor noise source was on and the data can not be used in the analysis.

Nine out of twenty two road traffic sites had to be rejected because an indoor noise source was identified in all samples collected

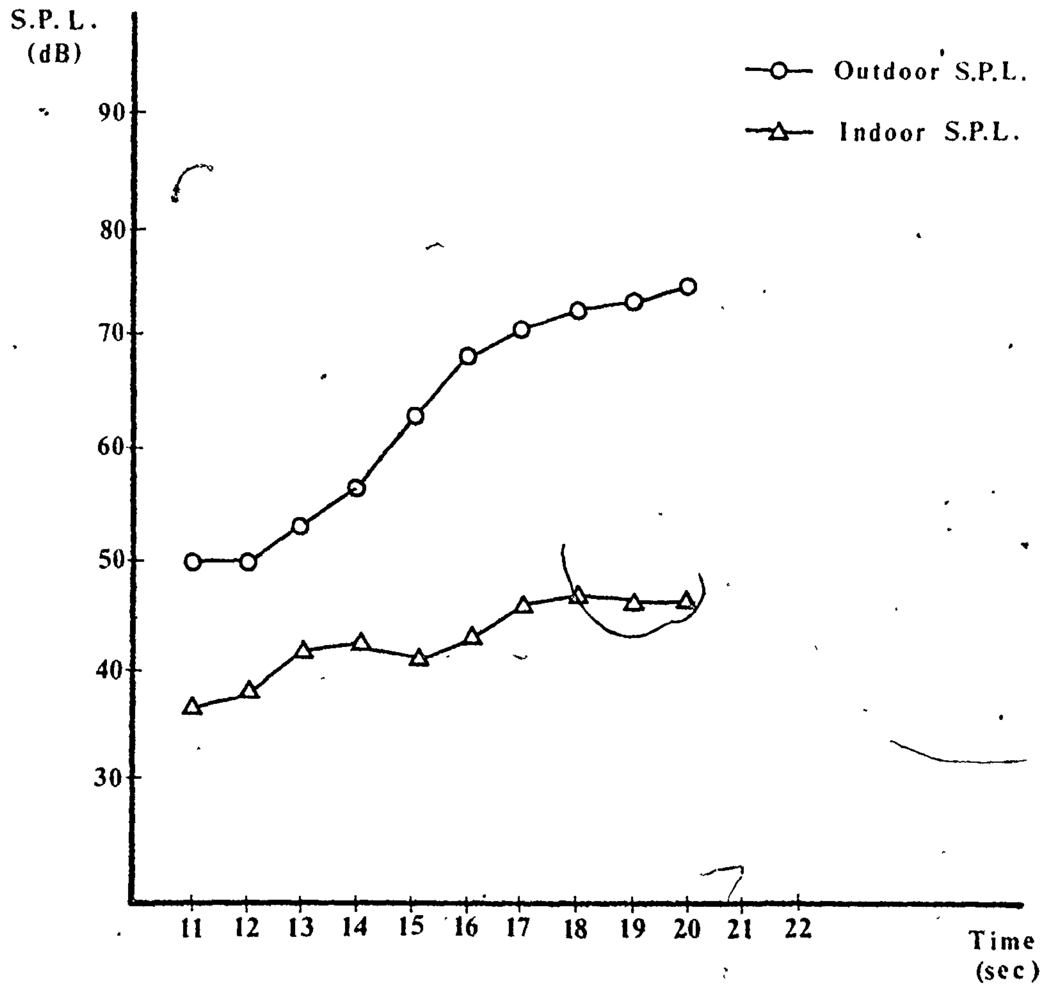

FIGURE 3.4. Indoor-outdoor S.P.L. over time for band #24 (250 HZ). Parallel aircraft case. Site #14. One second interval beginning of flyover.

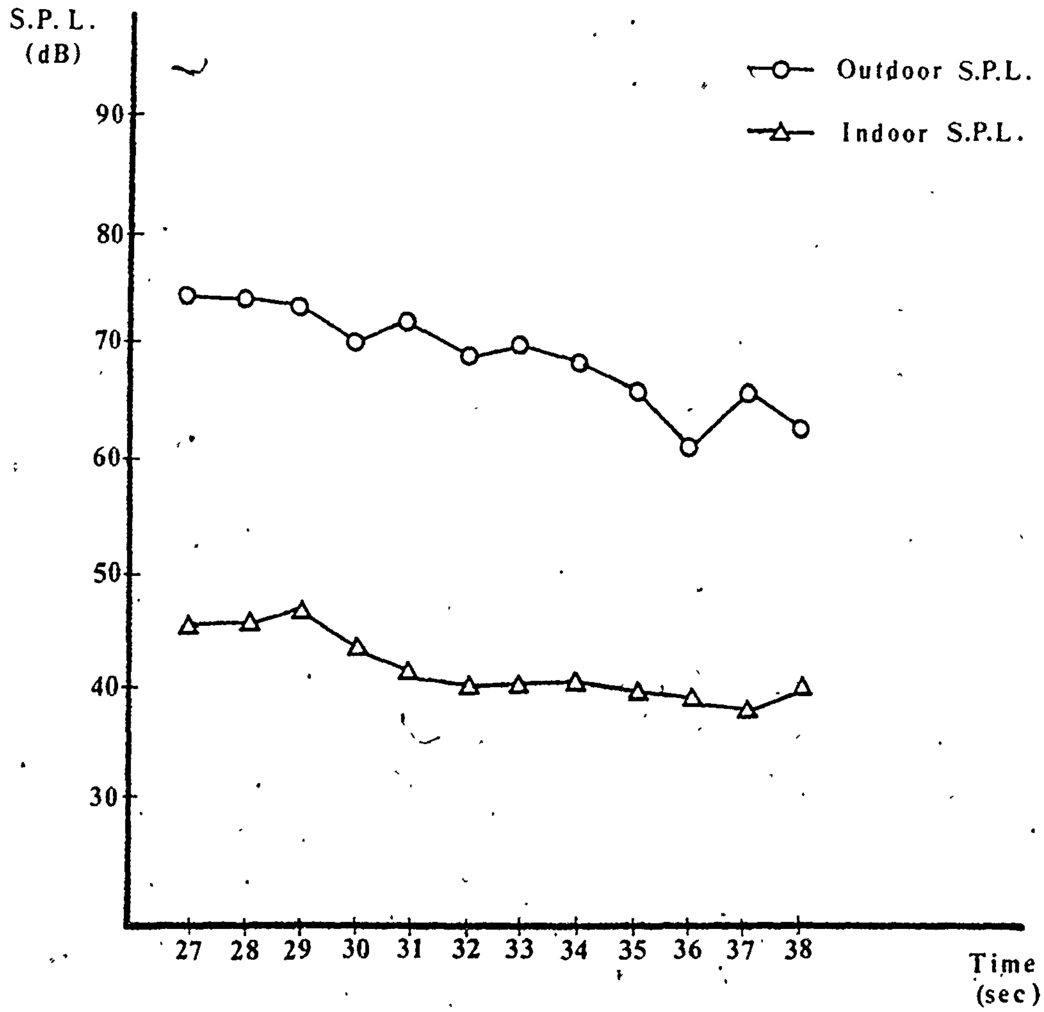

FIGURE 3.5. Indoor-outdoor S.P.L. over time for band #24 (250 HZ). Parallel aircraft case. Site #14. One second interval, end of flyover.

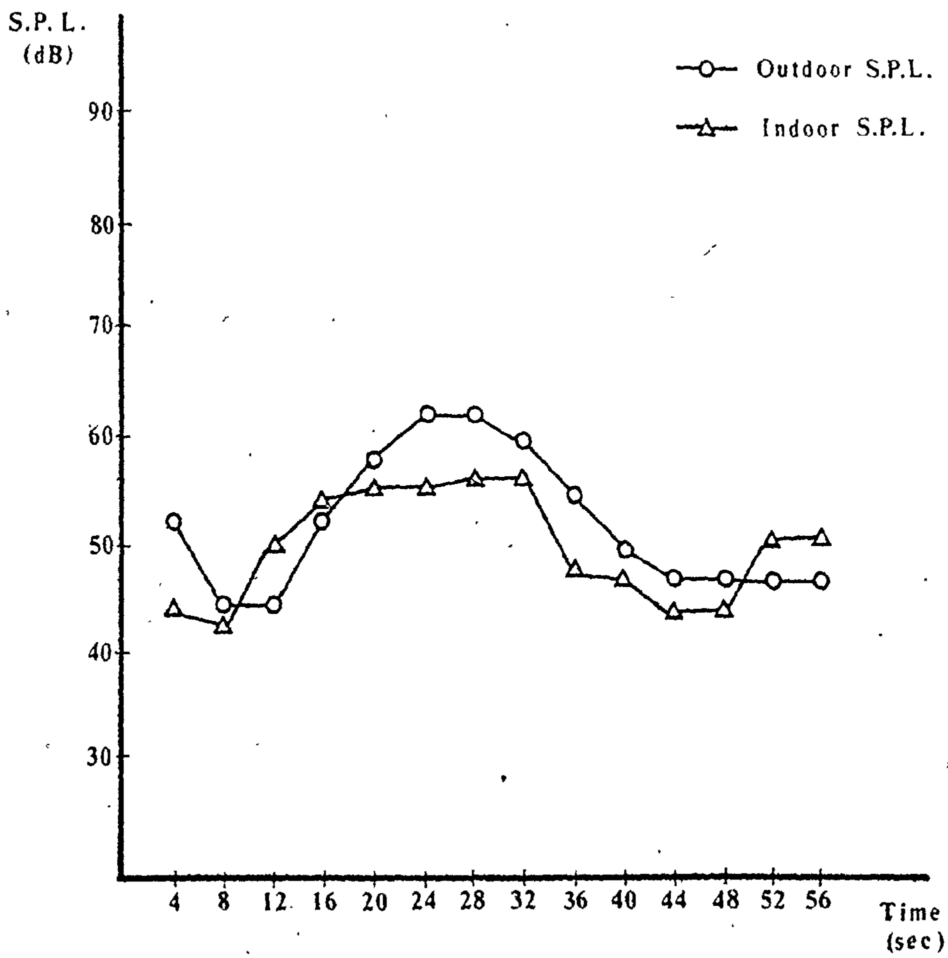

FIGURE 3.6. Indoor-outdoor S.P.L. over time for band #24 (250 HZ). Road traffic case. Site #22.

in these sites. Thus the fact that indoor noise sources were not identified during the data collection caused a considerable reduction of the data to be used in the analysis.

A summary of all collected samples and their reduction is illustrated in Table 3.1

3.5 Recommendation

It was previously mentioned that a high number of the collected samples had to be rejected. All rejections occurred for one reason. An unidentified indoor noise source occurred during the data collection. Thus ten sites had to be rejected. (see Table 3.1)

One recommendation can be drawn from these observations, so that the number of rejected sites will be minimized. The identification of any indoor noise source as described in section 3.4 should be made at site. Thus each collected sample will be tested as regards any indoor noise source that contaminates it. If it is contaminated, the sample has to be deleted and a new one collected.

