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TRUCK NOISE - 1B

# SPECTRAL AND DIRECTIONAL CHARACTERISTICS OF NOISE GENERATED BY TRUCK TIRES

WILLIAM A. LEASURE, JR.
DANIEL M. CORLEY

FINAL REPORT
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This report is the third in a series of reports published as a result of Department of Transportation sponsored truck tire noise research conducted by the National Bureau of Standards. The previous reports (OST-ONA-71-9 and OST/TST-72-1) contained details of the test design, test procedures, and an inventory of maximum A-weighted sound level data for typical rib, cross-bar, and retread type truck tires. A test sample of nine tread designs, estimated to represent 70-80% (based on discussions with fleet owners) of the truck tire population on the road today, was investigated considering noise levels as a function of the following variables: wear, loading, speed, pavement surface, and tire location. Test vehicles included both single-chassis vehicles and tractor trailers. The existing data base is expanded in this report to include one-third octave band spectral data, directionality data in the form of equal A-weighted sound level contours and other refined analysis of the data. Such data can serve as the groundwork for understanding the generation mechanisms by which tires produce noise -- the first step in developing the necessary data to design quiet tires scientifically.


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| FIGURE | FREQUENCY RANGE | TREAD DESIGN | DEGREE OF WEAR | NUMBER OF TIRES | LOADING CONDITION | SURFACE | PAGE |
|---|---|---|---|---|---|---|---|
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| C-2 | 500-1000 | Rib-A | New | Single | Unloaded | Concrete | 133 |
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| C-10 | 500-1000 | Rib-C | New | Dual | Unloaded | Concrete | 141 |
| C-11 | 0-500 | Rib-C | New | Single | Unloaded | Concrete | 142 |
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| C-13 | 0-500 | Rib-C | New | Single | Unloaded | Asphalt | 144 |
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| C-24 | 500-1000 | Cross-Bar-F | New | Dual | Unloaded | Concrete | 155 |
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| FIGURE | FREQUENCY RANGE | TREAD DESIGN | DEGREE OF WEAR | NUMBER OF TIRES | LOADING CONDITION | SURFACE | PAGE |
|---|---|---|---|---|---|---|---|
| C-31 | 0-500 | Cross-Bar-F | Fully-Worn | Single | Unloaded | Concrete | 162 |
| C-32 | 500-1000 | Cross-Bar-F | Fully-Worn | Single | Unloaded | Concrete | 163 |
| C-33 | 0-500 | Retread-I | New | Dual | Loaded | Concrete | 164 |
| C-34 | 500-1000 | Retread-I | New | Dual | Loaded | Concrete | 165 |
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Abstract

This report is the third in a series of reports published as a result of Department of Transportation sponsored truck tire noise research conducted by the National Bureau of Standards. The previous reports (OST-ONA-71-9 and OST/TST-72-1) contained details of the test design, test procedures, and an inventory of maximum A-weighted sound level data for typical rib, cross-bar, and retread type truck tires. A test sample of nine tread designs, estimated to represent 70-80% (based on discussions with fleet owners) of the truck tire population on the road today, was investigated considering noise levels as a function of the following variables: wear, loading, speed, pavement surface, and tire location. Test vehicles included both single-chassis vehicles and tractor trailers. The existing data base is expanded in this report to include one-third octave band spectral data, directionality data in the form of equal A-weighted sound level contours and other refined analysis of the data. Such data can serve as the groundwork for understanding the generation mechanisms by which tires produce noise -- the first step in developing the necessary data to design quiet tires scientifically.

## 1. Introduction

The goal of this tire noise research program is the identification and quantification of the physical parameters which affect the noise generation characteristics of truck tires and the development of an information base that may lead to standardized tire-noise procedures and to highway noise reduction criteria, standards, and regulations.

An extensive data base of maximum A-weighted sound levels due to truck tires has been established as a result of a field study carried out in two phases during the summer/fall of 1970 and 1971. These data, previously reported in earlier DOT reports [1,2][1/], supplemented the existing data on total truck noise and in conjunction with data developed concerning testing procedures can serve as the basis for meaningful vehicle noise regulations.

This report expands the existing data base to include spectral data -- one-third octave band and narrow band, and directionality information in the form of octave-band and equal A-weighted sound level contours. These data serve as additional information to our superficial understanding of tire noise generation mechanisms -- understanding which is vitally necessary if the tire engineer is to be provided with the data to design quiet tires scientifically. In addition, this information can be utilized by the urban planner as input data for the prediction of noise levels in nearby communities at various distances from present and proposed highways. The highway designer also can utilize these data as the basis for optimum location of roadways and for the proper design of roadside barriers to lower overall community noise levels.

Since this report serves as a companion document to the initial reports in this series [1,2], the details of the program, including a discussion of the test design, the operational aspects of the test, and the test procedure, which were discussed in detail in the earlier reports, are not repeated here. However, a summary of the pertinent material covered in the previous reports is presented in Appendix D.

---

[1/] Figures in brackets indicate the literature references at the end of this report.

## 2. Test Results

The initial reports [1,2] in this series presented the maximum A-weighted sound level data for typical rib, cross-bar, and retread type truck tires in various degrees of wear. This data base has been expanded to include the spectral and directional characteristics of these tires and the results are reported herein. The detailed results are presented in graphical form in Appendix A. In this section the general trends are investigated and the implications of the data are discussed.

### 2.1 Directional Characteristics

The directionality characteristics of truck tire noise are important since such data provide some insight into the noise generation mechanisms for tires and also provide additional information for urban planners and highway designers who are responsible for: (1) determining optimum highway routes to ensure minimum environmental impact; (2) specifying noise barrier materials, dimensions and locations; (3) and predicting community noise levels resulting from new highways or changing traffic flow patterns on existing roadways.

One would like to study a single tire at near maximum rated load running on typical road surfaces at various speeds. Ideally, at a given instant of time a large number of measurements would be made simultaneously at various angles and distances in the horizontal plane surrounding the tire.[2/]

It was not possible, however, to test a single tire. In all cases the test tires were mounted on single-chassis vehicles (four or six tires) or tractor trailer combination vehicles (eighteen tires). Since the single-chassis vehicle approaches the single tire goal more closely than does the tractor-trailer, the directionality contours shown in Appendix A are for coasting (engine shut off) single-chassis vehicles equipped with quiet tires on the steering axle and either two (single) or four (dual) test tires on the drive axle. The DOT/NBS test program was designed such that while the test vehicle, equipped with the tires of interest, coasted through the 1000 foot test section, voltages corresponding to the sound pressures at six microphone locations, at different distances from the path of vehicle travel, were recorded on magnetic tape in analog form. In addition to the microphones, which were located midway in the test section on a line perpendicular to the path of the vehicle (see Appendix C for a detailed description of the test section), a photosensor system (five photosensors located 250 feet apart along the vehicle path activated by a light source on the test vehicle -- which provided truck position and speed data versus time) was designed and utilized. By sampling the analog data [3/] and utilizing the photosensor data to convert the A-weighted sound level versus time data to A-weighted sound level versus distance data, it was possible to simulate an instantaneous measurement at a large number of microphone locations.

---

[2/] Results of feasibility studies [1] indicated that the A-weighted sound level was relatively independent of angle -- for ranges of $0^\circ$ - $25^\circ$ -- in the vertical direction.

[3/] For details on the procedure utilized in the development of the equal A-weighted sound level contour plots, see Appendix B.

It should also be noted at this time that the major concern at the onset of this program was the establishment of a data base of maximum A-weighted sound levels for typical truck tires. The directionality information, which was acquired during the same parametric study, was to be primarily utilized to assess the impact of tire noise on the community. For these reasons, the dynamic range of the instrumentation system was established such that the maximum A-weighted sound level was measured at each microphone location. This decision resulted in a limited amount of data being recorded for the 6 and 12 foot microphone locations. At these two positions, the maximum A-weighted sound level was recorded but little information was obtained on the noise level as the truck approached or receded from the microphone array due to the available dynamic range [approximately 40dB] of the data acquisition system. Therefore, the contour plots shown in Appendix A are derived chiefly from data for the remaining four microphones. These plots identify the sideward lobe of the characteristic directionality patterns for truck tires. Such lobes of maximum noise would have a greater effect on community noise levels, in general, then lobes fore and aft of the vehicle along the roadway.

Even though the emphasis was on community noise, it is important to gain a better understanding of the shape and magnitude of all of the lobes that exist in a characteristic directionality pattern for a given set of tires -- lobes to the front and rear of the vehicle as well as those to the side. Accepting the constraints imposed by the dynamic range of the instrumentation system, the following procedure was utilized to develop the directionality contour map shown in Figure 1. Two identical coastby runs were made at 45 mph on an asphalt surface. Four fully-worn, pocket-tread tires were mounted on the drive axle of the loaded, single-chassis vehicle. Neutral rib tires were mounted on the steering axle. During the first run the 6 and 12 foot microphones were set up to read the maximum A-weighted sound level during the passby. During the second run, these two microphones were allowed to saturate in the vicinity of the microphone array, however, they measured the sound level as the truck approached the microphone array and as the truck receded from the array. The data resulting from these two runs were merged to form the basis for the directionality pattern shown in Figure 1.

Four significant observations can be made from reviewing this directionality contour plot: [4/]

1. Tire noise is directional.

2. The forward lobe (along the vehicle path) is of short duration compared to the lobe behind the tires.

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[4/] The scales chosen for the ordinate and abscissa are not identical and it should be noted that the sideward lobe is exaggerated by the scale selection.

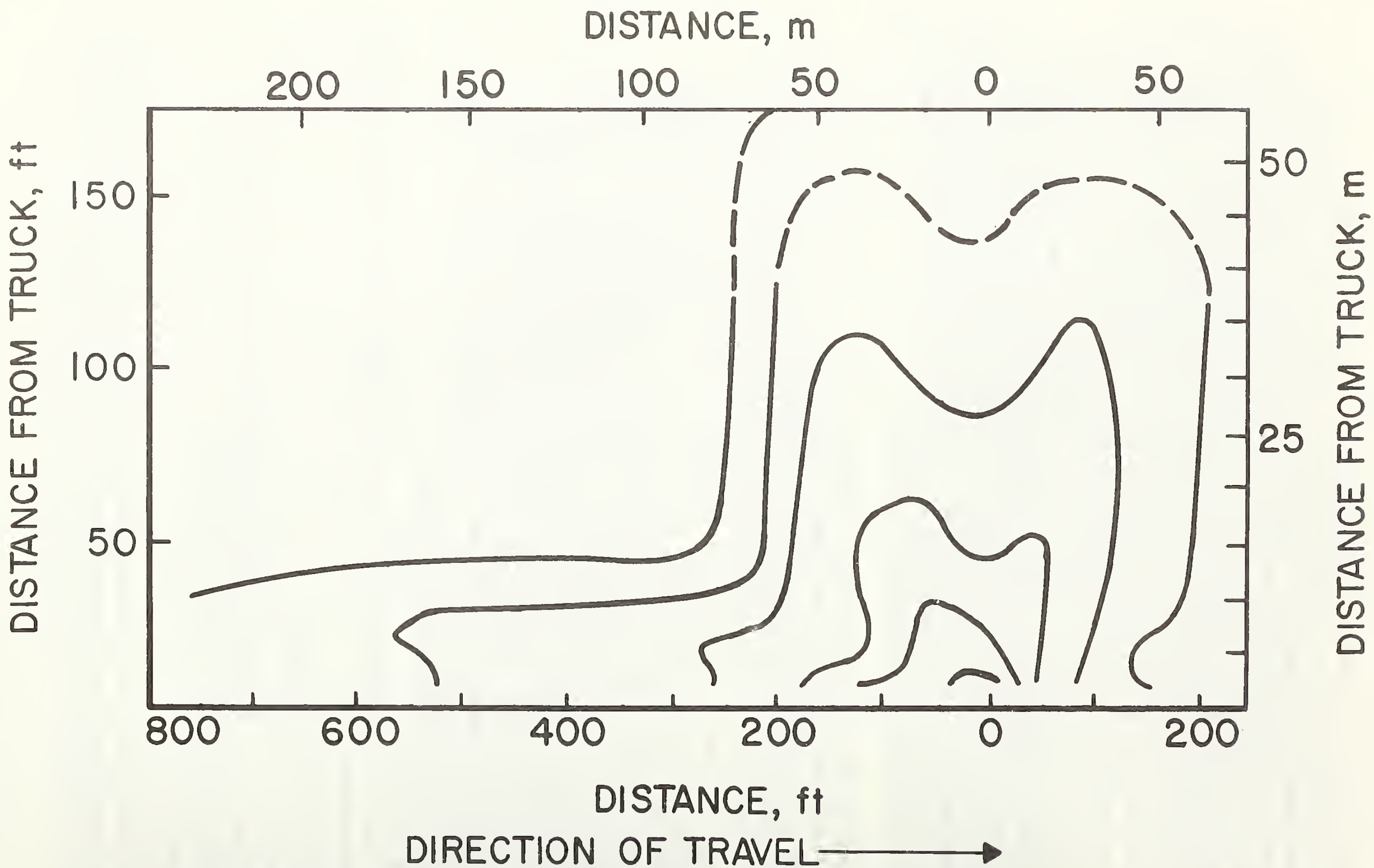


Figure 1. Equal A-weighted sound level contours (in dB re 20 μPa) characteristic of a single-chassis vehicle coastby at 45 mph on an asphalt surface. The test tires were fully-worn, pocket-treads (see Figure D-1 of Appendix D for tread design).

