The Journal of the Acoustical Society of America

DECEMBER 01 1999

Statistical structures of indoor traffic noise in a high-rise city

S. K. Tang; W. H. Au

J. Acoust. Soc. Am. 106, 3415–3423 (1999)
https://doi.org/10.1121/1.428195

Statistical structures of indoor traffic noise in a high-rise city

S. K. Tang and W. H. Au
Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

(Received 3 February 1998; revised 1 April 1999; accepted 1 August 1999)

Noise measurements were conducted in seven residential flats close to the traffic in Hong Kong. Noise-level time variations and their statistics are discussed. The results of the overall noise level statistics reveal that Gaussian noise-level distribution can only be found under the free traffic-flow condition while some characteristics of gamma noise-level distributions are observed when the flow is of the interrupted type. Short-duration noise-level time variation statistics reveal a well-defined relationship between skewness and kurtosis for each traffic-flow pattern identified. Results also suggest that the Pearson type I and IV distributions are useful for describing the short-duration noise-level distributions. © *1999 Acoustical Society of America.* [S0001-4966(99)00512-3]

PACS numbers: 43.50.Lj, 43.50.Jh [MRS]

INTRODUCTION

In a densely populated high-rise city such as Hong Kong, the acoustical environment under the influence of traffic noise may differ from those of the smaller cities. This is largely due to the proximity of trunk roads to large buildings[1,2] and the effect of city reverberation.[3]

The importance of traffic noise in environmental control has attracted the attention of many acousticians and scientists in the past few decades. Griffiths *et al.*[4] studied the subjective effects of traffic-noise exposure on human beings in the London area. A similar study focused on the behavior of human beings exposed to traffic noise was carried out in two French cities by Lambert *et al.*[5] Traffic-noise criteria for assessing the annoyance caused by traffic noise have also been studied. Scholes[6] found that the A-weighted equivalent sound-pressure level L_{Aeq} and the traffic noise index (TNI) calculated from the A-weighted percentile levels L_{A10} and L_{A90} correlate satisfactorily with human annoyance. The use of percentile levels as the noise criteria was further investigated by Langdon and Griffiths.[7] L_{A10} is widely used in traffic noise-control practices nowadays.

Physical noise measurements were also conducted by researchers all over the world. Examples are the works of Ko[1] in Hong Kong, Ishiyama *et al.*[2] in Tokyo, Cannelli[8] in Rome, and more recently, Chakrabarty *et al.*[9] in Calcutta. Scale-model studies have also been done by Liu[10] and Yamashita and Yamamoto.[11] However, this list is by no means exhaustive. Empirical formulas for the estimation of L_{A10} under known traffic volume have also been developed.[12]

Statistical modeling of traffic noise is also a research topic. Foxon and Pearson[13] concluded from the results of a site measurement that the distribution of traffic-noise level is Gaussian-like. However, Kurze[14] has showed both mathematically and experimentally that the noise-intensity fluctuation due to free-flowing traffic is gamma-distributed. It should be noted that Foxon and Pearson[13] and Kurze[14] were using different quantities for describing the noise statistics. Foxon and Pearson[13] used the noise level in dB while Kurze[14] discussed the noise intensity. The noise level L is related to the noise intensity I by the well-known logarithmic relationship

$$L = 10\log_0(I/I_{\mathrm{ref}}),$$

where I_{ref} denotes the reference noise intensity. The more recent results of Don and Rees[15] suggest complicated noise-level distributions depending on the compositions of road vehicles, and they have developed a model based on the superposition of Gaussian distributions for the estimation of traffic-noise probability distribution. However, their proposed model has not been widely adopted in the traffic-noise prediction practice. Despite the efforts of previous researchers, a commonly agreed-upon distribution function for traffic noise has not been sought, nor its shape under different traffic-flow patterns.

Most of the measurements mentioned above were not conducted at the facades of buildings. In a high-rise and densely populated city, the transmission of traffic noise the indoor built environment through the building facades is a big problem. Owing to the large variation of the indoor acoustical conditions, results of indoor traffic noise in existing literature are very limited. One example is due to Ko,[16] who showed the existence of a fairly good correlation between indoor and outdoor traffic-noise levels in the open window case. The present study is an attempt to find out whether a fixed traffic-flow pattern will lead to a certain general shape of the indoor traffic noise-level distribution. It is hoped that the present results can provide information for further development of the traffic-noise prediction method.

I. SITE MEASUREMENTS

A. Methodology

In the present study, seven site measurements were carried out within the urban area of Hong Kong where the major source of noise was traffic. Simultaneous recording of outdoor and indoor $L_{\mathrm{Aeq},\,T=2\ \mathrm{s}}$ was done using two Metrosonics dB-3100C integrating sound-level meters. They also measured noise-level probability distributions, the overall L_{A10} and L_{A90}. The outdoor noise levels were measured 1 m from the building facades while the indoor ones were recorded close to the centers of the indoor environments. Duration of each measurement was at least 25 min. A video recording of the traffic flow was carried out in parallel with each noise

TABLE I. General features of measurement sites.

Site	A	B	C	D	E	F	G
Road type	Main trunk	Main trunk	Main trunk	Distributor	Distributor	Distributor	Distributor
Speed limit (km/h)	70	70	70	50	50	50	50
Anticipated traffic flow	Free	Free	Free	Free	Interrupted	Interrupted	Interrupted
Number of lanes	6 (3 in each direction)	6 (3 in each direction)	6 (3 in each direction)	4 (2 in each direction)	6 (3 in each direction)	4 (2 in each direction)	4 (2 in each direction)
Distance from traffic light (km)	>1	>1	>1	~0.5	0.05	0.07	0.05
Traffic light duration[a] (s) 37G+60G near side 20G+60R far side	···	···	···	···	60G+60R both sides	30G+80R near side 20G+90R far side	37G+60R near side 20G+60R far side
General building clearance (m)	>10	>10	>10	~5	generally no clearance	<5	>10
General building height (m)	80	80	65	35	34	40	65
Indoor reverberation time	0.8	0.8	0.4	0.5	0.4	0.4	0.8

[a]G: green light; R: red light.

measurement for later traffic count and other analyses. Mean speeds of the vehicles were also estimated from their passage time between two lampposts with a known separation. In addition, reverberation measurement was carried out in each indoor environment using the Brüel & Kjær 2144 frequency analyzer in the multispectrum mode. Open window condition was adopted in the present study.