TABLE 3.1 SUMMARY OF DATA

SITE NUMBER	SAMPLE NUMBER	MEASURED DURATION (SECONDS)	AVAILABLE DURATION (SECONDS)	REASONS FOR REDUCTION
1	1	60	60	-
	2	60	60	-
	3	60	0	C
	4	60	60	-
	5	60	60	-
2	1	60	50	B
	2	60	50	B
	3	60	50	B
3	1	60	50	B
	2	60	50	B
	3	60	50	B
4	1	60	60	-
	2	50	50	B
	3	60	0	C
5	1	60	60	-
	2	60	60	-
	3	60	60	-
6	1	60	50	B
	2	60	60	-
	3	60	40	B
7	1	60	60	-
	2	60	60	-
	3	60	60	-
	4	60	60	-
8	1	60	0	C
	2	60	0	C
	3	60	60	-
	4	60	60	-
9	1	60	60	-
	2	60	60	-
	3	60	60	-
10	1	60	60	-
	2	60	60	-
	3	60	30	B
11	1	60	0	C
	2	60	30	B
	3	60	30	B
	4	60	0	C
12	1	60	60	-
	2	60	60	-
	3	60	60	-
	4	60	60	-
13	1	60	0	C
	2	60	0	C
	3	60	60	-

cont'd

SITE NUMBER	SAMPLE NUMBER	MEASURED DURATION (seconds)	AVAILABLE DURATION (seconds)	REASONS FOR REDUCTION
14	1	60	0	C
	2	50	28	B
	3	50	13	B
15	1	60	0	C
	2	30	9	B
	3	24	0	C
	4	20	20	-
	5	23	9	C
	6	23	23	-
16	1	60	60	-
	2	50	50	-
	3	55	44	B
17	1	40	25	A
	2	35	18	A
	3	20	19	A
	4	57	37	A
18	1	30	13	A
	2	40	22	A,B
	3	45	23	A,B
19	1	60	17	A,B
	2	60	17	A,B
20	1	36	7	A,B
	2	60	10	A,B
	3	60	30	A,B
21	1	40	0	C
	2	30	0	C
	3	35	0	C
	4	35	0	C
	5	35	0	C
22	1	60	0	C
	2	60	0	C
	3	60	0	C
23	1	60	0	C
	2	60	0	C
	3	60	0	C
24	1	60	0	C
	2	60	0	C
	3	60	0	C
	4	60	0	C
25	1	45	0	C
	2	50	0	C
	3	60	0	C

cont'd

SITE NUMBER	SAMPLE NUMBER	MEASURED DURATION (seconds)	AVAILABLE DURATION (seconds)	REASONS FOR REDUCTION
26	1	60	0	B,C
	2	60	0	C
	3	60	0	C
	4	60	0	C
27	1	60	0	C
	2	60	0	C
	3	60	0	C
	4	60	0	C
28	1	60	0	B,C
	2	60	0	B,C
	3	60	0	C
29	1	60	0	B,C
	2	60	0	B,C
	3	60	0	C
30	1	60	0	C
	2	60	0	C
	3	60	0	C

NOTE: The reasons for reduction are A,B,C and correspond to the three above mentioned conditions, as follows:

A: outdoor measurements (see section 3.2)

B: indoor background noise (see section 3.3)

C: possible contamination of indoor measurement (see section 3.4).

CHAPTER 4

ANALYTICAL METHODS

This chapter describes the approach used in this study to compute the Acoustical Insulation Factor of a room from the reduced field data.

The first section of this chapter presents the assumptions on which the room A.I.F. is based and the equation used for its computation. The second section presents the equation used to calculate the field transmission loss of a room, which is the major variable in the room A.I.F. computations. The third section presents the approach used to calculate the decay rate of each band for each room. An example is also presented in this section. The fourth section describes the procedures followed in the computation of the room A.I.F. In the fifth section some comments as regards the accuracy of the computed quantities are made. In the final section the procedure followed for determining the A.I.F. of each room from the C.M.H.C. guideline is presented.

4.1 Room acoustical insulation factor (A.I.F.)

The concept of the A.I.F. allows the use of two different indices. The first one is the element A.I.F. and the second one is the room A.I.F. Each of them is based on different assumptions and indicates different acoustical insulation (12, sections B and C).

The element A.I.F. is based on the assumption that the major component of the structure transmitting sound indoors is the element on which the outdoor noise measurements are collected, and indicates the acoustic insulation provided by the specific element. For laboratory measurements this assumption can be satisfied, but in field measurements it can provide misleading information.

In contrast the room A.I.F. is based on the assumption that all components of the structure are transmitting sound indoors and indicates the acoustical insulation provided by the room envelope as a set of different components. This assumption is more valid for the field measurements of this study than is the previous one, simply because it does take into account all possible components that transmit sound indoors.

The recommended formula for calculating the A.I.F. is: (14, Fig. 2)

$$A.I.F. = L - 10\log \left[\sum_{i=1}^{n} 10^{(L_i - FTL_i)/10} \right] \qquad 4.1.1$$

where

L	:	A-weighted outdoor standard sound pressure level (over 20 bands), corresponding to free field conditions	[dB]
L_i	:	A-weighted outdoor standard sound pressure level for band i, corresponding to free field conditions	[dB]
FTL_i	:	field transmission loss for band i, corresponding to free field conditions	[dB]
n	:	number of bands used to calculate transmission loss	
A.I.F.	:	acoustical insulation factor	[dB]

If the field transmission loss for each band is only for the element of interest, then the A.I.F. is the element A.I.F. If the field transmission loss for each band takes into account all components of the room, then the equation 4.1.1 will give the room A.I.F.

From equation 4.1.1 it can be observed that the second term represents the calculated indoor A-weighted sound pressure level, based on the field transmission loss information and the outdoor A-weighted standard sound pressure level for each band. The difference between this standard pressure and the calculated, indoor A-weighted sound pressure level is the A.I.F..

Quirt states (12, page 827) that shifts in the spectrum balance were observed in aircraft sites. Due to the fact that the first term of equation 4.1.1 is always based on 20 bands, these shifts of the spectrum balance can cause an error because each term of this equation will not always be based on the same range of bands. It can be observed that the second term of equation 4.1.1 is based on the number of bands over which transmission loss is calculated, which varies not only between different sources but also over time for each flyover.

To overcome this difficulty the first term of equation 4.1.1 was changed to cover the same bands as the second one. Thus the equation used for the room A.I.F. calculation is as follows:

$$\text{room A.I.F} = 10\text{Log}\left[\sum_{i=1}^{n} 10^{L_i/10}\right] - 10\text{Log}\left[\sum_{i=1}^{n} 10^{(L_i - FTL_i)/10}\right] \qquad 4.1.2$$

where

FTL_i : field transmission loss of the room for band i, corresponding to free field conditions [dB]

L_i : A-weighted outdoor standard sound pressure level for band i, corresponding to free field conditions [dB] n : number of bands for which field transmission loss is calculated.

From equation 4.1.2 it can be observed that the first term represents the A-weighted outdoor standard sound pressure level based on the same bands as the calculated field transmission loss of the room. Thus, given the field transmission loss, the A.I.F. can be calculated using equation 4.1.2.

Quirt (12, page 827) also states that if the A.I.F. is not based on the standard spectrum, but on the actual outdoor one, any major shift of the source spectrum can cause a variation on the A.I.F. In order to isolate the effect of the angle of incidence from affects caused by shifts in the source spectrum, the standard spectrum was used.

4.2 Field transmission loss of the room of interest

The field transmission loss of an element can be calculated using the following formula, as suggested by A.S.T.M. E 33 (2, section 7.4.2) .

$$(FTL)_i^E = (L_1)_i - (L_2)_i + 10\text{Log}(^S/A_i) \qquad 4.2.1$$

where

$(FTL)_i^E$: field transmission loss of element E for band i, corresponding to free field conditions [dB]

$(L_1)_i$: outdoor sound pressure level measured 2m from the element, for band i [dB]

$(L_2)_i$: indoor sound pressure level for band i [dB]

S : area of the element of interest [m^2]

A_i : absorption of the room for band i [metric sabins]

The absorption of the room for each band can be calculated using the following formula, as suggested by A.S.T.M. E 336 (18, section 5.9.1).

$$A_i = 0.921\ Vd_i/c \qquad 4.2.1a$$

where

A_i: absorption of the room for band i [metric sabins]

V : volume of the room [m^3]

d_i: decay rate of band i [dB/s]

C : speed of sound in air [m/s]

From formula 4.2.1. it can be observed that the field transmission loss of an element is the difference between the outdoor and indoor sound pressure levels, when the outdoor sound pressure level is measured 2m from the element, adjusted by a factor which incorporates the size of the element of interest as well as acoustical properties of the room in which the indoor sound pressure level was measured.

The field transmission loss of a room is based on the same concept as the field transmission loss of an element, but it does not take into account the size of the element, simply because it is based on the assumption that all elements of the room transmit sound indoors. In addition it must be in accordance with the concept of the room A.I.F. Inherent in the A.I.F. concept are two assumptions.

1. The outdoor sound pressure level is measured in the free field (16).
2. The absorption of the "typical" furnished room, according to which the room A.I.F. is normalized, is 80% of the floor area of the room of interest. (12, page 826).

It is stated by ASTM E-33 (2, section I.3,a,b) that the outdoor sound pressure level measured at the surface of the element of interest is 6dB higher than that measured in the free field.

As regards the normalization based on the "typical" furnished room, Quirt (12, pages 823, 824) states that the "typical" furnished room shows a room absorption equal to 80% of the floor area, which corresponds to a decay rate of 120 dB/s and a room height of 2.4 m. Thus he used the following term

$$+ 10 \text{ Log } (\frac{A_r}{A})$$

where

A_r : standard absorption corresponding to 80% of the floor area

A : measured absorption

to normalize the measured sound pressure levels.

ASTM E336-77 (17, section 5.5) states another term based on the corresponding standard decay rate 120 dB/s and the measured one, as follows:

$$+ 10 \text{ Log } (\frac{120}{d_i})$$

where

d_i : the measured decay for band i

Schultz (18, page 7) states that the term based on the standard decay rate of 120 dB/s appears better as regards building code requirements, because the total absorption of the room tends to be proportional to the floor area in occupied appartments.

Hence the formula used in this thesis to calculate field transmission loss of the room is

$$(FTL)_i^R = (L_s)_i - (L_2)_i + 10 \text{ Log } (\frac{120}{d_i}) - 6 \qquad 4.2.2$$

where

$(FTL)_i^R$: field transmission loss of room for band i, corresponding to free field conditions [dB]

$(L_s)_i$: outdoor sound pressure level for band i, as measured at the surface of the element of interest [dB]

$(L_2)_i$: indoor sound pressure level for band i [dB]

d_i : decay rate of band i [dB/s]

4.3 Decay rate for each band

The decay rate of sound pressure level in each band is needed in equation 4.2.2 for calculating the field transmission loss of the room, for each band. As was mentioned in section 2.3.3 an impulse sound and its decay were recorded in a UHER tape recorder. It was then analyzed in the laboratory, and the sound pressure level for each band was transferred to the mini-computer every 125 milli-seconds. This time interval is the minimum provided by the analyzer used in this study. Using the program presented in Appendix C, the decay rate of each band was calculated and stored on mini-computer cassettes.

This program identifies the maximum sound pressure level and the time at which it occurs for each band. It then assumes the end of the decay of each band as one time interval before the first local minimum of the sound pressure level at this band. The time interval at which the first local minimum occured was not used as it could have been biased by the following increase of the sound pressure level. Then the decay rate of each band was calculated using the following formula:

$$d_i = \frac{\Delta L_i}{\Delta t_i} \qquad 4.3.1$$

where

d_i : the decay rate of band i [dB/sec]

ΔL_i: difference between the maximum and minimum sound pressure levels as previously defined, for band i [dB]

Δt_i: elapsed time between maximum and minimum sound pressure levels for band i [sec]

To increase the accuracy of the decay rate calculation for each band, the lowest available speed of 2.38 cm/s was used in the tape recorder. Due to the fact that the recording speed was 8 times higher than the one used in the analysis a shift was incorporated in the frequency. The lowest band available in the analyzer was band 14 (25 Hz). Thus the minimum frequency at which the decay rate was calculated was band 23 (200 Hz). If the lowest available speed was not used in the analysis, then the error in the decay rate calculations would have been considerably higher. Due to the limitations of the spectrum produced by the noise source during the reverberation time measurements the maximum frequency at which the decay rate was calculated was 10 kHz (band #40).

