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NOISE NUISANCE CAUSED BY ROAD TRAFFIC IN RESIDENTIAL AREAS: PART II

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As part of a survey dealing with the effects of road traffic noise, 2933 persons resident at 53 sites in Greater London were interviewed, noise levels at the dwelling façades were measured and the volume and composition of the traffic at each site were counted.

After preliminary study of the data, the total sample was subdivided into two subsamples according to the flow and arrival pattern of traffic. The first subsample, in which free flow conditions prevailed, has already been reported in a companion paper [1]. The second subsample, where free flow conditions were not maintained, consisted of 1574 persons resident at 29 sites. For this subsample it was not found possible to obtain predictions of nuisance from existing noise measures of sufficient accuracy to be of practical use. However, a measure of traffic composition was found to yield useful predictions.

The total sample was subsequently re-examined and a measure using a weighted combination of noise levels and traffic composition was found to give useful predictions for a wide range of traffic conditions. Possible reasons for the findings are discussed, together with the results of applying unified noise nuisance indices to the survey data.

1. INTRODUCTION

A survey of nuisance occasioned by road traffic noise was carried out by the Building Research Station in the spring and summer of 1972 and the initial results of this study have been reported in Part I of these companion papers [1]. The 53 sites constituting the total sample exemplified a wide variety of traffic conditions ranging from free flow, similar to those studied by Building Research Station in 1968 [2], to disordered, spasmodic and congested flows. It was shown that the total sample could not be analysed so as to yield useful predictions of nuisance by means of existing noise measures.

In consequence, the sample was divided on the basis of studies of flow and arrival pattern into two subsamples, the first consisting of 24 sites where generally free flow conditions prevailed, and the second subsample of 29 sites where they did not. The present paper is devoted to the examination of data from the second sample, which may be termed "non-free flow" traffic, and to an attempt to apply the results of this analysis to the original total sample. Since many of the more general findings related to traffic noise and environmental nuisance have already been reported in Part I, the detailed results derived from correlating noise measures with dissatisfaction scores may be introduced without further preamble.

2. PRESENTATION OF RESULTS: ANALYSIS OF TOTAL SAMPLE

It is necessary to repeat in a less detailed form some of what has already been presented in Part I. For the total sample data from 53 sites, the product-moment correlations between median scores from a seven-point semantic differential scale of dissatisfaction and three noise measures over five time-periods are given in Table 1.

As will be seen, although all correlations reach high levels of significance, due to the large sample size, the values of r are not high enough to enable useful predictions of nuisance to be

TABLE 1
Product moment correlation of median dissatisfaction with noise level

Time period	L_{10}	L_{eq}	L_{NP} (L_{eq} + 2·56σ)
24 hours	0·521***	0·506***	0·55***
06.00–24.00	0·51***		
08·00–20.00	0·537***		
22.00–06.00	0·496***		
22.00–01.00	0·503***		

$N = 53$; ***$p = <0{\cdot}001$; **$p = <0{\cdot}01$; *$p = <0{\cdot}05$.

made for any given noise level. In this connection, the subdivision of the total sample derived from traffic flow and arrival pattern studies, which is illustrated graphically in Figure 1, is relevant.

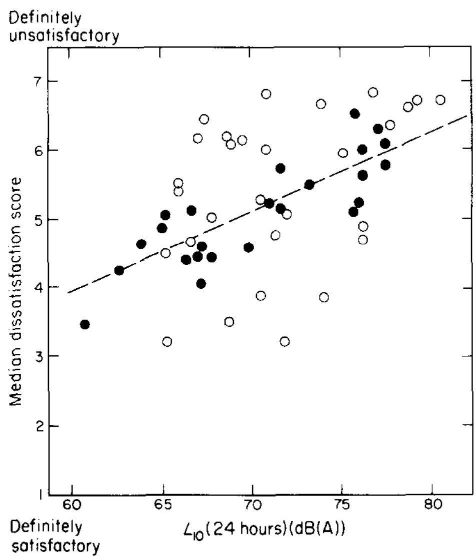

Figure 1. Group dissatisfaction scores for total sample plotted against noise level and subdivided according to traffic flow pattern. ●, Free flow sites; ○, non-free flow sites. Total sample 53 sites 2933 respondents.

In Figure 1 median dissatisfaction scores for all sites are plotted against L_{10} over 24 hours. The sites identified as free flow are indicated by the solid circles and the remainder by the unfilled circles. While the former are clustered about the total sample regression line and correlated as a separate subsample yield a value of $r = 0{\cdot}84$, the dispersion responsible for the low correlation of the total sample derives mainly from those sites earlier identified as ones where free flow conditions did not prevail. Of these 29 sites, only 12 fall within the confidence limits associated with correlation of the free flow sample. The likelihood of predicting nuisance with the aid of existing noise measures where traffic does not flow freely is therefore extremely low, as is shown by Table 2 which gives the correlation coefficients for both median (site) and individual dissatisfaction scores for the two subsamples, using a number of noise and traffic measures.

In the case of non-free flow traffic, only two measures, L_{10} and L_{NP}, attain significance with median dissatisfaction scores, the former reaching only a borderline value at the 0·05 level. For the individual scores the difference between the two subsamples is also considerable, though significance is less affected because of the very large sample sizes. It is however,

TABLE 2

Product-moment correlations of group and individual scores of dissatisfaction with seven physical measures

Physical variable		Group: Free flow	Group: Disordered	Individual: Free-flow	Individual: Disordered
L_{10}	12 h (08.00–20.00)	0·848***	0·37*	0·204***	0·14***
L_{50}		0·848***	0·251 n.s.	0·205***	0·09***
L_{90}		0·817***	0·145 n.s.	0·201***	0·05*
L_{10}	18 h (06.00–24.00)	0·845***	0·324 n.s.	0·203***	0·13***
L_{50}		0·838***	0·198 n.s.	0·203***	0·075***
L_{90}		0·797***	0·111 n.s.	0·194***	0·035 n.s.
L_{10}	24 h	0·845***	0·337 n.s.	0·206***	0·129***
L_{50}		0·821***	0·224 n.s.	0·197***	0·079***
L_{90}		0·774***	0·135 n.s.	0·187***	0·037 n.s.
L_{eq}		0·84***	0·32 n.s.	0·203***	0·125***
L_{NP}		0·746***	0·425*	0·176***	0·195***
Traffic (VPH)		0·797***	0·216 n.s.	0·206***	0·091***
Traffic (log VHP)		0·801***	0·162 n.s.	0·205***	0·072***
N		24	29	1359	1574

***, **, * as for Table 1.

worthy of note that here L_{NP} is markedly superior to all other measures, accounting for more variance than it does with free flow traffic, where its performance is less outstanding whether for grouped or individual data.

