APPENDIX B

THE USE OF TRAFFIC DENSITY INFORMATION AS A NOISE PREDICTOR

The levels and other characteristics of man-made radio noise, as has been seen, are quite variable with location and time. It is not feasible to make long-term measurements at all possible locations, and therefore some prediction of the noise is needed for locations where receiving terminals of various communications systems are planned. As has been shown, a general estimate of the noise environment can be obtained by assuming that the characteristics of the noise will be the same as those measured at another place similar in nature to the particular area of interest. If additional information is available for the receiving terminal location on distribution of noise sources and the amount of radiation from these sources, a much better estimate of the radio noise environment could be obtained. Going one step further, a valid estimate of future changes in these sources would give a good estimate of the expected future environment. It is not generally possible to actually catalog all noise sources in a given area that would affect a given system.

In 1968 the Institute for Telecommunication Sciences completed a detailed noise measurement program in San Antonio, Texas. The noise measurements were made under mobile conditions on most of the thoroughfares within specified areas called SLA's (standard location area). The SLA's are areas defined by the Census Bureau for counting population and generally vary between 1 and 5 square miles in area. Various SLA's were chosen to give as wide a range of population density as possible. Figure B1 shows, as an example, the lack of correlation at 5 MHz between the average noise level, $F_{a\mu}$, within an SLA and the population density of that SLA. The $F_{a\mu}$ is the mean of all F_a values measured within an SLA. Similar results were obtained at the other frequencies of measurement (250 kHz to 48 MHz). Figure B2 shows the linear regression of $F_{a\mu}$ at 48 MHz for 26 thoroughfares with the average hourly traffic count. Here, $F_{a\mu}$ denotes the mean of all F_a values measured along the thoroughfare. The traffic count was obtained by averaging the traffic counts at various locations along the thoroughfares. These counts were obtained from past traffic records. Figure B3 shows the correlation coefficient and its 95 percent confidence bound as a function of frequency for $F_{a\mu}$ versus the average vehicular density for all the measurements taken (Spaulding et al., 1971). More recent measurements have shown the same high correlation at 102 and 250 MHz. Figure B4 also shows the correlation of noise level with traffic density. This figure shows three days of continuous measurements taken 100 ft from the center of Broadway. Broadway is the highway directly to the east of the Department of Commerce, Boulder, Laboratories. Comparing the traffic count (10 log vehicles/hr) with the received noise power, one sees obvious correlation at 20 and 48 MHz and an obvious lack of correlation at 10 MHz. At 10 MHz, the noise is primarily due to power lines in the area. Figure B4 shows the "instantaneous" correlation for a given highway, that is, the traffic density was measured simultaneously with the noise measurements. Figure B3, on the other hand, shows the correlation of the average measured F_a's along a large number of thoroughfares with the average traffic density on these thoroughfares (for the time of day for which the measurements were taken) obtained from past traffic studies.

Traffic counts for most highways generally are available from traffic or highway engineering departments. Also the expected growth and change in traffic patterns are used for highway planning and are available. Using this information, an estimate of the man-made noise levels can be obtained for present traffic conditions and for changes due to expected changes in traffic density.

We can make use of the additivity of power to calculate the received noise at a distance, d, from a highway. If many highways, or many lanes of one highway are involved, the total power spectral density can be obtained by adding the contributions from each. Therefore, without loss of generality, we will consider a single highway, straight and infinite in extent. Of course, the automobiles far away (along the highway) from the receiving point of interest contribute negligible power to the total.

To calculate the received noise power spectral density at a distance, d, from a highway, let x be the power spectral density radiated from a single automobile as measured at some distance, d_m. Figures B5 and B6 show the distribution of the radiated power spectral density, F_a, from 958 individual automobiles measured by OT/ITS at 50 ft for frequencies of 20 and 48 MHz. A log normal distribution (dB values normally distributed) is a good approximation for the distribution of x, and figures B5 and B6 show the best fit normal distribution, along with its mean, μ(dB), and standard deviation, σ(dB).