A.S.T.M. E336 (17, section 6.1.3) states that there is a low frequency limit for determining field transmission loss. This limit depends on the size of the room of interest. The larger the room, the lower the limiting frequency. The limit used in this study of 200 HZ was found to be one 1/3 octave band higher than that recommended by A.S.T.M. for the smallest room studied. Thus the lowest frequency used meets the A.S.T.M. requirements.

An example of the decay rate calculation for a recorded frequency of 250 Hz (band 24) played back as frequency 31.25 Hz (band 15) is illustrated in figure 4.1.

The maximum level occured at 375 ms from the beginning of the analysis, while the first local minimum occured at 2250 ms. The program used assumed that the minimum sound pressure level occured one interval before, at 2125 ms. Thus the level difference is 35 dB and the elapsed time during the analysis is 1625 ms which corresponds to 218.75 ms of elapsed time based on the recording speed. Using equation 4.3.1 the decay rate for band 24 will be in this case 160 dB/s.

As was mentioned in the data collection section, three reverberation time measurements were recorded at each room. Each of them was analyzed three times using the above mentioned procedure in order to minimize any possible error. The mean values of each band for each room were used in the analysis.

In 14 bands the measured difference between the maximum and minimum sound pressure levels was always more than 30 dB. This is the minimum decay value for reverberation time measurements, as suggested by the manufacturer of the analyzer (19, page 4-5).

Only in the two lowest and two highest bands was this limit not achieved, probably due to the limitations of the noise source which did

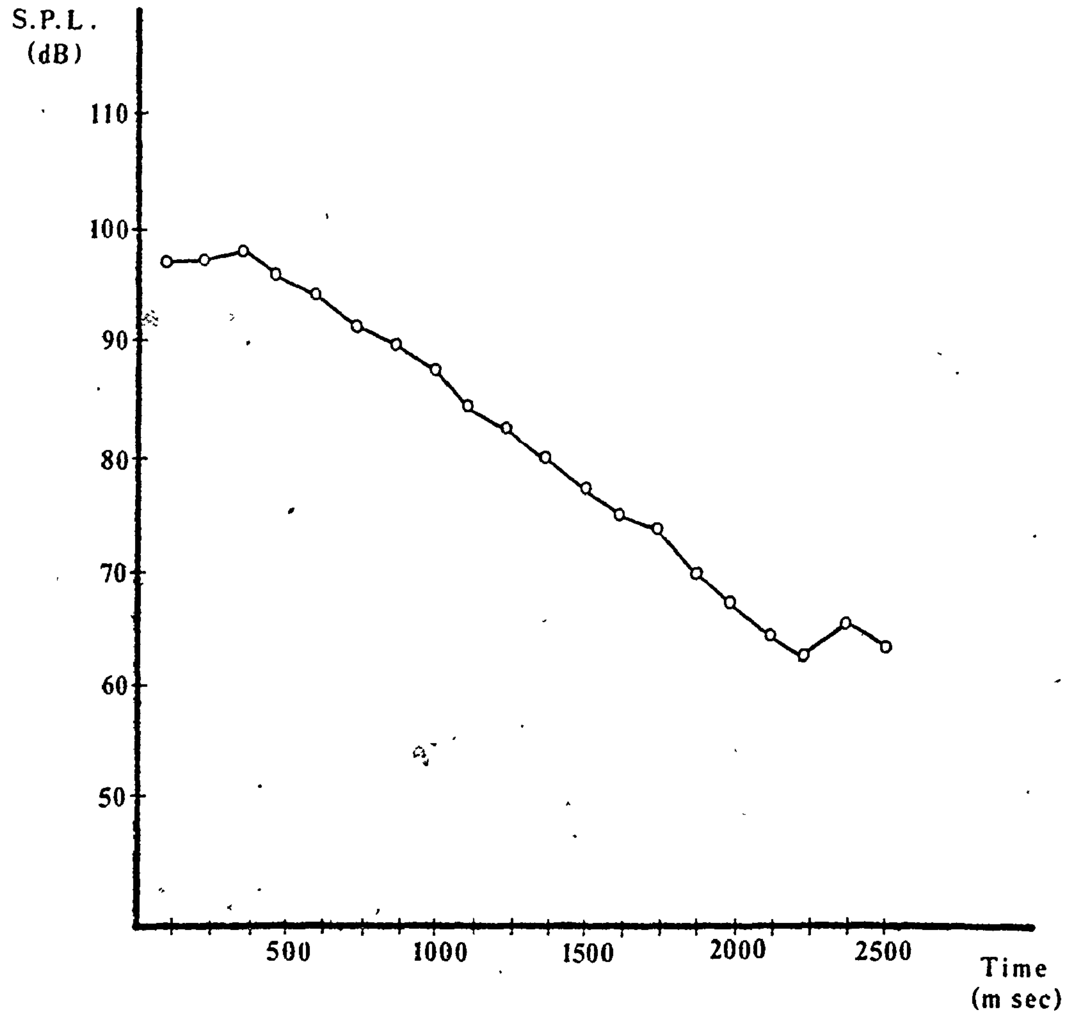

FIGURE 4.1. Decay rate of S.P.L. in band #15. An example.

not produce high enough sound pressure level in these bands.

In Table 4.1 an example of the mean values, the standard deviations and the corresponding percentage error at the 5% level of significance are illustrated. The percentage error is based on the range the estimate of the calculated mean can have for 5% level of significance assuming a t-distribution.

Table 4.1 Mean, Standard deviation and percentage error of decay rate for each band. Site #11.

Number of band	Mean decay rate [dB/s]	Standard deviation of decay rate [dB/s]	% error for 95% confidence
23	217	19.4	6.9
24	168	42.3	19.3
25	168	20.4	9.3
26	166	17.6	8.1
27	178	21.2	9.1
28	152	17.1	8.7
29	167	9.5	4.4
30	174	11.3	5.0
31	172	6.9	3.1
32	163	6.3	2.9
33	167	11.2	5.2
34	170	8.6	3.9
35	175	12.8	5.6
36	182	10.5	4.4
37	166	9.8	4.5
38	191	13.9	5.6
39	213	12.5	4.5
40	215	13.8	4.9

It can be observed that in only one band (24) is the error higher than 10%. Since the decay rate appears in a logarithmic term in the field transmission for calculations (equation 4.2.2), an error of 10% in all bands corresponds to an error of less than 0.5 dB in the field transmission loss. The one band where the error is approximately 20% corresponds to an error of less than 1 dB in the field transmission loss, of the specific band.

4.4 Average levels.

As was discussed in chapter 2 the outdoor and indoor sound pressure levels for each band were collected approximately three times at each room.

Equation 4.2.2 requires the use of average outdoor and indoor levels to calculate field transmission loss of a room for each band.

Two different procedures, depending on the outdoor source, were used to calculate the average values of the outdoor and indoor levels to be used in equation 4.2.2.

In aircraft sites an energy average value over each sample, and an arithmetic average over all samples of each room were used. The energy average levels over each sample were calculated using the formula suggested by A.S.T.M. E336 (18, section 5.3)

$$L_j = 10 \text{ Log } [\frac{P_1{}^2/P_o{}^2 + P_2{}^2/P_o{}^2 + ... + P_n{}^2/P_o{}^2}{N}] \qquad 4.4.1$$

where

L_j: energy average sound pressure level for sample j [dB]

P_o: the reference sound pressure 20 Pa [Pa]

n : number of measurements in each sample

$P_1^2, P_2^2 \ldots P_n^2$: the mean-square pressure of the n measurements in each sample [μPa]

Then the arithmetic averages of the sound pressure levels over all samples collected at the same room were calculated and used in equation 4.2.2 to find the field transmission loss of the room for each band.

For these calculations the program presented in Appendix D was used. After the field transmission loss of the room was calculated the program used equation 4.1.2 to calculate the room Acoustical Insulation Factor.

In road sites each sample was divided into 10-second sections and energy average sound pressure levels were calculated for each section (equation 4.4.1). Then an arithmetic average was calculated over all intervals and was used in equation 4.2.2 for calculating the field transmission loss of the room for each band.

The program used in road sites is presented in Appendix E and also uses the equation 4.1.2 to calculate the room Acoustical Insulation Factor.

As was mentioned in section 2.2 the analyzers used in this study have a 53.5 dB range of measurements. The settings used in this study (see section 2.3.2) for the simultaneous outdoor-indoor noise measurements provide base levels of 46.5 dB and 26.5 dB for outdoor, indoor sound pressure levels respectively. Any levels below the base ones were recorded as equal to the base levels. Thus in both programs used to calculate the room A.I.F. whenever a base level was detected (either outdoor or indoor) both outdoor and indoor levels were ignored, since no meaningful difference between the two could be calculated.

4.5 Comments on the accuracy of the measurements

The accuracy of the measured quantities for equation 4.2.2 have an effect on the field transmission loss and consequently on the A.I.F. values.

As can be observed from equation 4.2.2 two quantities directly affect the field transmission loss:

the measured sound pressure levels; and

the calculated decay rate for each band.

Due to the fact that the analyzers were calibrated before each measurement, the accuracy of the measured sound pressure levels is assumed to be sufficiently high.

The accuracy of the calculated decay rate for each band is affected by three variables:

the accuracy of the measured drop in dB;

the accuracy of the measured elapsed time between the maximum and the minimum levels; and

the internal decay of the analyzer.

The accuracy of the first one is already assumed as extremely high. The accuracy of the measured elapsed time depends on:

the accuracy of the analyzer to measure for exactly 125 ms; and

the time interval used to analyze the recorded decay rate of the sound.

Five tests were made of the analyzer's timing. For each test the analyzer was run for 5 minutes using 125 ms intervals, and a stopwatch was also working for the same time. The results showed an accuracy higher than 99.99%. Thus it can be assumed that there is no error in the timing of the analyzer.

Due to the fact that the speed of the tape recorder when the decay of the sound was analyzed was 8 times less than the recording speed (see section 4.1.2), the actual time interval used to analyze the recorded decay of the sound was 1/64th of a second.

Thus the elapsed time was measured with an accuracy of $\pm$15.625 ms. This can cause a maximum error, for the lowest calculated decay of 110.6 dB/s, of 14.13% in the decay rate calculation, which corresponds to a maximum possible error of 0.57 dB in the field transmission loss of the corresponding band.

The internal decay of the analyzer was measured as suggested by the manufacturer's manual (17, page 4-4) as 38.96 dB/s. Using the correction formula suggested by the manufacture, the maximum error was 3.56% of the actual decay rate, which corresponds to a possible error of less than 0.15 dB in the field transmission loss of the corresponding band.

If all these possible errors combined in the worst direction, it is estimated that a total error of less than 1 dB in the A.I.F. values would result.

4.6 Determination of A.I.F. from the C.M.H.C. guideline.

The C.M.H.C. guideline (1) recommends three steps for determining the A.I.F. of each component of the room of interest from the structural characteristics and the dimensions of the room.

1. Identification of the components which make up the exterior envelope of the room of interest.
2. Calculation of the percentage of each component area to total floor area of the room.
3. Based on the type of component and the above mentioned area of the component expressed as percentage of the floor area, identify from tables the suggested A.I.F. for each component.

Quirt (12, page 829) states that the A.I.F. of all components of the room can be combined to provide the A.I.F. of the room using the following equation

$$\text{room A.I.F.} = -10 \log\left(\sum_{i=1}^{n} 10^{-A_i/10}\right) \qquad 5.6.1$$

where

A_i: A.I.F. of component i [dB]

n : number of components of exterior envelope of the room of interest.