B. General site information

The seven sites selected in the present study are either near a main trunk road or a road junction with buildings on both sides of the associated roads. Thus, the results are mainly related to two types of traffic-flow patterns—the free flow[14] and the interrupted flow.[17] The latter flow pattern describes the situation in which the vehicles decelerate, stop, and accelerate again.[17] This phenomenon is common for road junctions. These two mentioned traffic-flow patterns are also typical in high-rise and densely populated cities. It is not intended to subdivide the interrupted flow pattern into banked and pulsed flow patterns as in Don and Rees.[15] This will be discussed later.

Table I summarizes the general features of these sites and Fig. 1(a) to (c) show the survey maps for sites C, D, and E which illustrate all the essential features of the present surveyed sites. Effect of traffic interruption by traffic light is important at sites E to G, which are close to road junctions. However, the traffic pattern for site D was unavoidably affected by a traffic light located about 500 m away from the measurement point, though the vehicles could move with speeds similar to those in sites A to C. Sites A to C are close to main trunk roads where there is no traffic light within 1 km from measurement points. It should also be noted that the buildings surrounding site E are packed very closely to each other so that the clearance between them is very small. In addition, the results from the reverberation time measurements reveal that a great variety of indoor environments has been covered in the present study. The indoor environments associated with sites A, B, and G are unfurnished. The general heights of the buildings shown in Table I reflect a feature of a high-rise city. The road junctions studied by Chakrabarty *et al.*[9] are surrounded by low-rise buildings.

C. Traffic-flow data

Traffic count and vehicle-speed estimation were done after the site measurements by playing back the video recordings. Traffic volume, the decomposition of traffic, and average vehicle speed for each site are tabulated in Table II. The average vehicle speeds for the sites close to road junctions are obtained during the green traffic light condition. Also, a majority of the vehicles fell into the category ''passenger car and taxis.'' In general, the average vehicle speed under the free-flow condition is higher than that under the interrupted flow. However, as stated before, the traffic flow at site D was affected by a traffic light 500 m away from the noise measurement point so that the vehicles may not have attained their normal speeds in the free-flow situation. It should also be noted that the speed limit enforced by the local government will limit the speeds of the vehicles and since the road at site D is not a main trunk road, the lower traffic volume will lead to a partially continuous flow pattern. This type of traffic flow is referred to as the partially continuous free flow in the foregoing discussions. It will be shown later that the results obtained at site D show the features of both the free and interrupted flows.

II. RESULTS AND DISCUSSION

Both the equivalent sound-pressure levels at 1 m from the building facade and in the indoor environments were recorded every 2 s in the present study. In the following sections, their time variations and statistical characteristics are discussed. In the present investigation, the time variations of the indoor noise levels follow closely those of the

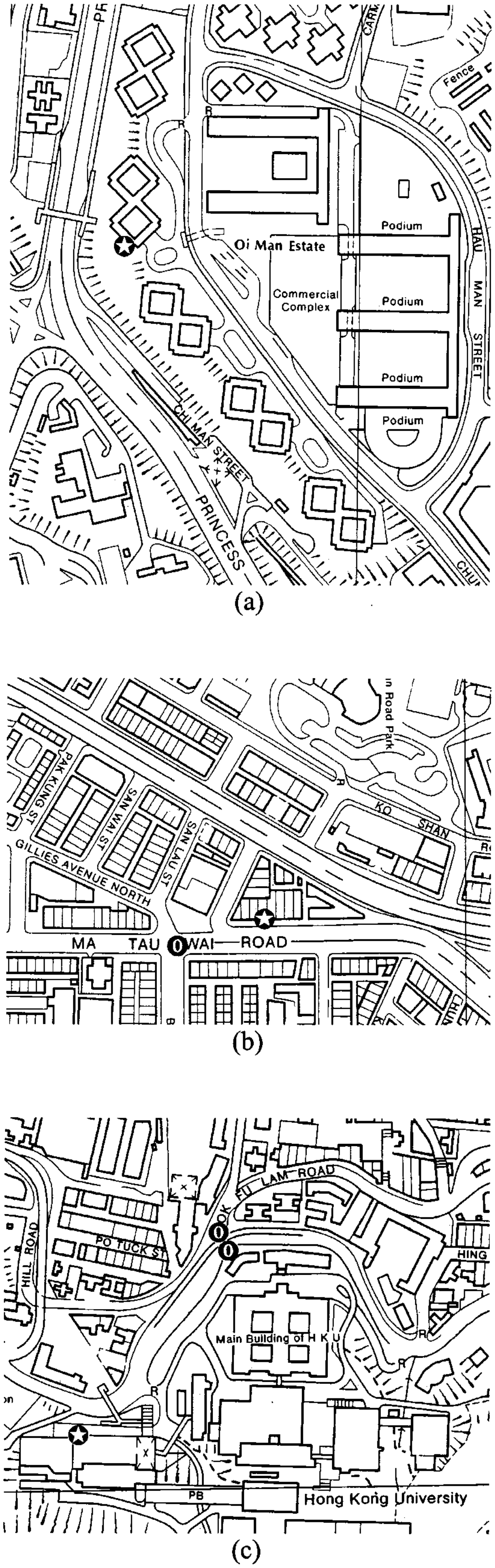

FIG. 1. Examples of measurement site locations. (a) site C; (b) site E; (c) site D. ✪: Measurement location; **O**: traffic light.

outdoors, as discussed in Ko.[16] Also, it is found that the indoor reverberation characteristics do not affect this relationship, though it does affect the difference between L_{Aeq} in the indoor environment and at the building facade (not shown here). In order to simplify the following discussion, the results presented hereinafter, unless otherwise stated, are those obtained indoors.