3. A double-peaked lobe is present to the side of the truck (peaks at approximately $\pm$ 45° fore and aft of the perpendicular, drawn through the zero point) as well as a possible third side lobe at a shallow angle (approximately 2°) with the roadway to the rear of the vehicle.

4. The maximum sound level is recorded after passage of the rear axle of the test vehicle past the microphone point (zero represents the centerline of the drive (rear) axle of the truck).

With the exception of the fourth observation, this is the characteristic pattern for all tires. Tire noise is directional. A majority of the contours exhibit the double peak to the side of the vehicle although some are much more pronounced than others. With the exception of the pocket-tread (retread-I), which served as the basis for the contour shown in Figure 1, the maximum level one would measure at 50 feet occurs prior to the passage of the tires past the microphone point. Due to the manner in which the contours were constructed, the third sideward lobe and the lobes fore and aft of the truck are not evident in the data in Appendix A and the angles at which the lobes are observed are not constant among tires.

At first, it was surprising that the maximum A-weighted sound level occurs prior to the passage of the tires past the observation point. Subjectively most people associate tire noise with the highly tonal tires whose high-pitched "singing" persists long after a truck has passed. Recently an analysis of tire tread noise based on tread element impact with the road surface was reported in the literature [3]. The analysis resulted in an equation for the impact energy loss. Part of this energy must be radiated from the tire as sound and it would seem that, since the impact occurs on the front end of the contact area, the front part of the tire is the principal radiating surface.

The directionality contour plots shown in Appendix A indicate that even at a distance of 130 feet from the noise source -- which is many times the length of the noise source -- one does not observe a constant decrease in sound level as the distance from the source is doubled along any given angle. Thus, the widely utilized rule of thumb that far-field conditions exist roughly at distances of more than one wavelength away from a source or at 2 to 3 times the largest linear dimension of the noise source, whichever is the greater, should be applied with caution.

Although small changes are observed in the characteristic A-weighted sound level directionality contours for a given tire type as parameters such as load or pavement surface are varied, gross changes are not typical. In general, the effect of parameter variation is evidenced only by a change in the location of any given contour with respect to the source.

Departures from relatively smooth contours -- evidenced by the existance of irregularities in contour shape -- are observed on occasion. One expects the contours further from the source to be irregular since the distance is such that one is approaching the limits of available signal-to-noise ratio. However, a review of the tabular data from which the directionality contours were constructed indicates that, in general, in those cases where the irregularity is confined to a single contour line, these irregularities are caused by isolated atypical data points which the contour plotting routine does not ignore.

To further investigate the directional characteristics of truck tires, a representative tread design was selected from each of three generic tread catagories -- rib (rib-B), cross-bar (cross-bar-F) and pocket (retread-I) type tread designs -- and equal sound pressure level contour plots were generated for the eight octave bands between 31.5 Hz and 4 kHz. The resultant contour plots are shown in Figures 2-13. Octave band rather than one-third octave band plots were developed to avoid the difficulty of tonal components shifting from one band to an adjacent band due to Doppler shifts as the truck passed through the test section. Figure 14 shows a plot of one-third octave band sound pressure level versus frequency versus time for a truck passby as measured at a 50 foot microphone location. The truck was equipped with tires with a representative cross-bar type tread pattern. The Doppler shift of the fundamental from one third-octive band to another is obvious.

As might be expected, the contours, in general, are rather omnidirectional at the lower frequencies and more directional at higher frequencies. However, the contour map for the octave band containing the fundamental is very complex and highly directional. Similar, although not as pronounced, effects are seen in octave bands containing harmonics of the fundamental which represent significant peaks in the spectrum for that tire. It should be obvious that use of the A-weighting network tends to mask some of the detailed information which will be necessary to identify the tire noise source mechanisms.

At this point in time our understanding of the tire noise generation mechanisms is such that we have no basis to attach any further meaning to these contours, especially since they do not represent (due to practical reasons) the directionality contour for a single tire.

The directionality plots also provide data pertinent to the establishment of minimum requirements for measurement test sites suitable for tire certification testing. The important factors in tire certification testing are that the vehicle be at the proper speed and that the maximum noise generated by the tire be observed at the microphone while the vehicle is in the test zone. For the majority of the data reported in the literature, no information is reported regarding vehicle position when maximum noise is recorded during a passby. In this study, however, care was taken to ensure that vehicle position and speed were recorded throughout the series of tests.

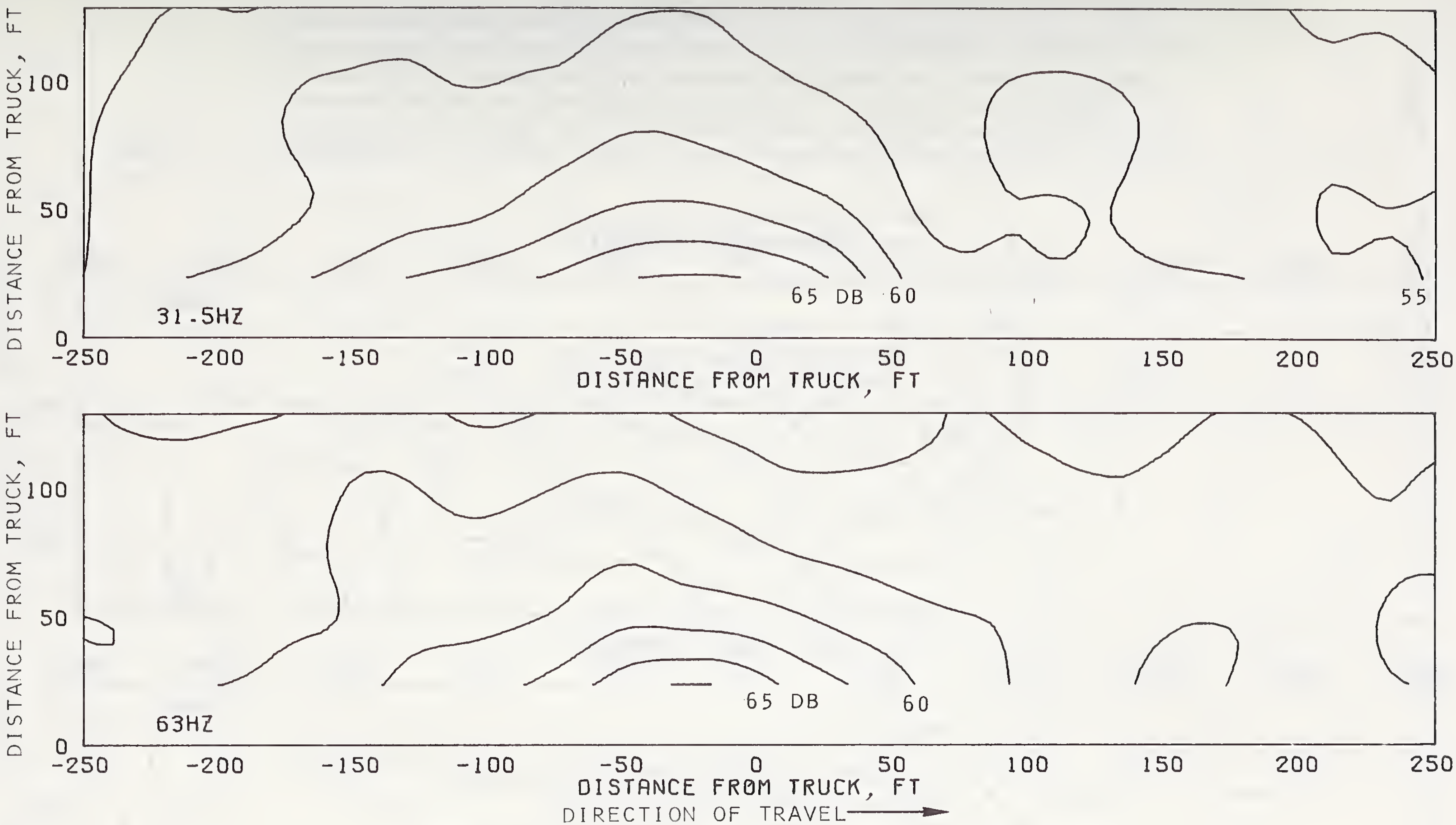


Figure 2. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 31.5 Hz octave band while the lower plot shows a similar contour for the 63 Hz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, rib-B, tires on the drive axle.

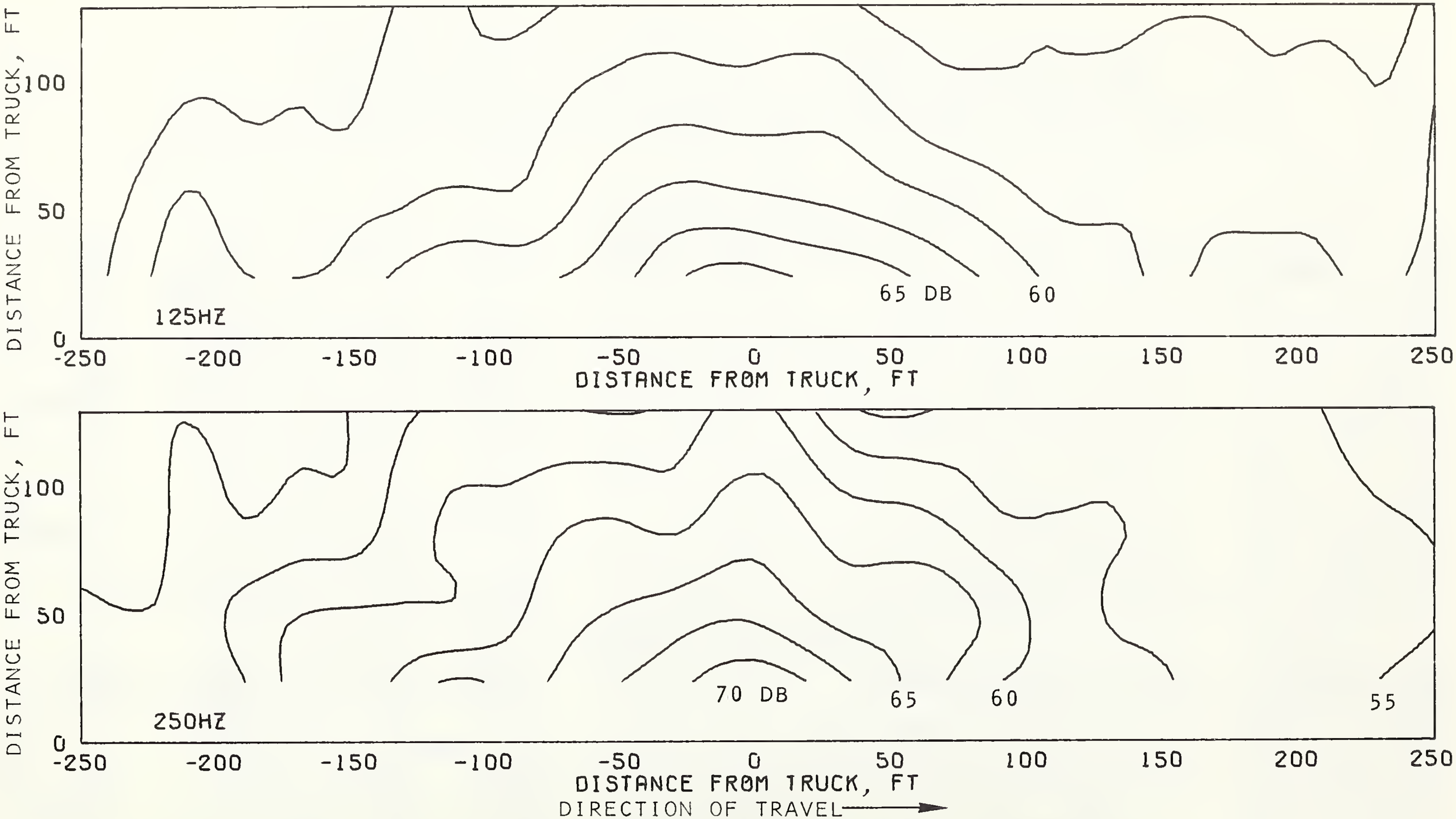


Figure 3. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 125 Hz octave band while the lower plot shows a similar contour for the 250 Hz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, rib-B, tires on the drive axle.