The equation 5.6.1 is used in this study to calculate the A.I.F. of each room, by combining the A.I.F. values of each component forming the exterior room envelope as they are estimated by the C.M.H.C. guideline.

CHAPTER 5

RESULTS

The results for both objectives introduced in the beginning of this study are presented and discussed in this chapter.

The first section presents and discusses the results of the first objective, to study the effect of the angle of incidence on the measured acustical insulation in residential construction. The second section deals with the results of studying the variation between the A.I.F. as calculated from field transmission loss data and that suggested by the C.M.H.C. guideline due to the structural characteristics of each room.

5.1 The effect of the angle of incidence on the acoustical insulation.

As was stated in section 2.6, it was not always possible to make a direct comparison between different angles of incidence and the acoustical insulation, simply because the angles could not be recorded. Thus another approach was used for the sites where the angle of incidence was not recorded. The variation of the acoustical insulation over time was studied. In all the aircraft sites where the flightpath is perpendicular to the plane defined by the element of interest, at the very end of the reduced sample the angle of incidence is large while in the beginning of the sample it is smaller.

The variation of the A.I.F. over time was studied using the energy averaging method presented in section 4.4 for calculating the average indoor and outdoor sound pressure levels. The time interval used was 4 seconds. This was selected on the basis of covering some fluctuations in the observed levels while still being small enough to cover only a small range of angles during the flyover.

The variation of the A.I.F. was also studied for the road traffic sites where a wide range of angles of incidence is incorporated at one time because the noise source is not a single vehicle but rather a line of vehicles. To ensure the comparability of the results the same time interval was used in road traffic sites.

As was previously mentioned there is no effect of the angle of incidence on the A.I.F. in the road traffic sites. Studying the variation of the A.I.F. for these sites will show if there is any effect because of the shifts in the source spectrum. If there is no effect and the A.I.F. varies in aircraft sites, then this should be from the angle alone.

The variation of the A.I.F. was expected to be small in all road traffic sites. An example of the variation of the A.I.F. over time is illustrated in Figure 5.1 for site #7. In the same figure the A-weighted and flat outdoor sound pressure levels are also presented. A comparison between these two levels provides useful information on the changes of the outdoor source spectrum. When these levels have the same value, the outdoor source spectrum is dominated by middle range frequencies. As their difference increases, with the A-weighted level lower than the flat, the outdoor source spectrum is dominated by low range frequencies.

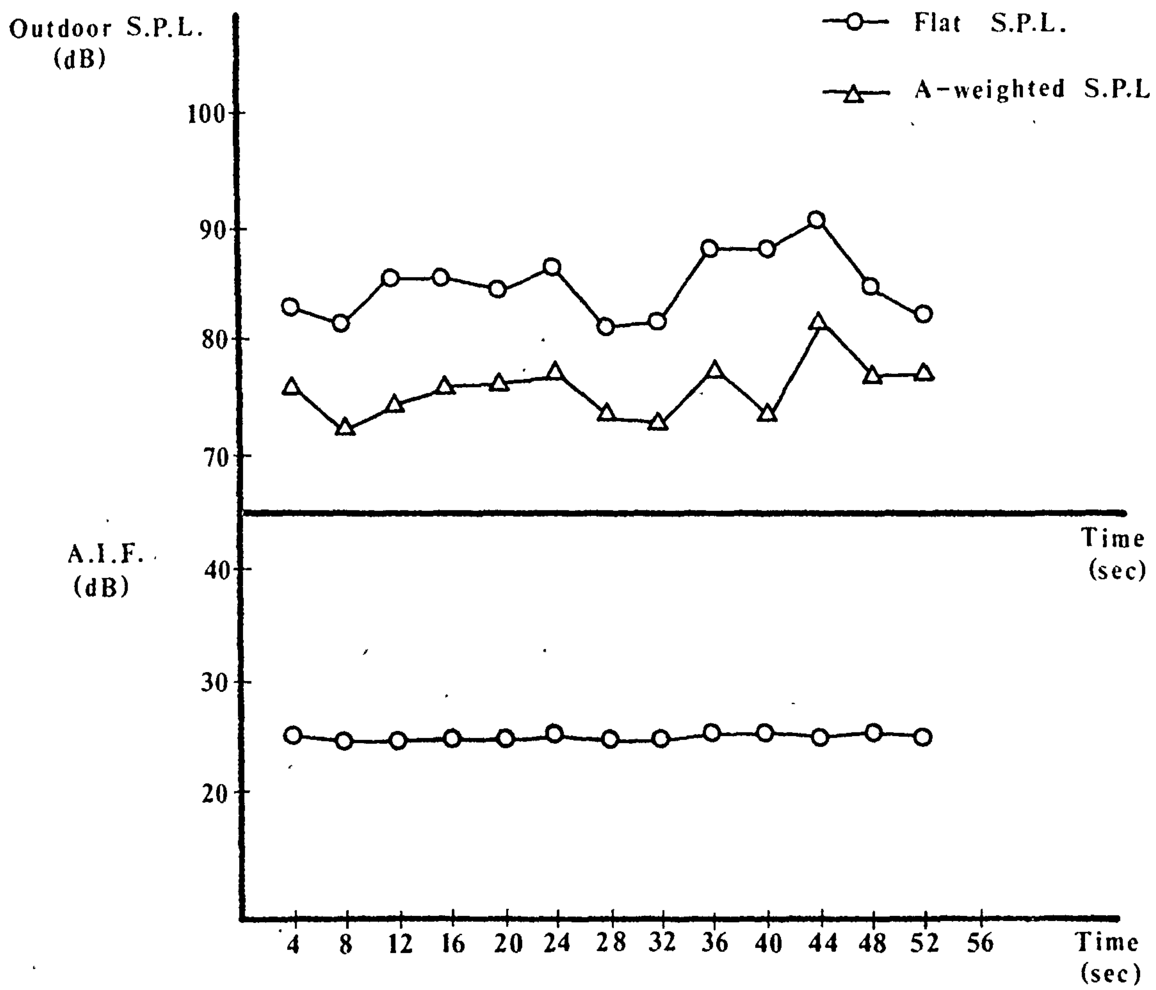

FIGURE 5.1. Variation of A.I.F. and outdoor S.P.L. over time. Road traffic case. Site #7.

In Figure 5.1 it can be observed that the A.I.F. does not deviate more than 1 dB over time, and is at the level of 25 dB. During the same time period, the outdoor A-weighted level varies between a minimum of 71 dB and a maximum of 81 dB. Comparing the A-weighted with the flat outdoor levels it can be observed that the outdoor noise is dominated by low frequencies, while some shifts in the outdoor spectra occur. More specifically at the 8th, and 40th seconds, the difference between the flat and the A-weighted levels increases, indicating a shift for even lower frequencies probably caused by heavy vehicles, while at the 52nd second this diffference decreases, indicating a shift to middle frequencies. This shift, as expected, has no effect on the A.I.F., which is stable over time.

In Figure 5.2 the variation of the A.I.F. in another road traffic site is illustrated. It can be observed that the A.I.F. deviates between a minimum of 26 dB and a maximum of 28.5 dB. Again the outdoor noise is dominated by low frequencies, while no major shifts can be observed in the outdoor spectra.

In several other road traffic sites a relatively high variation of the A.I.F. is observed. In Figure 5.3 the results of such a site are illustrated. It can be observed that the A.I.F. deviates between a minimum of 21 dB and maximum of 26 dB. The A-weighted and flat outdoor sound pressure levels indicate that the outdoor noise is dominated by low frequencies with some shifts in the spectrum.

All the road traffic sites at which this relatively high variation was observed had more than one window in the exterior envelope of the

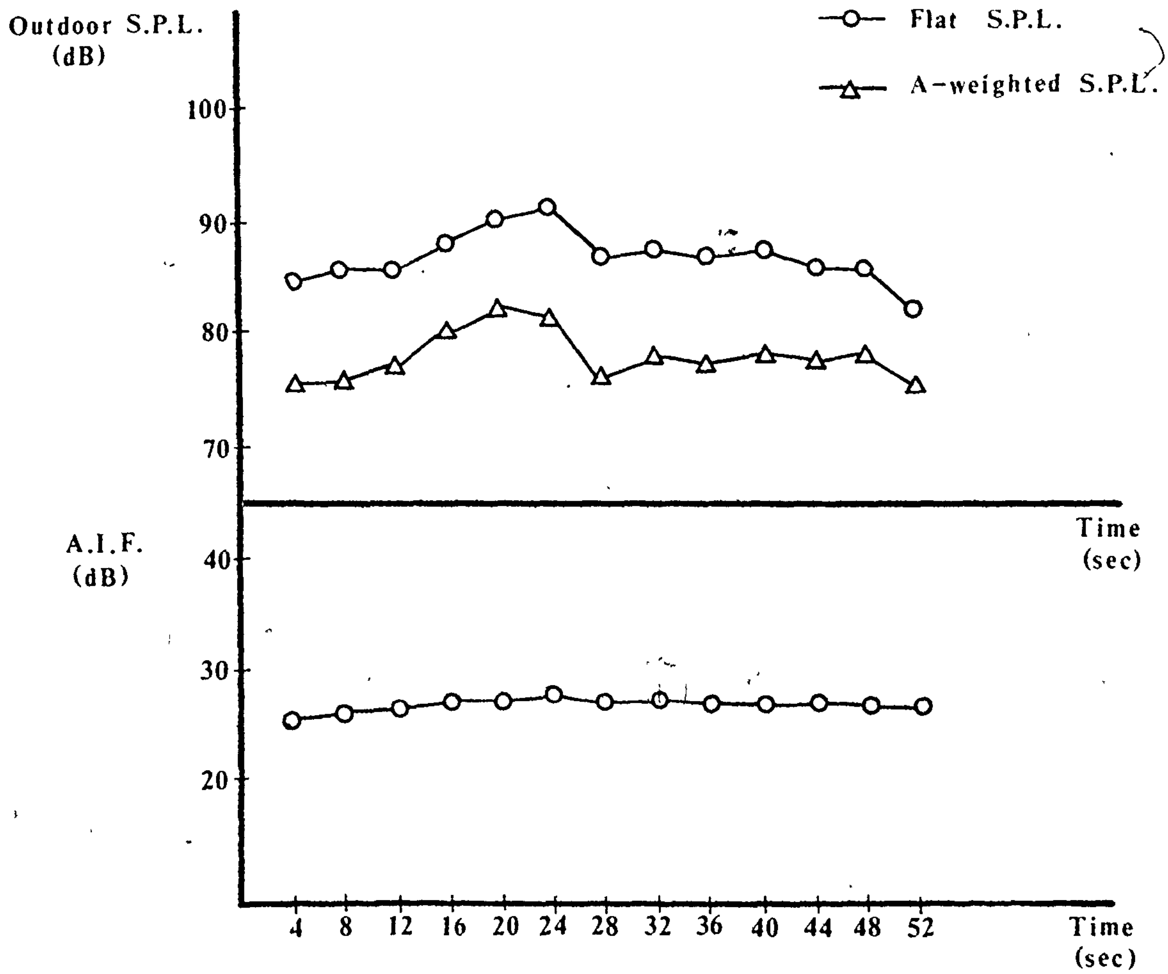

FIGURE 5.2. Variation of A.I.F. and outfoor S.P.L. over time. Road traffic case. Site #9.