The term "non-free flow" has been applied to the second subsample since the failure to maintain free flow conditions is due to extremely varied causes. Some of the roads were loaded beyond capacity, producing constrained flows, congestion and eventual halting of traffic for short periods. Other sites are crossed by major roads, often controlled by lights or roundabouts, or are intersected by pedestrian crossings. The general effect is to substitute for a smooth traffic flow, dense platoons of vehicles followed by quieter periods, together with much slow running, stopping, starting and acceleration in low gears. Traffic flow follows an extremely complex pattern and is hardly amenable to simple description.

While it does not necessarily follow that noise nuisance resulting from non-free flow conditions of the kind described cannot be predicted accurately from existing noise measures, nevertheless this would appear to be the case for the present sample. Possible reasons for this will be discussed in section 6 but for the present the potentialities of other physical parameters will be examined.

When reports of noise nuisance occasioned by various types of road vehicle are analysed it is found that the most frequently mentioned sources are trucks and buses. Thus of the 2059 respondents of the total sample who report hearing road traffic noise, 1405 also say

TABLE 3

Report of noise heard and causing nuisance

Noise reported heard	No.	No. bothered	Percentage bothered
Road traffic (unspecified)	2059	1405	68
Private cars	421	153	36
Motorcycles	171	77	45
Trucks and buses	731	603	83

that they are bothered by it. But this overall proportion of 68 % is divided very unequally when broken down according to different types of road vehicle, as shown in Table 3.

It therefore seems that commercial vehicles are rarely reported as being heard without the concomitant experience of nuisance, in sharp distinction from other types of vehicle. In the light of what has been said above concerning the type of traffic conditions prevailing at the 29 non-free flow sites it would appear that the presence of heavy vehicles, measured by absolute numbers or as a proportion of the total flow, merits examination.

3. THE NON-FREE FLOW SAMPLE: ALTERNATIVE MEASURES OF NUISANCE

3.1. TRAFFIC PARAMETERS

From the total sample of 53 sites data for traffic flows were available in varying degrees of detail, classified by types of vehicle. All vehicles exceeding a gross weight of 1525 kg were listed as "heavy vehicles" and counted separately from private cars and light commercial vehicles. Thus, as used here, the term "heavy vehicle" is not restricted to buses and very large trucks but covers a range of vehicles almost all of which have diesel engines. In the case of the 29 non-free flow sites, data covering 12 hours (08.00–20.00) over 2 days of the week, 45 minutes of each hour being counted, were available for 10 of the sites. For the remaining 19 sites, counts of 10-minute periods sampled at five occasions between 08.30 and 21.30 for a number of days at each site were available. Thus data of the highest quality were available for 10, and of lower quality for 19, of the sites.

Computation of correlations between median dissatisfaction scores and a variety of traffic measures indicated that one measure alone, the percentage of heavy vehicles, yielded useful predictions. When results were plotted graphically it was noted that the 10 sites which had received more intensive counting showed far less dispersion than the 19 sites which had only been sampled. It was concluded that although nearly 2 years had elapsed since the original counts were made, more complete traffic counts might yield better results. The 19 sampled sites were therefore revisited and traffic counted to the same standards as the 10 more intensively counted sites. It was found that there had been relatively little alteration either in traffic volume or in proportions of heavy vehicles for the same sampling periods as the original sample counts. Large differences resulted however, from the availability of almost complete data over the full 12 hours. At 5 sites the entire traffic pattern had changed due to new road schemes and/or the exclusion of heavy vehicles. At these sites therefore, the existing 1972 sample counts were retained as the only relevant data.

The data for analysis therefore consisted of traffic flow and composition for 45 minutes of each hour for 12 hours at 10 sites, counted in 1972, similar data for a further 14 sites obtained in 1974, and sample counts for 5 sites made in 1972 giving a total of 29 sites. Table 4

TABLE 4
Product-moment correlations of group and individual dissatisfaction with four traffic measures

12-hour period (08.00–20.00)	*r* (Group)	*r* (Individual)
No. of heavy vehicles	0·514**	0·203***
log no. of heavy vehicles	0·573***	0·228***
% Heavy vehicles	0·70***	0·281***
log (% heavy vehicles)	0·74***	0·298***
N	29	1574

***, **, as for Table 1.

gives correlations for group median and individual scores of dissatisfaction at these 29 sites with four measures of traffic composition.

It is apparent that the best result is obtained from the logarithm of the percentage of heavy vehicles, the correlation for grouped data attaining a level which permits useful prediction of nuisance. In the case of individual responses, values of r^2 are considerably higher than those obtained from noise measures with free flowing traffic (for L_{10} over 24 hours in free flow, $r^2 = 0{\cdot}042$: log % heavy vehicles over 12 hours in non-free flow, $r^2 = 0{\cdot}088$), variance accounted for being more than doubled.

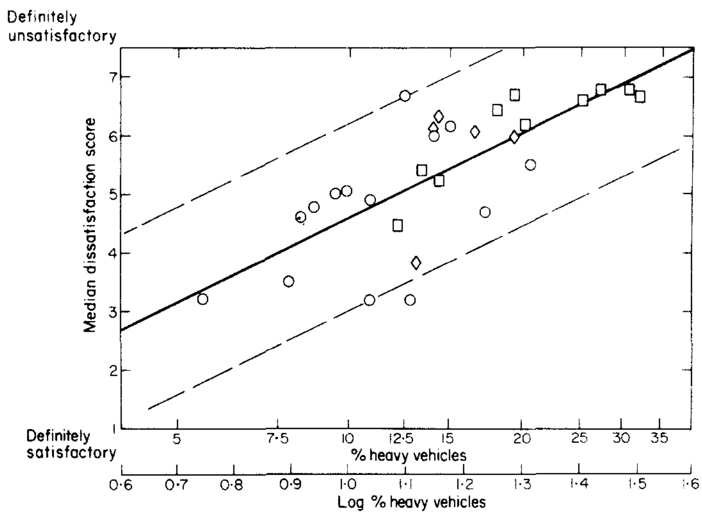

Figure 2. Group dissatisfaction scores for non-free flow sample plotted against log percentage heavy vehicles. □, Counted 1972; ◇, sampled 1972; ○, counted 1974; $r = 0{\cdot}74$; $N = 29$.

Figure 2 shows the median dissatisfaction scores plotted against a log scale with a linear regression as the best fitting line given by the equation:

$$\text{Dissatisfaction} = 4{\cdot}82\log(\%\text{ heavy vehicles}) - 0{\cdot}2. \quad (1)$$

Inspection of the figure shows that the sites most fully counted give the best fit to the line and if correlated alone would yield a value of $r = 0{\cdot}825$. The greatest part of the dispersion is due to the 14 sites counted 2 years later. It should also be noted that the range of traffic conditions covered by the 10 sites counted originally is restricted, none of these sites having less than 12% of heavy vehicles, thus reducing the likelihood of high correlation. It would seem that even better results would have been achieved had all 29 sites received the same standard of traffic counting in 1972.