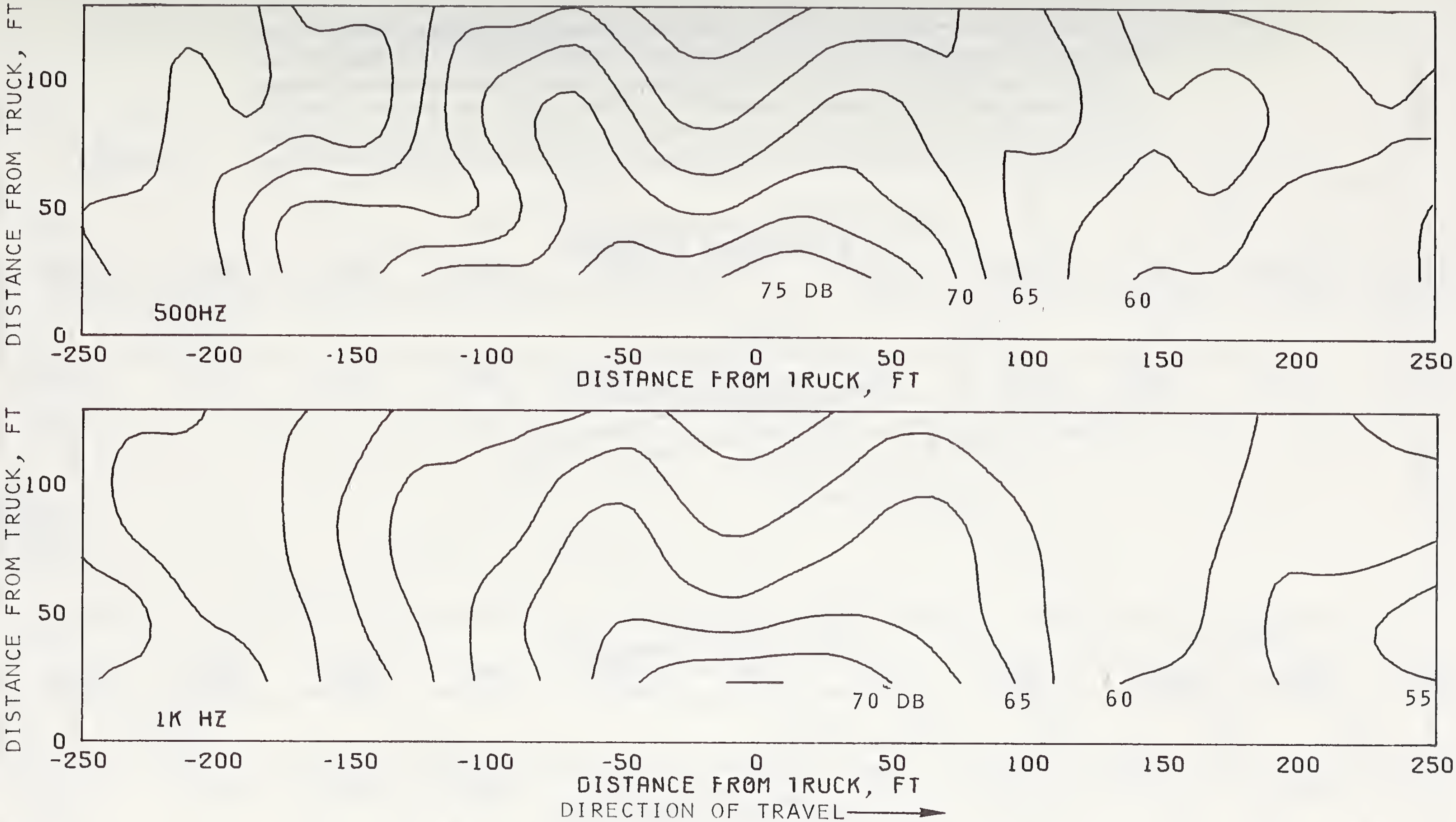


Figure 4. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 500 Hz octave band while the lower plot shows a similar contour for the 1 kHz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, rib-B, tires on the drive axle.

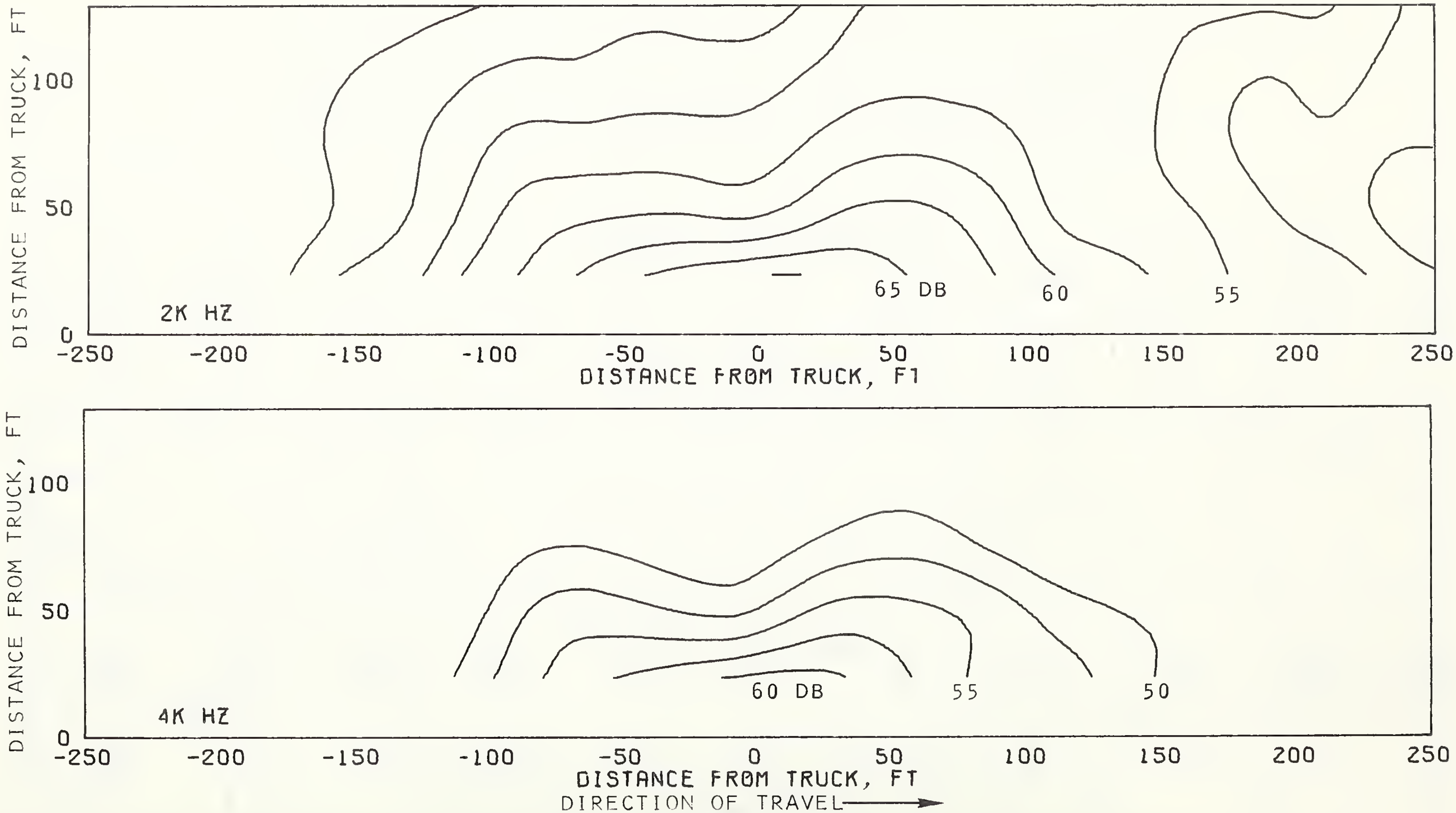


Figure 5. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 2 kHz octave band while the lower plot shows a similar contour for the 4 kHz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, rib-B, tires on the drive axle.

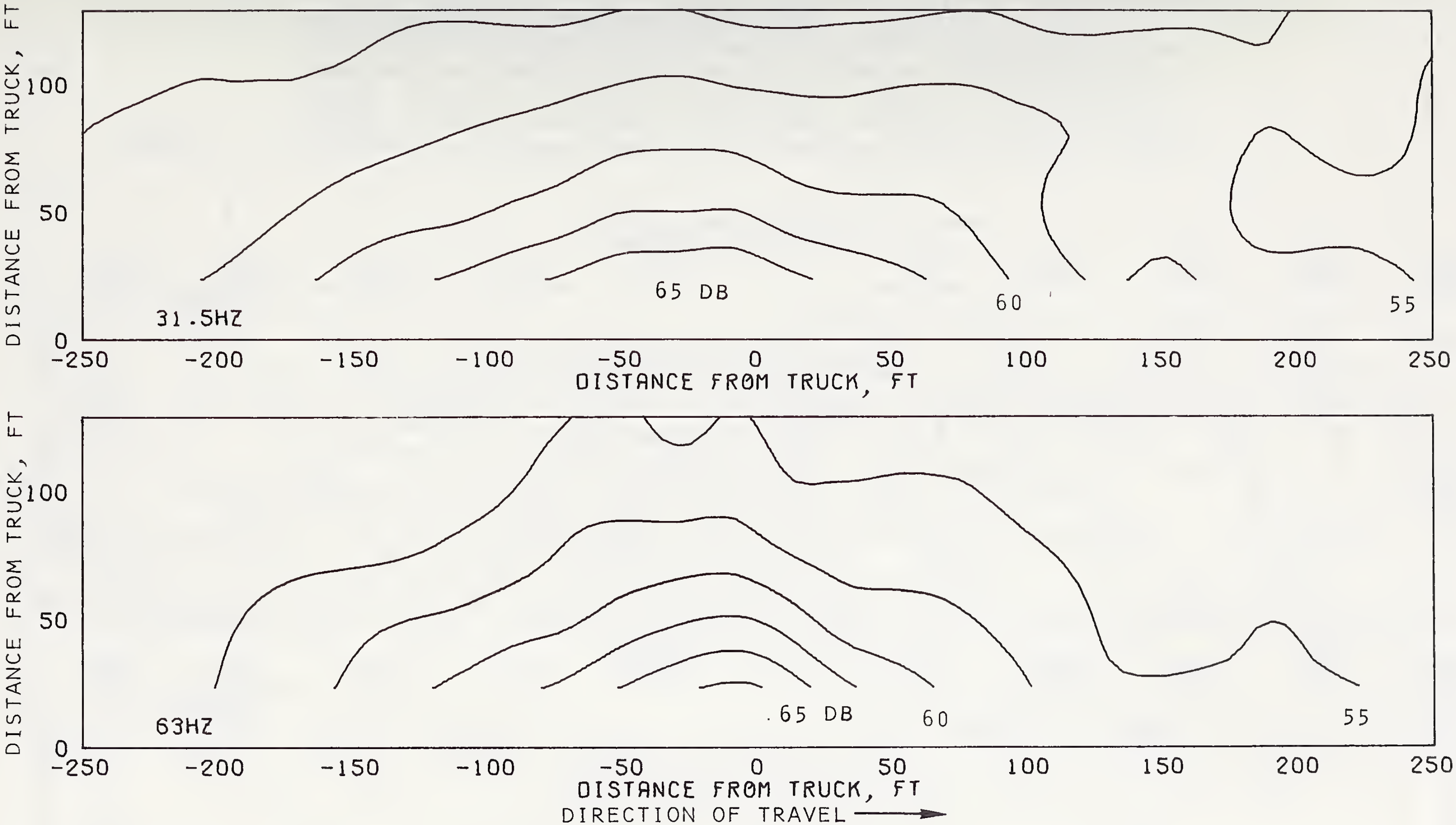


Figure 6. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 31.5 Hz octave band while the lower plot shows a similar contour for the 63 Hz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, cross-bar-F, tires on the drive axle.