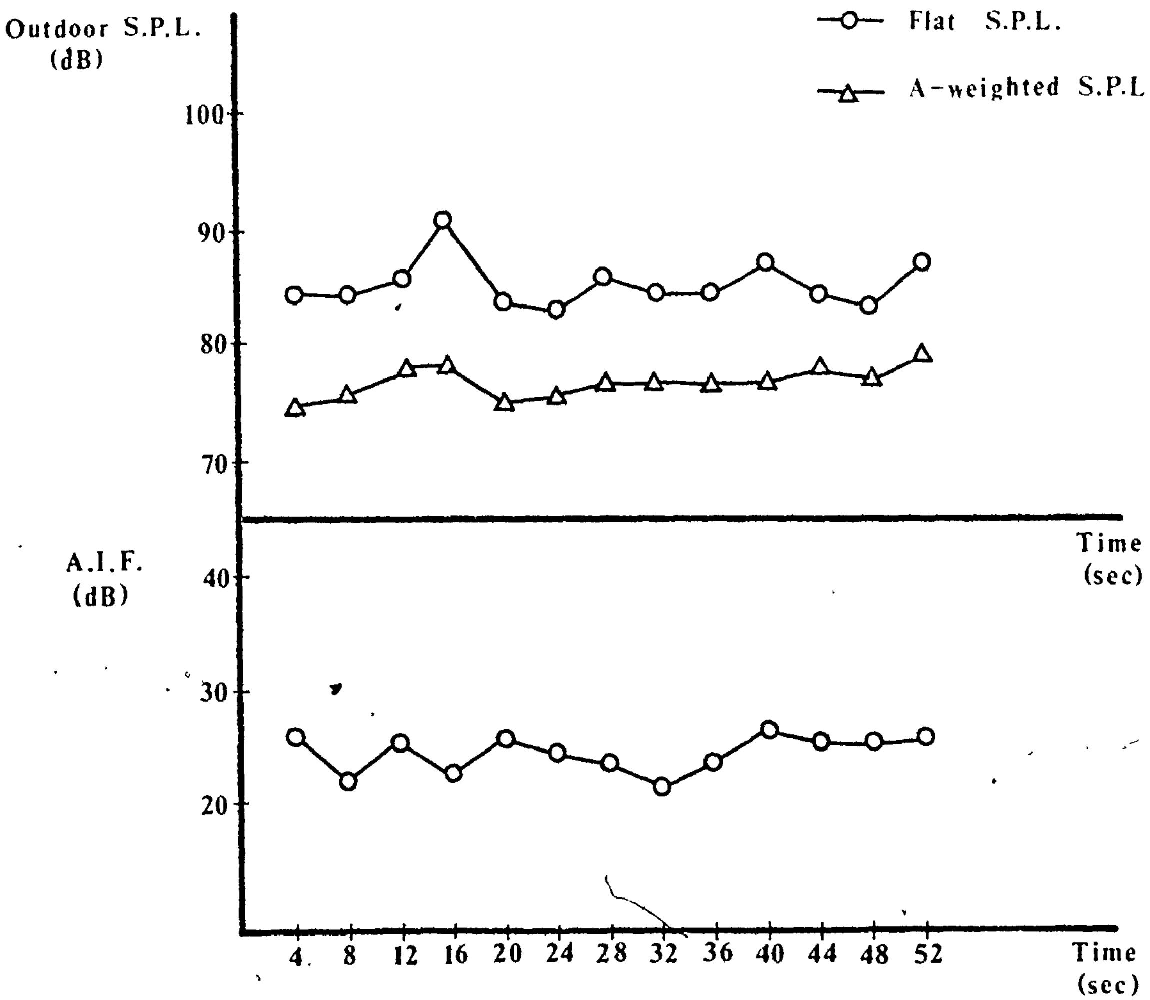

FIGURE 5.3. Variation of A.I.F. and outdoor S.P.L. over time. Road-traffic case. Site #11.

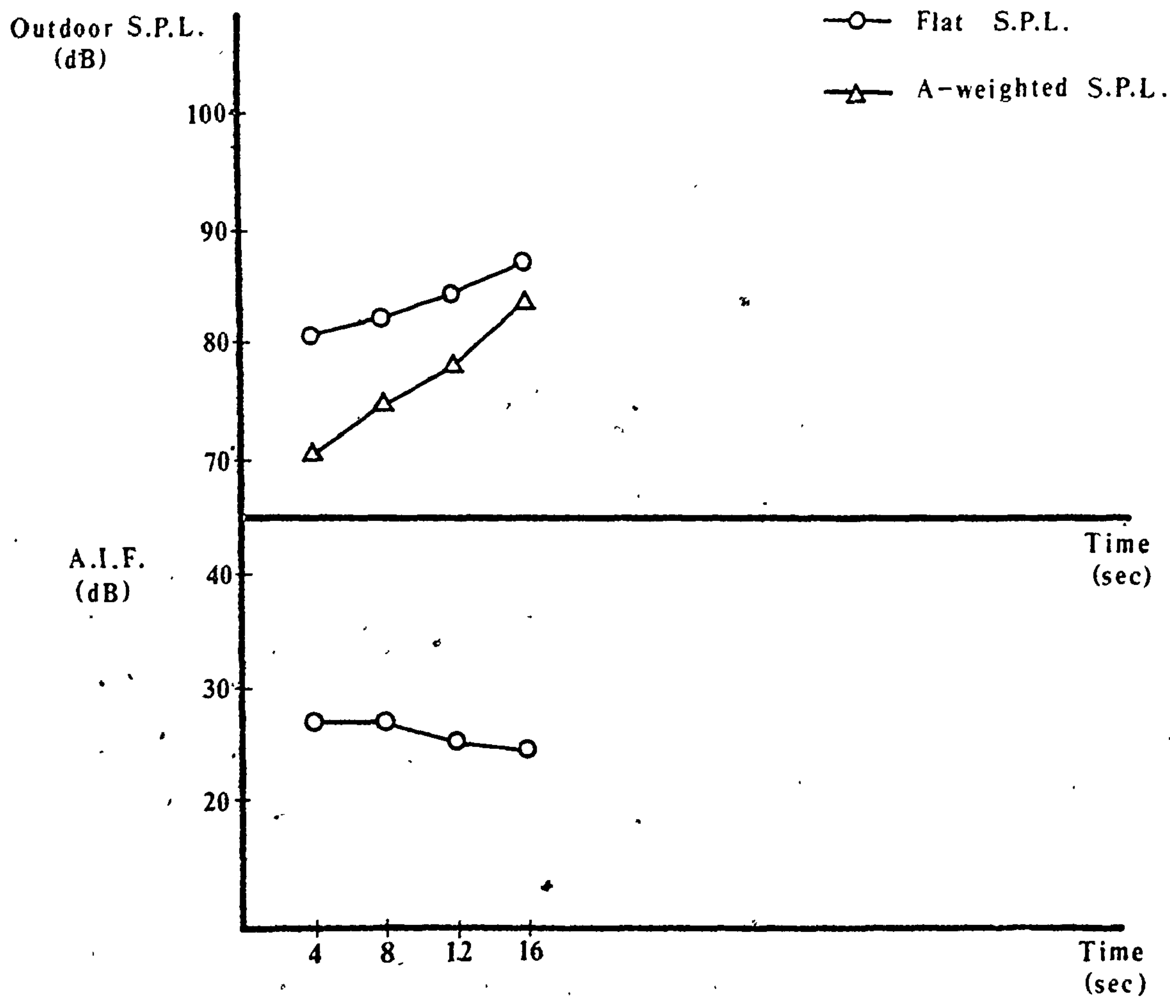

FIGURE 5.4. Variation of A.I.F. and outdoor S.P.L. over time. Perpendicular aircraft case. Site #19.

room of interest. This suggests that the second window, which was normally located on one side wall of the room, may cause the variation in the measured A.I.F. Although some shifts in the outdoor spectrum were observed, as expected, they did not affect the A.I.F.

In Figure 5.4 the variation of the A.I.F. over time from an aircraft site is illustrated. At this site the flightpath is perpendicular to the plane defined by the element of interest. Thus at the time the outdoor sound pressure level reaches its maximum, the angle of incidence, as measured from the normal to the surface of the element of interest, is close to maximum as well. It can be observed that in the first two time intervals (4th and 8th second) the A.I.F. is stable, while when the outdoor level reaches a maximum the A.I.F. decreases by almost 2.5 dB. It can also be observed that as the aircraft is approaching the house the difference between the flat and A-weighted level decreases, which indicates a shift of the outdoor spectra in the middle frequencies.

Figure 5.5 illustrates the results of the A.I.F variation for another similar aircraft case. In this site the angle of incidence was recorded as 70° approximately at the end of the 10th second. It can be observed that for angles of incidence higher than 70° the A.I.F. decreases by almost 4 dB. At the largest angle, where the outdoor sound pressure level reaches its maximum, a major shift in middle frequencies can also be observed.

In Figure 5.6 the variation of the A.I.F. for the same site, but for another sample, is illustrated. In this case the angle of incidence

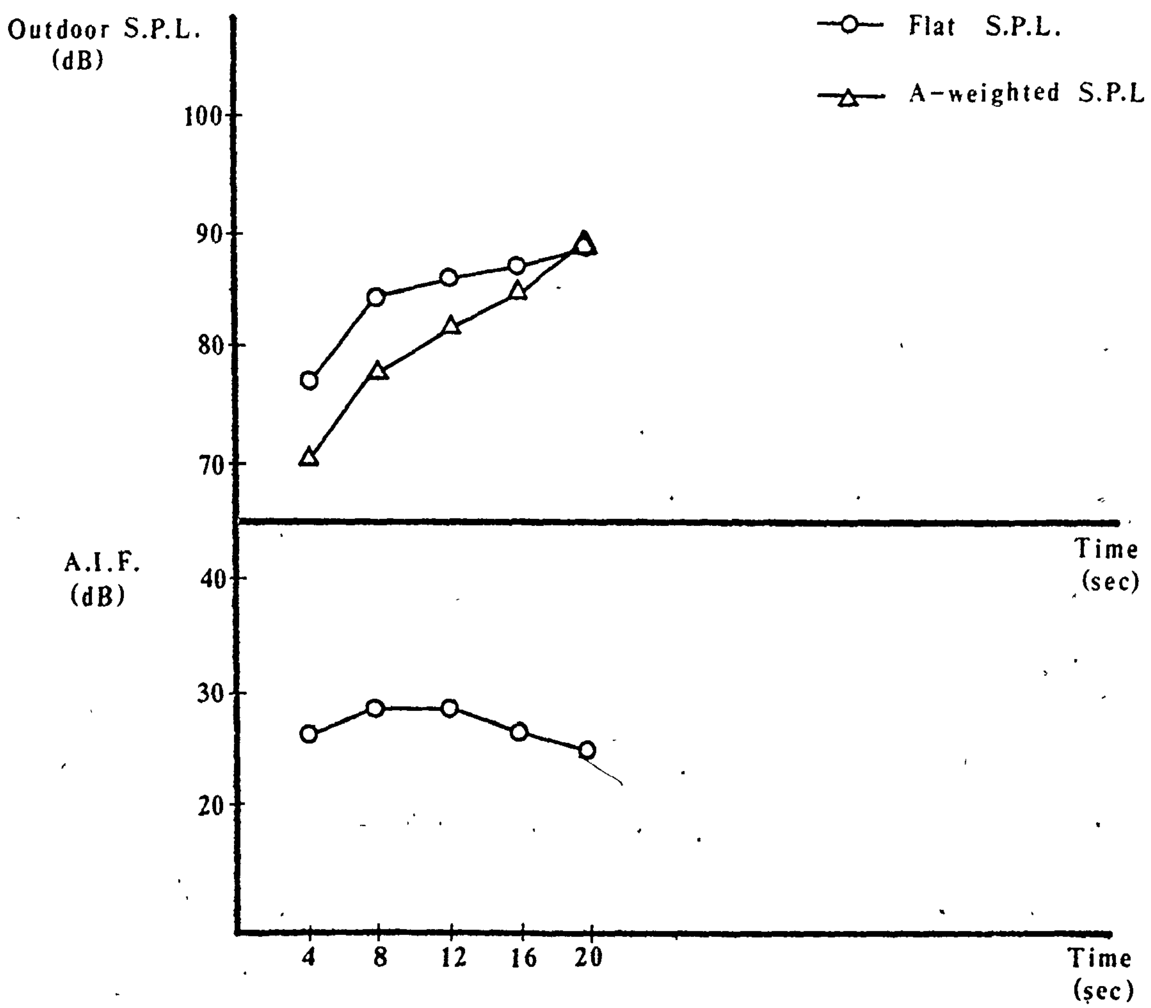

FIGURE 5.5. Variation of A.I.F. and outdoor A.I.F. over time. Perpendicular aircraft case. Site #18. Second sample.