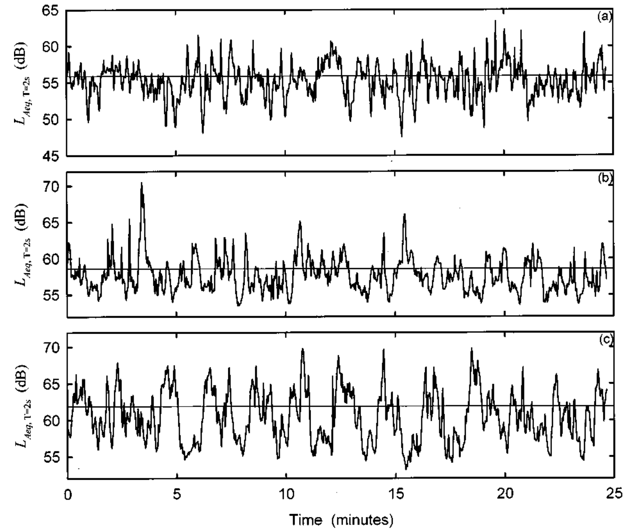

FIG. 2. Time variations of $L_{\mathrm{Aeq},T=2\ \mathrm{s}}$. (a) site C ($L_{\mathrm{Aeq},T=25\ \mathrm{min}}=55.9$ dB); (b) site F ($L_{\mathrm{Aeq},T=25\ \mathrm{min}}=58.6$ dB); (c) site E ($L_{\mathrm{Aeq},T=25\ \mathrm{min}}=61.9$ dB). Horizontal straight line: $L_{\mathrm{Aeq},T=25\ \mathrm{min}}$.

A. Noise-level variations and their overall statistics

Occasional lulls in the traffic flow result in reduced levels, which appear as downward-pointing spikes in the time trace of noise-level variations. A typical example of this is that obtained at site C (free flow) shown in Fig. 2(a). Bursts of accelerating or decelerating traffic, especially prevalent near traffic lights, produce the spikes of increased noise observed in Fig. 2(b) (site F, interrupted flow). Such spikes can have a magnitude as high as 15 dB. Figure 2(c) illustrates the noise-level time variation obtained at site E, which is affected by a traffic signal with equal duration of red and green light. The noise level varies periodically with nearly constant amplitude, resulting in a relatively uncommon statistical distribution. It will be discussed later.

The partially continuous free-flow traffic pattern at site D contains both lulls and bursts resulting from the traffic light located far away from the measurement point and the lower traffic volume (not shown here). A similar phenomenon is observed in an additional measurement conducted at site A when the traffic volume was only about 3300 vehicles per h and the nominal vehicle speed was 65 km/h. Such excursions from the average level significantly affect the shape, and thus influence the higher moments of the traffic noise-level distribution. Skewness, s, and kurtosis, k, as defined by Stuart and Ord[18]

$$s=\frac{\Sigma f(x-\overline{x})^3}{\sigma^3} \quad \text{and} \quad k=\frac{\Sigma f(x-\overline{x})^4}{\sigma^4}-3, \tag{1}$$

where f is the probability distribution, $\{x\}$ the sample, σ the standard deviation of $\{x\}$, and $\overline{x}$ the sample mean, have been calculated for the free-flowing (sites A, B, and C) and the interrupted flow (sites E, F, and G) traffic situations as well as for site D, which appears to be a mixture of both flow conditions. Results are presented in Table III. The skewness

TABLE II. Traffic-flow data summary.

Site	Number of vehicles/hour[a] V1	V2	V3	V4	V5	V6	V7	V8	Total	Mean speed (km/h)
A	95	2304	816	0	96	960	517	242	5030	64
B	52	1620	1188	0	84	1080	480	186	4690	63
C	29	1992	84	0	0	36	7	0	2148	72
D	58	636	216	312	120	84	30	0	1456	45
E	8	780	0	144	204	36	34	4	1210	29
F	7	660	132	144	72	60	19	0	1094	30
G	2	336	48	12	48	24	4	0	472	23

[a]V1: Motorcycle; V2: passenger car and taxis; V3: light truck or van of unladen weight$<$2.8 tons; V4: light bus; V5: double deck bus; V6: median truck of unladen weight$<$5.5 tons; V7: heavy truck of unladen weight$>$5.5 tons excluding container vehicle; V8: container vehicle.

for the interrupted traffic-flow cases is always positive. Figure 3 illustrates some typical examples of the indoor noise-level distributions for the three types of traffic conditions at 1-dB bin range. The corresponding distributions for the outdoor noise levels are very similar to those shown in Fig. 3 and are not presented.

For a gamma-distributed noise-intensity time record, the resulting noise-level distribution will have a negative skewness s. Therefore, Fig. 3 shows that the noise-intensity fluctuation may be gamma-distributed only for the case with a continuous free-traffic flow. However, the skewness of the present distributions is very much higher than that of the noise-level distributions having the same kurtosis but with gamma-distributed noise-intensity fluctuations as shown in Table III. This suggests that the present noise intensity does not follow the gamma distribution proposed theoretically by Kurze.[14] Also, the present distributions differ from those presented by Ko,[1] which show significant positive skewness. However, it should be noted that although there is no agreement with the gamma distribution in these overall statistics, the noise-level distributions within short time intervals do follow some common probability density distributions. This will be discussed in the next section.

The corresponding noise-level distributions for the partially continuous free-traffic flow cases are Gaussian-like with small skewness and kurtosis (Table III). This is probably due to the randomness in the arrival time and spatial distribution of vehicles so that the results tend to agree with those of Johnson and Saunders.[19] The Gaussian-like traffic noise-level distribution of Foxon and Pearson[13] appears to be due to this partially continuous flow pattern. Their measurement site was located in an area with both free flow and interrupted traffic—a situation similar to site D.