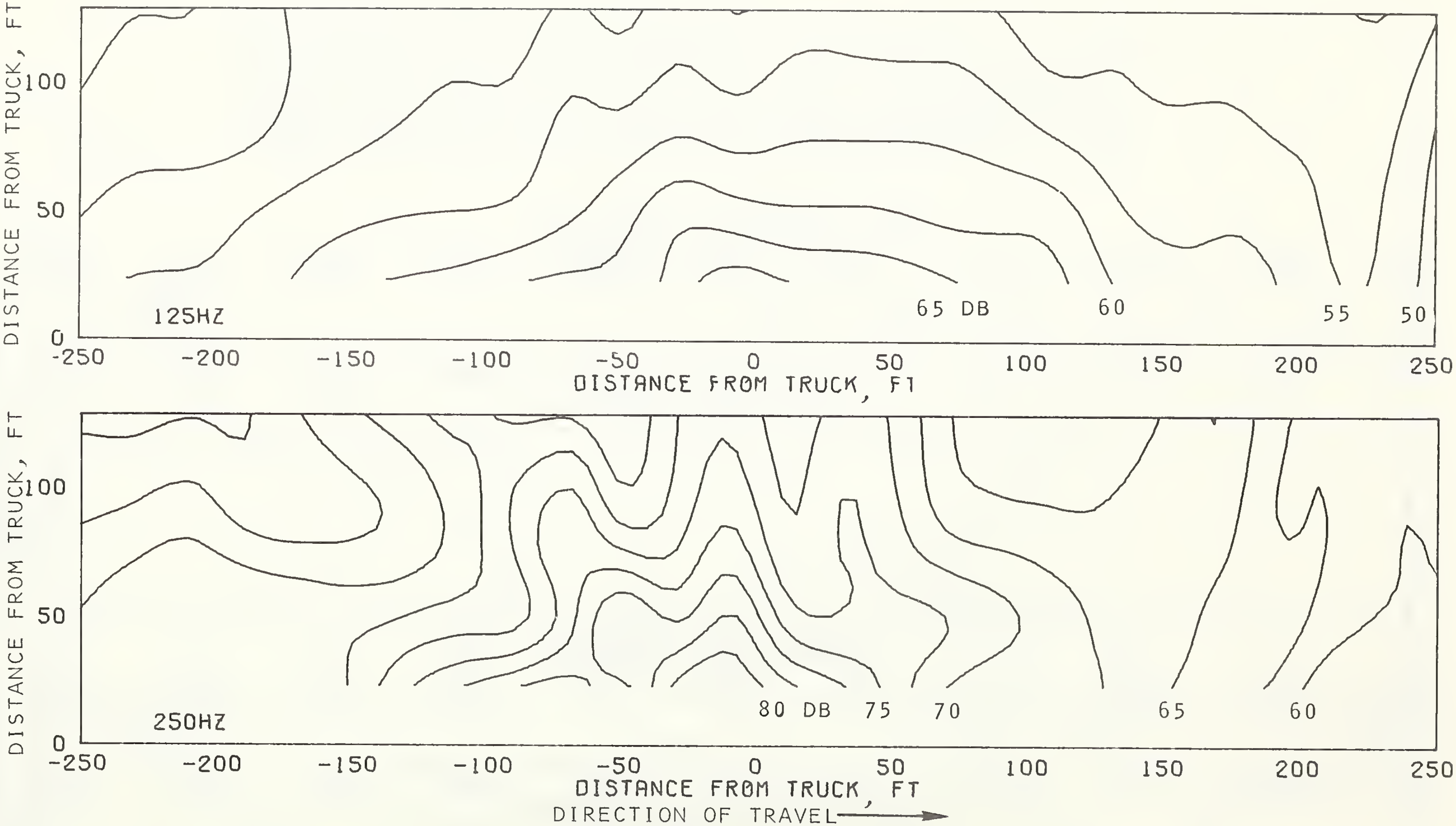


Figure 7. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 125 Hz octave band while the lower plot shows a similar contour for the 250 Hz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, cross-bar-F, tires on the drive axle.

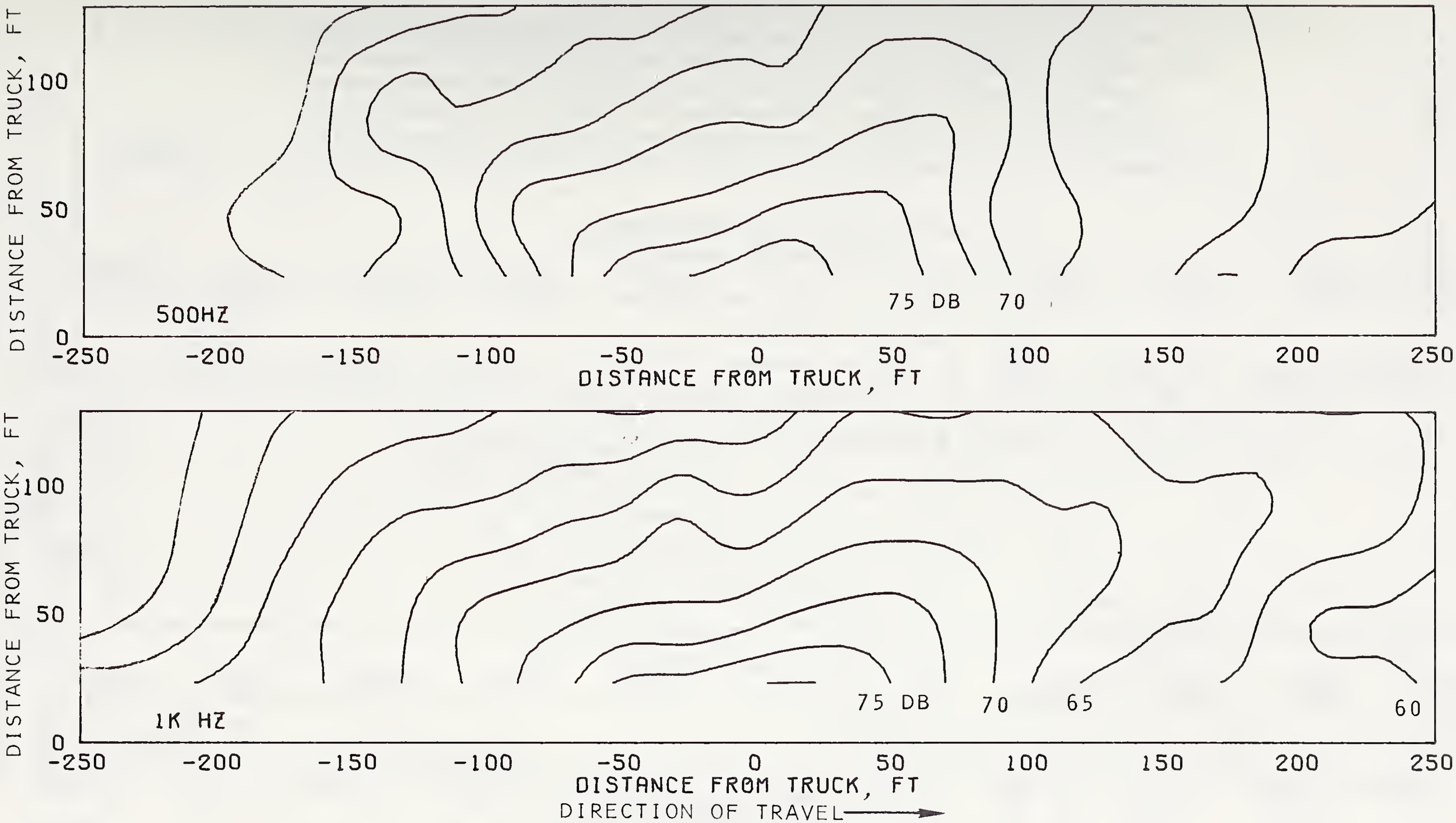


Figure 8. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 500 Hz octave band while the lower plot shows a similar contour for the 1 kHz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, cross-bar-F, tires on the drive axle.

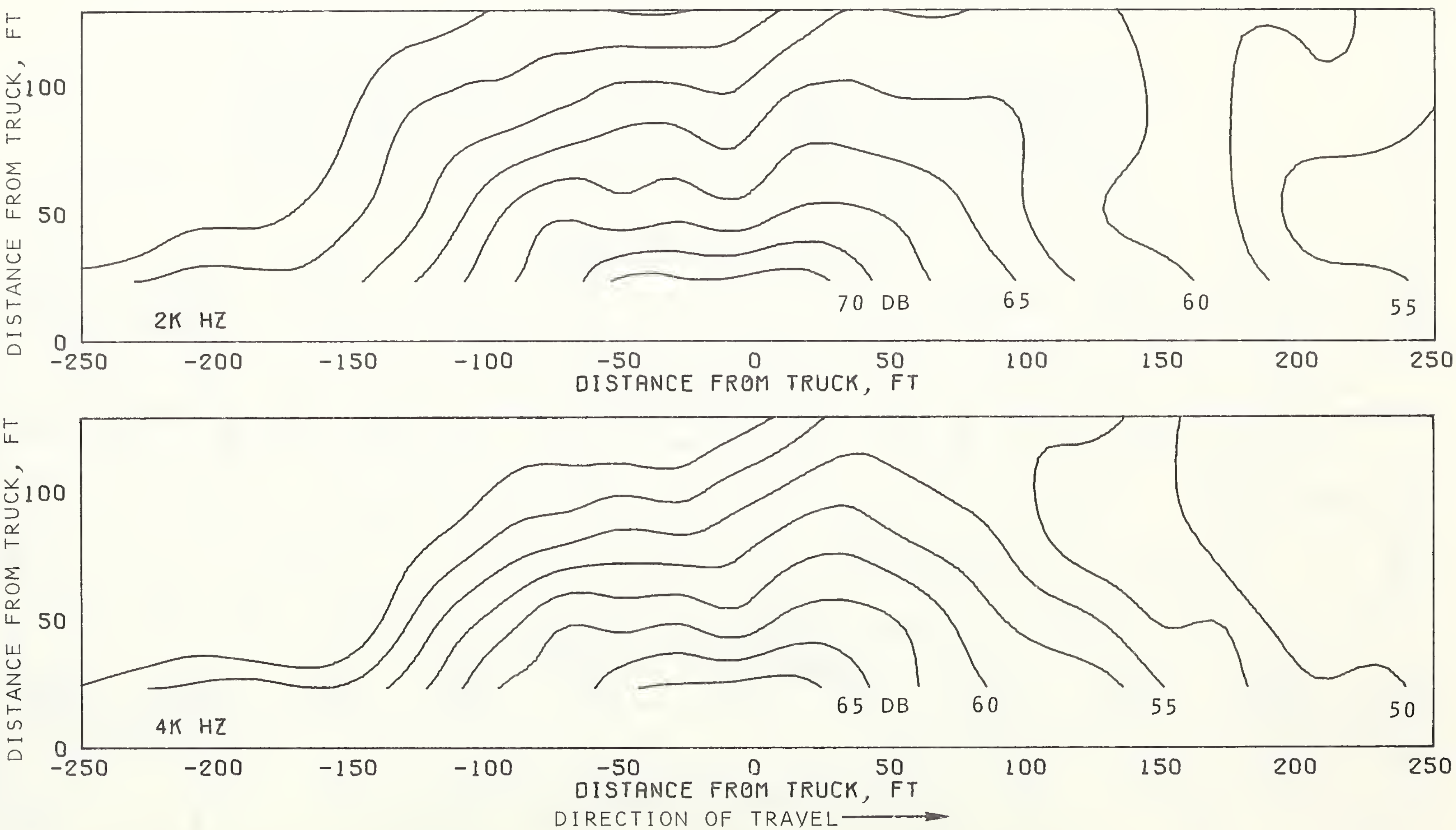


Figure 9. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 2 kHz octave band while the lower plot shows a similar contour for the 4 kHz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, cross-bar-F, tires on the drive axle.