3.2. COMBINED PHYSICAL MEASURES

An attempt was made to see whether prediction might be improved by combining measures of noise or other physical variables with those of traffic composition in a multiple regression equation. The results of this procedure are shown in Table 5 which considers five noise measures, one of traffic flow and one of street width.

None of the values for group or individual scores are significantly increased so that combining the traffic composition measure with other physical variables adds nothing. Inspection of the partial correlations showed that in no case is the value for the second term of the multiple correlation significant. For example, in the case of L_{10} over 12 hours, the partial r for group data is 0·07 and the value of t is 0·34, neither of which are significant, and the values for the second term variables of the other measures considered are of the same order.

TABLE 5
Multiple correlation of dissatisfaction with seven physical measures

Multiple correlation of % heavy vehicles	Group	Individual
$+L_{10}$ 24 hours	0·74	0·298
$+L_{10}$ 06.00–24.00	0·74	0·298
$+L_{10}$ 08.00–20.00	0·741	0·298
$+L_{eq}$	0·703 ***	0·298 ***
$+L_{NP}$	0·74	0·299
+Vehicles per hour	0·748	0·298
+log (stress width)†	0·747	0·312

† Defined: distance from façade to far kerb; ***, as Table 1.

3.3. THE EFFECTS OF ENVIRONMENT

In the paper reporting the results of the survey of free flow conditions it was shown that the perceived quality of the local neighbourhood had a measurable effect on dissatisfaction with traffic noise [1, see section 5]. The non-free flow data may be analysed in the same way by entering scores from either the five-point rating scale (Excellent–Very poor) or the 14-item checklist of neighbourhood amenities as the second term of a multiple regression equation and comparing the results with those of Table 4. These are given in Table 6.

TABLE 6
Effect of environmental quality on response to traffic noise, using two measures of amenity

Condition	r (log % H.V.)	Environmental measure	Multiple r
Group	0·74	5-point scale	0·747
Individual	0·298		0·333
Group	0·74	14-item list	0·76
Individual	0·298		0·3

The effects are similar to those reported earlier, yielding a significant increase in variance accounted for from individual responses. While the increases in the values of r for group data are not significant the multiple regression equations do have the effect of shifting the regression line. Two equations may be given for group data, viz:

$$\text{Diss.} = 4{\cdot}95 \log(\%\ \text{H.V.}) - 0{\cdot}267\ \text{Env.} + 0{\cdot}2\ \text{(5-point scale)}, \tag{2}$$

$$\text{Diss.} = 5{\cdot}13 \log(\%\ \text{H.V.}) + 0{\cdot}175\ \text{Env.} - 2{\cdot}1\ \text{(14-item list)}. \tag{3}$$

The differences in sign arise from the manner in which the environmental rating scales were constructed. The relation between the traffic and the environmental terms may be expressed as a ratio of the regression coefficients to indicate the effects of perceived differences in quality of the local environment.

For the sample studied the range of group mean rating scores was 1·4 points of the 5-point scale, few neighbourhoods being rated "very poor" and most being rated "good". Given this range of variation, the ratio between the traffic and environment terms indicates that differences in perceived quality of the neighbourhood could be expected to influence dissatisfaction with noise to an extent equivalent to about ±2% of heavy vehicles, a higher standard of amenity compensating for more noise nuisance.

3.4. INDIVIDUAL DIFFERENCES DUE TO NOISE SENSITIVITY

As described in Part I, dealing with free flowing traffic, a self-rating schedule was used to differentiate the total sample population with respect to their sensitivity to noise. The results of this test may equally be applied to the 1574 respondents of the present sample who are thereby divided into three nearly equal sub-populations termed "sensitive", "neutral", or "non-sensitive" to noise. Group and individual scores of dissatisfaction may be correlated with log % heavy vehicles for the three populations separately, or alternatively the scores of the self-rating test may be entered as the second term of a multiple regression equation.

The results of these procedures are shown in Table 7 and Figure 3.

TABLE 7

Effect of sensitivity on response to noise from non-free flow traffic

Condition	r, log (% heavy vehicles)	log (% heavy vehicles + sensitivity)
Group data ($N = 29$)	0·74	0·74 n.d.
Individuals ($N = 1574$)	0·298	0·449*** gain

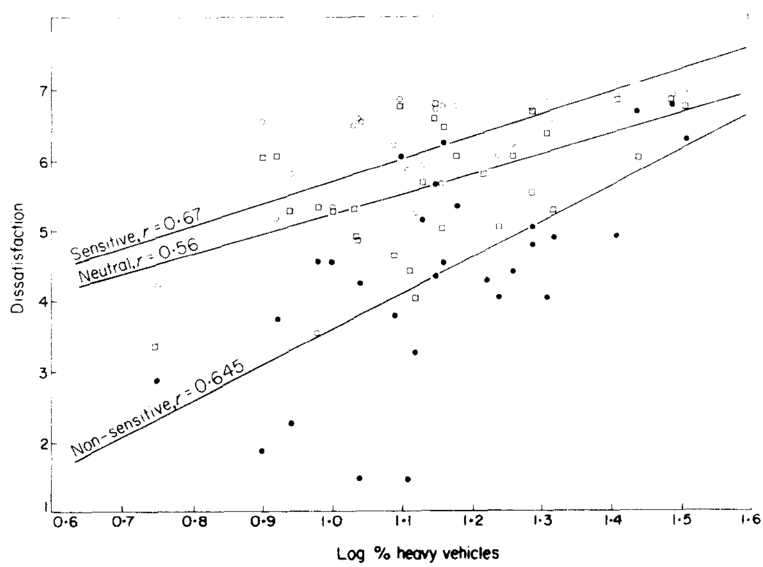

Figure 3. Group dissatisfaction scores for three sub-populations. ○, Sensitive; □, neutral; ●, non-sensitive.

As with the free flow sample, the effect of taking sensitivity into account is to reduce greatly the dispersion of individual dissatisfaction scores without affecting the group scores. Thus the variance accounted for is more than doubled, sensitivity accounting for more of the individual response than noise level, or the correlate of traffic composition itself. The actual increase in variance of 12 % is notably less than with free flow conditions, though this appears to be due to the fact that more variance is accounted for here by the traffic parameter.

While the correlational effects of including noise sensitivity are the same for the two sub-samples, Figure 3 indicates that the regression relationships for the three groups are very different from those found under free flow conditions. The free flow subsample indicated that the "non-sensitive" and "sensitive" groups failed to show a graded response over the range of noise levels, the graded response being exhibited mainly by the "neutral" group. In the present case, the "sensitive" and "neutral" groups have regression lines which do not differ significantly and can therefore be regarded as a single group. The "non-sensitive" population shows the most sharply graded response, though the value of r for this group is not increased, mainly because of the much greater dispersion of scores.