The distribution of y, y = 10 log x, is

$$p(y) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[- \frac{(y-\mu)^2}{2\sigma^2} \right], \quad -\infty \le y \le \infty \; . \tag{B1}$$

Therefore, the distribution of x is

$$p(x) = \frac{4.343}{x\sigma\sqrt{2\pi}} \exp\left[- \frac{1}{2\sigma^2} (10 \log x - \mu)^2 \right], \quad 0 \le x \le \infty \; , \tag{B2}$$

and the mean value of x, $\overline{x}$, and the variance of x, Var[x], are given by

$$\overline{x} = 10^{0.1\mu + 0.0115\sigma^2} \; , \tag{B3}$$

and

$$\mathrm{Var}[x] = \left(10^{0.2\mu + 0.023\sigma^2}\right)\left(10^{0.023\sigma^2} - 1\right) . \tag{B4}$$

Since, for surface wave propagation and for distances and frequencies of primary interest here (above 20 MHz), the received power falls off essentially as distance to the fourth power (Norton, 1959), the power, p_i, received from the i^{th} car along the highway is

$$p_i = \frac{x_i d_m^4}{\left(d^2 + s_i^2\right)^2} , \tag{B5}$$

where d is the perpendicular distance from the point of interest to the highway, d_m is the distance (outside the induction field) at which x was measured, and s_i is the distance along the highway to the i^{th} car.

At lower frequencies, the power will fall off as distance squared (Norton, 1959), at least for the closer cars which contribute most of the power. We will, therefore, consider the total receiver power, p_T, to be given by

$$p_T = \sum_{i=-\infty}^{\infty} p_i = \sum_{i=-\infty}^{\infty} x_i \left(\frac{d_m^2}{d^2 + s_i^2} \right)^{\ell} , \tag{B6}$$

where $\ell = 1$ or 2 and the x_i are log normally distributed. Depending on the situation (i.e., car density, distance of interest, etc.), we might expect the total power, p_T, to be approximately normally distributed via the central limit theorem. This approximation will be valid for values of p_T around the mean value of p_T, but obviously cannot be correct very far out on the tails of the actual distribution of p_T. In any case, we want to calculate the mean and variance of p_T.

The spacing between cars will have some distribution. In traffic studies, the car spacings are taken usually to be either equal or exponentially distributed. Which car spacing assumption is best will depend on the particular traffic situations. We will evaluate the mean and variance of p_T (B6) for both cases, starting with equal car spacing, s; i.e., $s_i = i\,s$.

The mean and variance of p_T are, therefore, given by

$$\bar{p}_T = \bar{x} \sum_{i=-\infty}^{\infty} \left(\frac{d_m^2}{d^2 + (i\,s)} \right)^{\ell} \tag{B7}$$

and

$$\mathrm{Var}[p_T] = \mathrm{Var}[x] \sum_{i=-\infty}^{\infty} \left(\frac{d_m^2}{d^2 + (i\,s)^2} \right)^{2\ell} \quad . \tag{B8}$$

For $\ell = 1$ and 2, the above summations can be evaluated in closed form by the standard methods of contour integration and successive differentiation (see also Wheelon, 1954). The results are

$$\sum_{i=-\infty}^{\infty} \frac{d_m^2}{d^2 + (i\,s)^2} = \frac{\pi d_m^2}{s\,d} \coth\left(\frac{\pi d}{s}\right) , \tag{B9}$$

$$\sum_{i=-\infty}^{\infty} \left(\frac{d_m^2}{d^2 + (i\,s)^2} \right)^2 = \frac{\pi d_m^4}{2 s\, d^3} \coth\left(\frac{\pi d}{s}\right) + \frac{\pi^2 d_m^4}{2 s^2 d^2} \operatorname{csch}^2\left(\frac{\pi d}{s}\right), \tag{B10}$$

$$\sum_{i=-\infty}^{\infty} \left(\frac{d_m^2}{d^2 + (i\,s)^2} \right)^3 = \frac{3\pi d_m^6}{8 s\, d^5} \coth\left(\frac{\pi d}{s}\right) + \frac{3\pi^2 d_m^6}{8 s^2 d^4} \operatorname{csch}^2\left(\frac{\pi d}{s}\right)$$

$$+ \frac{\pi^3 d_m^6}{4 s^3 d^3} \operatorname{csch}^2\left(\frac{\pi d}{s}\right) , \tag{B11}$$