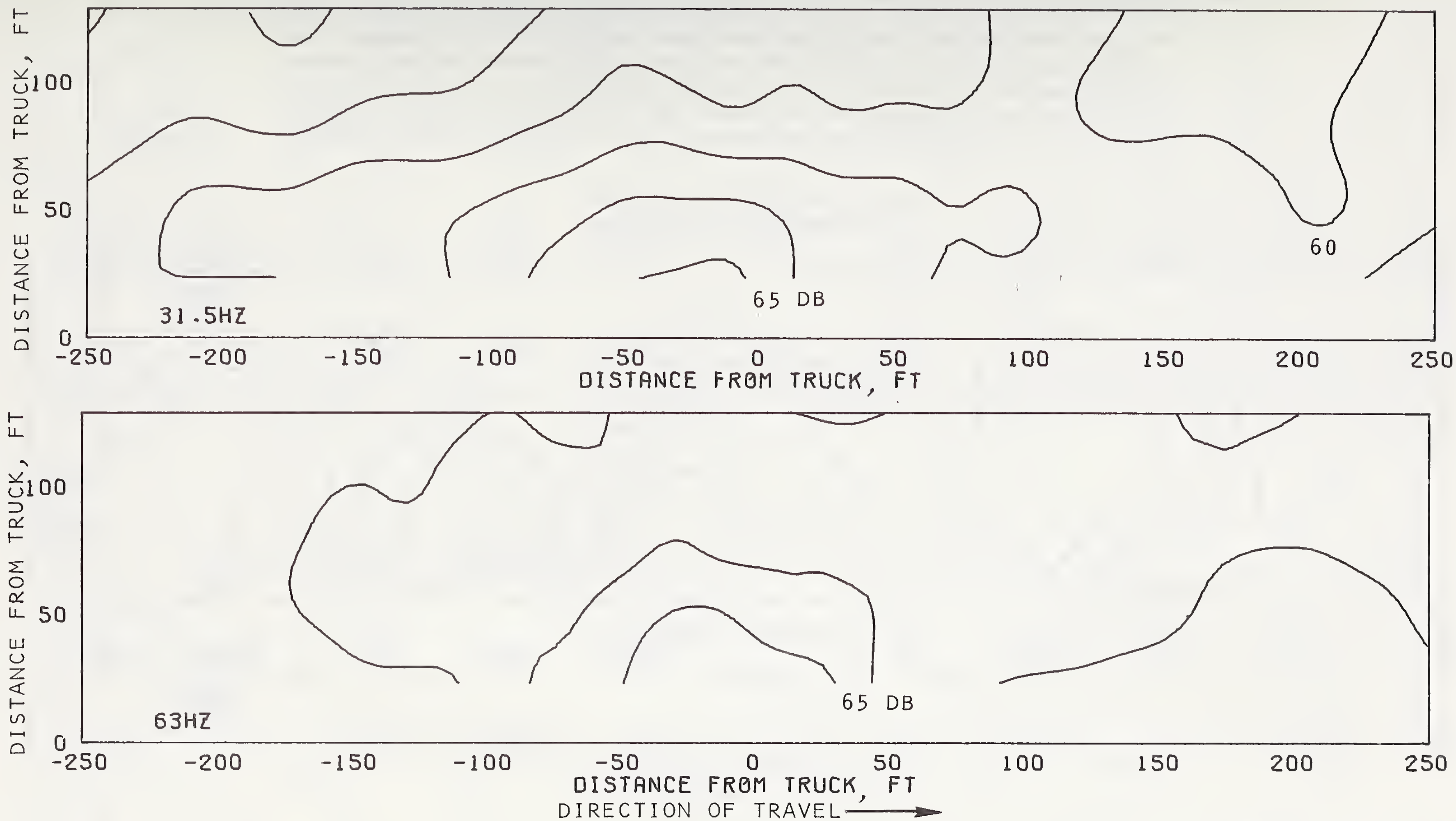


Figure 10. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 31.5 Hz octave band while the lower plot shows a similar contour for the 63 Hz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, retread-I, tires on the drive axle.

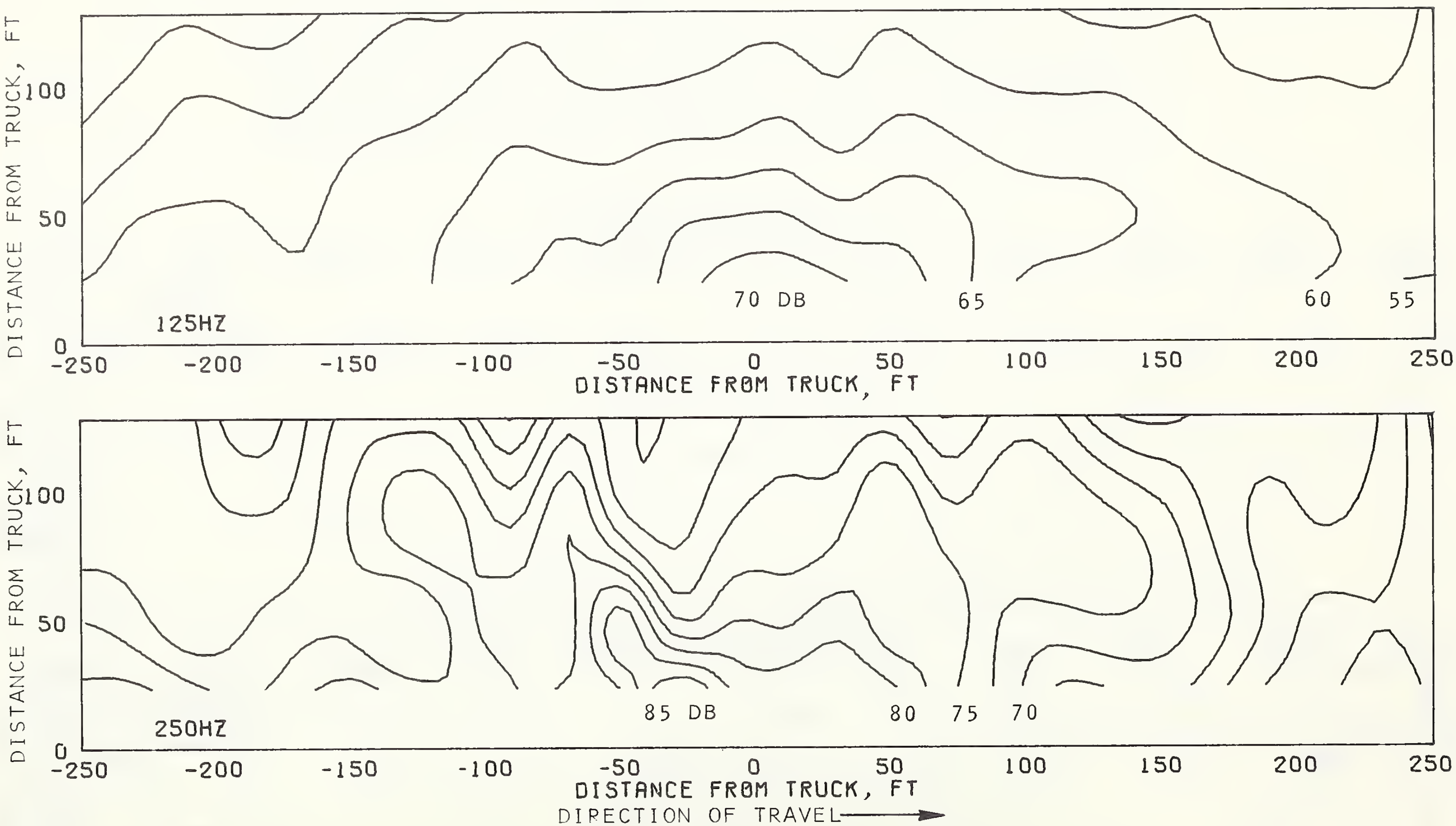


Figure 11. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 125 Hz octave band while the lower plot shows a similar contour for the 250 Hz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, retread-I, tires on the drive axle.

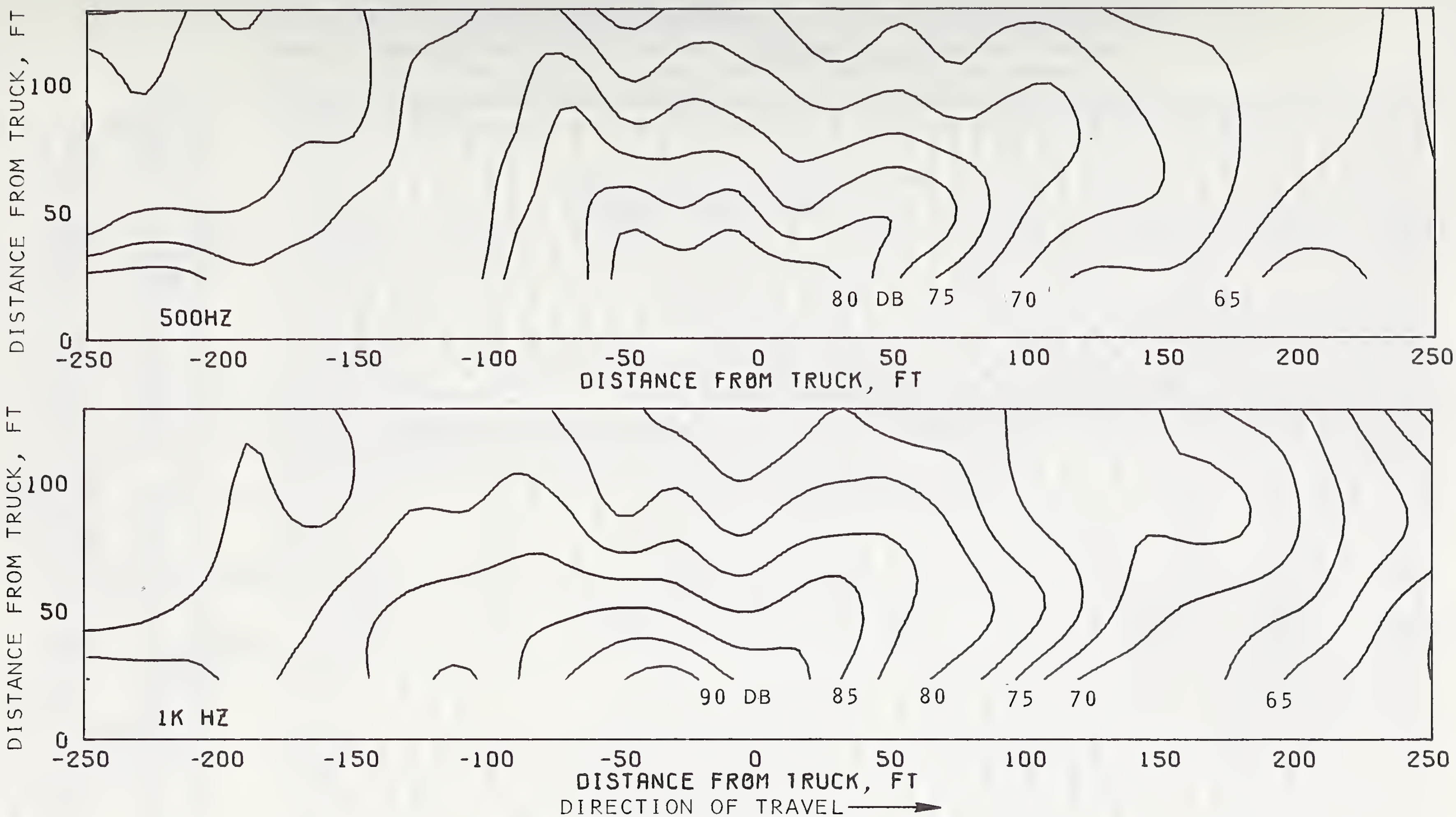


Figure 12. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 500 Hz octave band while the lower plot shows a similar contour for the 1 kHz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, retread-I, tires on the drive axle.