It is relevant to point out that while the population was subdivided on the basis of a test referring to noise as a form of nuisance, the dissatisfaction scores are correlated with a non-acoustic parameter. On the other hand, the general analysis has shown that traffic composition is, so far as dissatisfaction is concerned, a useful alternative to noise measures. Whether, therefore, the relationships displayed in regression for the subpopulations for the free and non-free flow samples are comparable or not is a question to be deferred for discussion in section 6.

4. NOISE NUISANCE PREDICTED FROM THE TOTAL SAMPLE FOR ALL TRAFFIC CONDITIONS

It was shown at the outset that noise nuisance could not be predicted accurately for the whole range of traffic conditions by means of existing noise measures. Nevertheless, the insights gained through separate analysis of free and non-free flow conditions may be used to develop measures capable of yielding such predictions. This would enable noise nuisance to be evaluated without prior classification or consideration of traffic conditions.

Existing noise measures yield good predictions in free flow conditions normally associated with new road construction but perform indifferently on existing roads where traffic may be disordered or congested. On the other hand, parameters of traffic composition perform well in these conditions but less well in free flow conditions. Table 8 gives product-moment correlations for group and individual dissatisfaction scores for the two subsamples with measures of traffic composition.

TABLE 8

Product-moment correlations for varying traffic conditions with four measures of traffic composition

	Free-flow		Non-free flow		All traffic	
Traffic variable	Group	Individual	Group	Individual	Group	Individual
No. heavy vehicles	0·795	0·201	0·514	0·203	0·578	0·197
log (No. heavy vehicles)	0·78	0·205	0·573	0·228	0·613	0·214
% Heavy vehicles	0·535	0·158	0·70	0·281	0·646	0·233
log (% heavy vehicles)	0·515	0·156	0·74	0·298	0·657	0·293
N	24	1359	29	1574	53	2933

For free flow traffic the number of heavy vehicles counted over 12 hours from 08.00 to 20.00 yields the best prediction, approaching that for group data from L_{10} over 12 hours ($r = 0·85$). But it performs less well for non-free flow traffic, where the best measure is the logarithm of the percentage of heavy vehicles measured over the 12 hours. For the total sample neither of the traffic parameters attain the same values, nor were significant improvements obtained by combining them in a multiple correlation.

Some further combination of parameters was therefore sought which would yield useful predictions for the total sample. Table 9 gives the results of this procedure by showing the selected best measures correlated with group and individual dissatisfaction scores for the total sample.

For free flow conditions, the best results were obtained from L_{10} over the period 08.00 to

TABLE 9

Multiple correlations of group and individual dissatisfaction scores with various traffic parameters

(53 sites: 2993 respondents)

Variable	Multiple r (group)	1st term partial r	t	2nd term partial r	t	Multiple r (individuals)
log (% H.V.) + L_{10} 24 h	0·701	0·55	4·64	0·32	2·42	0·246
+ L_{10} 18 h	0·704	0·56	4·82	0·33	2·51	0·248
+ L_{10} 12 h	0·712	0·55	4·70	0·36	2·76	0·249
% H.V. + L_{10} 12 h	0·706	0·54	4·57	0·37	2·84	0·244
log (% H.V.) + L_{eq}	0·703	0·57	4·84	0·33	2·48	0·247
+ L_{NP}	0·706	0·55	4·6	0·34	2·58	0·254
+ V.P.H.	0·693	0·61	5·41	0·29	2·15	0·244

20.00 ($r = 0{\cdot}85$) and for non-free flow conditions by the log percentage heavy vehicles over the same period ($r = 0{\cdot}74$). These same variables also produce the best estimate when combined in multiple correlation, as is shown by Table 9, and the result is almost as good if the percentage of heavy vehicles rather than the log transform is used. The relationships described by these measures may be expressed as regression equations, viz:

$$\text{Diss.} = 0{\cdot}078\, L_{10}\ 12\ \text{h} + 3{\cdot}34 \log(\%\ \text{H.V.}) - 4{\cdot}5, \tag{4}$$

$$\text{Diss.} = 0{\cdot}081\, L_{10}\ 12\ \text{h} + 0{\cdot}09\,\%\ \text{H.V.} - 2{\cdot}19. \tag{5}$$

A three term equation may be constructed by excluding the acoustic parameter and combining both traffic composition and flow with a measure of distance from the source† and this yields a value of $r = 0{\cdot}727$. The relationship may be expressed as a regression equation:

$$\text{Diss.} = 3{\cdot}72 \log(\%\ \text{H.V.}) + 1{\cdot}65 \log(\text{VPH}) - 2{\cdot}16 \log(\text{SW})\dagger - 1{\cdot}287. \tag{6}$$

Although the value of r is marginally superior to those yielded by the two term equations, the result is not of the first importance since it requires three physical measures.

Table 9 also shows that the combined measures account for more individual variance in the total sample than does L_{10} for free flowing traffic, and inspection of the partial correlations and the associated values of t indicate that all reach significant values, though the greater part of the variance is in all cases accounted for by the traffic composition measure. Lastly, it will be seen that, together with the log percentage of heavy vehicles, L_{NP} performs nearly as well as L_{10} for group data, and accounts for more individual variance than any other measure. The relationship for group data may be expressed by the equation

$$\text{Diss.} = 0{\cdot}7\ L_{NP} + 3{\cdot}34\ \log\ (\%\ \text{H.V.}) - 4{\cdot}86. \tag{7}$$

From the regression equations the predicted scores of dissatisfaction for any site may be calculated and the values compared with those actually measured. Figure 4 illustrates the result of applying this procedure to equation (4). The filled circles represent the 18 sites for which the best data were available and the hollow circles the 35 less well sampled sites.

For 95% of cases, the predicted score is within ± 1 scale point of measured values over the whole range of survey conditions. One reason for presenting the results in this way is that the response is related to more than one physical measure. Plotting dissatisfaction scores against values of the combined measure has no practical meaning since the 53 sites studied are but one selection from an infinite number of possible combinations.

The results may be summarized however by use of a nomogram as shown in Figure 5. The series of contours in this figure represent best fitting lines for each half-point interval of the

† Street width from façade to far kerb.