and

$$\sum_{i=-\infty}^{\infty}\left(\frac{d_m^2}{d^2+(i\,s)^2}\right)^4 = \frac{5\pi d_m^8}{16s\,d^7}\coth\left(\frac{\pi d}{s}\right) + \frac{5\pi^2 d_m^8}{16s^2 d^6}\,\mathrm{csch}^2\left(\frac{\pi d}{s}\right)$$

$$+\frac{\pi^3 d_m^8}{4s^3 d^5}\,\mathrm{csch}^2\left(\frac{\pi d}{s}\right)\coth\left(\frac{\pi d}{s}\right)$$

$$+\frac{\pi^4 d_m^8}{24s^4 d^4}\left[\mathrm{csch}^4\left(\frac{\pi d}{s}\right)\right.$$

$$\left.+\,\mathrm{csch}^2\left(\frac{\pi d}{s}\right)\coth^2\left(\frac{\pi d}{s}\right)\right] . \qquad \text{(B12)}$$

Note, now, that for $d/s > 1$, $\coth(\pi d/s) \approx 1$ and $\mathrm{csch}(\pi d/s) \approx 2\exp(-\pi d/s) \approx 0$, so we obtain the simple results (for the case $d/s > 1$)

for (B9):

$$\sum \cong \frac{\pi d_m^2}{sd} ;$$

for (B10):

$$\sum \cong \frac{\pi d_m^4}{2s\,d^3} ;$$

for (B11):

$$\sum \cong \frac{3\pi d_m^6}{8s\,d^5} ;$$

and for (B12):

$$\sum \cong \frac{5\pi d_m^8}{16s\,d^7} . \qquad \text{(B13)}$$

We can now easily compute $\overline{p}_T$ and $\mathrm{Var}[p_T]$ from the distribution of power radiated from individual vehicles for whichever propagation law ($\ell = 1, 2$) is appropriate.

As an example during quiet hours, consider (fig. B4) 48 MHz at 0300, Thursday. The traffic count was about 31.6 vehicles per hour. The speed limit on Broadway, where the measurements were taken, is 35 mph; therefore,

$$s = \frac{5280 \times 35}{31.6} = 5850 \text{ ft/vehicle} .$$

Since the distance at which the measurements were made (100 ft) is less than s, we cannot use the approximation (B13) and must use (B10). From figure 6 we have, for 48 MHz, $\mu = 20.2$ dB and $\sigma = 10.8$ dB. So from (B3),

$$\overline{x} = 10^{3.36} = 2170 \text{ kT}_o (1 \text{ kT}_o = 3.97 \times 10^{-21} \frac{\text{watts}}{\text{Hz}}) .$$

From (A10), with d = 100 ft, $d_m = 50$ ft, s = 5850 ft, we obtain

$$\sum_{i=-\infty}^{\infty} \left(\frac{d_m^{\;2}}{d^2 + (i\,s)^2} \right)^2 = 0.0627 .$$

Therefore,

$$\overline{p}_T = 2170 \times 0.0627 = 136 \text{ kT}_o$$

$$\overline{P}_T = 21.3 \text{ dB} > \text{kT}_o .$$

The actual measured value was 18 dB > kT_o. Likewise, at 0300, Thursday, for 20 MHz, we obtain $\overline{P}_T = 30.6$ dB > kT_o, while the measured value was 31 dB > kT_o.

If we now consider 48 MHz, 0800, Thursday, we obtain from (B10) (with $\overline{x} = 2170 \text{ kT}_o$, d = 100 ft, $d_m = 50$ ft, s = 185 ft) that $\overline{P}_T = 21.8$ dB > kT_o, while the measured value was 26.5 dB. The $\overline{P}_T$ plus one standard deviation [from (B12)] is 28.5 dB.

In general, the lower measured values are matched quite well by the calculated values, but the calculated values are substantially lower (up to 8 dB) than the measured values during the busiest portions of the day. This is due, in part at least, to noise contributions from the many noise sources other than the automobile present on the laboratory grounds during the working day. There are also many other considerations which we will discuss later.

