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MEASUREMENTS OF AMPLITUDE PROBABILITY
DISTRIBUTIONS AND POWER OF AUTOMOBILE
IGNITION NOISE AT HF

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Stanford Research Institute

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ABSTRACT

Measurements of the amplitude probability distribution (APD) of the envelope and measurements of other parameters of automobile ignition noise were made at frequencies between 24 and 30 MHz. The measurements were conducted at a quiet site where several single stationary vehicles were operated at engine speeds corresponding to idle and cruise. Measurements were also made at two distances near a freeway, for light traffic (approximately 20 vehicles per minute) and for heavy traffic (approximately 45 vehicles per minute). The principal instrumentation consisted of several phase-stable receivers with coherent quadrature detectors whose outputs were digitized at a rate of 200 samples per quadrature component per second and recorded on magnetic tape for computer processing. About ten minutes of data (about 120,000 samples) were obtained during each measurement. The computer plotted the APD on a Rayleigh scale in dB relative to thermal noise and calculated the mean noise power available at the antenna terminals (related by a constant to the noise factor, F_a) and V_d -- the ratio in dB of rms to average voltage.

The average power of the ignition noise increases with engine rpm and V_d decreases. Near a freeway, most of the noise is contributed by a small number of very noisy vehicles. The APDs for various situations are strikingly similar; all show that most of the noise envelope samples in a measurement are Rayleigh distributed. A small percentage of the noise samples do not follow the Rayleigh distribution, but are of higher amplitude. This percentage is higher for an engine at cruise speed than at idle speed, and higher for heavy traffic than for light traffic.

I INTRODUCTION

Lately, the automobile has been receiving much attention because of the increasing efforts to reduce the levels of exhaust pollutants resulting from its proliferation. The electromagnetic pollution of the radio spectrum--produced by the automobile's ignition system--is not as well known. Therefore, it receives very little attention, except from radio communicators and from the manufacturers, who make great efforts to decrease the automobile ignition noise and to make the automobile a good neighbor to the radio user. While this latter pollution problem is not a spectacular threat to human welfare, it is perhaps equally pervasive and is properly a source for concern.

Various parameters have been used to characterize ignition noise, including peak values and quasi-peak values of field strength, average noise power,¹ and the ratio of the rms noise voltage to the average noise voltage. Pulse counting techniques have also been used;² recently, experimenters at General Motors have begun to measure the distribution of the pulse peak amplitudes.^{3,4,5} Others have measured the amplitude probability distribution (APD) of the detected ignition noise.^{6,7} Quantitative degradation measurements of land mobile radio by ignition noise have been recently reported.⁸

This paper describes a set of measurements of the APD--and some other parameters--of automobile ignition noise at frequencies between 24 and 30 MHz, and at effective noise bandwidths of 16, 8, and 1.2 kHz. These measurements were made for single stationary vehicles (with engines operating at idle and at cruise speeds) and for freeway traffic (light and heavy). The basic data collection method was to digitize and record the output of coherent quadrature detectors at a rate of 200 samples per detector per second. This digitized data was then available for the off-line computation of the APD and a number of other parameters.

The purpose of this paper is to briefly describe the instrumentation and software used to measure automobile ignition noise, and it will also present some of the measured data.

Some of these measurements were made in support of mathematical modeling work of digital communication systems being done by the Electromagnetic Compatibility Analysis Center (ECAC) for the U.S. Navy. However, the bulk of the data shown here was developed using Stanford Research Institute's (SRI) internal funds.

II NOISE MEASURING SYSTEM

The noise measurement system consists of a hardware (or measurement) portion and a software (or data processing) portion. Magnetic tape is the medium for conveying measured raw data from the field to the data processing center. After processing, the data is presented in the form of computer printout and computer-drawn plots.

A. Instrumentation

The block diagram of Figure 1 indicates the principal instrumentation used to measure automobile ignition noise; a single antenna was used. The antenna was a simply constructed, 16 foot fan dipole, which was always mounted vertically. Calibration was always performed at the antenna terminals so that the entire system downstream of--but not including--the antenna was calibrated.

The receiver system was originally developed as an HF channel measurement system. It consists of four individual HF receivers that are phase-stable and separately-tunable. Each receiver had two coherent quadrature analog detectors so that amplitude, and also phase of a signal, could be obtained. We used both detectors to obtain amplitude and phase of the noise. Both quadrature components from each receiver were sampled simultaneously at 200 times per second, converted from analog to digital form, and recorded on magnetic tape for later processing by computer. The sampling aperture (the time during which the analog signal was sampled for later conversion to digital form) was 1 μ s. Each sample had 9 bits plus the sign bit, so there was a maximum usable dynamic range of about 54 dB.

B. Data Processing

The computer used each pair of component samples to find the equivalent amplitude and phase. The amplitudes were converted to relative dB (20 log amplitude) followed by the accumulation of counts in an array according to each sample's amplitude and phase. The two-dimensional array had cells 2 dB wide in the amplitude dimension and 45° wide in the phase dimension. The array was converted into a joint amplitude-phase

density by dividing the number of counts in each cell by the total number of samples during a data collection period. From this information an APD, as well as some more unusual plots, was obtained.

The APD was calculated using two steps:

- (1) Obtaining the amplitude density by summing the counts in all the phase cells for each 2 dB-wide amplitude range (to remove phase dependence).
- (2) Integrating the density (actually summing again) by starting at the high-amplitude end and proceeding in 2 dB steps to the low-amplitude end.

After each 2 dB step the computer had determined the percentage of samples that were above that level; by the time the low amplitude end was reached, 100 percent of the samples had been accumulated and the data was available for an as-yet-uncalibrated APD. System calibration is described in the next section.

We used the same joint amplitude-phase density array to develop what we termed a CAPD--a family of eight phase-conditional APDs. Each member of the family was computed by dividing the number of counts in each cell by the total number of counts in its corresponding phase segment, and then accumulating percentage in 2 dB steps from the high- to the low-amplitude end separately for each of the eight phase segments. We plotted this information, using eight point-symbols, as eight APDs on the same graph. Each set of points showed an APD for that 45° phase segment, and if they overlaid each other, they indicated that the noise amplitude was independent of its phase.

The joint amplitude-phase density array was also used to determine whether or not the noise was uniformly distributed in phase. The sum of all the amplitude samples for a particular phase segment gave the total number of samples in that 45° phase segment. If the noise was uniformly distributed in phase, 1/8 or 12.5 percent of a large group of samples would be included in each segment.

Two other noise parameters, which did not make use of the amplitude-phase array, were computed. One was the mean noise power at the antenna terminals. It was computed by relating the rms noise voltage to the system's response to a known noise power density at the antenna terminals. The other parameter was V_d , the ratio in dB of the rms noise voltage to the average noise voltage. It required finding both the average and the rms noise voltage for the data collection period.

C. Calibration

System calibration was performed by substituting a thermal noise source for the antenna at the antenna end of the feed cable. This particular source provided wide-band Gaussian-distributed noise with a power spectral density of 35 dB above kT_0 per cycle of bandwidth; it allowed simultaneous calibration of all receivers, independent of bandwidth, for the entire hardware and software system beyond the antenna terminals. Before each data collection run, we calibrated the system by connecting the noise source--in place of the antenna--and then recording about a minute (12,000 samples) of the noise from each of the four receivers simultaneously on the magnetic tape.

As one of the first steps during data processing, the computer calculated the relative dB of the rms value of the amplitude of the digitized thermal noise signal and was told, by means of card input, that this amplitude value represented a noise power at the antenna terminals of 35 dB above kT_0 . The later (actual data) signals were then referred to this known input noise level, providing calibration for the APD and for the mean noise power measurement.

D. Check-Out Using Gaussian Noise

As a test for the entire operation system--from the antenna terminals through the computer programming--we used our 35 dB kT_0 Gaussian noise source as a source of data to determine if the system could correctly measure its parameters. After calibrating the system, the source was allowed to remain connected, in place of the antenna, and the system was operated for a little more than five minutes (more than 60,000 samples). Measuring the Gaussian noise source as data, the system overestimated its power level by amounts less than a half dB, and in one receiver by only 0.03 dB. Unlike the average power, the V_d ratio measurement was not prompted since the system was required to compute the rms noise voltage and the average noise voltage, and obtain their dB ratio. The system provided actual V_d figures ranging from 1.052 dB to 1.066 dB in comparison with the theoretical ratio 1.049 dB for the envelope of a Gaussian noise process, so at worst there was an error of a very few hundredths of a dB.

We expected the phase of the Gaussian noise relative to our frequency standard to be uniformly distributed, so that any failure of our system to confirm this would reflect upon the system's reliability. The phase was divided into eight 45° segments; each segment should have

contained 12.5 percent of the noise samples. The checkout showed this to be nearly so: some of the segments had as little as 11 percent, or as much as 13.5 percent of the samples. These discrepancies were found to occur in our system as a result of low-amplitude noise only. They were partly the result of receiver bias and partly caused by the software's handling of noise in which one quadrature component was low enough to be digitized as zero.