The higher the discontinuity of the traffic flow, the more positive the noise-level distribution skewness will be. In general, the shapes of the noise-level distributions do not really agree with those suggested by Don and Rees.[15] Though the noise-level distribution for site E has two peaks, the present data were recorded in the afternoon instead of in the evening as in Don and Rees.[15] Such discrepancy may be due to the fact that the results of Don and Rees[15] are noise-level statistics within 300 s so that they are sensitive to the intermittent changes in the traffic-flow pattern. However, it will be shown in the next section that their proposed noise-level distribution shapes can occur in the short-time statistics. Noise-level distributions at site G and, in particular, site F have skewness close to unity and approximate more closely a gamma distribution (for a gamma distribution with mean $p=4.9$, $s=0.90$, and $k=1.22$). The positive skewness results from the high-magnitude upward spikes in the $L_{\mathrm{Aeq},T=2\,\mathrm{s}}$ time variation such that the overall equivalent sound-pressure level L_{Aeq} is higher than the mode of the level distribution [e.g., Fig. 2(b)].

B. Short-time statistics

Since the noise levels keep on changing throughout the whole measurement period, it is worthwhile to investigate

TABLE III. Skewness and kurtosis in overall indoor noise-level statistics.

Site	Skewness s[a]	Kurtosis k	Standard deviation σ (dB)	$L_{\mathrm{Aeq},\,T=25\,\mathrm{min}}$ (dB)
A	−0.45 (−0.77)	0.23	1.49	73.1
B	−0.38 (−0.65)	0.06	1.92	51.6
C	−0.12 (−0.78)	0.39	2.38	55.9
D	0.06 (−0.51)	−0.39	2.27	73.7
E	0.25 (−0.44)	−0.79	3.55	61.9
F	0.88 (no solution)	1.35	2.41	58.6
G	0.99 (−0.86)	1.02	4.13	65.0
Additional measurement	0.02 (−0.71)	0.44	1.89	71.3

[a]Data in parentheses denote skewness of noise-level distribution with same k but obtained from gamma-distributed noise-intensity time fluctuation.

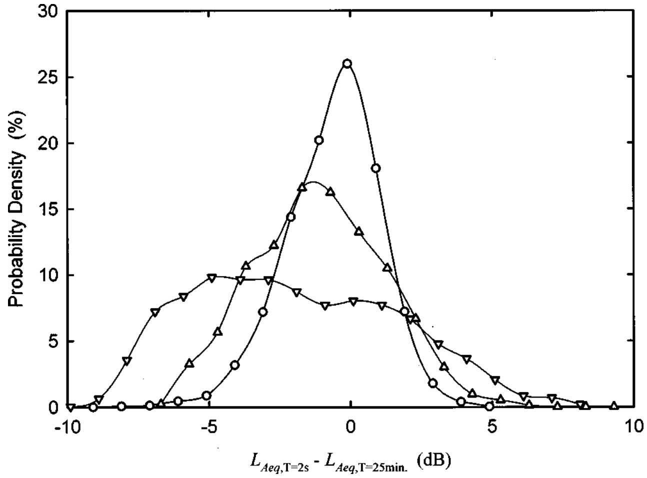

FIG. 3. Examples of probability density distributions from overall statistics of 25-min averages. ○: site A; △: site D; ▽: site E.

how the statistical properties of the noise-level variations will change with time for a deeper understanding on the nature of traffic-noise fluctuations. This section is an attempt to look into the variations of such properties and to look for their common characteristics. Statistical parameters, such as the standard deviation, skewness, and kurtosis, are calculated within any 5-min consecutive intervals of the recorded indoor $L_{\mathrm{Aeq},\,T=2\ \mathrm{s}}$ time variations. It is not believed that shorter calculation intervals are suitable to ensure reliable statistics because transient noises and pulses will then contaminate the results so obtained. Five-minute intervals have been adopted for the measurement of unsteady noise inside office buildings[20] as well as in the traffic-noise study.[15]

The standard deviations of the noise levels in the present study are lower than those of Don and Rees[15] (Fig. 4). It can also be observed from Fig. 4 as well as from Table III that higher σs are found at sites E and G where the durations of the red traffic light are relatively short (Table I) and the nominal speeds of the vehicles are low (Table II). Deviation of the present short-time noise-level statistics from the Gaussian distribution is observed where the noise climate

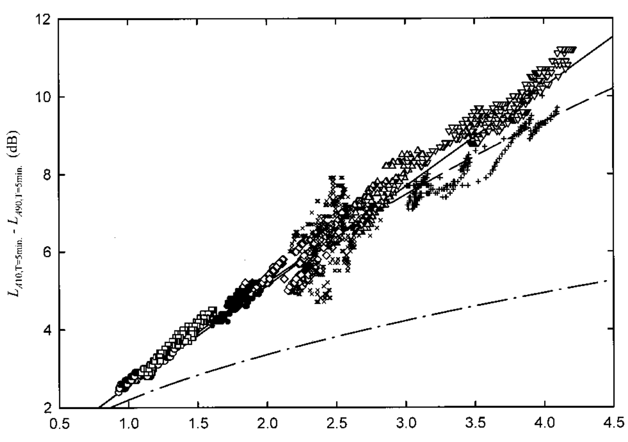

FIG. 4. Variation of 5-min noise climate with noise-level standard deviation. ○: site A; □: site B; ×: site C; △: site D; ▽: site E; ◇: site F; +: site G; ●: additional measurement at site A; ———: Gaussian; – –: Weibull (Ref. 22); –·–: gamma.

$L_{\mathrm{A10},T=5\ \mathrm{min}} - L_{\mathrm{A90},T=5\ \mathrm{min}}$ is concerned (Fig. 4). The noise climate can be assumed to be proportional to σ only when the latter is small ($\sigma \leq 1.5\ \mathrm{dB}$). This is different from the results of Don and Rees.[15] Gamma noise-level distribution is not valid in the present case. Relatively large scattering is observed at $\sigma \approx 2.4$, where the variation range of the noise climate is around 4 dB. This results from the free-flow traffic at site C. This will be further discussed later.

Examples of the 5-min noise-level distributions, in 0.5-dB bins, indicate substantial differences with time at the same site [Fig. 5(a) and (b)]. An approximately uniform distribution with a small U-shape obtained from an interrupted traffic flow at site E [Fig. 5(e)] differs from profiles reported elsewhere (for instance, Don and Rees[15]). It is found from a replay of the video recording that the vehicles stopped and started periodically with a distinctive frequency because of the traffic signal (Table I). The time variation of the noise levels therefore appears approximately sinusoidal with nearly constant amplitude [Fig. 2(c)]. Since a sinusoidal time variation of noise levels will tend to produce a U-shaped distribution, the occurrence of the distribution observed in Fig. 5(e) is explained.