We will now evaluate the mean of p_T (B6) when the car spacings are exponentially distributed. The distribution of s_i is (Parzen, 1962)

$$p(s_i) = \frac{s_i^{\,i-1}}{s^i (i-1)!} e^{-s_i/s} , \tag{B14}$$

and the mean value of s_i is given by i s. Then, with E denoting the mean value operation,

$$\overline{p}_T = E[p_T] = E \sum_{i=-\infty}^{\infty} x_i \left(\frac{d_m^{\,2}}{d^2 + s_i^{\,2}} \right)^{\ell}$$

$$= d_m^{\,2\ell} E[x] \left\{ \frac{1}{d^{2\ell}} + 2 \sum_{i=1}^{\infty} E\left[\left(\frac{1}{d^2 + s_i^{\,2}} \right)^{\ell} \right] \right\} . \tag{B15}$$

Now

$$\sum_{i=1}^{\infty} E\left[\left(\frac{1}{d^2 + s_i^{\,2}} \right)^{\ell} \right] = \sum_{i=1}^{\infty} \int_0^{\infty} \frac{1}{(d^2 + z^2)^{\ell}} \frac{z^{i-1}}{s^i (i-1)!} e^{-z/s} dz . \tag{B16}$$

Interchanging summation and integration, we obtain the general result from (B15) and (B16),

$$\overline{p}_T = \overline{x} \left[\frac{d_m^{\,2\ell}}{d^{2\ell}} + \frac{d_m^{\,2\ell} (2\ell - 2)! \pi}{s 2^{2\ell - 2} (\ell - 1)! (\ell - 1)! d^{2\ell - 1}} \right] . \tag{B17}$$

Note, that, with the exception of the term $d_m^{2\ell}/d^{2\ell}$, (B17) is identical to (B13). The term $d_m^{2\ell}/d^{2\ell}$, however, as we will discuss later, often dominates. While the above (B17) gives the mean value of p_T, the variance appears to be much more difficult to calculate and is not done here.

On figure B4, again, equation B17, with $\ell = 2$, gives an average value of F_a of 21.5 dB compared with the previous value of 21.3 dB > kT_o for 0300, Thursday, 48 MHz. Likewise, (B17) gives 30.8 dB > kT_o compared with the previous 30.6 dB for 0300, Thursday, 20 MHz. For 48 MHz, 0800, Thursday, (B17) gives 24 dB > kT_o compared with the previous 21.8 dB. With the very limited measurements available, it would appear that (B17) gives a somewhat more accurate prediction of the mean value of p_T for high traffic density.

In the above analysis, there are a number of points to consider. First, we note that the results are heavily dependent on the propagation. Results have been given for $\ell = 1$ and 2, i.e., inverse distance squared and inverse distance to the fourth power. We would expect $\ell = 1$ to apply for low frequencies and $\ell = 2$ to apply at the higher frequencies for the distances of interest, but recent measurements (Shafer et al., 1972) at 900 MHz by RCA have indicated that, in an urban area, ℓ can vary anywhere between 0.75 and 2.25 for the distances of interest. Once one decides what propagation law fits his situation, good approximations probably can be made by interpolating between the results given here for integer values of ℓ.

In spite of the close fit between the lowest measured noise values and the predicted values, the results are based on the assumption that there is essentially always one automobile at a distance, d, from the receiver. This is the $d_m^{2\ell}/d^{2\ell}$ terms in (B17) and is also inherent in (B9) through (B12). The result is that this term dominates, giving essentially the same $\overline{p}_T$ for any traffic density between 10 and 200 vehicles/hour (at normal speeds). For proper consideration of very low traffic densities, this assumption would need to be modified. The analysis gives results [(B13) and (B17)] which should be valid for relatively high traffic densities.

In order to use the above results, knowledge of the power radiated from individual automobiles is required. From (B3) the mean and standard deviations of F_a are required for any particular frequency of interest. There appears to be very little such information (other than that given here) available. Measurements of individual automobiles have been made by the Automobile Manufacturers Association (AMA, 1969, 1970, 1971), but, in general, parameters other than power were measured; in any case, a very limited number of individual vehicles were measured. Detailed measurements of individual vehicles were recently made by Stanford Research Institute (Shepherd et al., 1973). References to some earlier measurements can be found in the bibliographies (Part II of this report and Thompson, 1971).