Figure 2 shows the computer-drawn Gaussian-noise APD and CAPD for two of the receivers (equivalent noise bandwidths of 8 and 1.2 kHz). As indicated, we obtained a fairly straight line, with only a small amount of roughness near the low-amplitude end caused by poor resolution of the A/D converter there. This may be seen on the CAPD as a nonuniform phase at low-amplitude. We did not adjust the vertical scale to obtain the commonly-used slope of $-1/2$ for the Gaussian APD, but rather accepted the slope obtained in this test as the proper slope for Gaussian noise. Note as expected,⁹ that the curves indicate that the noise exceeds the computed rms values of 35.03 and 35.34 dB above kT_b about 37 percent of the time, and that the level exceeded 99 percent of the time is almost exactly 20 dB below this at 15 dB above kT_b .

On these APDs, and others that will follow, there is a line representing receiver noise, which is itself a distribution rather than a specific level. Since receiver noise is thermal noise, its envelope is Rayleigh distributed and thereby its slope is well defined. Therefore, it was necessary to find only one point on the distribution so that the line could be drawn. Since the rms value of the envelope of thermal noise (or equivalently, the average noise power) is exceeded about 37 percent of the time,⁹ a measurement of the average receiver noise power supplied the point to define the line. We made this measurement by:

- Substituting a dummy load in place of the antenna.
- Noting the rms value of the detected output using a true rms voltmeter.
- Comparing it with the rms output for the 35 dB noise source.

* The amplitude of Gaussian noise has a Rayleigh distribution. Straight lines on Rayleigh paper imply a Weibull distribution, of which a Rayleigh distribution is a special case.⁴

III MEASUREMENTS

We conducted measurements of automobile ignition noise both from single stationary vehicles and from freeway traffic. In both cases the measurement location was chosen well away from other sources of radio noise, such as power lines and machinery.

A. Single Stationary Vehicle Measurements

We will describe the single stationary vehicle measurements first. Figure 3 shows the antenna and one of the test vehicles in the position we used. The center of the vertically polarized antenna was 3 m above the ground and the distance to the nearest metal on the body was 10 m, as the SAE¹⁰ recommends. Usually we positioned the car with one side toward the antenna--with the antenna just opposite the engine. But, we also made some measurements with the vehicle facing the antenna. All measurements were made with the vehicle's hood closed, although it is shown open here while the engine speed is being adjusted by a mechanical attachment to the throttle linkage. The instrumentation van was about 30 m from the antenna (about 40 m from the vehicle) and was connected with RG8/U feedline.

The three vehicles used in these single stationary vehicle measurements were not selected for any particular characteristics, but rather because they were readily available to us. They were:

- A 1962 Chevrolet V-8 pickup with its distributed-resistance ignition cabling replaced by copper wires to make it noisy.
- A 1967 Mercury Cougar with a V-8 engine.
- A 1962 Volkswagen with a flat, 4-cylinder engine, in which two cylinders oppose the other two.

The results listed below were observed from the single stationary vehicle tests; a discussion of those results follows. Figure 4 illustrates some of the results. (In this figure the vehicle's APD is shown with X's and an atmospheric noise APD at the same average power and almost the same V_d (CCIR 322)¹¹ is included for comparison.)

- The ignition noise APD consists principally of two straight-line segments: a low amplitude Rayleigh-distributed part and a high-amplitude, low-probability part that bends over at the top.
- The breakpoint between the two main segments is well defined, compared with the APD for atmospheric noise, and it moves toward the right (increasing percentage) as the engine rpm is increased.
- The level of the Rayleigh part of the APD increases as the engine rpm is increased.
- There is little difference in the APD from front view to side view for the noisy pickup.
- The pickup's average power measured at the antenna terminals at spot frequencies between 26- and 30-MHz varies irregularly by several dB.
- There is a considerable difference from one car to another in the APD and in the way the APD changes with engine speed.
- The average power of the ignition noise increases with the engine rpm, but V_d decreases.
- As bandwidth decreases or as the ignition pulse rate increases the APD becomes more nearly Rayleigh.

1. APD Shape and Engine rpm

The APD of ignition noise from a single stationary vehicle has a low-amplitude Rayleigh-distributed part, which is smoothly faired onto a high-amplitude Weibull-distributed part contributed by the impulses themselves. Atop the Weibull section, the APD bends over again to reach a maximum level (corresponding with pulse peaks) which, for some vehicles, will vary with engine rpm. The break between the Rayleigh and Weibull sections is usually rather abrupt; it divides the ignition noise APD into its two main parts much more clearly than the APD of atmospheric noise for a similar V_d is divided (CCIR Report 322).¹¹ As Figure 5 shows, the location of the breakpoint in percent of time between the Rayleigh and the Weibull sections shifts with the rpm (and hence, the rate of ignition pulses) of the engine. As the engine speed increases, the Rayleigh section of the APD shifts to the right to indicate that the low-amplitude, Rayleigh-distributed values are exceeded more often at high rpm than at low rpm and may also raise to indicate a greater level of Rayleigh-distributed noise. The source of the Rayleigh-distributed part of the APD is not totally clear. It is entirely conceivable that it may originate with the electrical system of the automobile (generator, voltage

regulator, etc.), or it may be ambient background noise. In the absence of either of these noise sources, the source of the Rayleigh part would be the receiver noise itself. The effect of adding high-amplitude ignition noise pulses to the pre-existing Rayleigh noise will always cause the Rayleigh portion of the curve to shift to the right. The more pulses per unit time (increased rpm), the further to the right the Rayleigh part must be displaced. This forces an effective rise in that part of the APD, since any lower level that was formerly exceeded a certain percent of the time becomes exceeded a greater percent of the time. Therefore, the APD of ignition noise could never drop all the way to the receiver noise APD, even if the vehicle radiated no Rayleigh distributed noise.

Although the maximum value shown on the APD does not change appreciably with the vehicle rpm, clearly, the average power increases as the rpm (or pulse rate) increases. Concurrently, the V_d ratio decreases.

2. Front to Side APD Comparison

It is commonly known that radiation levels of vehicles vary with the orientation. The SAE J551a measurement technique¹⁰ requires peak measurements from the left and the right sides of the vehicle; the IEEE Standard No. 263¹² requires peak measurements at the front and rear. Egidi and Nano¹³ rotated motorcycles about a vertical axis as measurements were made, and Minozuma¹⁴ presents an example of the 360° radiation pattern of a car. All of our measurements were made from the right side of the test vehicles, except one series at 29.9 MHz in which the pickup was facing the antenna. This showed that the average power was about 1 dB greater at the front of this vehicle than at the right side. Figure 6 shows the similarity of front and side APDs. Slightly higher pulses were seen from the front of this vehicle at both idle and cruise speeds and there is also an apparent increase in the level of the Rayleigh portion. If these two measurements had been made one after the other on the same day, instead of several days apart, we would have to ascribe the increase in the Rayleigh part to the vehicle (since there was no increase in the pulse rate to displace the curve to the right). However, since there is also the possibility of some change in the ambient noise level from one day to the next, the matter is not settled.

3. Power Variations with Frequency

Bauer¹⁵ mentions that the radiation from a vehicle is a property of the entire vehicle and that the nature and placement of wiring and

other metallic parts within an engine compartment will affect the noise output. The interactions between the radiating ignition wires--having different lengths and placements--and all the other various reflecting and reradiating elements associated with a particular automobile, result in a great variation in the output noise with frequency. This may vary considerably in individual cars of the same make.¹⁵ Figure 7 is an example of the variation in average noise power that we found on the front exposure of the pickup using receivers spaced at 1 MHz intervals from 25.9 MHz to 29.9 MHz. This general spectral shape for the emission from this vehicle was verified using a spectrum analyzer, which also showed that the general structure of the spectrum does not change with engine rpm. The APDs changed very little in appearance from one frequency to the next.

4. Car-to-Car APD Comparisons

There is a great difference in the noise characteristics of individual cars, particularly when they are of different types. Bauer suggested in 1967¹⁶ that the noise increases with the number of cylinders; this probably holds true when the rpm is about the same. At the same pulse rate, however, factors other than the number of cylinders may prevail.

By means of the APDs we can notice some of the car-to-car differences in noise characteristics. Figure 8 is a superposition of the APDs from all three of the test vehicles in the same test position so that they may be compared with the engines idling and with the engines racing. All of the vehicles display an increase in the noise power with the rpm. The pickup, with its ignition system deliberately made noisy, can be seen on these plots to have maximum values and an average power about 15 dB above the other two cars.

The other two vehicles have standard ignition systems and are probably typical of cars of that vintage, from the standpoint of noise emission. The Mercury has eight cylinders as compared with the VW's four cylinders, and its average noise power is about 3 dB greater than the VW's when both are idling. (The Mercury also has a somewhat higher idling rpm and, therefore, has greater than twice the ignition pulse rate of the VW.) This agrees with Bauer's article,¹⁵ which showed that eight-cylinder cars were noisier than six-cylinder cars and presumably noisier than four-cylinder cars. However, as we compare the measurements at a much higher rpm--with the VW running at 4,000 rpm so that it was producing the same pulse rate as the Mercury at 2,000 rpm--the four-cylinder Volkswagen was

4 dB noisier than the V-8 Mercury. The Mercury's noise power increased only 0.5 dB with the rpm increase and its pulse peaks seem to have decreased slightly. The peaks for the pickup also decreased 2 or 3 dB from idle to race, while those of the VW appeared unchanged.