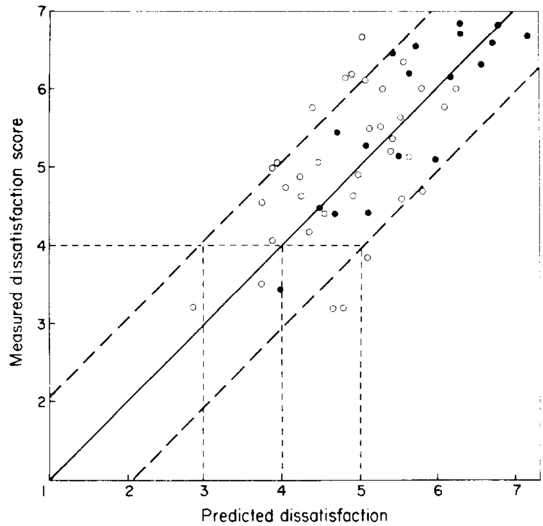

Figure 4. Measured group dissatisfaction scores plotted against predicted scores using combined noise/traffic composition measure. ●, BRS sites (18), $r = 0{\cdot}861$; ○, other sites (35), $r = 0{\cdot}711$.

dissatisfaction scale from 2·0 to 7·0 and the co-ordinates are provided by the two physical measures, in this case L_{10} over 12 hours and the log percentage of heavy vehicles. For any combination of these two variables group dissatisfaction is predicted by interpolation between pairs of adjacent contours.

Thus, the mid-point of the dissatisfaction scale relates to the same noise level as that predicted for free flow conditions with approximately 12% heavy vehicles—the actual average for the traffic composition found in the free flow subsample. It is also possible to predict changes in dissatisfaction which would result from varying either noise level or traffic composition. Taken together with the limits of confidence shown in Figure 4 it may be concluded that for most traffic conditions, the level of nuisance may be predicted with an accuracy roughly

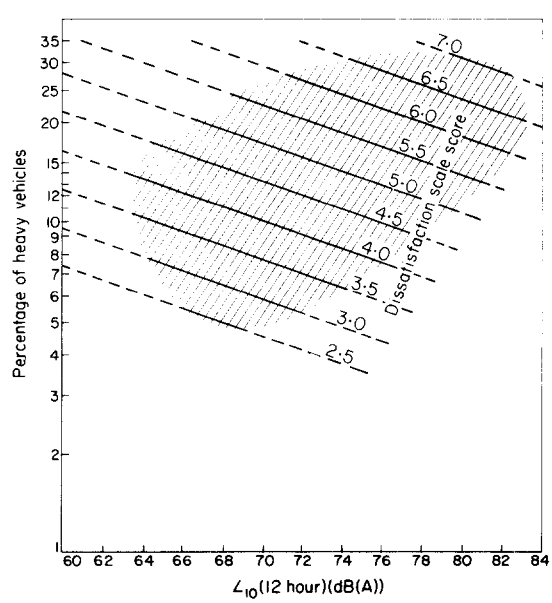

Figure 5. Nomogram for prediction of noise nuisance from noise level and traffic composition. ▩, Traffic conditions covered by survey. Dissatisfaction scale; 1·0 = definitely satisfactory, 7·0 definitely unsatisfactory.

equivalent to ±6 % in the proportion of heavy vehicles, as capable of producing a significant difference in dissatisfaction. As may be seen from the slope of the nomogram, changes in noise level have less influence on dissatisfaction than changes in traffic composition.

5. UNIFIED NOISE NUISANCE INDICES

In traffic conditions where free flows do not prevail it has been found useful to resort to non-acoustic parameters, going beyond existing noise measures. Possible reasons for this finding will be discussed in section 6. Before embarking on this however, it is appropriate to consider the potentialities offered by two proposed indices, the Noise Pollution Level (L_{NP}) and the Day/Night Level (L_{DN}). Both these measures have been developed to provide predictions of nuisance from a wide range of different types of noise without the need to resort to a multiplicity of specialized units appropriate to only one type of noise.

5.1. THE NOISE POLLUTION LEVEL (L_{NP})

The Noise Pollution Level [3] has been employed throughout the data analyses of the present survey. The results have shown that in free flow conditions it yields marginally lower correlations with dissatisfaction than measures such as L_{10} or L_{eq}. In non-free flow conditions however, it performs better than any other acoustic measure employed, though failing to yield practically useful predictions.

L_{NP} can be expressed by the formula $L_{eq} + 2{\cdot}56\,s$, where s represents "the standard deviation of the instantaneous level considered as a statistical time series" over a period during which noise events are reasonably homogeneous. The weighting applied is that which produces the best fit to survey data.

Throughout the analyses values of L_{NP} were employed which had been obtained by the use of this formula. The originally suggested value of 2·56 was derived from the attempt to optimize nuisance predictions for traffic and aircraft noise by use of existing survey data [2, 4]. However, it seemed possible that a different value might yield higher correlations with the present data than those so far obtained, while it had been stated (reference [3], p. 6) that this value was not critical.

L_{NP} may be computed in a number of ways. Of these, Robinson (personal communication) is inclined to favour $L_{NP} = L_{eq} + k(\overline{s^2})^{1/2}$. In order to optimise the value of the coefficient, hourly L_{eq} values were averaged logarithmically over each of the time periods considered (24, 18 and 12 hours) to obtain the first term, while for the second term the r.m.s. values of the standard deviations of the instantaneous levels for each hour within these periods were determined arithmetically. From the resulting values for the "energy" and the "fluctuation" terms, multiple correlations with dissatisfaction scores were computed for all traffic conditions for each of the three time periods. By this procedure the optimum value of k is obtained for each case. The results are given in Table 10.

These results present a number of interesting features. For free flow traffic the result is marginally superior to that obtained previously, though no better than that yielded by L_{10} or L_{eq}. On the other hand, in non-free flow conditions the outcome is not significantly different from that obtained with $k = 2{\cdot}56$. More importantly however, the optimum values of k for free flow and total traffic are all considerably smaller than that initially suggested by Robinson, tending to decrease as the time period is shortened. In the case of free flow traffic the optimum values of k for the survey data become negative for 18- and 12-hour periods, the trend suggesting that somewhere between 24 and 18 hours k would equal zero.

Inspection of the partial correlations and their significance values reveals further cause for concern. For all traffic and time conditions, only the energy term contributes to the multiple correlation, the "fluctuation" term apparently playing no significant role. It is pertinent to

TABLE 10

Multiple and partial correlations of dissatisfaction with L_{NP} and its components for three time periods and three traffic conditions

Time period	Value of k	Multiple r	Partial r (L_{eq})	t (L_{eq})	Partial r (k)	t (k)
Free flowing traffic, $N = 24$						
24 hours	+0·47	0·843***	0·84	7·05	0·13	0·6
06.00–24.00	−0·32	0·843***	0·77	5·55	−0·11	0·5
08.00–20.00	−0·76	0·848***	0·75	5·22	−0·24	1·16
Non-free flow traffic, $N = 29$						
24 hours	+2·34	0·423*	0·39	2·16	0·29	1·55
06.00–24.00	+2·06	0·423*	0·39	2·19	0·27	1·45
08.00–20.00	+1·81	0·405	0·38	2·07	0·23	1·22
All traffic, $N = 53$						
24 hours	+1·69	0·557***	0·55	4·68	0·27	1·98
06.00–24.00	+0·9	0·537***	0·53	4·44	0·17	1·19
08.00–20.00	+0·53	0·526***	0·52	4·26	0·1	0·69

***, * as for Table 1.

add that this outcome does not derive from the particular method used to calculate L_{NP}, for a very different method ($L_{eq} + k\bar{s}$) yields results not significantly different from those shown above. A possible explanation for the results shown in Table 10 will be discussed in section 6.