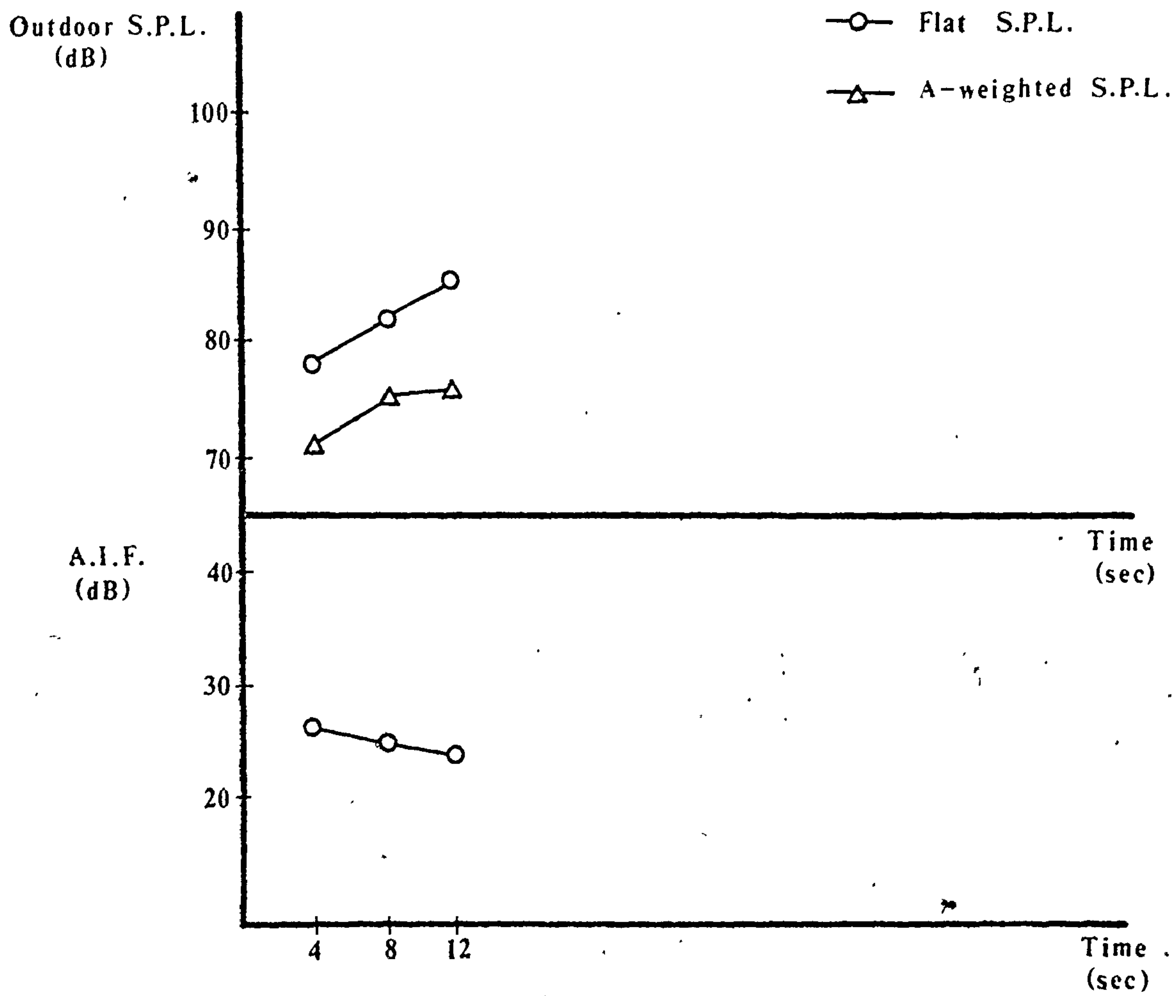

FIGURE 5.6 Variation of A.I.F. and outdoor S.P.L. over time. Perpendicular aircraft case. Site #18. First sample.

was recorded in the beginning of the sample as 70°. It can be observed that the A.I.F. decreases by almost 2 dB in the large angles of incidence. In addition, in this sample, when the outdoor sound pressure level reaches its maximum, a shift into lower frequencies can be observed.

In all the aircraft sites where the flightpath is perpendicular to the plane defined by the element of interest, the A.I.F. decreased at the time the angle of incidence was at its maximum. At the same time in some sites shifts in the outdoor spectrum were also observed.

A more comprehensive comparison between A.I.F. values of different angles of incidence can be made from the results presented in Table 5.1. for all samples collected in such aircraft sites. One A.I.F. corresponds to the lowest angle of incidence of each sample, while the second corresponds to the largest angle. The third column of this table shows if any shift in the outdoor spectrum was observed between the two angles in each sample as indicated by changes in the difference between the flat and A-weighted levels. It can be observed that in all sites the A.I.F. is lower in the largest angles than in the lowest ones. The difference varies between a maximum of 10 dB and a minimum of 1 dB. The fact that there is no effect of shift in the outdoor source spectrum on the A.I.F., combined with the observation that the A.I.F. decreases at largest angles, indicate that there is an effect of the angle of incidence on the acoustical insulation in normal residential construction.

In sites 17 and 20 there were two windows in the exterior room envelope while in sites 18 and 19 there was only one. In the previously presented analysis of road traffic sites there was an indication that the existance of a second window on one side wall may cause some variation on the A.I.F. The results of Table 5.1 indicate that the A.I.F. is lower in largest than in lowest angles of incidence independently of the number of windows in the exterior room envelope.

From this Table it can also be observed that there is a difference in the A.I.F. calculated for the same site between different samples.

TABLE 5.1. A.I.F. for lowest and largest angles of incidence in perpendicular aircraft sites.

SITE NUMBER	SAMPLE NUMBER	SPECTRUM SHIFTS $L_F - L_A$	A.I.F. for LOWEST ANGLE	A.I.F. for LARGEST ANGLE
17	1	inc.	33	23
	2	N.S.	24	21
	3	dec.	24	21
	4	N.S.	32	26
18	1	N.S.	28	26
	2	dec.	27	25
	3	N.S.	29	25
19	1	dec.	28	25
	2	N.S.	24	23
20	1	N.S.	36	33
	2	dec.	34	33
	3	N.S.	30	26

In site 17 this difference is 9 dB between samples 1 and 2 in the lowest angles. For the largest angles the A.I.F. is almost the same in all samples of the same site except in one site. The range between the lowest and largest angles is from 20^{o} up to 85^{o}. In site 20 there is a difference of 7 dB between sample 3 and samples 1 and 2. The fact that in site 20 there were two windows in the exterior room envelope, combined with the results of road traffic sites, where a second window caused such a variation can be an explanation of this difference.

A t-test was conducted to test the hypothesis that there is no difference between the A.I.F. for low and large angles. The difference was found to be significant at the level of 95% and it can not be attributed to chance. At the same level of confidence it was found that the difference is 3.5 ± 3.5 dB, which is consistent with the suggestion by A.S.T.M. (2) that the $10 \text{ Log}(\cos(\theta))$ term can only be used for angles up to 70°, while in this study the largest angles were approximately 85°.

Thus the results strongly indicate that there is an effect of the angle of incidence on the acoustical insulation of residential constructions. This effect was found to be independent of any shifts in the outdoor source spectrum, as well as of the existence of a second window in the exterior room envelope of the room of interest. The fact that in the cases where the flightpath is perpendicular to the element of interest the highest outdoor sound pressure level occurs at the same time that the angle of incidence is large, and consequently when there is the lowest acoustical insulation, indicates that an estimation of the acoustical insulation based on the overall flyover can overestimate the acoustical insulation of the room. An estimation of the acoustical insulation based on the maximum levels seems to be more representative, in these cases.

The decision to include the effect of the angle of incidence on the acoustical insulation in a guideline like that by C.M.H.C. depends on the magnitude of the effect, which seems not to be consistent with the one suggested by A.S.T.M. E-33 (2). Further research is suggested that will include a variation of relative locations between the flightpath and the housing, as well as different construction types with combinations of more than one window on the exterior room envelope. Measurements taken on both elements of interest will indicate if there is any possible effect of the existence of a second window on the A.I.F., while it can also permit the use of larger segments of each flyover in the analysis.

5.2 Comparison of measured and estimated A.I.F. values

The A.I.F. as estimated using the C.M.H.C. guideline was determined using the procedures described in section 4.6.

In Table 5.2 the A.I.F. values calculated from field transmission loss data as well as the A.I.F. calculated by the C.M.H.C. guideline are illustrated for all aircraft sites.

For six out of seven sites the A.I.F. calculated from field transmission loss data was lower than the one suggested by C.M.H.C. The difference varies between a minimum of 3 dB and a maximum of 12 dB. In only one site is the A.I.F. calculated from field transmission loss data higher than that suggested by C.M.H.C. procedures.

A t-test was conducted to test the hypothesis that the difference between the two procedures is negligible. The difference was found to be significant at the 95% level. At the same level of confidence it was found that the difference is 5.7 ± 3.6 dB. The difference is considered as high and indicates that the C.M.H.C. guideline overestimates the acoustical insulation of the different rooms. One possible reason for this difference might be the improper installation of the components which reduces their acoustical insulation. It also has to be noticed that the calculated difference is based on the assumptions discussed in section 4.2, that the outdoor sound pressure level measured at the surface of the element of interest is 6dB higher than that measured in the free field. If this assumption is not valid and the C.M.H.C. used the same assumption, then the C.M.H.C. guideline has to be adjusted, but it will still overestimate the acoustical insulation of the rooms. If the C.M.H.C. used a different assumption, then the difference decreases, but no more than one or two decibells. Thus even in this case the C.M.H.C. will overestimate the acoustical insulation of the rooms.

TABLE 5.2. A.I.F. from field transmission loss data and A.I.F. estimated by C.M.H.C. guideline for aircraft sites.

SITE NUMBER	A.I.F. CALCULATED BY C.M.H.C. GUIDELINE	A.I.F. CALCULATED FROM FIELD TRANSMISSION LOSS DATA
14	30	21
15	33	21
16	30	26
17	33	30
18	35	27
19	31	25
20	31	33

CHAPTER 6

SUMMARY AND CONCLUDING REMARKS

The present study had two objectives regarding the acoustical insulation of residential construction near to airport facilities.

The first objective was the effect of the angle of incidence on the acoustical insulation of residential construction. The second objective was the difference between the acoustical insulation calculated from field transmission loss data and the one based on the structural characteristics of the room as estimated in the C.M.H.C. guidelines.

Field transmission loss measurements were taken for thirty rooms in the Toronto area. Twenty of them were used in the analysis. Seven were aircraft sites, while thirteen were road traffic sites.

The Acoustical Insulation Factor was used as the index for rating the acoustical insulation of each room.