Since the short-time noise-level distributions vary substantially with time, it is not possible to analyze each of them individually. In order to characterize these distributions, the method of Pearson is employed. The type of distribution function for describing a set of sampled data is determined by analyzing the skewness and kurtosis of the sample on a skewness–kurtosis chart called the (β_1,β_2) chart of Pearson,[18] where $\beta_1 = s^2$ and $\beta_2 = k$. Details of the procedure and the importance of the relationship between skewness and kurtosis can be found in standard textbooks on advanced statistics (for instance, Elderton and Johnson[21]). The present analysis is started off by comparing the (s,k) relationships of the present data with those of the common distributions.

Though many different shapes of the noise-level distributions can be observed and they seem to appear randomly, their skewness s and kurtosis k are bounded and, to a large extent, related for each type of traffic flow identified in the present study. Figure 6(a) is a plot of k against s for the interrupted traffic cases. Essential features of this plot are that s is always positive and k can be negative or positive but it increases and shows a definite relationship with s. The noise-level distributions are neither Gaussian nor gamma, although some of the overall statistics tend to reveal the characteristics of these two well-known distributions (Fig. 3 and Table III). The (s,k) relationships of some common distribution functions[18] are also included in Fig. 6(a) but none of them agrees with the present results. Though some agreements with the noise-level distribution with a gamma-distributed noise-intensity time variation are observed for small positive s, this type of level distribution is in general not really valid in the positive s range. It should be noted that a similar (s,k) relationship is also observed for the outdoor measurements and thus they are not presented. It can also be noted from Fig. 6(a) that the data for site E show negative k with small s, showing that the associated noise-level distributions are quite uniform.

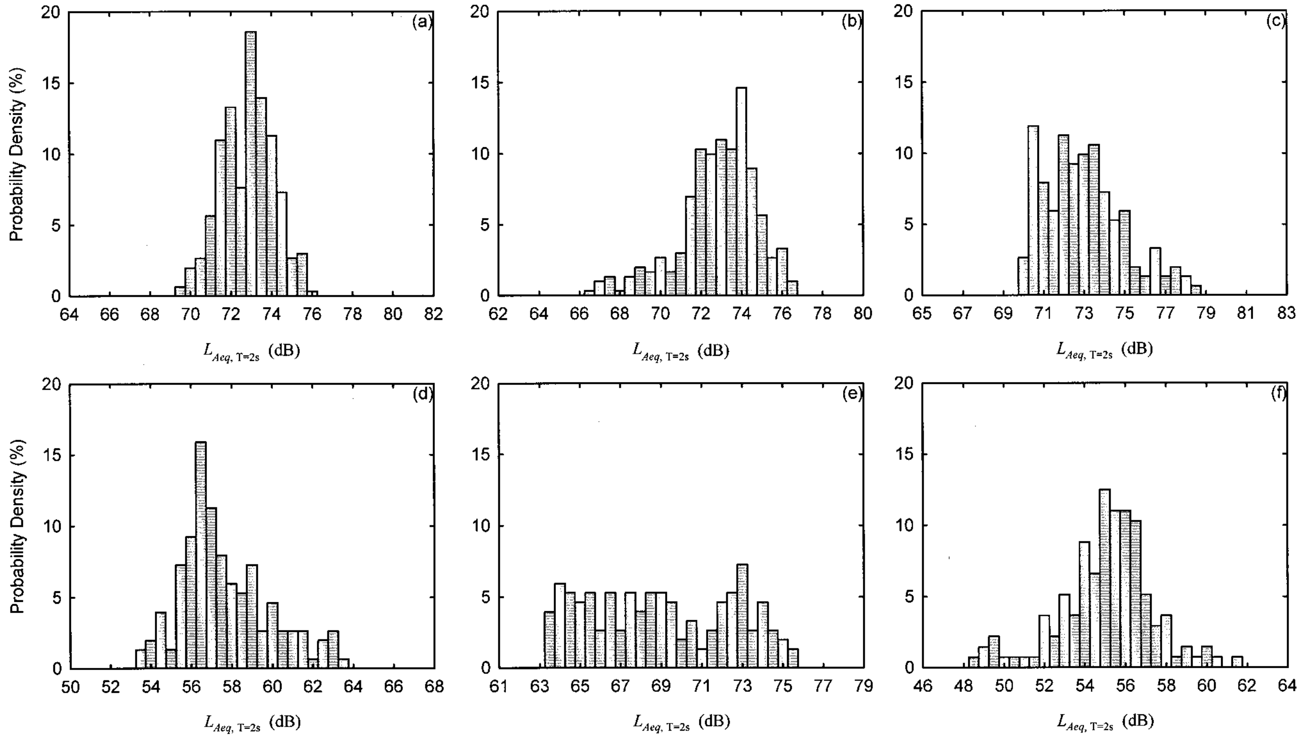

FIG. 5. Examples of 5-min noise-level distributions. (a) site A; (b) site A; (c) site D; (d) site F; (e) site E; (f) site C.

Figure 6(b) shows the (s,k) relationship for the free-traffic-flow cases, which is less ordered than that shown in Fig. 6(a). Unlike the case for interrupted traffic, skewness s in this case can be positive or negative and $-1 \leqslant s \leqslant 1$. This coexistence of positive and negative s, together with a relatively large variation in the kurtosis k and a less-ordered (s,k) relationship in the 5-min statistics will result in a large variation in the shape of the noise-level probability density and cumulative distributions. These two distributions have a significant effect on the noise climate, resulting in the large scattering of data associated with site C observed in Fig. 4 ($\sigma \approx 2.4$).