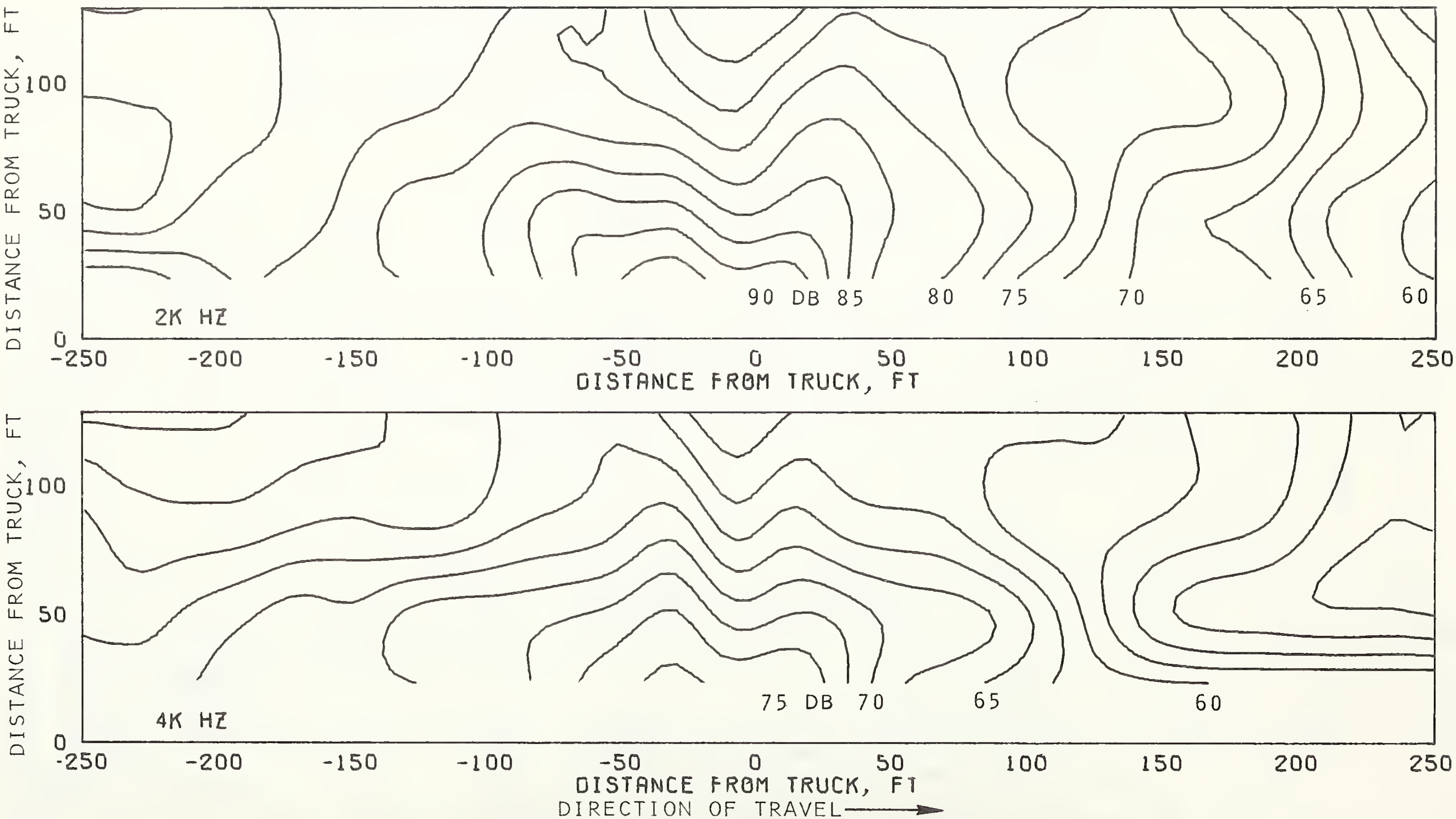


Figure 13. The upper plot presents equal octave band sound pressure level (in dB re 20 μPa) contours for the 2 kHz octave band while the lower plot shows a similar contour for the 4 kHz octave band. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, retread-I, tires on the drive axle.

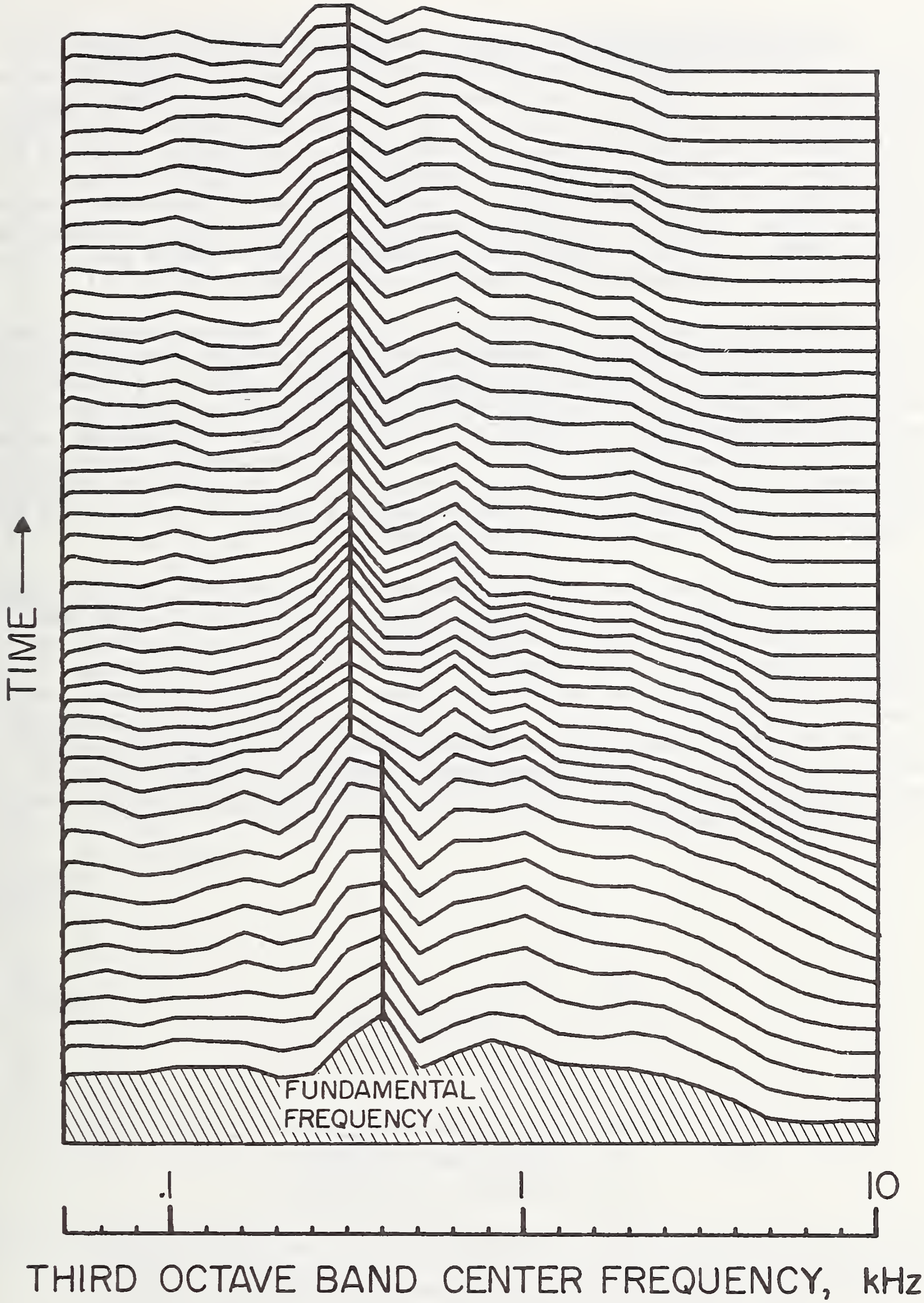


Figure 14. One-third octave band sound pressure levels (in dB re 20 μPa) versus time for a truck coastby as measured at 50 feet. The truck was equipped with tires with a representative cross-bar type tread pattern.

Utilizing this data base, equal A-weighted sound level contours whose levels corresponded to the maximum A-weighted sound level observed during the truck passby at the specific microphone locations at 25, 50, 80, and 130 feet were generated for each tire tread design in that state of tread wear which corresponded to the maximum noise level produced by that tire. These plots, shown in Figures 15-17, correspond to the loaded single-chassis vehicle coasting at a speed of 50 mph on a concrete surface. The test tires were mounted in dual pairs on the drive axle of the truck while neutral rib (rib-A) tires were mounted on the steering axle. These contours are supplementary to those presented in Appendix A.

From these data it is evident that for a 50 foot measurement location the maximum A-weighted ["FAST" response] sound levels generated by truck tires are typically measured prior to the passage of the drive axle of the truck past the microphones when tires with rib or cross-bar tread patterns are mounted on the vehicle. On the average, such maximum noise levels are recorded 30 to 40 feet prior to the passage of the drive axle. The lobe of maximum noise for pocket tread tires (retread-I) is usually the rearward lobe and maximum sound levels are typically measured 50 to 75 feet behind the truck (or after passage of the drive axle).

Realizing that these pocket-tread tires are presently being phased out, it would appear that the minimum vehicle path should be 100 feet [± 50 feet on either side of the microphone location] if one hopes to achieve a measurement of maximum tire noise on a 50 mph coastby of a single drive axle, loaded vehicle utilizing a 50 foot microphone location. If other vehicle speeds or microphone locations are utilized in the future, the minimum test site requirements stated here may not be valid; therefore, the situation would have to be reevaluated based on the directionality contours characteristic for the chosen vehicle speed and microphone location.

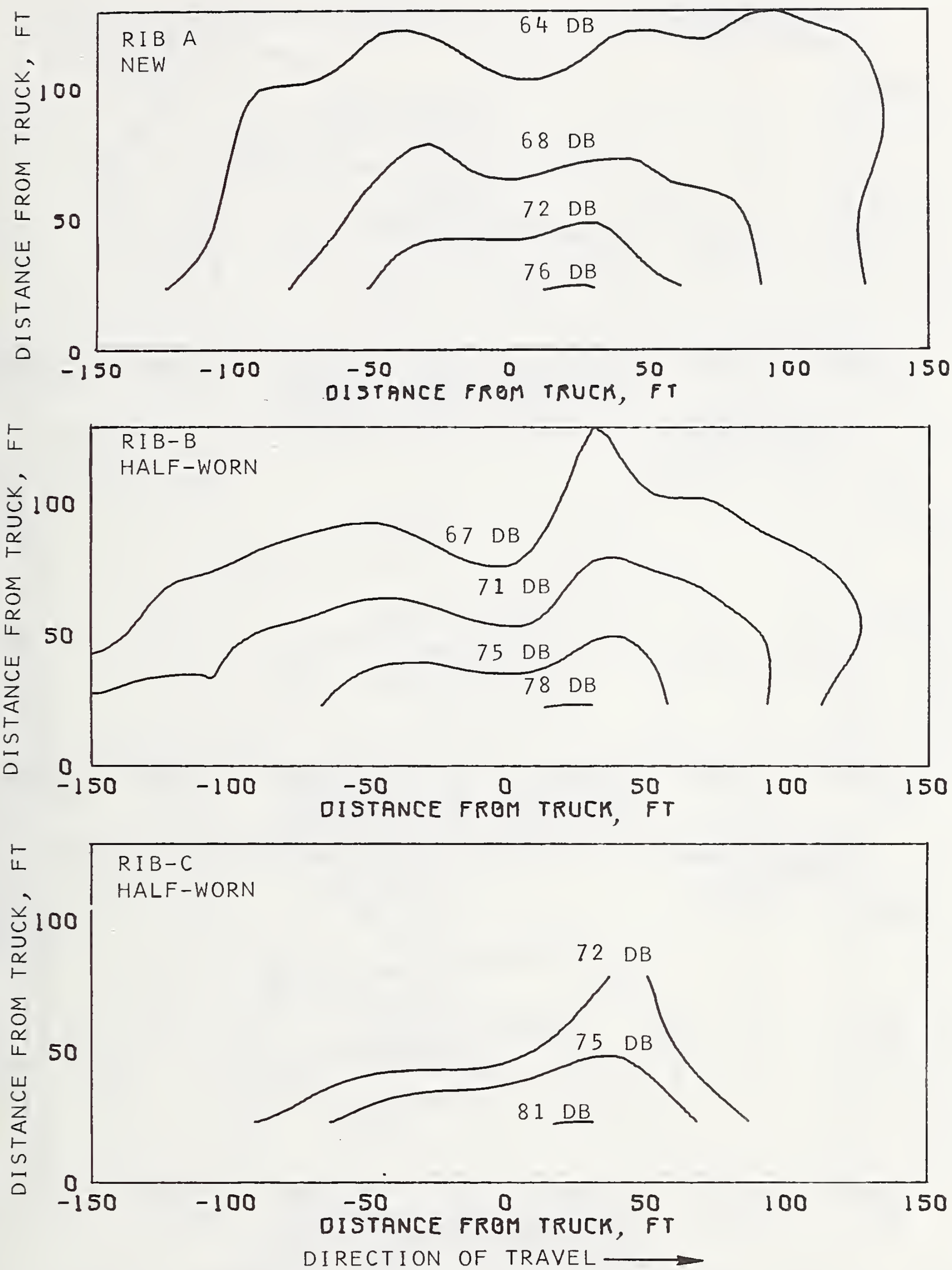


Figure 15. Maximum A-weighted sound level contours as measured at the 25, 50, 80, and 130 foot microphone locations. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface with various rib tires mounted in dual pairs on the drive axle.