Our use of the term "peak" refers to the upper part of the APD; it is some value that is exceeded by about 0.001 percent of our samples. It is not known just how this corresponds to peak measurements as measured using other instrumentation.

The low-level part of the APD for the idling pickup does not parallel the Rayleigh noise behavior of the other two vehicles. This vehicle was measured on a different day than the other two, and the appearance of the APD leads us to suspect that there was some low-level signal contaminating the measurement.

We have found that the average noise power increases monotonically with engine speed, although the peak value seen on the APD may not increase or may actually decrease. Egidi and Nano¹³ observed that "the measured value did not, to a significant extent, depend upon the engine speed, provided it was sufficiently above idling speed." However, it is not clear whether they were measuring a peak value or some other parameter.

5. APD Variation with Bandwidth

The shape of an APD depends upon the bandwidth of the system. Figure 9 shows APDs measured simultaneously at four different detector bandwidths. The vehicle engine was run at two different rpm's, so that it provided pulse rates of about 40 and 200 pulses per second (pps). Both of these plots indicate that at narrower bandwidths a detector becomes increasingly unable to resolve the ignition pulses and the successive pulses (of variable amplitude) begin to overlap to yield a nearly Gaussian noise output (i.e., a Rayleigh-distributed envelope). The lower pulse rate shows the progression much better than the higher pulse rate; the APDs for the two narrower bandwidths both show a recognizable impulse-noise shape at 40 pps but not at 200 pps. At 200 pps the APD in the 50 Hz detector bandwidth still shows a slight indication of peaking at the higher amplitudes, but the 25 Hz APD is very near to a Rayleigh distribution, as evidenced by its slope and by the V_d , which is near the Rayleigh V_d of 1.049 dB.

As the bandwidth narrows or the pulse rate increases the trend in the APD is toward an overall flattening--the high-amplitude part drops, reflecting the inability to respond as fully to a pulse, and the low-amplitude part rises, indicating the slower recovery time following a

pulse. This trend is shown very well on the 40 pps APD family, except for some seemingly anomalous behavior at the low-amplitude end of the 6 kHz curve. It fails to drop below the 3 kHz curve because of the high noise level associated with that particular receiver. So the 6 kHz APD drops down to--but not below--its receiver noise APD.

Since our unit of measurement of ignition noise power is in dB relative to thermal noise power in the same bandwidth, we should observe the same average noise power in each of the four receivers. The results are relatively close, particularly at the high rpm, considering that four different receivers were used.

B. Freeway Measurements

Figure 10 shows the location on Interstate 280 near Palo Alto, California, where we made measurements of the noise from passing traffic. This figure shows the antenna on a six-meter mast "near" the freeway--about 16 meters from the nearest of the three northbound lanes. Our "far" position was about 42 m from the freeway. There is a slight up-grade and traffic passes the site at speeds estimated between 80 and 110 Km per hour (50 and 70 mph). The heaviest traffic amounts to about 50 vehicles per minute in the northbound lanes during the early morning. It quickly drops off to about 15 vehicles per minute for the rest of the day. The automobiles were the principal source of noise at this site, since there were no power lines or other obvious noise sources nearby. Power was provided for the measurements by a portable gasoline generator placed within a copper screen box equipped with rfi filters to suppress its ignition noise. It was placed about 100 m from the antenna.

The freeway traffic noise measurements illustrate several points which are listed below and then discussed in the following three sections.

- Only a small percent (perhaps 10 percent) of the automobiles that pass along the freeway contribute noticeably to the noise environment. Some of the noisy vehicles radiate average noise 30 or 40 dB above the quiet ones.
- The APD of ignition noise from the freeway traffic consists of a lower (Rayleigh) portion and an upper (Weibull) portion that rises to levels 20 or 30 dB above the Rayleigh curve extended. It does not bend over as prominently as the top of a stationary single vehicle APD, nor is the break between the Rayleigh part and the Weibull part as clear.

- The APDs for various situations appear strikingly similar, although it can be seen that the point at which the Weibull portion breaks away from the Rayleigh portion is a function of the traffic density.
- Noise power was about 2 dB higher at 24.1 MHz than at 29.7 MHz. V_d was in the range of 6.5 to 8.7 dB.

1. Time Variations

A modified Stoddart (now Singer) NM-25T noise meter was auxiliary to our phase-stable receiving system, but it used the same antenna by being fed from one of the ports of the multicoupler. Its average power meter output was recorded on a paper chart recorder--often at the same time the complex envelope was being recorded in digital form for the APDs and other processing. This record provided a real-time monitor of the noise history (in relative dB) of the passing cars, and Figure 11 is an example.

Most of the vehicles are quiet and pass with no noticeable noise; the relatively flat spots on the trace of Figure 11 are not necessarily devoid of cars. Other vehicles have average powers 40 dB, or more, above the quiet ones and can be seen coming and going for a period of 30 seconds or so. If we assume a speed of 100 km/hr (60 mph) for such a noisy vehicle, then its average noise begins to exceed that of the quiet cars while it is still about 400 meters (1300 feet) away. In other words, some cars 400 meters away are noisier than most of the other cars about 17 meters (50 feet) away. Rosa¹⁷ determined that about 20 percent of the vehicles in a large group he measured were "serious radiators"; Deitz⁸ refers to the existence of "super-noisy" vehicles that degrade land-mobile reception much more seriously than the majority of vehicles.

In the traffic passing the site there were usually many vehicles in view, making it difficult to identify which one (or more) of a group was a "super-noisy" car, but it was sometimes possible when the traffic was less dense. When possible, we indicated identifiable noise sources on the chart.

We compared the noisy pickup (used in the single stationary vehicle tests) with a random selection of traffic; we had it driven past the site as we made NM-25T chart recordings. The antenna was in its near-the-freeway position. We chose a period when traffic was very light and tried to have the pickup pass the site alone and not within a group of other vehicles. Figure 11 shows two northbound (near lanes) passes.

We were unable to coordinate a good southbound (far lanes) pass that was not suspected of noise contamination by other vehicles. Our deliberately noisy pickup (with copper ignition wire) was certainly not the noisiest vehicle on the road.

Spaulding¹ has also noted the great variability in noise from car-to-car. He has been able to calculate distributions of the average noise power from many vehicles individually showing that--taken over a large number of cars--the power expressed in dB is normally-distributed with a standard deviation on the order of 10 dB. Although our instrumentation does not permit a direct comparison, our observation that noisy cars have average powers of 40 dB or more above the quiet cars is highly credible in regard to this previous data.

2. APD Shape

We found that in the vicinity of a freeway the APDs of ignition noise are quite similar in appearance at the two distances and at the two frequencies we used, but differ a little with the traffic intensity. Figure 12 shows a comparison of a typical freeway APD with a typical single car APD. The amplitude scales have been adjusted so that the APDs coincide at the average power level. The features that tend to distinguish a freeway APD from a single stationary vehicle APD are: the Weibull portion of the freeway APD is usually less steep, and rather than bending over at the top, it seems to continue on to higher amplitudes at essentially the same slope, resembling the APD for atmospheric noise. This difference in shape may be understood by considering the characteristics of the noise sources. At the freeway, the noise sources approach from far away and pass by to recede into the distance; the receiver sees pulses that range broadly in peak amplitude--from those that just barely exceed receiver noise to those pulses from the noisiest car during the measurement period at its point of closest approach. This gives a greater continuum in the scale of received pulse heights than is obtained from the single stationary vehicle, even though these also vary widely, as shown by several authors.^{3,4,5}

3. Freeway APDs

Figure 13 shows four APDs measured at 29.7 MHz during approximately ten minute periods. We used our widest bandwidth (approximately 16 kHz equivalent noise bandwidth) receiver at two distances during light and heavy traffic. There is very little difference from one APD

to the next and only by superimposing the plots can the slight differences be noticed. The computer printout that accompanied the computer-drawn plots, however, showed that the average power varied from one situation to the next in the manner that we would have expected--noise power increased with traffic intensity and with proximity to the freeway.

For light traffic, at this frequency (29.7 MHz) and at 24 MHz, there was about one dB less average noise power at 42 meters from the freeway than at a distance of 16 meters; there was about 3 or 4 dB less when the traffic was heavy. This difference between heavy and light traffic in distance loss may be more apparent than real, since the data were collected on several days for only about ten minutes per situation, and we never had simultaneous measurements at two distances. We do not have enough data here to draw conclusions concerning the rate of attenuation of ignition noise with distance, a matter already covered by others.¹⁷

At 24.1 MHz the same general relationships between near and far and heavy and light traffic were observed. The average power for 24.1 MHz APDs was 2.2 to 2.3 dB higher than the corresponding APD for 29.7 MHz, except for one instance where the noise was more than 4 dB higher. During this particular measurement near the freeway during heavy traffic, a "super-noisy" refrigerated ice cream truck passed. It was so noticeably noisy that it aroused comment at the time; we speculate that the truck's refrigeration unit may have been the source of much of the excess noise.