5.2. THE DAY/NIGHT NOISE LEVEL (L_{DN})

To facilitate broad comparisons of nuisance occasioned by different sources of noise, the U.S. Environmental Protection Agency have proposed a measure, the Day/Night Noise Level, expressed as L_{DN} [5]. It is not envisaged by the Agency that L_{DN} should replace existing indices where it is recognized that their characteristics are essential to accuracy in prediction or design [5, see App. IV]. The index is intended merely to provide a simple and easily computed way of comparing noise nuisance "across the board". It is not therefore essential that L_{DN} should correlate more highly with dissatisfaction than existing measures, but it is clearly desirable that it should not perform significantly worse.

L_{DN} is defined as the equivalent A weighted level over the 24-hour period with a 10 dB(A) positive weighting applied to the noise levels during the period 22.00 to 07.00. Thus L_{DN} values are not merely uniform increases of 24 hour values of L_{eq}, since there is no inherent reason why noise levels at night should co-vary at the different sites with the daytime levels. For the 53 sites of the present survey L_{DN} values have been computed. Table 11 gives product-moment

TABLE 11

Comparison of correlations and regressions obtained from L_{DN} and existing noise measures

Unit	Total sample 53 sites r	Total sample 53 sites Regression	Free flow 24 sites r	Free flow 24 sites Regression	Non-free flow traffic 29 sites r	Non-free flow traffic 29 sites Regression
L_{10} 24 h	0·52	$0{\cdot}108L_{10} - 2{\cdot}49$	0·845	$0{\cdot}124L_{10} - 3{\cdot}67$	0·337	$0{\cdot}087L_{10} - 0{\cdot}89$
L_{10} 18 h	0·51	$0{\cdot}126L_{10} - 4{\cdot}01$	0·845	$0{\cdot}147L_{10} - 5{\cdot}67$	0·324	$0{\cdot}098L_{10} - 1{\cdot}87$
L_{eq} 24 h	0·506	$0{\cdot}124L_{eq} - 3{\cdot}54$	0·84	$0{\cdot}147L_{eq} - 5{\cdot}2$	0·32	$0{\cdot}096L_{eq} - 1{\cdot}44$
L_{NP}	0·534	$0{\cdot}13L_{NP} - 6{\cdot}14$	0·746	$0{\cdot}141L_{NP} - 7{\cdot}19$	0·425	$0{\cdot}117L_{NP} - 4{\cdot}93$
L_{DN}	0·51	$0{\cdot}11L_{DN} - 2{\cdot}81$	0·846	$0{\cdot}132L_{DN} - 4{\cdot}62$	0·319	$0{\cdot}082L_{DN} - 0{\cdot}745$

correlations and the associated regression equations for group dissatisfaction scores for each of the three traffic conditions studied, together with results employing four other noise measures.

So far as accuracy of prediction is concerned, it will be seen that for each traffic condition the correlations are almost identical to those produced by L_{eq}, from which L_{DN} is derived, and in the case of non-free flow traffic L_{DN} is, like the other measures, markedly inferior to L_{NP}. More importantly however, the regression weights of L_{eq} and L_{DN} do not result in slopes which differ significantly: that is to say, the relationship between noise and nuisance is effectively the same. All that has changed is the weighting coefficient, placing the regression line in a slightly different position.

This is merely the outcome of the difference in relative magnitude of noise levels measured in L_{eq} and L_{DN}. The effect of computing L_{DN} is in fact to increase L_{eq} values for the 53 sites by approximately 4 dB(A), on average, the range of levels still being 20 dB(A). This difference is simply the proportion of the 10 dB(A) weighting represented by the 9 weighted hours of the total 24. Lastly, it will be noted that the poor correlations between dissatisfaction and existing noise measures in non-free flow conditions are again evident in the case of L_{DN}.

6. DISCUSSION

6.1. PREDICTION OF NUISANCE FROM NON-FREE FLOW TRAFFIC

The appraisal of methods for predicting noise nuisance occasioned by traffic which is not free flowing but disordered and congested must take account of the finding that existing noise measures fail to yield useful predictions: that is, predictions which indicate significant differences in dissatisfaction arising from differences of around 5 dB(A) in noise levels. At the same time, traffic composition measures do appear to yield useful predictions and it is relevant to speculate as to why this might be so.

Quite apart from the fact that heavy vehicles, and in the present context this signifies vehicles with a gross weight exceeding 1525 kg, make more noise than light vehicles, particularly in non-free flow conditions, it is very possible that residents object to their presence on general grounds. It is not unreasonable to suppose that for reasons such as fumes, dirt, danger, visual appearance, and overall perceived incompatibility with the domestic environment, such vehicles are deemed unacceptable in close proximity to the dwelling.

Granted however, this general incompatibility, the close correlation between the measured proportion of heavy vehicles in the traffic stream and dissatisfaction scores on a noise nuisance scale suggests that the chief indication that heavy vehicles are present is the noise they make in passing. For unless residents spend their time looking out of the windows it seems reasonable to assume that it is the noise made by these vehicles which plays a major part in the residents' evaluation. But if this is so it is necessary to ask why measured noise levels fail to correlate with dissatisfaction scores. For whatever the real grounds for dissatisfaction with the presence of heavy vehicles, if their passage is indicated by the noise they make, their relative contribution to the overall noise level should be accounted for in the noise measured.

A number of possible explanations for this suggest themselves. It may well be that the difference between the noise from heavy and light vehicles, most noticeable in non-free flow conditions, is even further increased when the noise is heard indoors. At the same time, although the passage of heavy vehicles may be distinctly perceptible to residents, variations in traffic composition have but a moderate influence on the noise level of the traffic stream. Thus in the present survey, the correlation between the proportion of heavy vehicles and noise levels measured in L_{10} is only 0·43 for the total sample of 53 sites, and 0·28, a non-significant value, for the 29 sites of the non-free flow subsample.

These considerations are likely to be most significant where traffic conditions are typified by slow running in low gears, stopping, starting and accelerating through the gears, and so on. As against this, the more conditions approximate to free flow, particularly at traffic volumes sufficient to generate noise nuisance, the less noticeable becomes the contribution from heavy vehicles. This trend is even more marked at higher speeds, typical of motorway conditions, for as speed increases, the noise emitted by petrol engine vehicles increases sharply as compared with diesel engine vehicles [6].