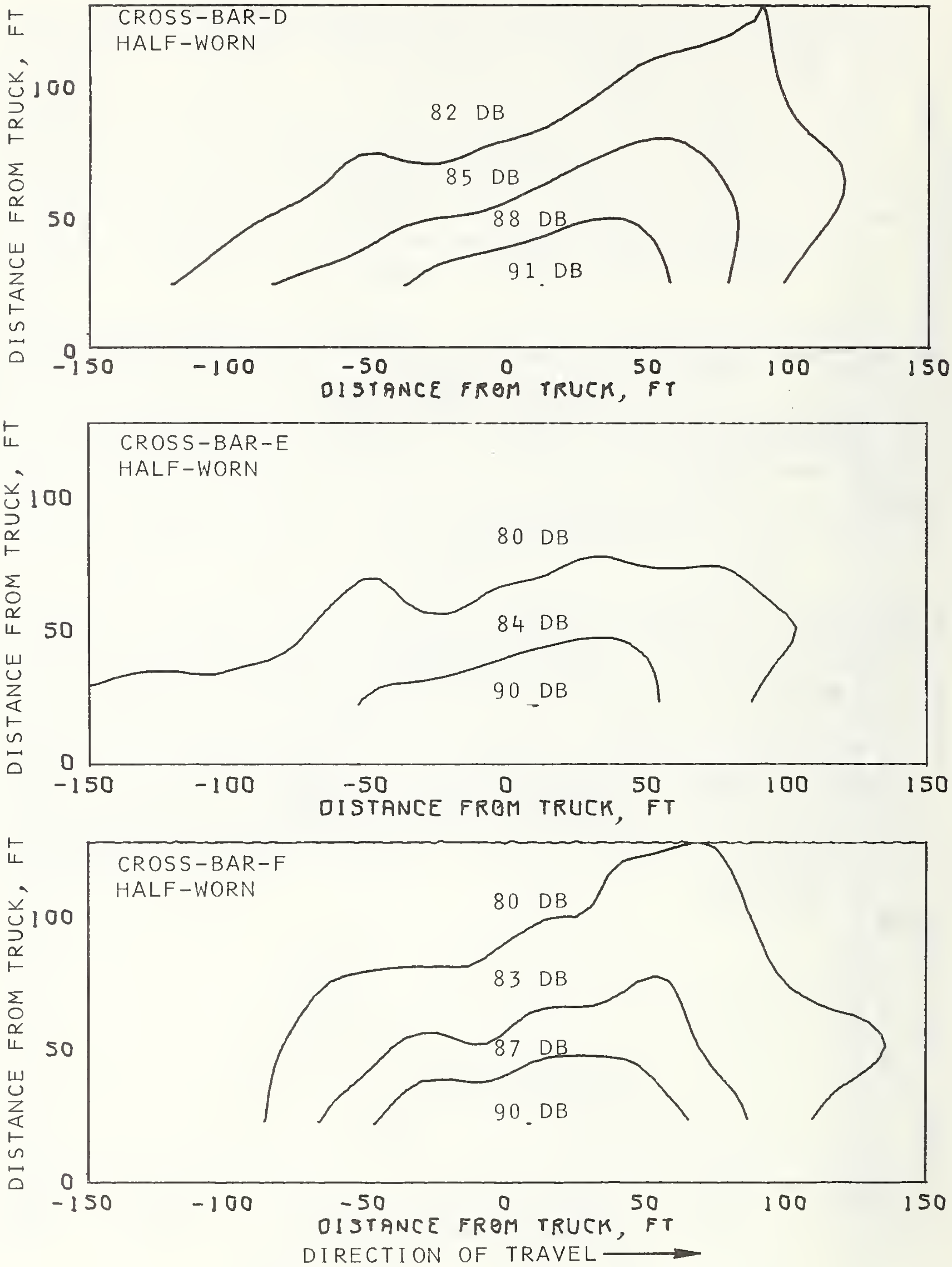


Figure 16. Maximum A-weighted sound level contours as measured at the 25, 50, 80, and 130 foot microphone locations. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface with various cross-bar tires mounted in dual pairs on the drive axle.

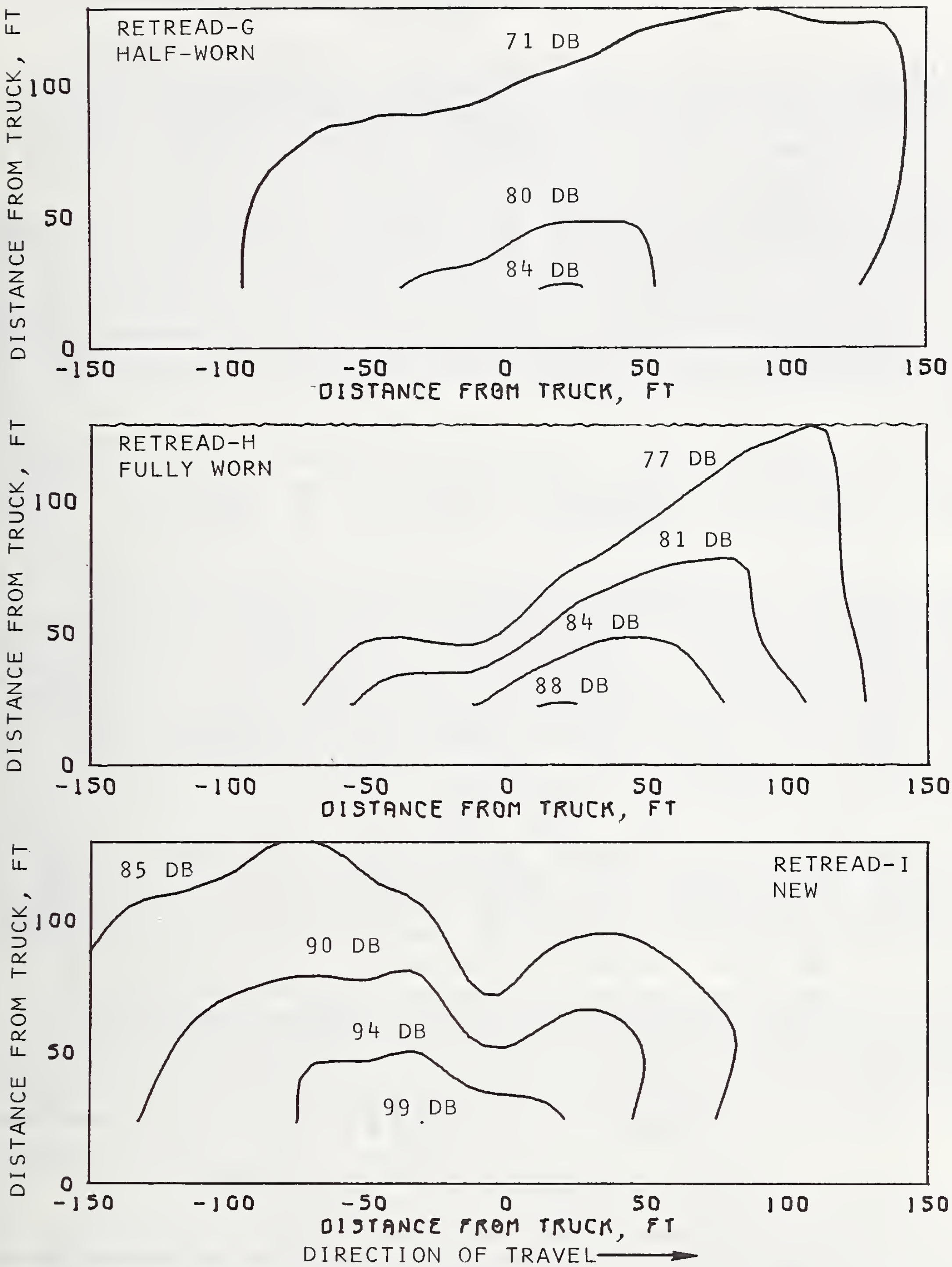


Figure 17. Maximum A-weighted sound level contours as measured at the 25, 50, 80, and 130 foot microphone locations. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface with various retread tires mounted in dual pairs on the drive axle.

## 2.2 Spectral Characteristics

In order to gain an understanding of the mechanisms by which tire-road interaction noise is generated, one cannot simply look at single number descriptors such as the A-weighted sound level but must analyze the noise in finer detail through spectral analysis. The data for all runs have been analyzed in one-third octave bands. These data, for the single-chassis vehicle at the time corresponding to the occurrence of the maximum A-weighted sound level, are reported in Appendix A. Spectral measurements on tire sounds by a stationary observer along the roadway are complicated by the motion of the source of sound -- the spectrum changes with time as the relative positions of the tire and the observer change. The Doppler effect contributes an additional shift in frequencies which also changes as the relative position of the tire and observer change.

The evaluation of tire noise source mechanisms is a very complex task. At present, three generic types of tire noise source mechanisms have been postulated -- aerodynamic, air pumping and vibration.

Aerodynamic sources refer to unsteady flow over the tire, attributable largely to the whole-body motion of the tire through nearly-stationary air. Siddon [4] speculates that fluctuating pressures from vortices generated at the trailing edge of a tire near the road are sufficient to contribute substantially to roadside noise. While this may be the case for smooth tires operating on smooth roads, it hardly seems likely to be a major source in view of the overwhelming data demonstrating a dependence of tire noise on road roughness and tread design.

Investigators are in general agreement that air pumping is a major contributor to tire noise. As a tire tread segment contacts the road surface, air is squeezed out of the small depressions in the road and tire interstices. As the tread segment leaves the surface, air rushes back to fill the voids. Hayden [5] modeled this oscillating flow by assuming a compact array of monopole sources of noise associated with the leading and trailing parts of the contact area and developed an expression for estimation of the overall sound pressure radiated by a single tire as:

$$\begin{aligned} SPL = 68.5 = 20 \log \left(\frac{\delta w}{S}\right) + 40 \log v \\ + 20 \log f + 10 \log m - 20 \log r \end{aligned} \tag{1}$$

Where, $\delta$ = tread depth, w = width of a single cavity or groove in the tread, S = circumferential distance between tread grooves, v = vehicle velocity, f = fractional change in cavity volume, m = cavities per tire width and r = distance from tire to observation point.

A similar expression applies when one treats the roadway depressions in the same manner as the tread interstices.

Vibration of the tire carcass (caused by tire/road interaction) is believed to be a third source of noise. There exist numerous possible excitation and radiation mechanisms as well as types of tire response that could characterize tire vibration and attendant sound generation.