In general, the simple results given here can be used to obtain good approximations of the noise at a receiver site due to automotive traffic in the area. As with any such prediction method, however, the proper input statistics must be available. Here, the requirement is for only the mean and variance of the power spectral density (in dB at some measurement distance) radiated from individual vehicles for the frequency of interest. The traffic density (cars/hr) and the average speed must, of course, also be known.

Finally, it should be noted that all the measurements referred to here were made with vertical monopole antennas. For other antennas the basic expression (B6) can be modified by the antenna gain pattern. When this is done, the analysis can be carried through exactly as before, but, except for special cases, the resulting summations (and integrations) require numerical evaluation.

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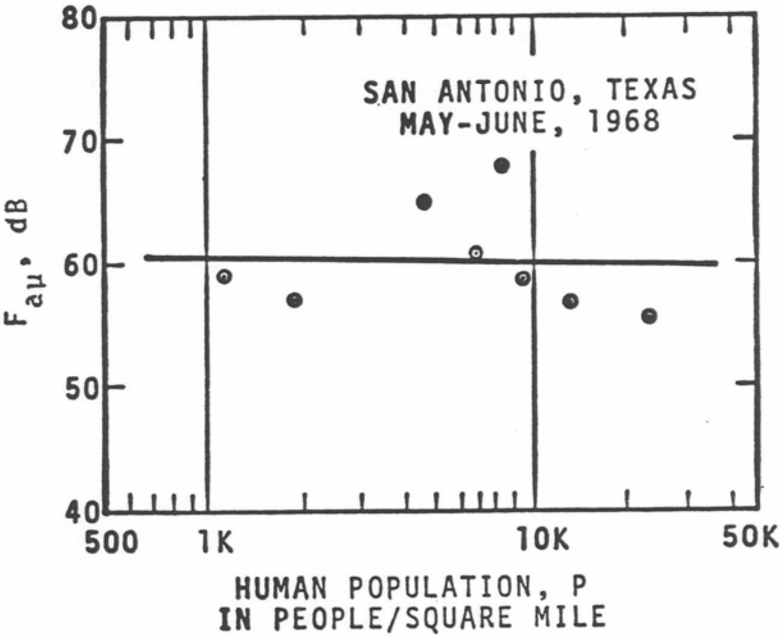

Figure B1. Regression of 5.0 MHz $F_{a\mu}$ with log population density of SLA's.

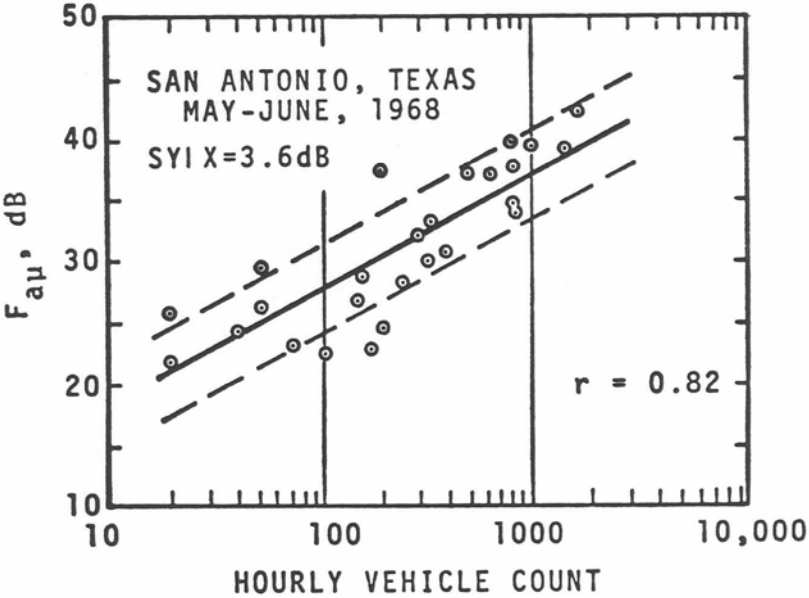

Figure B2. Linear regression of $F_{a\mu}$ vs. log hourly traffic count along 26 thoroughfares at 48 MHz.