The first objective was investigated by studying the variation of the A.I.F. over time, corresponding to different angles of incidence, for aircraft sites where the flight path is perpendicular to the plane defined by the element of interest. The calculation of the A.I.F. was based on a standard outdoor spectrum, so that any effect of shift in the outdoor spectrum was eliminated.

The results strongly indicate that there is an effect of the angle of incidence on the A.I.F. even in normal residential areas with many reflected paths of the sound waves. More specifically it was found that the A.I.F. decreases at large angles of incidence.

From the presented results it was also observed that the magnitude of the effect of the angle of incidence on the acoustical insulation of residential construction seems to be consistent with the suggestion of A.S.T.M. (2) that the logarithmic function can not be used for angles larger than 70^{o}. One recommendation can be also made from the results of the first objective. The fact that, in aircraft sites where the flightpath is perpendicural to the plane defined by the element of interest, the acoustical insulation decreases when the outdoor levels reached their maximum suggests that the outdoor maximum levels may be a better indicator than the average levels for predicting the annoyance of the residents as well as calculating the acoustical insulation of the room.

The calculated A.I.F. from field transmission loss measurements was found to be lower than the one determined by the structural characteristics of each room as suggested by the C.M.H.C. guideline. The assumption made in this study, as recommmended by A.S.T.M. (2), that the outdoor sound pressure level is 6dB higher if measured on the surface of the element of interest than if measured in free field, does not highly affect the difference between the calculated A.I.F. from field transmission loss measurements and the A.I.F. suggested by the C.M.H.C. guideline.

Although the present study has investigated some questions, it has undoubtedly posed some new ones. Thus further research is suggested in at least two points.

1. The effect of the existence of a second window has to be examined by taking measurements at the same time on more than one window.
2. Testing the assumption used by A.S.T.M. (2, see section 4.2) that the outdoor sound pressure level is 6 dB higher if measured on the surface of the element of interest than measured in free field.

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APPENDIX A

Listing of the data collection program

```
0: prt " Data
 collection prog
 ram "
1: wait 1000
2: dsp "insert
 data tape";stp
3: ent "track
 to record on";S
4: trk S
5: ent "1st file
  to record on";
 R
6: lcl 720;rem
 720
7: lcl 710;rem
 710
8: ent "aircraft
 =1, road=2",N
9: if N=2;gto 19
10: 121→A
11: ent "inside=
 1,outside=2",M
12: if M=2;gto
 15
13: cmd 7,"?U*",
 "K4K2K1F2C2A2B4
 A5B5G5I5L4T1"
14: gto 16
15: cmd 7,"?U*",
 "K4K2K1H2C2A2B4
 A5B5G5I5L4T1"
16: cmd 7,"?U4",
 "K4K2K1H2C2A2B4
 A5B5G5I5L4T1"
17: wait 1000
18: gto 27
19: 61→A
20: ent "inside=
 1,outside=2",O

22: cmd 7,"?U*",
 "K4K2K1F2C2A2B4
 A5B5H5I5L4T1"
23: gto 25
24: cmd 7,"?U*",
 "K4K2K1H2C2A2B4
 A5B5H5I5L4T1"
25: cmd 7,"?U4",
 "K4K2K1H2C2A2B4
 A5B5H5I5L4T1"
26: wait 1000
27: dim A$[33A+
 16];dim B$[33A+
 16]
28: buf "in1",
 A$,3
29: buf "in2",
 B$,3
30: dsp "press
 cont to start"
31: stp
32: cmd 7,"?U4",
 "E0T1"
33: cmd 7,"?U*",
 "E0T1"
34: for I=1 to A
35: tfr 720,"in1
 ",33
36: rds("in1")→C
 ;if C<33I;gto
 36
37: tfr 710,"in2
 ",33
38: rds("in2")→B
 ;if B<33I;gto
 38
39: next I
40: cmd 7,"?U4",
 "G0T1"
41: cmd 7,"?U*",
```

```
43: rcf R+1,B$
44: fxd 2
45: num(A$[1+
 33(A-1)])→M
46: prt M/2
47: for I=2+33(A
 -1) to 3+33(A-
 1)
48: prt num(A$[I
 ])/4+M/2
49: next I
50: spc
51: num(B$[1+
 33(A-1)])→N
52: prt N/2
53: for J=2+33(A
 -1) to 3+33(A-
 1)
54: prt num(B$[J
 ])/4+N/2
55: next J
56: spc
57: fxd 0
58: prt "last
 file used ",R+1
59: prt "on trac
 k ";S
60: lcl 720
61: lcl 710
62: end
*9289
```

APPENDIX B

Listing of the program used for screening
the data

```
0: prt "INDOOR-
 OUTDOOR";spc ;
 spc
1: dsp "insert
 tape with monit
 or readings";
 stp
2: ent "trk no.
 to read",T
3: trk T
4: ent "first
 file number",F
5: ent "averagin
 g interval",H
6: ent "start
 at time",C
7: ent "number
 of intervals",D
8: dim X[4,D];
 dim Y[4,D]
9: ent "1 for
 air,2 for road"
 ,U
10: if U=1;gto
 12
11: 61→A;1→K;
 gto 13
12: 121→A;2→K
13: dim A$[33A+
 16];dim B$[33A+
 16]
14: buf "in1",
 A$,3
15: buf "in2",
 B$,3
16: for I=1 to D
17: for J=1 to 4
18: 0→X[J,I];
 0→Y[J,I]
19: next J
20: next I

 f4.0,f4.0,f4.0,
 f2.0
24: for N=1 to D
25: num(A$[1])/
 2→G
26: num(B$[1])
 2→B
27: for J=(C+(N-
 1)H)*K+1 to (C+
 N*H)*K
28: for I=1 to 4
29: num(A$[14+
 33(J+1)+3(I-
 1)])/4+G+X[I,
 N]→X[I,N]
30: num(B$[14+
 33J+3(I-1)])/4+
 B+Y[I,N]→Y[I,N]
31: next I
32: next J
33: next N
34: 0→M
35: for I=1 to 4
36: spc
37: prt "BAND
 #",M+I+23
38: prt " t out
 in  ld c"
39: 0→E
40: for N=1 to D
41: if X[I,N]/
 (H*K)=G;1→E
42: if Y[I,N]/
 (H*K)=B;2+E→E
43: wrt 16.1,C+
 N*H/K*K,X[I,N]/
 (H*K),Y[I,N]/
 (H*K),X[I,N]/
 (H*K)-Y[I,N]/
```

```
44: [illegible]
45: ....
46: M+2→M
47: next I
48: spc ;spc ;
 spc ;spc ;spc
49: end
*15814
```

APPENDIX C

Listing of the program used for calculating the decay rate for each band

```
0: dsp "reverber
 ation time"
1: wait 1000
2: ent "track
 number",S
3: trk S
4: ent "first
 file number",Z
5: ent "ratio
 of speeds",H
6: lcl 710;rem
 710
7: 96→A;dim A$[3
 3A+16]
8: buf "in",A$,3
9: dim B[21A],
 S[21],E[21],
 I[21],F[21],
 T[21],D[21],
 Y[21]
10: for J=1 to 6
11: if J>1;buf
 "in"
12: cmd 7,"?U*",
 "J2K1K4E5B5A5B4
 H2A2C2L4T1"
13: wait 1000
14: dsp "pres
 cont to start"
15: stp
16: cmd 7,"?U*",
 "E0T1"
17: tfr 710,"in"
 ,33A
18: rds("in")→C;
 if C#33A;gto 18
19: num(A$[1])→B
20: for K=0 to
 A-2
21: for I=4+33K
 to 24+33K
22: num(A$[I])/
 4+B/2→B[I-3-
 12K]
23: next I
```

```
 21
26: B[K]→L
27: for I=1 to
 A-1
28: if B[K+21I]<
 L;gto 31
29: B[K+21I]→L
30: next I
31: K+21I→S[K]
32: B[K+21I]→I[K
 ]
33: next K
34: for K=1 to
 21
35: S[K]→N
36: B[N]→L
37: int(N/21)→W
38: for I=W+2
 to A-1
39: if B[K+21I]>
 =L;gto 43
40: B[K+21I]→L
41: next I
42: 0→E[K];0→F[K
 ];gto 49
43: if I>W+3;
 gto 47
44: K+21I→S[K]
45: B[K+21I]→I[K
 ]
46: gto 35
47: K+21I-42→E[K
 ]
48: B[K+21I-42]→
 F[K]
49: next K
50: fmt 2,c16
51: wrt 16.2,
 "#steps  dB
 dB/s"
52: for K=1 to
 21
```

```
 1→Y[K];gto 57
55: I[K]-F[K]→D[
 K]
56: D[K]/T[K]*
 8H→Y[K]
57: fmt 3,f4.0,
 f6.0,f5.0
58: wrt 16.3,
 T[K],D[K],Y[K]
59: next K
60: rcf Z+J-1,
 Y[*]
61: next J
62: dsp "end of
 program"
63: lcl 710
64: end
*25951
```