As an example of the repeatability of the freeway APD data, Figure 14 shows the superposition of three APDs taken at the same location near the freeway, at the same frequency (29.71 MHz), and using the same noise bandwidth (16 kHz), but with three different traffic intensities on three different days. Although the curves look very much the same, the computer's calculations show an increase in average noise power with the increase in the count of cars passing. There was almost 3 dB more noise power averaged over the heavy traffic period than over the light. This corresponds very well with 48 MHz measurements reported by Spaulding,¹ who showed that the noise power increased approximately 10 dB for each multiplication of the vehicle count by ten.

IV CONCLUSIONS

This paper presents a number of measured APDs, and some other digitally processed parameters, for the ignition noise radiating from single stationary vehicles and from the random occurrence of vehicles on a freeway. Comparisons were made between: the APDs and powers for different vehicles; the APDs and powers of vehicles operating at several engine speeds; the APDs and powers measured at different vehicle orientations; and, the APDs for several bandwidths and frequencies. APD and power comparisons were also made for the freeway traffic.

To summarize our findings on ignition noise APDs we note that:

- The APDs have two distinct straight-line segments.
- The breakpoint location depends upon rpm (or traffic intensity).
- The APD for stationary vehicles bends over at the top, but the APD for freeway traffic continues up at the same slope.
- The APDs vary in shape from car to car, but look quite similar for different traffic intensities.
- The shape of the APD depends upon the bandwidth of the system.

Our findings on the average power radiated from vehicles indicates that for a single stationary vehicle the average power:

- Varies greatly from car to car.
- Varies with frequency.
- Varies with the aspect angle.
- Increases monotonically with the rpm.

For freeway traffic, the average power:

- Increases with traffic intensity.
- Increases with proximity to the freeway.
- Is greatly influenced by very few "super-noisy" cars.

ACKNOWLEDGMENTS

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BIOGRAPHY

Richard A. Shepherd (S'59-M'60) was born in Philipsburg, Montana, on 25 June 1937. He received the B.S. degree in electrical engineering from Montana State University, Bozeman, Montana, in 1960 and the M.S. degree, also in electrical engineering, from Stanford University, Palo Alto, California, in 1969.

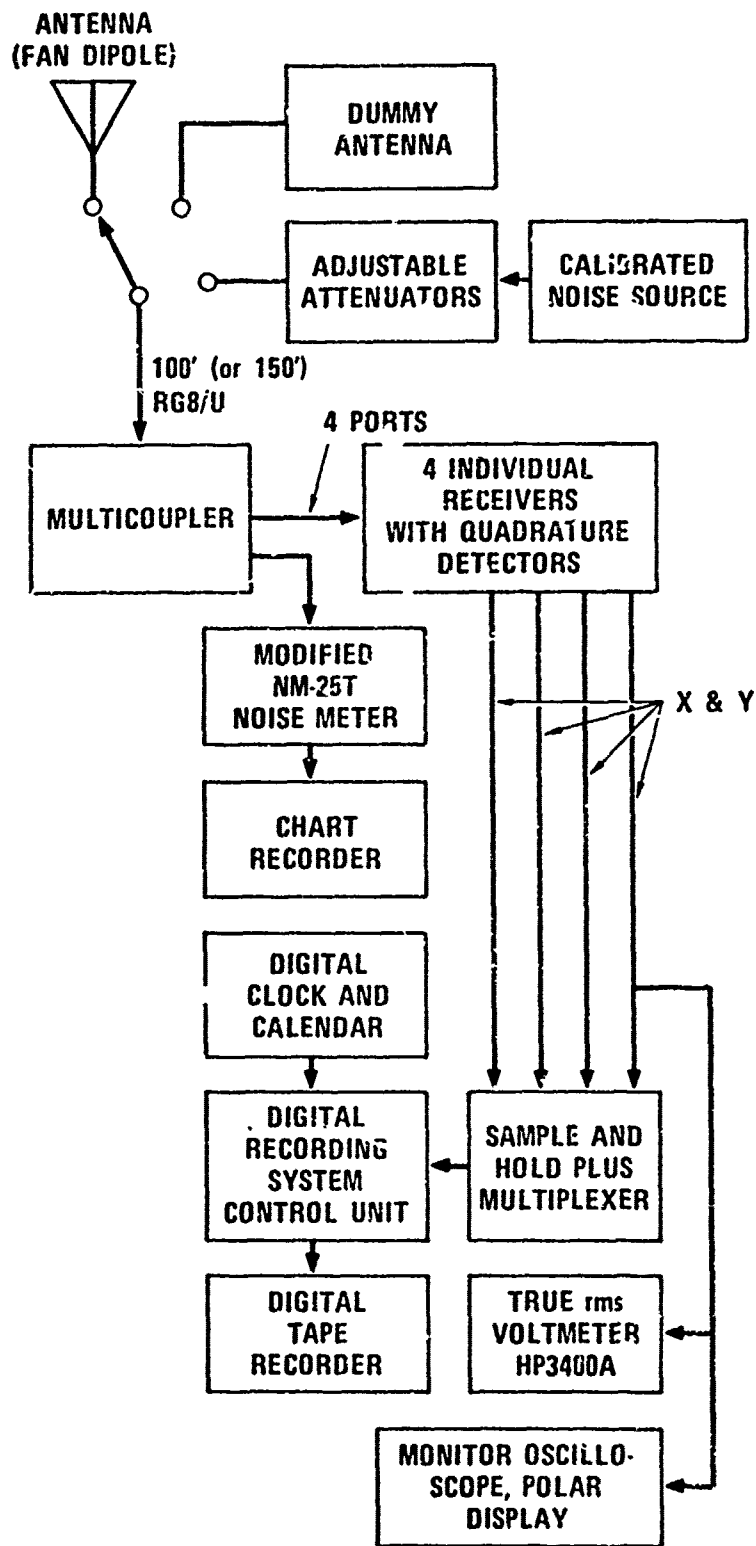
In 1959 he was a laboratory assistant in the Electronics Research Laboratory at Montana State University, where he was engaged in studies of meteor-burst communications. In April 1960 he joined Stanford Research Institute, Menlo Park, California, and is currently a Senior Research Engineer in the Telecommunications Department. During Operation Dominic, the U.S. high-altitude nuclear test series in 1962, he was Supervisor of a field site in the Fiji Islands with responsibility for the operation of an HF oblique incidence ionosphere sounder. In the latter stages of the test operation, he became Engineer in Charge of the SRI project office in Honolulu. At the conclusion of that assignment, he was involved in a study of the frequency dispersion of HF signals passing through the auroral zone and in the simulation of specialized HF communication networks through application of HF propagation prediction programs.

He has participated in SRI investigations of telephone traffic demand and telegram cost-of-service. Recently, he has been active in several studies of man-made radio noise--its quieting and its suppression.

Mr. Shepherd is a member of Tau Beta Pi.

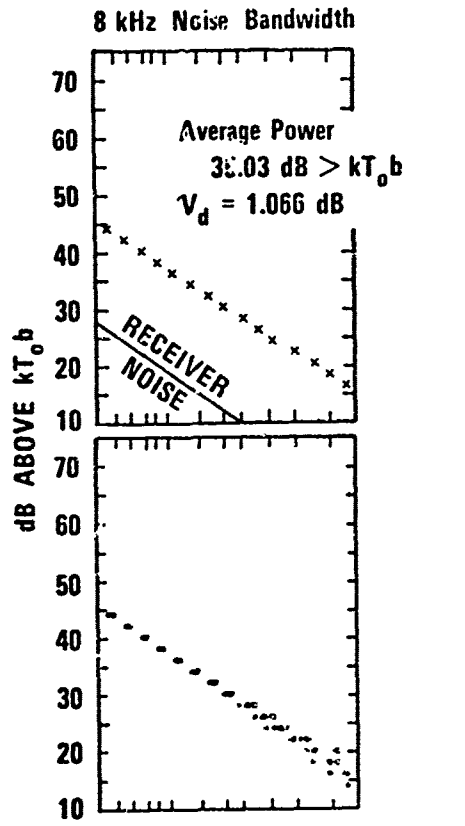
FIGURES

- 1 Block Diagram of Measurement System
- 2 APDs and CAPDs of Gaussian Noise, 29.91 MHz
- 3 Test Vehicle in SAE Position
- 4 Typical Stationary-Vehicle APD Compared with Atmospheric Noise APD
- 5 Variation in APD with Engine Speed
- 6 APDs for Front and Right Side of Pickup, 29.9 MHz, 8 kHz Noise Bandwidth
- 7 Variation of Average Power with Frequency, V-8 Pickup, Front View, 16 kHz Noise Bandwidth
- 8 APDs of Three Vehicles, Right Side, 24.11 MHz, 8 kHz Noise Bandwidth
- 9 APDs at Various Bandwidths, V-8 Pickup Facing Antenna, 29.91 MHz
- 10 Location for Freeway Measurements
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- 12 Typical Freeway and Single-Car APDs, 16 kHz Noise Bandwidth
- 13 APDs for Freeway Traffic, 29.71 MHz, 16 kHz Noise Bandwidth
- 14 APDs Showing Light, Moderate, and Heavy Traffic