Skewness s in this free-flow case is not as large as that for the interrupted cases. The variation of k with s tends to be bounded by the prediction of gamma-distributed noise-intensity fluctuations for negative s within reasonable tolerance. For positive s, no collapse of data is possible in reality, as the gamma-distributed noise-intensity time fluctuation will result in a negatively skewed noise-level distribution. This is because the noise intensity and noise level are related by a logarithmic relationship. Some data tend to agree with that of a Weibull-distributed noise-level time variation[22] and quite a number of the distributions have s and k close to zero, suggesting the presence of Gaussian noise-level distributions in the short-time statistics under the free-flow condition.

No agreement with the gamma-distributed noise-level prediction can again be observed under the free-flow condition. A Gaussian-distributed noise-intensity time fluctuation gives rise to a noise-level distribution with negative s and large k—a situation not observed in the present study. Thus, the associated (s,k) relationship is not included in the discussions. Also, a Weibull-distributed noise-intensity time fluctuation gives $s=-1.14$ and $k=5.40$, which are outside the range of the experimental results.

The (s,k) relationship for site D, which represents the case of a partially continuous free flow affected by a distant traffic light, is shown in Fig. 6(c). That for the additional measurement at site A agrees with Fig. 6(c) for small positive $s<1$ (not shown here). Skewness s for this additional measurement, which was done close to a highway without flow restriction of any form, is seldom larger than 1. The corresponding traffic volume was low. Though the noise in this case appears intermittent, the continuous generation of noise by the vehicles does not in general produce very positively skewed noise-level distribution, as L_{Aeq} in this case does not depend very much on the magnitudes of several specific spikes in the noise-level time variation. This is not the case for a traffic flow with serious interruption.

Though both s and k vary with time, the present observed (s,k) relationship, at least for a particular type of traffic flow, tends to suggest that both the indoor and outdoor noise-level distributions are not as random as one expects. The present (s,k) relationships appear much more organized than those of Don and Rees.[15] Also, the above (s,k) relationships are again found when the time interval for calculation is reduced to 4 or even 3 min, though a higher order of scattering can be anticipated (not shown here), suggesting the robustness of these relationships. For the shorter time-interval cases, the ranges of s and k become larger, in general.

It is observed that the short-time statistical structure of the noise-level time variation differs from the overall statistics quite significantly. It is expected, especially for the interrupted traffic-flow cases, because the short-time statistical

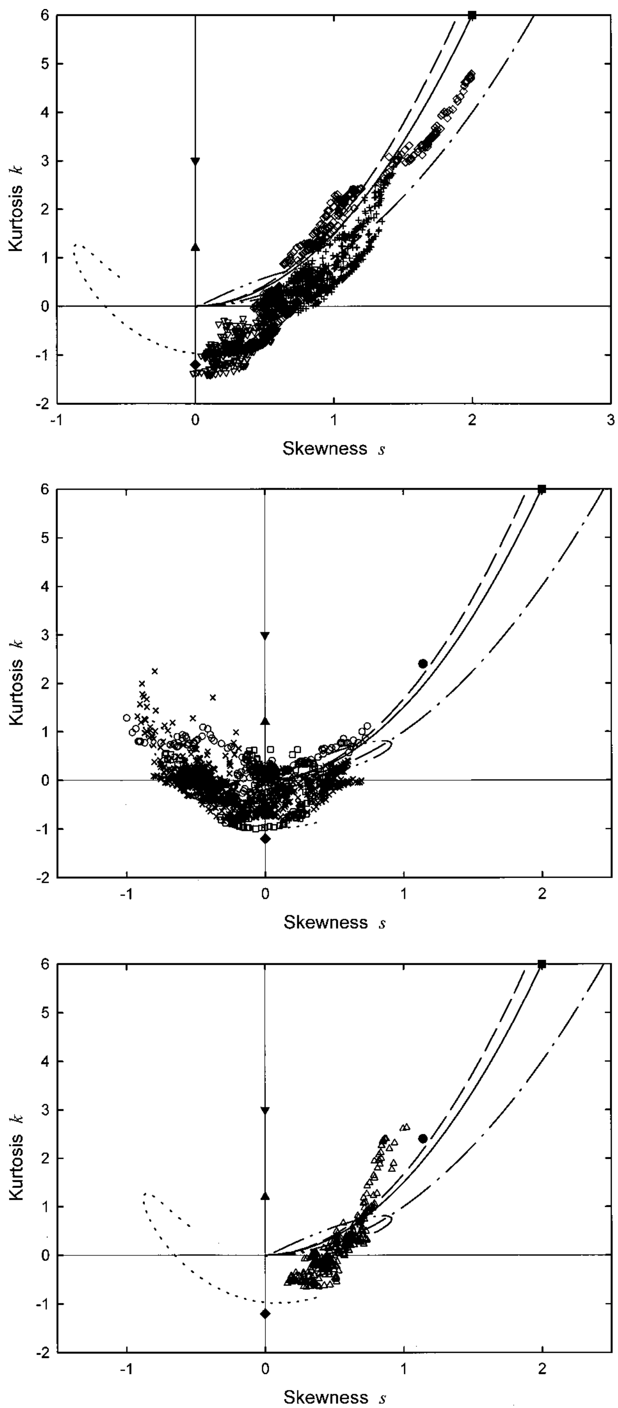

FIG. 6. Relationships between skewness and kurtosis. (a) interrupted traffic flow; (b) free flow; (c) partially continuous traffic flow. ○: site A; □: site B; ×: site C; △: site D; ▽: site E; ◇: site F; +: site G; ●: Extreme value; ■: exponential; ◆: rectangular; ▲: logistic; ▼: Laplace; ———: gamma-distributed noise level; –·–: Poisson-distributed noise level; ––: inverse Gaussian-distributed noise level; –··–: Weibull-distributed noise level; ·····: gamma-distributed noise-intensity time fluctuation.

parameters are sensitive to relatively short-duration high-energy-level acoustical signals and the intermittent changes in the traffic condition. The question of whether there is any relationship between these two sets of statistical results is left to further investigation.

In order to find out the type of distribution that may be able to describe the general forms of present noise-level distributions, the present (s,k) relationships are compared with those of the Pearson's family on the (β_1,β_2) chart.[18] Fine details of the present short-time noise level distributions are ignored. Though there are some other families of frequency curves,[21] the Pearson's family appears to be the most fundamental and is thus adopted in the present investigation.