Consequently, where more or less free flow conditions prevail, measured noise levels may be expected to correlate with residents' experience of noise nuisance. It may also be suggested that for the same reason, in free flow traffic the absolute number rather than the percentage of heavy vehicles correlates well with dissatisfaction. For in these conditions, the number of heavy vehicles, like traffic volume, also co-varies with noise level. In non-free flow conditions, often associated with roads used above their design capacity, a measure based on traffic composition yields better predictions since it represents more effectively the predominant source of nuisance within the dwelling.

Whether any of these speculations are confirmed or refuted—for which further studies would be needed—the fact remains that in densely populated areas where traffic noise is a major source of nuisance, traffic conditions resembling those studied by the present survey tend to be more typical than those described as free flow. And in these circumstances the findings emphasize strongly the importance of heavy vehicles—as here defined—as major sources of nuisance.

6.2. PREDICTION OF NOISE NUISANCE FOR ALL TRAFFIC CONDITIONS

The division of the sample into two subsamples on the basis of traffic flow and arrival pattern was made to facilitate the subsequent analysis. It is inevitable that any such subdivision must be to some degree arbitrary, since in reality traffic conditions vary over a continuum extending from orderly free flowing traffic to completely disordered and congested conditions.

A noise measure appropriate to either of these conditions should yield useful predictions over a wide range of traffic situations without the need for precise specification of the nature of the traffic pattern. This requirement appears to be met, within the range of conditions covered by the survey, by a measure combining noise measured as L_{10} or L_{eq}, and traffic composition measured as log percentage of heavy vehicles. Nevertheless, such a formula is of necessity a compromise to give the best overall prediction for all conditions. It follows that the effect of extreme conditions of free or non-free flows tend to lower the value for the multiple correlation since they are represented best by a single relevant parameter either of noise or traffic. The combined measure therefore aims only to give a rough indication of probable nuisance, most applicable in situations which cannot be identified as distinctively free or non-free flow. Where more accurate predictions are required, or the traffic pattern is fairly clear and distinctive, simple noise or traffic measures will produce superior results.

It will be seen from Figure 2 that, for the non-free flow sample, the 10 sites counted intensively in 1972 lie closest to the best fitting line, and the same may be seen from Figure 4 for the 18 intensively counted sites of the total sample. Fisher's z test [7] shows that the value of $r = 0{\cdot}86$ for the 18 sites is not significantly different from that of $r = 0{\cdot}712$ for all sites. Nevertheless prediction is in fact better for the intensively counted sites since the same level of significance is reached from data covering a smaller range of variation.

The 18 intensively counted sites cover the range from 12 to 32% heavy vehicles whereas the total sample of 53 sites extends this to 6% heavy vehicles. However, regression equations for the two sets of data do not yield notably different predictions:

$$\text{53 sites: Diss.} = 0{\cdot}078L_{10} + 3{\cdot}34\log(\%\ \text{H.V.}) - 4{\cdot}5, \tag{4}$$

$$\text{18 sites: Diss.} = 0{\cdot}089L_{10} + 4{\cdot}31\log(\%\ \text{H.V.}) - 6{\cdot}56. \tag{8}$$

These relatively small differences suggest that the percentage of heavy vehicles is a comparatively robust parameter which is not too critically dependent upon 100% sampling. At the same time, it would seem that intensive counting of traffic composition over the entire range of sites would have resulted in a significant improvement in accuracy of prediction.

Although the combined measure yields useful predictions over a wide range of traffic conditions, there remains the problem of how the expected effects of insulation or screening of buildings can be predicted. For the unit by which the effects of such procedures are evaluated is not itself a wholly acoustic measure.

To facilitate such procedures it would seem that existing measurements of external noise require to be supplemented to take account of the extra contribution made by heavy vehicles to the internal noise level. This would produce values in acoustic units in closer correspondence with residents experience. Such measures might initially be developed with the aid of data for external and internal noise levels obtained over a range of traffic composition and flow. This information would enable measurements of traffic composition to be transformed into acoustic quantities with which to supplement external noise measurements.

6.3. UNIFIED NOISE NUISANCE INDICES

It was shown that in non-free flow conditions, L_{NP} yielded correlations between measured noise levels and dissatisfaction marginally superior to those obtained from L_{10} or L_{eq}, though still too low to provide practically useful predictions. Optimising the value of k by multiple correlation yielded a significant improvement in correlation for all traffic conditions, though the final value achieved for r is still below that needed for practical purposes.

However, the salient feature to emerge from this analysis is the finding that for the present sample the "fluctuation" term plays no significant part in the correlation, and it is worthwhile considering why this is so.

The failure to perceive this fact at an earlier stage is explained by the employment of "ready made" values of L_{NP} as a single term in a product-moment correlation. Such a procedure obscures the separate contributions of the two components embodied in L_{NP}, only revealed by multiple correlation analysis.

Inspection of the data which determine the "fluctuation" term reveals that the reason why this term plays no part in the correlation is simply that the standard deviations of the instantaneous level expressed as s are not large enough. The r.m.s. values range from 5·5 to 9·5 and are significantly related to equivalent noise level ($r = 0{\cdot}3$: $p = <0{\cdot}05$), the regression line passing from 7·5 at 60 to 6·5 at 80 L_{eq}, a magnitude and range of variation too small to affect the outcome.

Furthermore, the effectiveness of the second term is reduced by the additional circumstance that part of the fluctuation is accounted for by L_{eq} itself. This may be shown by performing the multiple correlation with values of L_{50} in place of L_{eq}, with quite different results, as shown by Table 12.

TABLE 12

Multiple correlation of noise levels and fluctuations with group scores of dissatisfaction

Time period	Value of k	Multiple r	Partial r (L_{50})	t (L_{50})	Partial r (s)	t (s)
24 hours	3·43	0·565	0·56	4·78	0·39	2·97

$N = 53$.

Comparison of this table with Table 10 shows that while correlation is not significantly improved, the partial correlation and t value for the second term are now both significant, while k has a much larger value. In this case, the "fluctuations" are playing a significant part in the correlation, since their representation is now relegated wholely to the second term of the formula. It is therefore perhaps legitimate to speculate whether this finding provides a point of departure for further study of complex noise nuisance indices, not structurally dissimilar to L_{NP}.

The magnitude of changes in instantaneous levels would expectedly be greater for noise sources other than road traffic, such as railways and aircraft. In such cases it would also be expected that the second term of L_{NP}, or any related variant, would contribute significantly to correlation with measured dissatisfaction. Although offering no advantages over simpler units such as L_{10} or L_{eq} in the case of road traffic noise, L_{NP} therefore retains the potentialities for providing a single measure of nuisance from mixed or varied noise sources and merits continued study.