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FIGURE 1 BLOCK DIAGRAM OF MEASUREMENT SYSTEM



0.1 5 20 80 95 98 99
PERCENT OF TIME
ORDINATE IS EXCEEDED

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FIGURE 2 APDs AND CAPDs OF GAUSSIAN NOISE 29.91 MHz

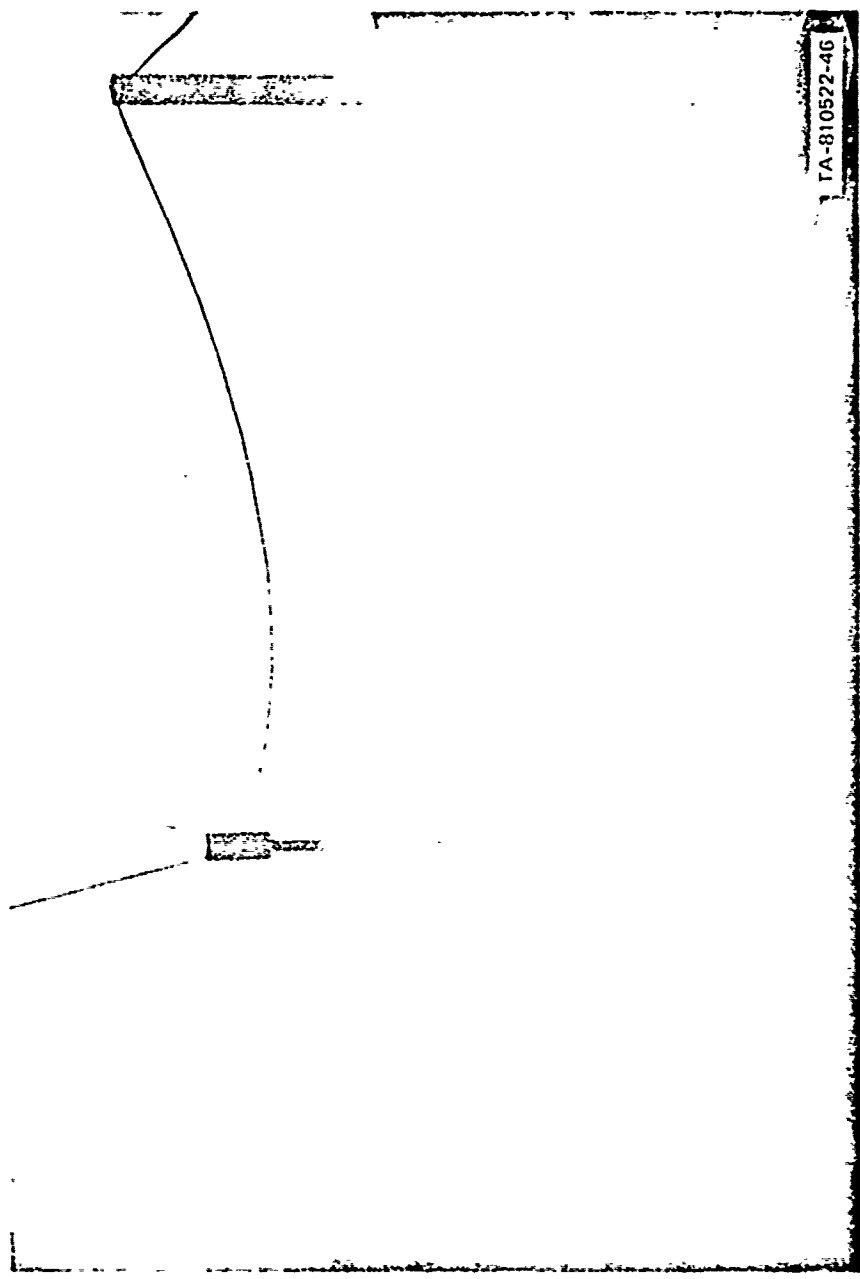


FIGURE 3 TEST VEHICLE IN SAE POSITION

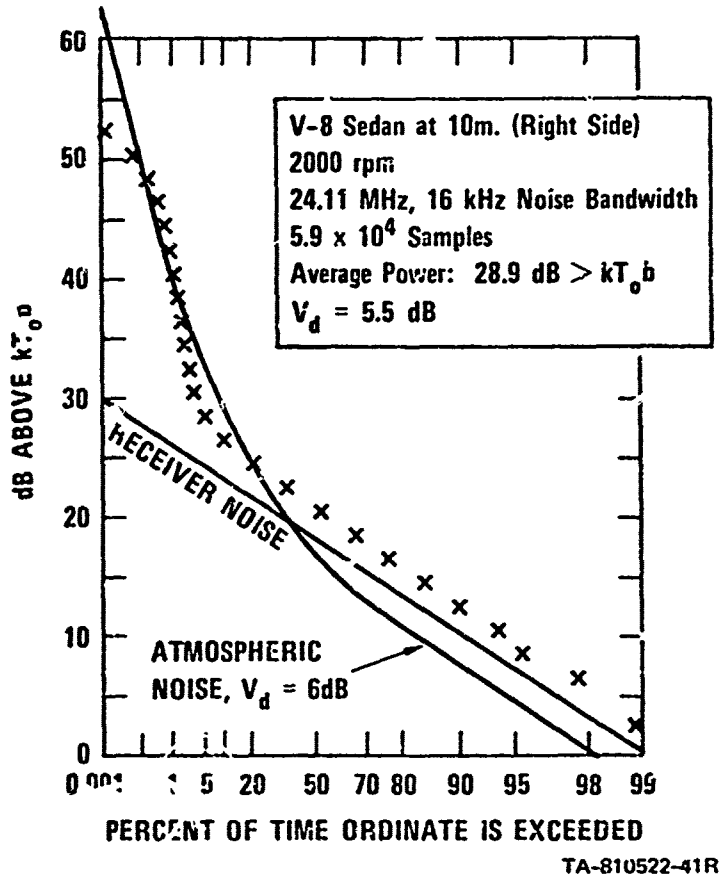


FIGURE TYPICAL STATIONARY-VEHICLE APD COMPARED WITH ATMOSPHERIC NOISE APD