APPENDIX D

Listing of the program used for calculating

the A.I.F. at aircraft sites

```
TRANSMISSION
LOSS"
1: dsp "INSERT
TAPE WITH DEC.R
ATES";spc ;stp
2: ent "TRK NUMB
ER FOR MEANS",T
3: trk T
4: ent "FILE
NUMBER FOR MEAN
S",F
5: dim T[21];
dim S[21];dim
A[21];dim E[21]
;dim F[21];dim
B[21];dim H[21]
6: dim C[20];
dim R[21];dim
X[21];dim Y[21]
;dim G[18];dim
K[21];dim L[21]
7: dim P[18];
dim W[18];dim
I[18];dim Z[21]
;dim D[21];dim
M[18];dim N[18]
8: dim U[18];
dim V[18];dim
O[20]
9: ldf F,T[*];
ldf F+1,S[*]
10: 47→A[1];53→A
[2];58→A[3];
61→A[4];63→A[5]
;65→A[6];67→A[7
];68→A[8]
11: 69→A[9]
12: for I=10 to
15
13: 70→A[I];next
I
14: 69→A[16];
68→A[17];66→A[1
8];64→A[19];
59→A[20];52→A[2
16: ent "FACADE
ELEMENT AREA",S
17: ent "ROOM
LENGTH",L
18: ent "ROOM
HEIGHT",H
19: ent "ROOM
WIDTH",W
20: HWL→V
21: prt "200 HZ
lowest"
22: S/LW→D
23: ent "TEMP.
IN DEGREES C",C
24: 20.06+r(273+
C)→C
25: prt "ROOM
CHARACT'S";spc
26: prt "room
volume",V;spc
27: fmt 2,c16
28: wrt 16.2,"
      room  sd"
29: wrt 16.2,
"#b rate abs
logA"
30: fmt 3,f2.0,
f4.0,f5.1,f5.1
31: for I=1 to
21
32: .921(V*T[I])
/C→E[I]
33: if T[I]=0;
prt "NO DATA
IN BAND",I+22;
gto 38
34: 10log(S/E[I]
)→F[I]
35: M+E[I]→M;K+
1→K
36: wrt 16.3,I+
22,T[I],E[I],
S[I]
37: 10log(60/
T[I]/.5)→B[I]
```

```
40: S/M→M
41: dsp "INSERT TAPE OF MONITORS READINGS";
 stp
42: ent "TRK NUMBER TO READ",T
43: trk T
44: ent "FIRST FILE NUMBER",F
45: ent "NUMBER OF FLYOVERS SAMPLED",N
46: fmt 1,c19,f3.0
47: for I=1 to N
48: wrt .1,"end time of flyover ",I
49: wait 1500
50: ent "IN SECONDS",C[I]
51: wrt .1,"beg time of flyover ",I
52: wait 1500
53: ent "IN SECONDS",O[I]
54: next I
55: ent "1 FOR AIR,2 FOR ROAD",U
56: if U=1;gto 58
57: 61→A;gto 59
58: 121→A
59: dim A$[33A+16];dim B$[33A+16]
60: buf "in1",A$,3.
61: buf "in2",
 f4.0,f4.0
63: for J=1 to N
64: if J>1;buf "in1";buf "in2"
65: if C[J]=0;gto 113
66: if J=1;gto 70
67: for I=1 to 21
68: 0→R[I]
69: next I
70: ldf F+2(J-1),A$
71: ldf F+2J-1,B$
72: if U=1;gto 75
73: C[J]+1→A;O[J]+1→E
74: gto 76
75: 2C[J]+1→A;2O[J]+1→E
76: for K=E to A-1
77: num(A$[1])/2→B
78: num(B$[1])/2→G
79: 29+16K+17(K-1)→L
80: for I=13+33K to 30+33K
81: num(A$[I])/4+B→X[I-L]
82: next I
83: 12+33(K-1)→L
84: for I=13+33(K-1) to 30+33(K-1)
85: num(B$[I])/4+G→Y[I-L]
```

```
 18
88: if X[I]=B;
 gto 93
89: if Y[I]=G;
 gto 93
90: R[I]+1→R[I]
91: M[I]+tn↑(X[I
 ]/10)→M[I];N[I]
 +tn↑(Y[I]/10)→N
 [I]
92: W[I]+(X[I]-
 Y[I])↑2→W[I];
 I[I]+X[I]-Y[I]→
 I[I]
93: next L
94: next K
95: for I=1 to
 18
96: if R[I]=0;
 gto 98
97: 10log(M[I]/
 R[I])-10log(N[I
 ]/R[I])→P[I]
98: next I
99: spc
100: prt "SAMPLE
 ",J
101: prt "
 mn    "
102: prt "#b
 LO  obs"
103: for I=1 to
 18
104: if R[I]=0;
 gto 108
105: wrt 16.4,I+
 22,P[I],R[I]
106: R[I]+G[I]→G
 [I]
107: U[I]+M[I]/
 R[I]→U[I];V[I]+
 N[I]/R[I]→V[I]
108: 0→P[I];0→R[
 I]
```

```
 18
111: 0→M[I];0→N[
 I]
112: next I
113: next J
114: spc
115: for I=1 to
 18
116: if G[I]=0;
 gto 123
117: 10log(U[I]/
 N)-10log(V[I]/
 N)→Y[I]
118: Y[I]+F[I]-
 3→D[I]
119: Y[I]+B[I]-
 3→Z[I]
120: if G[I]=1;
 0→W[I];gto 123
121: (W[I]-I[I]↑
 2/G[I])/(G[I]-
 1)→W[I]
122: √W[I]→W[I]
123: next I
124: for I=1 to
 18
125: if G[I]=0;
 gto 131
126: A[I]-Z[I]→K
 [I]
127: A[I]-D[I]→L
 [I]
128: O+tn↑(K[I]/
 10)→O
129: X+tn↑(L[I]/
 10)→X
130: A+tn↑(A[I]/
 10)→A
131: next I
132: spc
133: prt "ROOM
 SUMMARY";spc
134: prt "    mn
```

```
136: fmt 9,f2.0,
 f3.0,f6.1,f5.0
137: for I=1 to
 18
138: wrt 16.9,I+
 22,Z[I],W[I],
 G[I]
139: next I
140: spc ;prt
 "ACTUAL ROOM"
141: 10log(A)-
 10log(Q)→Q
142: prt "A.I.F.
 =",Q-3
143: spc ;spc ;
 prt "ELEMENT
 SUMMARY";spc
144: fmt 5,f2.0,
 f4.0,f4.0,f5.1
145: prt "   10
    "

146: prt "
 log  mn   sd"
147: prt "#b S/
 A  TL   TL  "
148: for I=1 to
 18
149: S[I]↑2+W[I]
 ↑2→H[I]
150: √H[I]→H[I]
151: wrt 16.5,I+
 22,F[I],O[I],
 H[I]
152: next I
153: spc ;prt
 "ELEMENT"
154: 10log(A)-
 10log(X)→P
155: prt "A.I.F.
 = ",P-3;spc
156: prt "ACTUAL
 ELEMENT"
157: prt "A.I.F.
 ",P-3-10log(S*
 H/V/,8)
158: end
*12065
```

APPENDIX E

Listing of the program used for calculating the A.I.F. at road traffic sites

```
0: prt "SUMMARY
 TRANSMISSION
 LOSS"
1: dsp "INSERT
 TAPE WITH DEC.R
 ATES";spc ;stp
2: ent "TRK NUMB
 ER FOR MEANS",T
3: trk T
4: ent "FILE
 NUMBER FOR MEAN
 S",F
5: dim T[21];
 dim S[21];dim
 A[21];dim E[21]
 ;dim F[21];dim
 B[21];dim H[21]
6: dim C[20];
 dim R[21];dim
 X[21];dim Y[21]
 ;dim G[18];dim
 K[21];dim L[21]
7: dim P[18];
 dim W[18];dim
 I[18];dim Z[21]
 ;dim D[21];dim
 M[18];dim N[18]
8: dim U[18];
 dim V[18];dim
 O[20];dim J[21]
 ;dim Q[18]
9: ldf F,T[*];
 ldf F+1,S[*]
10: 47→A[1];53→A
 [2];58→A[3];
 61→A[4];63→A[5]
 ;65→A[6];67→A[7
 ];68→A[8]
11: 69→A[9]
12: for I=10 to
 15
13: 70→A[I];next
 I
14: 69→A[16];
 68→A[17];66→A[1
 8];64→A[19];
 ELEMENT AREA",S
17: ent "ROOM
 LENGTH",L
18: ent "ROOM
 HEIGHT",H
19: ent "ROOM
 WIDTH",W
20: HWL→V
21: prt "200 HZ
 lowest"
22: S/LW→D
23: ent "TEMP.
 IN DEGREES C",C
24: 20.06+r(273+
 C)→C
25: prt "ROOM
 CHARACT'S";spc
26: prt "room
 volume",V;spc
27: fmt 2,c16
28: wrt 16.2,"
        room  sd"
29: wrt 16.2,
 "#b rate abs
 logA"
30: fmt 3,f2.0,
 f4.0,f5.1,f5.1
31: for I=1 to
 21
32: .921(V*T[I])
 /C→E[I]
33: if T[I]=0;
 prt "NO DATA
 IN BAND",I+22;
 gto 38
34: 10log(S/E[I]
 )→F[I]
35: M+E[I]→M;K+
 1→K
36: wrt 16.3,I+
 22,T[I],E[I],
 S[I]
37: 10log(60/
 T[I]/.5)→B[I]
38: next I
```

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```
S READINGS";
stp
42: ent "TRK
NUMBER TO READ"
,T
43: trk T
44: ent "FIRST
FILE NUMBER",F
45: ent "NUMBER
OF FLYOVERS
SAMPLED",N
46: fmt 1,c19,
f3.0
47: for I=1 to N
48: wrt .1,"end
time of flyover
",I
49: wait 1500
50: ent "IN SECO
NDS",C[I]
51: wrt .1,"beg
time of flyover
",I
52: wait 1500
53: ent "IN SECO
NDS",O[I]
54: next I
55: ent "1 FOR
AIR,2 FOR ROAD"
,U
56: if U=1;gto
58
57: 61→A;gto 59
58: 121→A
59: dim A$[33A+
16];dim B$[33A+
16]
60: buf "in1",
A$,3
61: buf "in2",
B$,3
64: if J>1;buf
"in1";buf "in2"
65: if C[J]=0;
gto 117
66: if J=1;gto
70
67: for I=1 to
21
68: 0→R[I]
69: next I
70: ldf F+2(J-
1),A$
71: ldf F+2J-1,
B$
72: if U=1;gto
75
73: C[J]+1→A;
O[J]+1→E
74: gto 76
75: 2C[J]+1→A;
2O[J]+1→E;gto
78
76: (C[J]-O[J])/
10→R
77: for Y=1 to R
78: for K=E+(Y-
1)*10 to 10Y
79: num(A$[1])/
2→B
80: num(B$[1])/
2→G
81: 29+16K+17(K-
1)→L
82: for I=13+
33K to 30+33K
83: num(A$[I])/
4+B→X[I-L]
84: next I
85: 12+33(K-1)→L
86: for I=13+
33(K-1) to 30+
33(K-1)
```

```
::
90: if X[I]=B;
 gto 95
91: if Y[I]=G;
 gto 95
92: R[I]+1→R[I]
93: M[I]+tn↑(X[I
 ]/10)→M[I];N[I]
 +tn↑(Y[I]/10)→N
 [I]
94: W[I]+(X[I]-
 Y[I])↑2→W[I];
 I[I]+X[I]-Y[I]→
 I[I]
95: next I
96: next K
97: for I=1 to
 18
98: if R[I]=0;
 gto 103
99: 10log(M[I]/
 R[I])-10log(N[I
 ]/R[I])→P[I]
100: if P[I]=0;
 gto 102
101: 1+V[I]→V[I]
102: P[I]+J[I]→J
 [I]
103: next I
104: next Y
105: spc
106: prt ". MPLE
 ",J
107: prt "
 mn .  ."
108: prt "#b
 LD  obs"
109: for I=1 to
```

```
 22;J[I]/V[I];
 V[I]
112: U[I]+J[I]→U
 [I]
113: R[I]+G[I]→G
 [I]
114: V[I]+Q[I]→Q
 [I]
115: 0→P[I];0→R[
 I];0→M[I];0→N[I
 ];0→J[I];0→V[I]
116: next I
117: next J
118: spc
119: for I=1 to
 18
120: if U[I]=0;
 gto 127
121: U[I]/Q[I]→Y
 [I]
122: Y[I]+F[I]-
 3→D[I]
123: Y[I]+B[I]-
 3→Z[I]
124: if G[I]<=1;
 0→W[I];gto 127
125: (W[I]-I[I]↑
 2/G[I])/(G[I]-
 1)→W[I]
126: rW[I]→W[I]
127: next I
128: for I=1 to
 18
129: if G[I]=0;
 gto 135
130: A[I]-Z[I]→K
 [I]
131: A[I]-D[I]→L
 [I]
132: O+tn↑(K[I]/
 10)→O
```

```
 10)→A
135: next I
136: spc
137: prt "ROOM
 SUMMARY";spc
138: prt "    mn
    sd      "
139: prt "#b TL
    LD    obs"
140: fmt 9,f2.0,
 f3.0,f6.1,f5.0
141: for I=1 to
 18
142: wrt 16.9,I+
 22,Z[I],W[I],
 G[I]
143: next I
144: spc ;prt
 "ACTUAL ROOM"
145: 10log(A)-
 10log(O)→Q
146: prt "A.I.F.
 =",Q-3
147: spc ;spc ;
 prt "ELEMENT
 SUMMARY";spc
148: fmt 5,f2.0,
 f4.0,f4.0,f5.1
149: prt "    10
    "
150: prt "
 log  mn  sd"
151: prt "#b S/
 A  TL  TL  "
152: for I=1 to
 18
153: S[I]↑2+W[I]
 ↑2→H[I]
154: √H[I]→H[I]
155: wrt 16.5,I+
 22,F[I],D[I],
 H[I]
155: 10log(A)-
 10log(X)→P
159: prt "A.I.F.
 = ",P-3;spc
160: prt "ACTUAL
 ELEMENT"
161: prt "A.I.F.
 ",P-3-10log(S*
 H/V/.8)
162: end
*21377
```

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