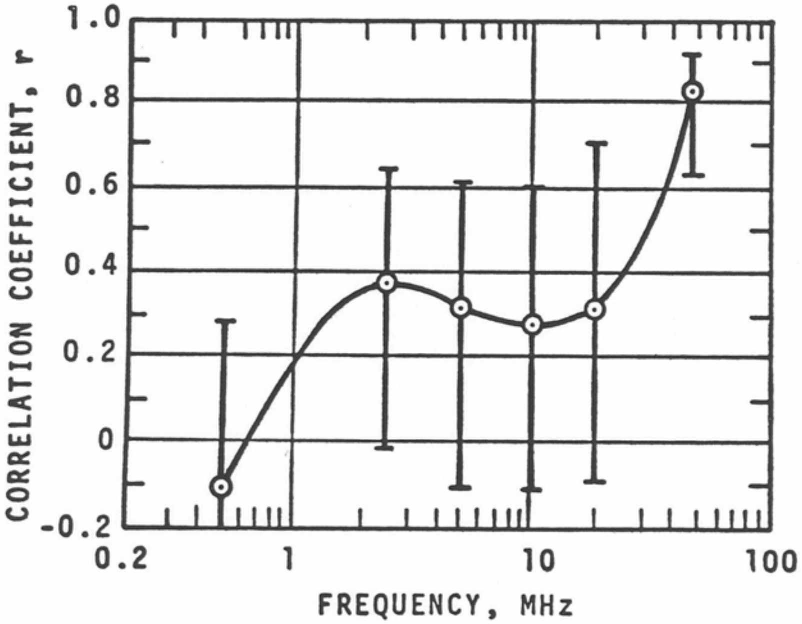

Figure B3. Correlation coefficients along with the 95 percent confidence limits for each of the measurement frequencies, $F_{a\mu}$ vs. log hourly traffic count.

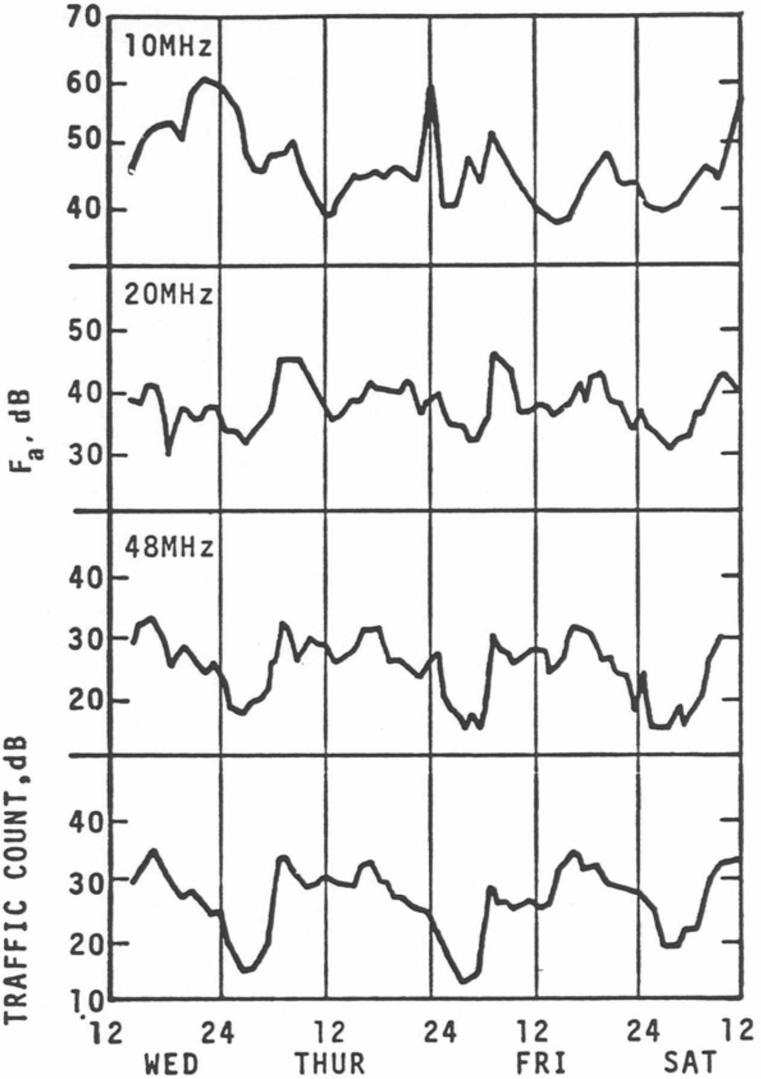

Figure B4. Hourly median values of radio noise power and hourly traffic count. Broadway, Boulder, Colorado, October 25-27, 1967, noise values recorded 100 ft west of highway center.