The case of L_{DN} appears somewhat different. Like L_{NP}, L_{DN} also yields results as good as, though no better than, L_{eq} from which it is derived. Despite the 10 dB weighting of night noise it yields identical predictions to L_{eq}. The reason for this is that although night noise levels between 02.00 and 07.00 need not necessarily co-vary with daytime levels at the same sites, for the present sample of 53 sites they do so. As a result, the effect of the weighting is merely to increase the values of L_{eq} by $10 \times 9/24$. Thus for the present sample a regression line generated from L_{DN} is almost a perfect fit to that obtained from L_{eq}.

A further point is that, as demonstrated in Part I of this paper [1, see section 5.2], principal component analysis of the dissatisfaction scale in terms of all activities disturbed by noise showed that disturbance of sleep does not contribute to the variance accounted for, a finding in accord with that of Aubree [8]. As measured, general dissatisfaction is governed effectively by what happens outside the hours of sleep.

Hence, so far as concerns traffic noise, L_{DN} does not cause predictions of nuisance at any particular site to vary as compared with L_{eq}, relative to those for any other site. Nor would such different predictions, had they occurred, relate to dissatisfaction measured by the overall 7-point scale.

This conclusion in no way diminishes the potential value of L_{DN} as a unified noise nuisance index applicable to a wide range of different noise sources, though it does suggest that for road traffic noise L_{DN} behaves no differently from L_{eq} and other simpler measures.

6.4. SOURCES OF RESIDUAL VARIANCE

Whether the two subsamples or the total sample are being considered, choice of an appropriate indicator enables 60 to 70% of group and a maximum of 10% of individual variance to be accounted for without introducing other factors such as the effects of perceived environmental quality. Nevertheless, although adequate predictions can be made for the community the proportion of individual variance in response accounted for by physical measures remains small. The limits to prediction do not appear to be set by the choice of physical parameter but arise mainly from the range of individual response. This derives from a variety of sources of which the most notable is differences in noise sensitivity.

Perhaps the first conclusion to be drawn from this is that further work to improve prediction accuracy is likely to be unprofitable. If a significantly greater proportion of variance can be accounted for only by resort to such factors as sensitivity, etc. no practical advantages will accrue. For such factors, even if identified by research studies, cannot be measured at any given location except by a social survey. For practical noise control the only data available are physical variables which can be directly measured or estimated, such as those described in this paper.

Leaving aside the needs of practical nuisance prediction however, it is desirable to account for as much variance as possible, to identify the principal factors and to develop a coherent and logically satisfying model of the noise nuisance relationship. Space for this is lacking here and such exhaustive analysis must be postponed to Part III of the report which will bring together data related to individual differences arising from sensitivity, environment, social, economic and ethnic factors.

For the present it is sufficient to draw attention to the problems and complexities raised by sensitivity to noise, the largest single source of variance in individual responses.

As measured by the self-rating schedule employed in the survey, sensitivity to noise generates three separate sub-populations or groups. Regression analysis applied to the dissatisfaction scores of each group generates two quite different pictures according to whether the free or non-free flow samples are being considered. For the former, where noise level is the physical parameter, the sensitive and non-sensitive groups remain dissatisfied and satisfied respectively over the range of levels.

In non-free flow conditions, measured by the proportion of heavy vehicles, all three groups show a graded dissatisfaction response to increasingly adverse conditions, the non-sensitive producing the sharpest response. In considering these two sets of conditions two points may be made straight away. First, for both subsamples, the three groups retain their relative positions, the "sensitives" having the highest and the "non-sensitives" the lowest dissatisfaction scores on average for all noise levels or traffic conditions. Second, the degrees of dispersion for the dissatisfaction scores of the three groups is such that in both conditions no great significance can be attached to the relative slopes of the regression lines, particularly as regards the non-free flow subsample. It would therefore seem that to apply regression analysis to this data is to push the technique beyond its limits.

Finally, there is the problem of whether replies to the self-rating schedule can be regarded as affected by traffic conditions of the two subsamples, and whether the classification of sites by the traffic composition parameter is dimensionally equivalent to classification by external noise levels. These questions cannot be answered without resort to much detailed analysis not possible here and must be deferred to the final paper reporting the survey results.

7. CONCLUSIONS

(1) Where road traffic is disrupted by intersections, or by congestion, etc., so that free flow conditions are not maintained, noise nuisance as reported by residents is not predicted accurately by existing noise units such as L_{10} or L_{eq}, measured externally. While the trend relationships exhibited are highly significant they do not permit of nuisance prediction for a particular noise level, and the same applies to measures of traffic volumes.

(2) A measure of traffic composition, the logarithm of the percentage of heavy vehicles in the traffic stream, yields more useful predictions of noise nuisance. This measure accounts for nearly as much group variance as do measures based on noise levels employed in free flow conditions, and a significantly greater proportion of individual variance.

(3) Although the proportion of heavy vehicles appears to be a comparatively robust measure which in most circumstances is not critically dependent on 100% time sampling, nevertheless the data gathered in the course of the survey related only to the hours between 08.00 and 20.00. Further work would be required to discover the effects of altering the times or the periods for which traffic is counted.

(4) It is suggested that the failure of existing noise measures to predict noise nuisance accurately where traffic does not flow freely is related to the characteristics of heavy vehicles operating in these conditions. It seems probable that the felt incompatibility of such vehicles in close proximity to the dwelling influences expressed dissatisfaction disproportionately to their relative contribution to overall noise levels, and it is also likely that the difference between noise from heavy and light vehicles is further increased when the noise is heard within the dwelling.

(5) It is recognized that the subdivision into free and non-free flow conditions applied to the

total sample is to some extent arbitrary, in that actual traffic conditions form a continuum from one extreme condition to the other. It is suggested that as traffic conditions approach those described as free flow, noise nuisance is governed increasingly by noise levels as measured externally. Correspondingly, as disordered and congested conditions tend to prevail the relevance of these measures declines, being progressively outweighed by a measure of the proportion of heavy vehicles.

(6) It is therefore suggested that noise nuisance occasioned by all road traffic conditions may be predicted, without prior classification of traffic, by means of a weighted combination of externally measured noise level and the proportion of heavy vehicles. In this connection, an equation employing as parameters the total traffic volume, the proportion of heavy vehicles, and the street width from dwelling façade to far kerb accounts for more variance for groups and for individual responses than any other measure studied.

(7) In order to evaluate the likely effects of building insulation or engineering works in reducing noise nuisance it is desirable to employ a nuisance measure utilizing purely acoustical parameters. In the light of the foregoing conclusions it is suggested that studies of the effect of the built structure, and of the representativeness of A-weighted levels measured externally for noise nuisance in the dwelling are required. Such work might lead to more effective measures of noise nuisance.

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