Figure 7(a), (b), and (c) show the (β_1,β_2) chart[18] and the (s,k) relationships of the interrupted flow, free-flow, and partially continuous flow, respectively. These (s,k) relationships are obtained by regression. The 95% confidence boundaries are also included here to provide for the data scattering. The Roman letters in Fig. 7 represent the types of Pearson distributions and the alphabets in parentheses denote the general shapes of the distributions described in Elderton and Johnson.[21] The thin solid lines are the boundaries separating different regions of Pearson distributions. For further details of the (β_1,β_2) chart and the properties of the Pearson distributions, please see Refs. 18 and 21.

Figure 7(a) suggests that a majority of the noise-level distributions obtained under the interrupted traffic-flow condition can be approximated by the Pearson type I curve which takes the form

$$f(x)\sim\left(1+\frac{x}{a_1}\right)^{m_1}\left(1-\frac{x}{a_2}\right)^{m_2}, \tag{2}$$

where $m_i s$ and $a_i s$ are constants to be evaluated from the sample $\{x\}$. The shape of such distribution depends on the values of $m_i s$ and $a_i s$. For $s^2 \gtrsim 2$, which is only found in the interrupted flow cases, the measured noise-level distribution remains close to the Pearson type I curve but there is a higher chance to have a J-shaped one (not shown here). For very small s, the distribution may also take the form of a U-shaped Pearson type I curve. When $s=0$, it becomes a Pearson type II distribution [$m_1=m_2$ and $a_1=a_2$ in Eq. (2)]. An example of a U-shaped noise-level distribution (which appears quite rectangular) has been shown in Fig. 5(e). It is obtained at site E with an interrupted traffic-flow condition. However, this region is very narrow and thus is not discussed further.

Figure 7(b) suggests that while it is possible to find noise-level distributions which take the forms of the Pearson type III, IV, V, and VI under the free-flow condition, the probability of having a bell-shaped Pearson type I distribution is still higher than those of the others. Some symmetrical Pearson type VII noise-level distributions can also be expected for small s. Unlike the case with interrupted traffic, a U-shaped Pearson type II distribution is not likely to be found.

The increase of k with s is relatively rapid under the partially continuous-flow condition, as shown in Fig. 7(c). Under this type of mixed-flow condition, no dominating distribution type exists and the noise-level distribution may take the form of Pearson type I, II, III, IV, V, or VI, depending on s. For $s^2>0.7$, Fig. 7(c) suggests the use of the Pearson type IV curve

$$f(x)\sim\left(1+\frac{x^2}{a_1^2}\right)^{-m_1} e^{-m_2 \tan^{-1}(x/a_1)}, \tag{3}$$

to approximate the noise-level distribution, while for $s^2<0.3$, the bell-shaped Pearson type I curve becomes more

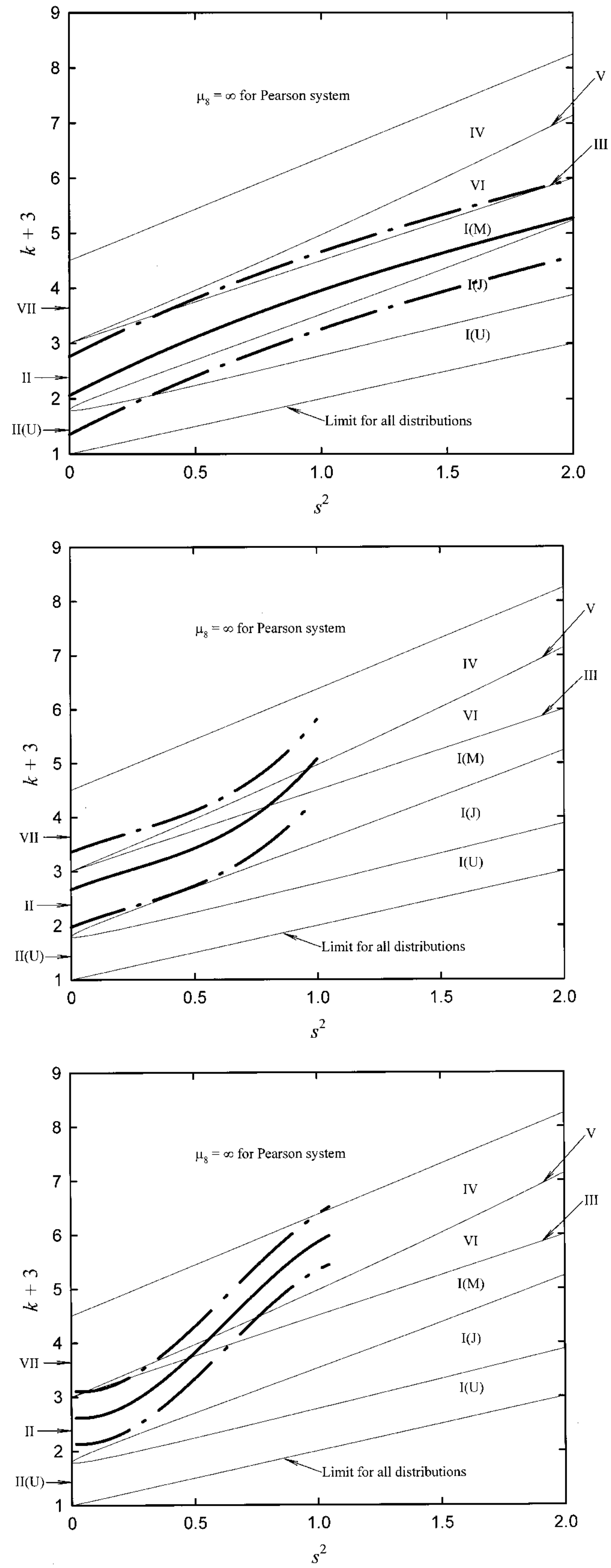

FIG. 7. Comparison between short-time level distributions and Pearson distributions. (a) interrupted traffic flow; (b) free flow; (c) partially continuous traffic flow. ———: Regression line; –·–: 95% confidence boundaries. M: bell-shaped; U: U-shaped; J: J-shaped; Roman letters: types of Pearson distributions; thin solid lines: boundaries separating regions of Pearson distributions (Ref. 19).

appropriate. The noise-level distributions obtained under this traffic condition are usually bell-shaped (a property of the relevant Pearson curves[21]). The Pearson type VII and the U-shaped type II distributions do not appear to be relevant.