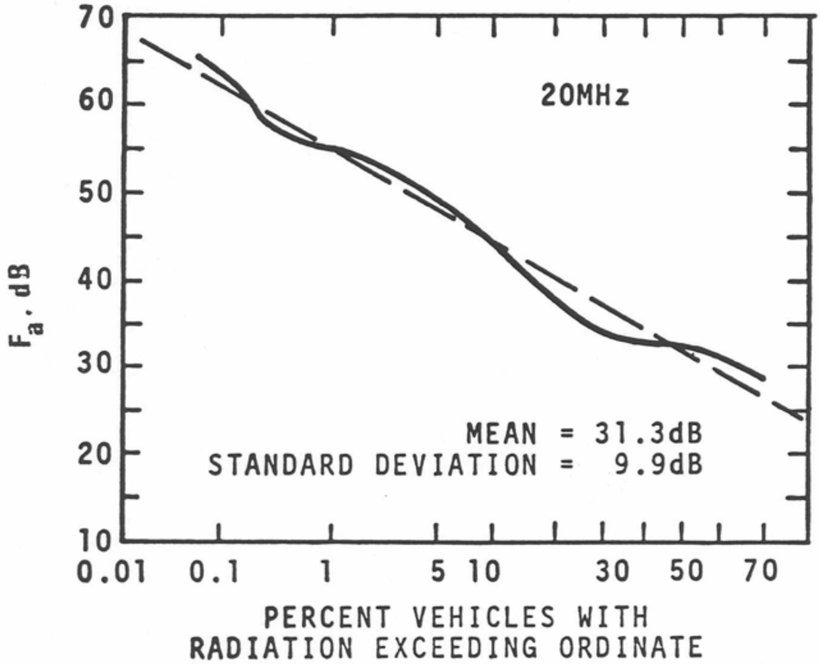

Figure B5. Distribution of radio noise power at 20 MHz radiated from 958 individual vehicles, values measured at 50 ft from vehicle.

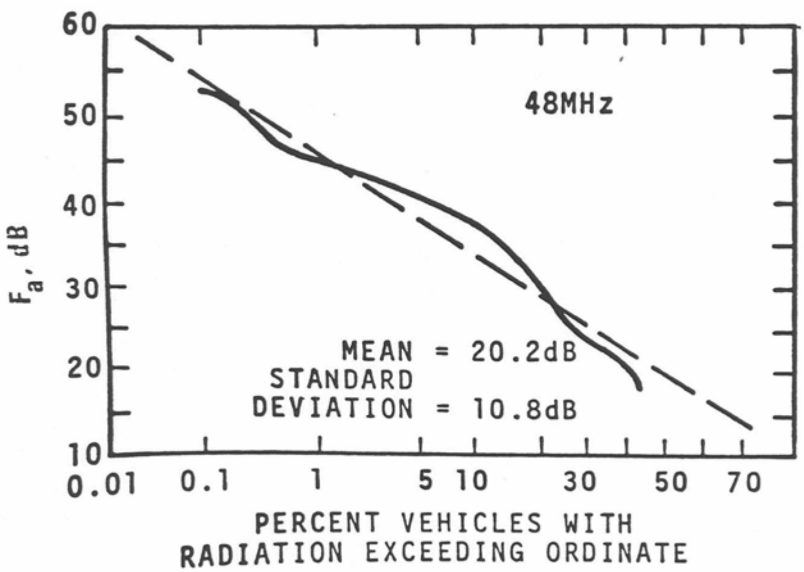

Figure B6. Distribution of radio noise power at 48 MHz radiated from 958 individual vehicles, values measured at 50 ft from vehicle.