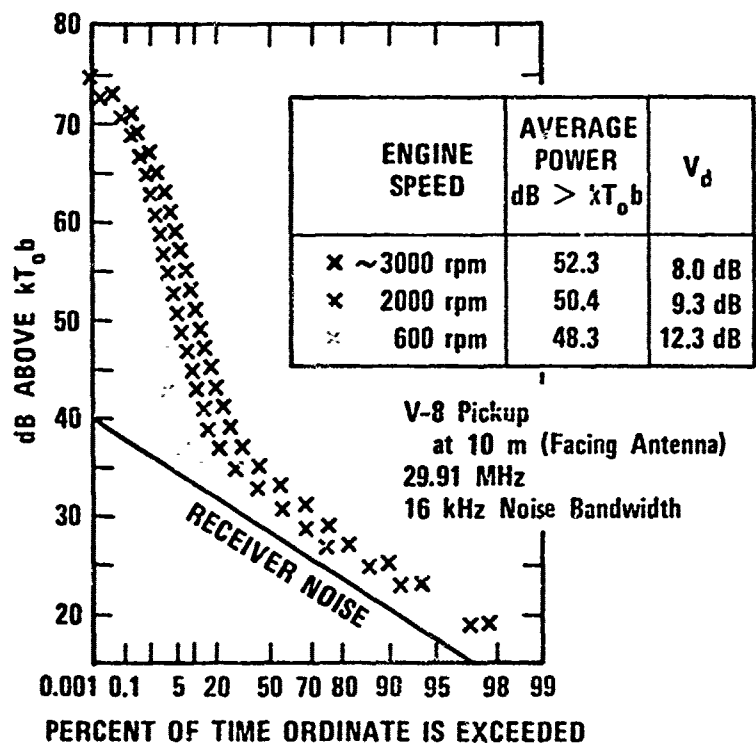
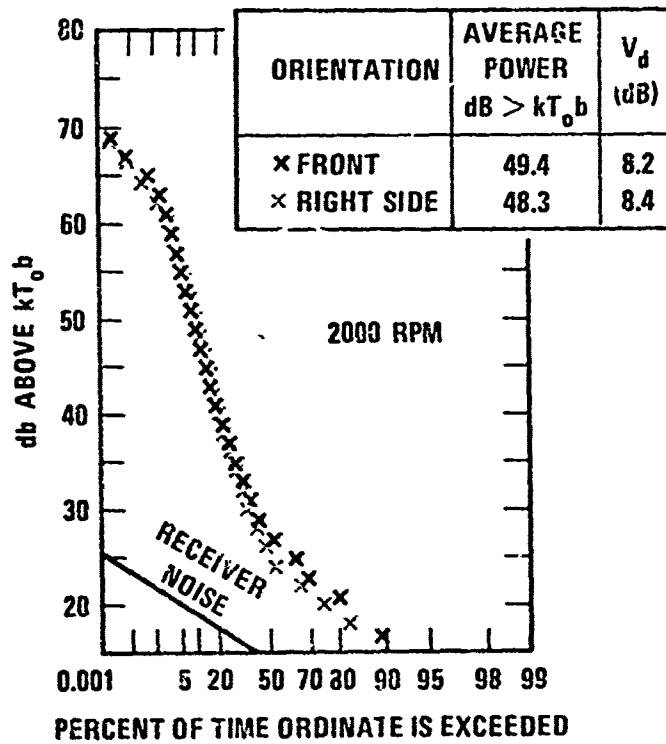
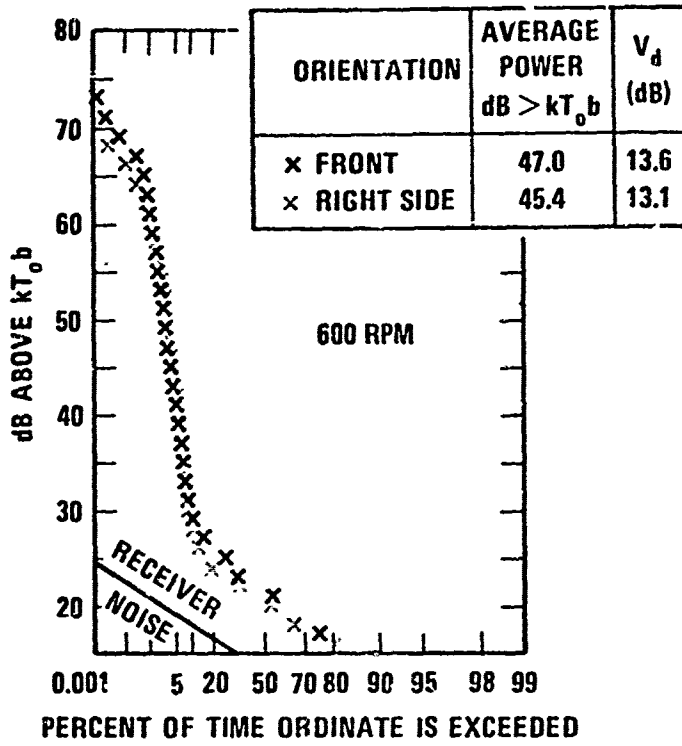
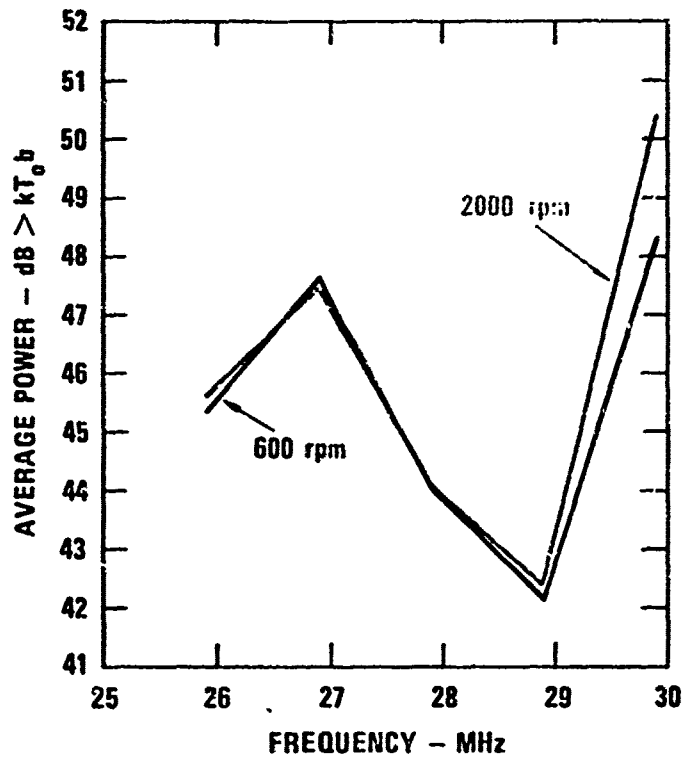


FIGURE 5 VARIATION IN APD WITH ENGINE SPEED



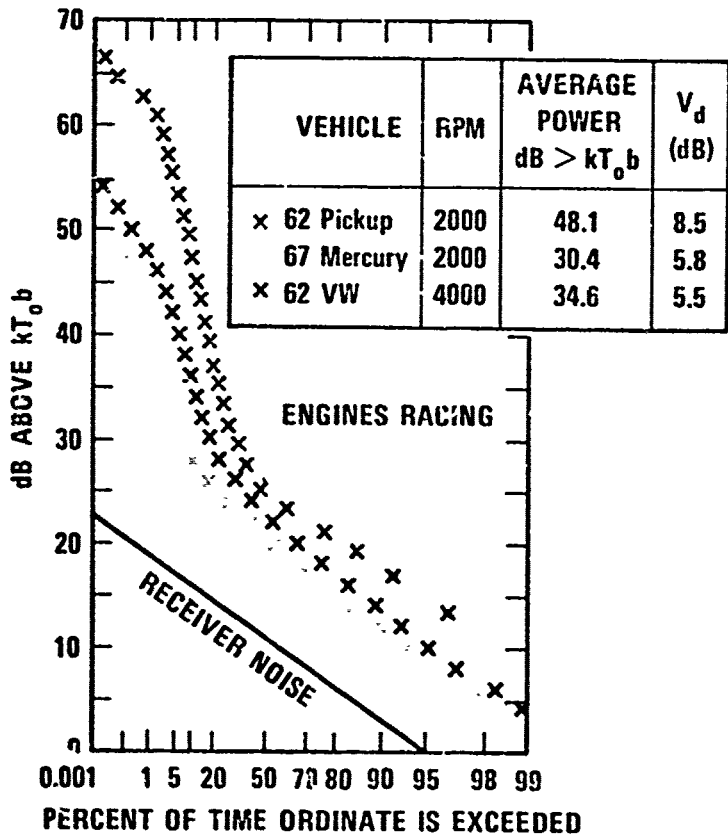
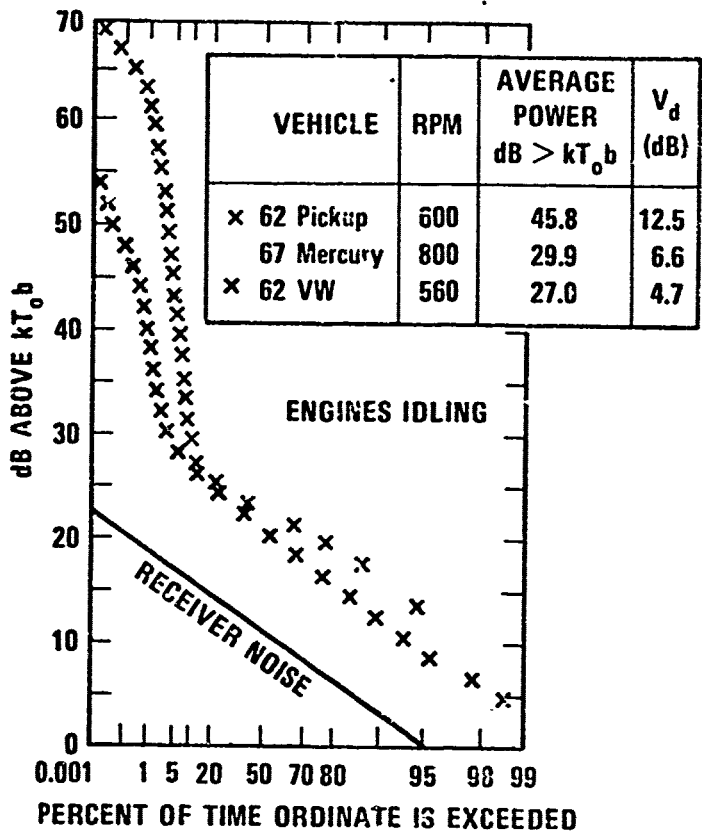
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FIGURE 6 APDs FOR FRONT AND RIGHT SIDE OF PICKUP,
29.9 MHz, 8 kHz NOISE BANDWIDTH