III. CONCLUSIONS

Simultaneous indoor and outdoor noise measurements with video recording were carried out at seven residential flats affected by traffic noise in the present study. The traffic-flow patterns on the main noise-producing roads can basically be divided into the free-flow and interrupted-flow types. The time variations of noise levels, their overall statistics, and the short-duration statistics are discussed. The short-duration statistics are also compared with those of the existing frequency distributions.

Upward noise-level spikes appear frequently in the interrupted-flow cases, giving rise to positive skewness in the noise-level statistics. For the free-flow cases, the noise level fluctuates about the equivalent sound-pressure level with occasional downward spikes due to short-duration lulls in the traffic flow. The present overall statistical results suggest that Gaussian noise-level distribution can only be found when the traffic volume is low and the flow is not interrupted very much. For the interrupted-flow case, the overall noise-level distributions show some characteristics of the gamma distribution.

Five-minute short-duration noise-level statistics are studied in the present investigation for a deeper understanding of the nature of the traffic-noise fluctuations. The relationships between skewness and kurtosis of the measured short-duration noise-level distributions are far from the Gaussian predictions. The results show some possibilities of having a gamma-distributed noise intensity or a Weibull-distributed noise-level time fluctuation under the free-flow condition. Skewness of the noise-level distribution is predominantly positive for the interrupted traffic-flow cases. No commonly used statistical functions can describe the corresponding relationship between skewness and kurtosis, though a gamma-like overall noise-level distribution is observed.

The skewness–kurtosis relationships of the present short-duration noise-level distributions suggest that a majority of these distributions, especially those for the interrupted flow, can be approximated by the Pearson type I curve instead of the Pearson type III or Gaussian distribution suggested in the existing literature. Gaussian noise-level distributions are likely to be found only under the free-flow traffic condition.

ACKNOWLEDGMENTS

This work was partially supported by a research grant from the Research Committee, The Hong Kong Polytechnic University. The constructive efforts and suggestions from the reviewers are greatly acknowledged.

[1] N. W. M. Ko, ''Traffic noise in a high-rise city,'' Appl. Acoust. **11**, 225–239 (1978).
[2] T. Ishiyama, K. Tateishi, and T. Arai, ''An analysis of traffic noise propagation around main roads in Tokyo,'' Noise Control Eng. J. **36**, 65–72 (1991).
[3] F. M. Wiener, C. I. Malme, and C. M. Gogos, ''Sound propagation in urban areas,'' J. Acoust. Soc. Am. **37**, 738–747 (1965).
[4] I. D. Griffiths, F. J. Langdon, and M. A. Swan, ''Subjective effects of traffic noise exposure: reliability and seasonal effects,'' J. Sound Vib. **71**, 227–240 (1980).
[5] J. Lambert, F. Simonnet, and M. Vallet, ''Patterns of behaviour in dwellings exposed to road traffic noise,'' J. Sound Vib. **92**, 159–172 (1984).
[6] W. E. Scholes, ''Traffic noise criteria,'' Appl. Acoust. **3**, 1–21 (1970).
[7] F. J. Langdon and I. D. Griffiths, ''Subjective effects of traffic noise exposure, II: Comparisons of noise indices, response scales, and the effects of changes in noise levels,'' J. Sound Vib. **83**, 171–180 (1982).
[8] G. B. Cannelli, ''Traffic noise pollution in Rome,'' Appl. Acoust. **7**, 103–115 (1974).
[9] D. Chakrabarty, S. C. Santra, A. Mukherjee, B. Roy, and P. Das, ''Status of road traffic noise in Calcutta metropolis, India,'' J. Acoust. Soc. Am. **101**, 943–949 (1997).
[10] X. Liu, ''Analysis of the acoustical environment of urban dwellings,'' Appl. Acoust. **29**, 273–287 (1990).
[11] M. Tamashita and K. Yamamoto, ''Scale model experiments for the prediction of road traffic noise and design of noise control facilities,'' Appl. Acoust. **31**, 185–196 (1990).
[12] Department of Transport Welsh Office, *Calculation of Road Traffic Noise* (Her Majesty's Stationary Office, London, 1988).
[13] J. Foxon and F. J. Pearson, ''A statistical model of traffic noise,'' Appl. Acoust. **1**, 175–188 (1968).
[14] U. J. Kurze, ''Statistics of road traffic noise,'' J. Sound Vib. **18**, 171–195 (1971).
[15] C. G. Don and I. G. Rees, ''Road traffic sound level distributions,'' J. Sound Vib. **100**, 41–53 (1985).
[16] N. W. M. Ko, ''Indoor traffic noise in a high-rise city,'' J. Sound Vib. **47**, 599–601 (1976).
[17] P. Kokowski and R. Makarewicz, ''Interrupted traffic noise,'' J. Acoust. Soc. Am. **101**, 360–371 (1997).
[18] A. Stuart and J. K. Ord, *Kendall's Advanced Theory of Statistics. Vol.1: Distribution Theory* (Charles Griffin, London, 1987).
[19] D. R. Johnson and E. G. Saunders, ''The evaluation of noise from freely flowing road traffic,'' J. Sound Vib. **7**, 287–309 (1968).
[20] R. Baldwin, *An Environmental Assessment for Existing Office Buildings* (Building Research Establishment, Watford, 1993).
[21] W. P. Elderton and N. L. Johnson, *Systems of Frequency Curves* (Cambridge University Press, Cambridge, 1969).
[22] W. Weibull, ''A statistical distribution function of wide applicability,'' Trans. ASME, J. Appl. Mech. **18**, 293–297 (1951).