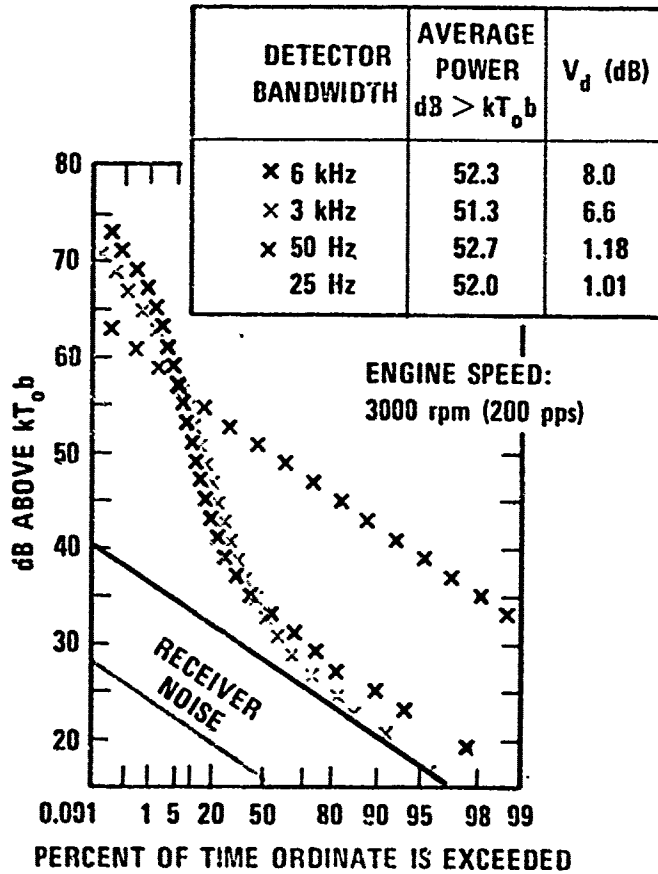
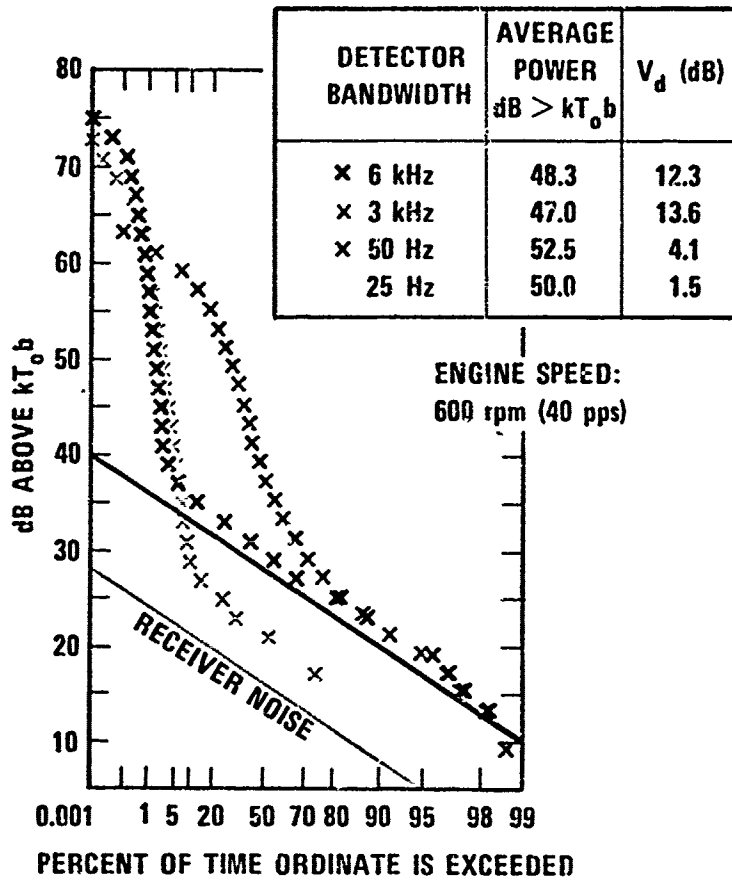
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FIGURE 7 VARIATION OF AVERAGE POWER WITH FREQUENCY V-R PICKUP, FRONT VIEW, 16 kHz NOISE BANDWIDTH



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FIGURE 8 APDs OF THREE VEHICLES, RIGHT SIDE 24.11 MHz, 8 kHz NOISE BANDWIDTH



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FIGURE 9 APDs AT VARIOUS BANDWIDTHS, V-8 PICKUP FACING ANTENNA, 29.91 MHz

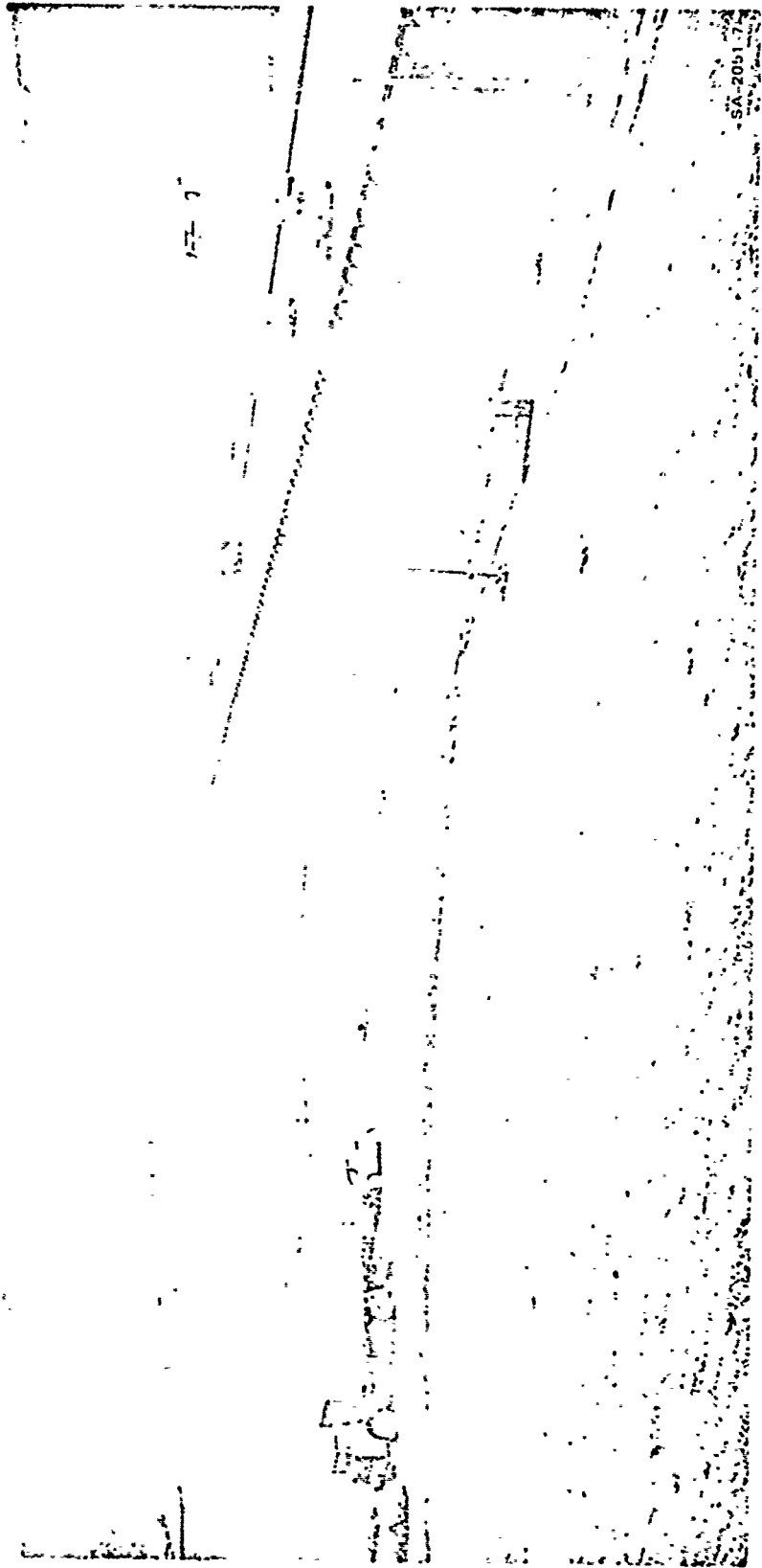
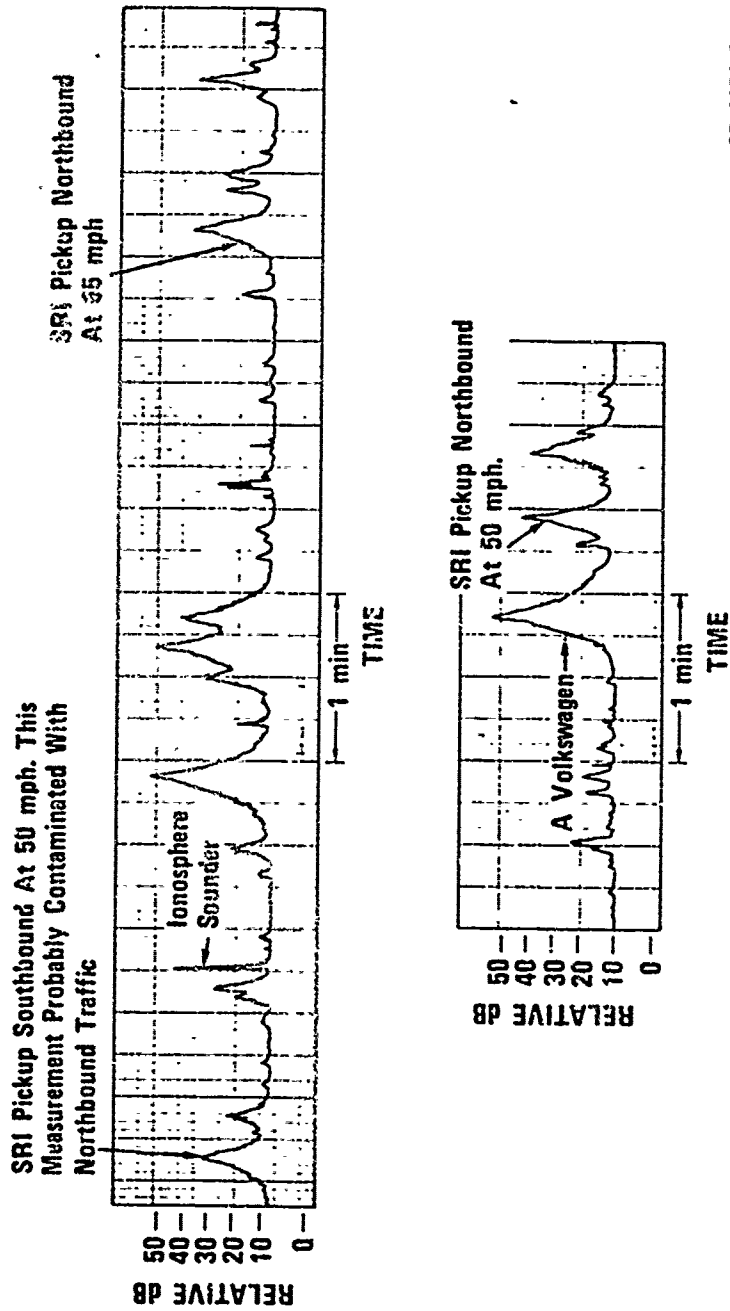
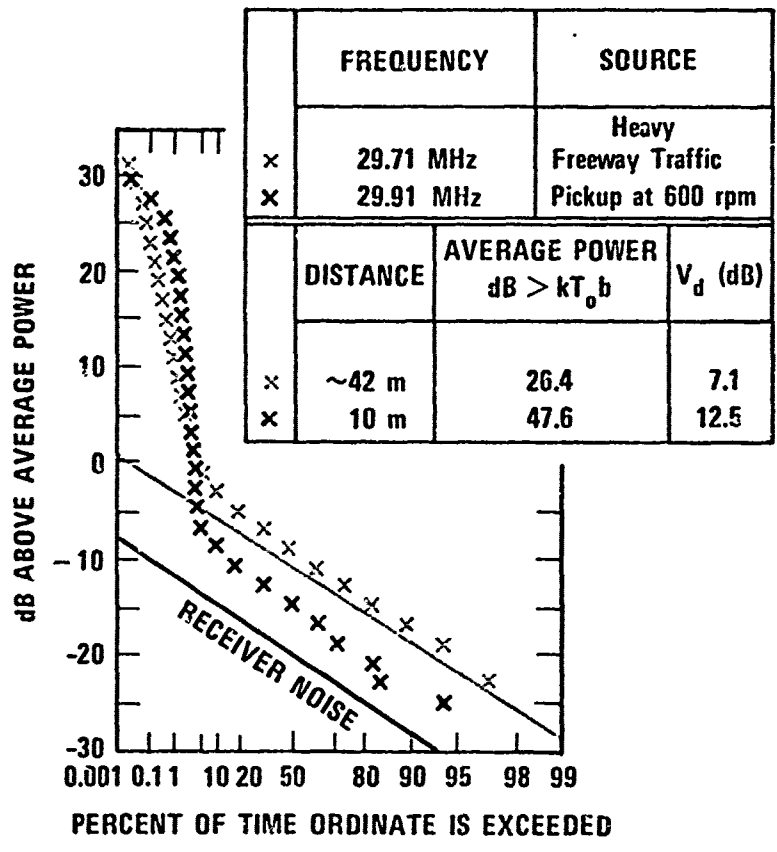


FIGURE 10 LOCATION FOR FREEWAY MEASUREMENTS



SB-2052-31R

FIGURE 11 AVERAGE POWER OF THE NOISY PICKUP ON THE FREEWAY



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FIGURE 12 TYPICAL FREEWAY AND SINGLE-CAR APDs, 16 kHz NOISE BANDWIDTH

22

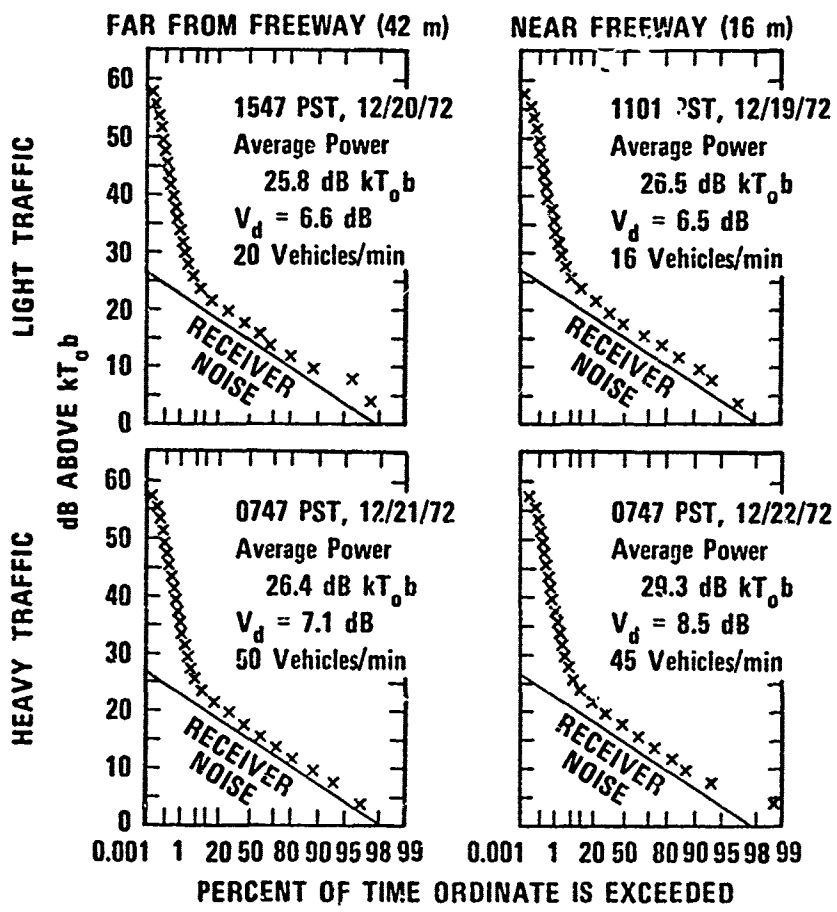
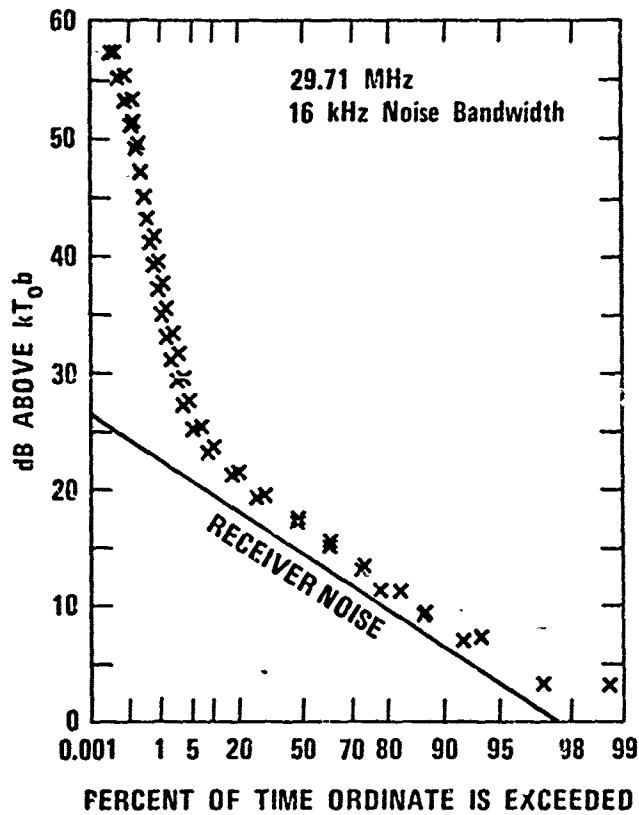


FIGURE 13 APDs FOR FREEWAY TRAFFIC, 29.71 MHz, 16 kHz NOISE BANDWIDTH

DATE	TIME	CARS/MIN	NOISE POWER dB > kT_{0b}	V_d (dB)
× 12/22/72	0747	45	29.3	8.5
× 12/20/72	0856	24	28.3	8.4
12/19/72	1101	16	26.5	6.5



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FIGURE 14 APDs SHOWING LIGHT, MODERATE AND HEAVY TRAFFIC