An initial excitation mechanism that should be considered is the interaction of the tread elements with roadway surface irregularities. As a tire rotates, the tread is pulled radially by centrifugal force for a large percentage of travel and then comes suddenly to rest on the ground. An impact occurs that is semi-elastic in nature and some of the energy must be lost through the tire tread and walls in flexural vibration which is radiated as sound. This mechanism is likely to be of major importance. Of probable lesser significance are nonuniformities of tire construction which give rise to fluctuating values of radial stiffness, with attendant force variations. The fundamental component associated with tire nonuniformities corresponds to tire rotation rate, which at highway speeds is very low frequency. It is unlikely that harmonics of this will be significant in the frequency range of substantial sound radiation.

Tire vibrational characteristics and mechanisms of sound radiation may be evaluated together in three frequency regimes. At low frequencies, below the first carcass mode, one would expect the tire to respond only in the vicinity of the contact area. This mechanism is not likely to be of consequence because these frequencies are so low. At higher frequencies, the carcass responds in a modal manner. Tire modes are inefficient radiators since the wavelength corresponding to the frequency of vibration is much greater than the distance between the contracting and expanding parts of the tire. At still higher frequencies, waves in the carcass will be generated at the roadway interface. If the phase velocity of these waves is above critical (i.e., above the speed of sound in air) the waves will radiate very efficiently. However, even subcritical waves may radiate significant sound levels owing to low wavenumber components associated with the excitation point.

Tire tread and carcass vibration as a source of tire noise is actively being investigated by researchers at North Carolina State University[6]. This on-going analytical and experimental program, under the sponsorship of the Office of Noise Abatement, Department of Transportation, should provide considerable insight into the role of tire vibration as a tire-noise source mechanism.

Since both the vibration and air pumping mechanisms result from the interaction of the tire with the roadway surface, the tire tread design and the surface texture of the roadway are very important determinants of the noise generated by a given tire. Many truck tire manufacturers do not use tread patterns possessing uniform pitch. In general randomized pitch lengths are utilized so as to produce a more pleasant, or at least less intrusive, sound than the pure tones associated with regular tread spacing.

The tire noise spectrum is composed of two parts: a periodic variation due to the tread pattern and tire nonuniformities and an aperiodic variation due to the road surface cavities. The periodic component exhibits spectral peaks at discrete frequencies and the aperiodic component exhibits a more continuous spectrum. The frequencies of the spectral peaks are associated with the tire design (tread spacing) and the tire rotational rate. The fundamental frequency can be predicted by calculating the number of tread elements which pass through the footprint per second. If the distance between consecutive tread elements is uniform, the sound produced is nearly a pure tone whose frequency is given by [7]:

$$f = \frac{17.6V}{a}$$

where, f = fundamental frequency, Hz
V = vehicle speed, mph
a = tread spacing, in.

Most tire manufacturers, however, do not utilize a uniform element spacing. The pitch lengths are usually varied in some manner so as to produce a less intrusive sound than a pure tone. The difficulty is defining the so-called tread spacing. Modern tires are produced by molding into the tread major grooves (in the case of rib tires major grooves are oriented in the circumferential direction while for cross-bars the grooves are oriented in the lateral direction) and secondary grooves or slots called siping, all of which contribute in some unknown way to the complex acoustic signature of the tread pattern.

Table 1 shows the major tread spacing for the tires tested when new, the predicted frequency of the fundamental based on major tread spacing, and the one-third octave frequency band in which the fundamental was actually measured. The calculations are based on a vehicle speed of 50 mph. Since there is some question as to what is meant by the term "major tread spacing", footprints of the tires tested along with identification of the major tread spacings as defined for the purposes of this report are presented in Figures 18, 19, and 20 for rib, cross-bar and retread tires, respectively. Although present understanding of tire noise source mechanisms does not allow one to identify the mechanism -- air pumping and/or vibration -- excited by the tread elements interacting with the road surface, in most cases the one one-third octave band in which the maximum signal level could be found was predictable on the basis of tread spacing considerations.

A reasonable question to pose at this time is whether one-third octave band analysis provides the discrimination necessary for pinpointing particular frequencies associated with noise generation mechanisms. Identification of specific frequencies rather than a range of frequencies should assist in the identification of the mechanisms associated with the frequencies observed. To address this question, a minimum of one run for each tire tread type studied (with the exception of retread-G) was selected for narrow band analysis. [5/]

[5/] The work was performed under contract with Hydrospace Research Corporation, Rockville, Maryland.

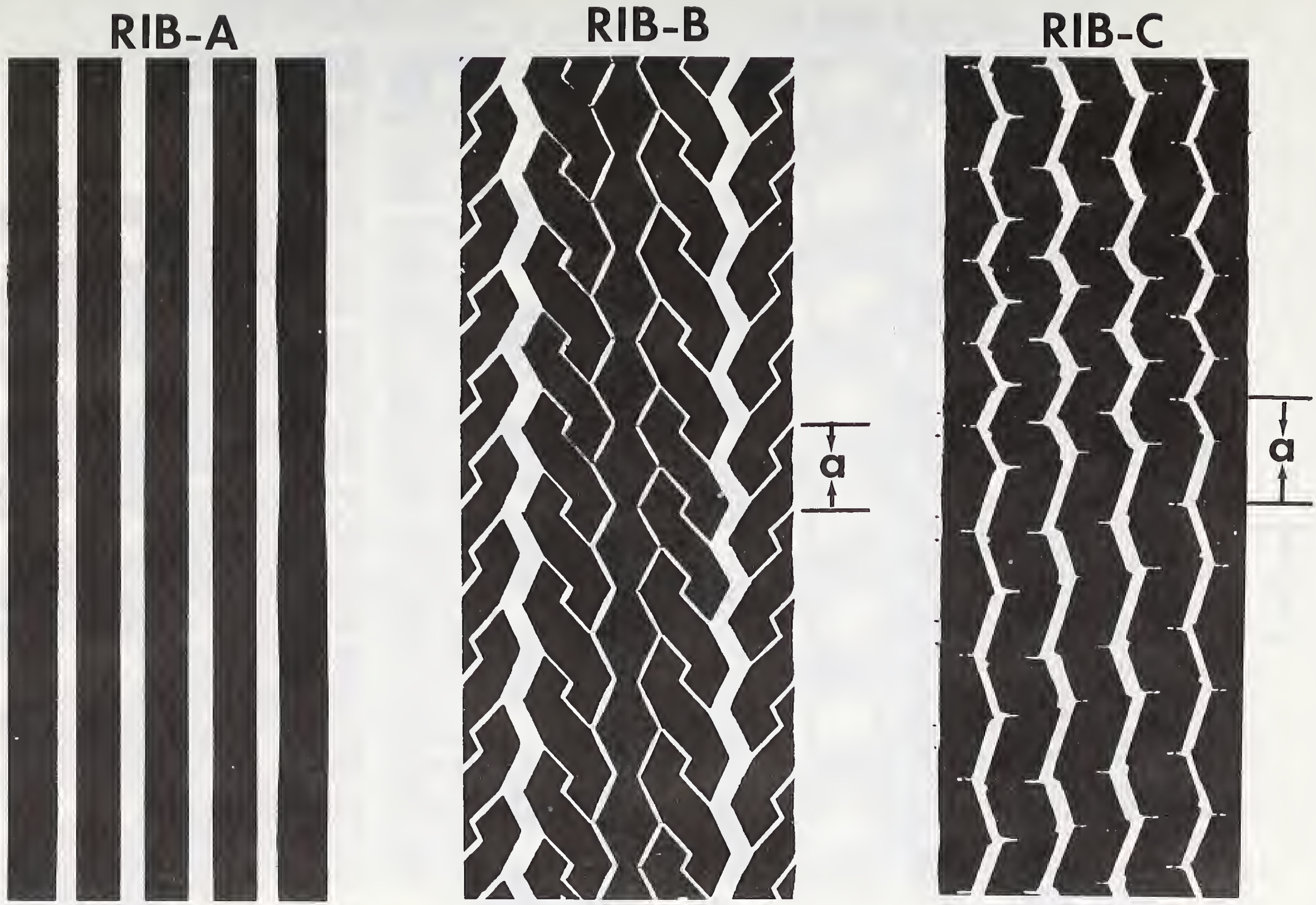


Figure 18. Test tires of rib tread design with the major tread element spacing, designated as "a", identified. See Table 1 for the "a" values for these tires.

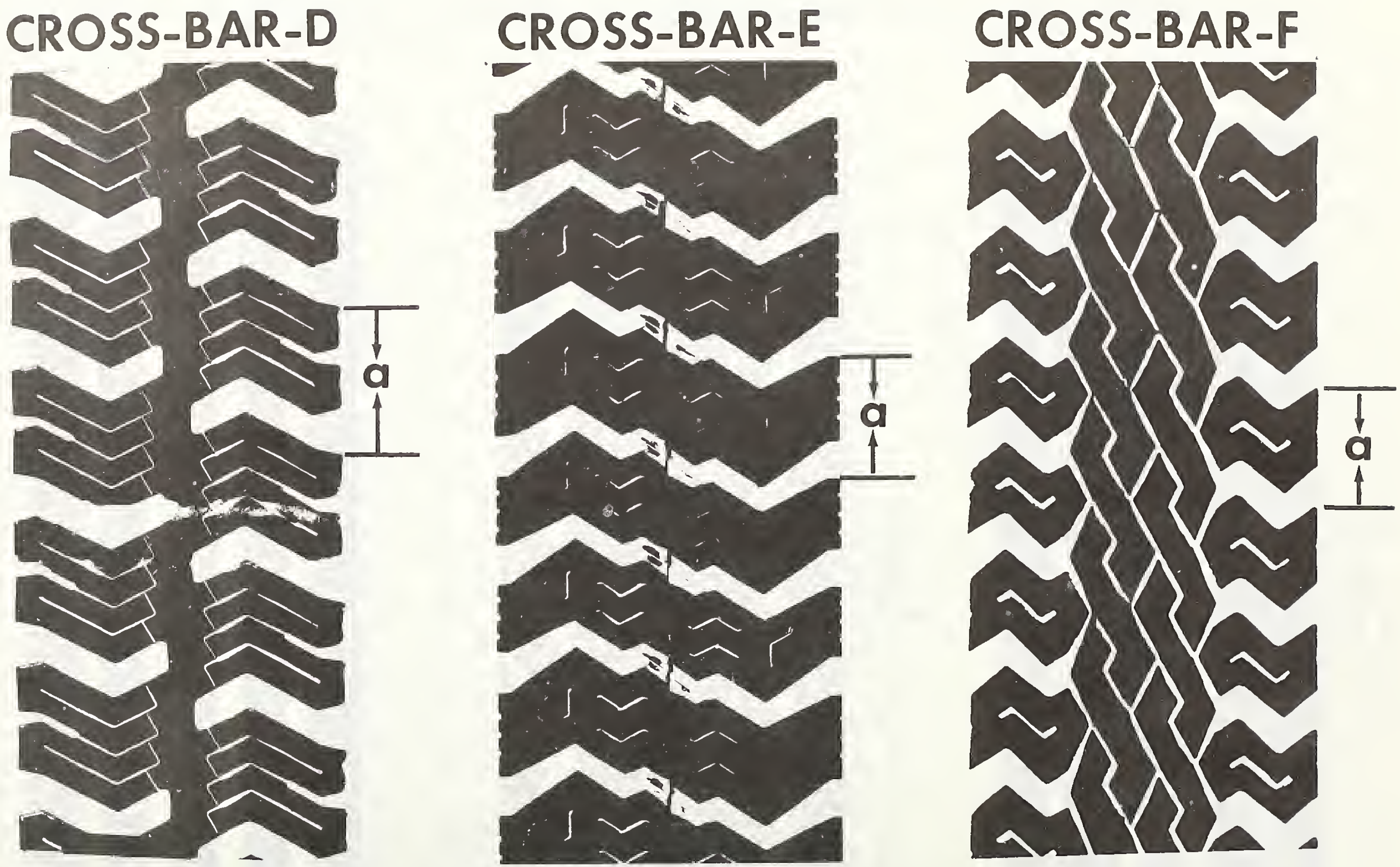


Figure 19. Test tires of cross-bar tread design with the major tread element spacing, designated as "a", identified. See Table 1 for the "a" values for these tires.

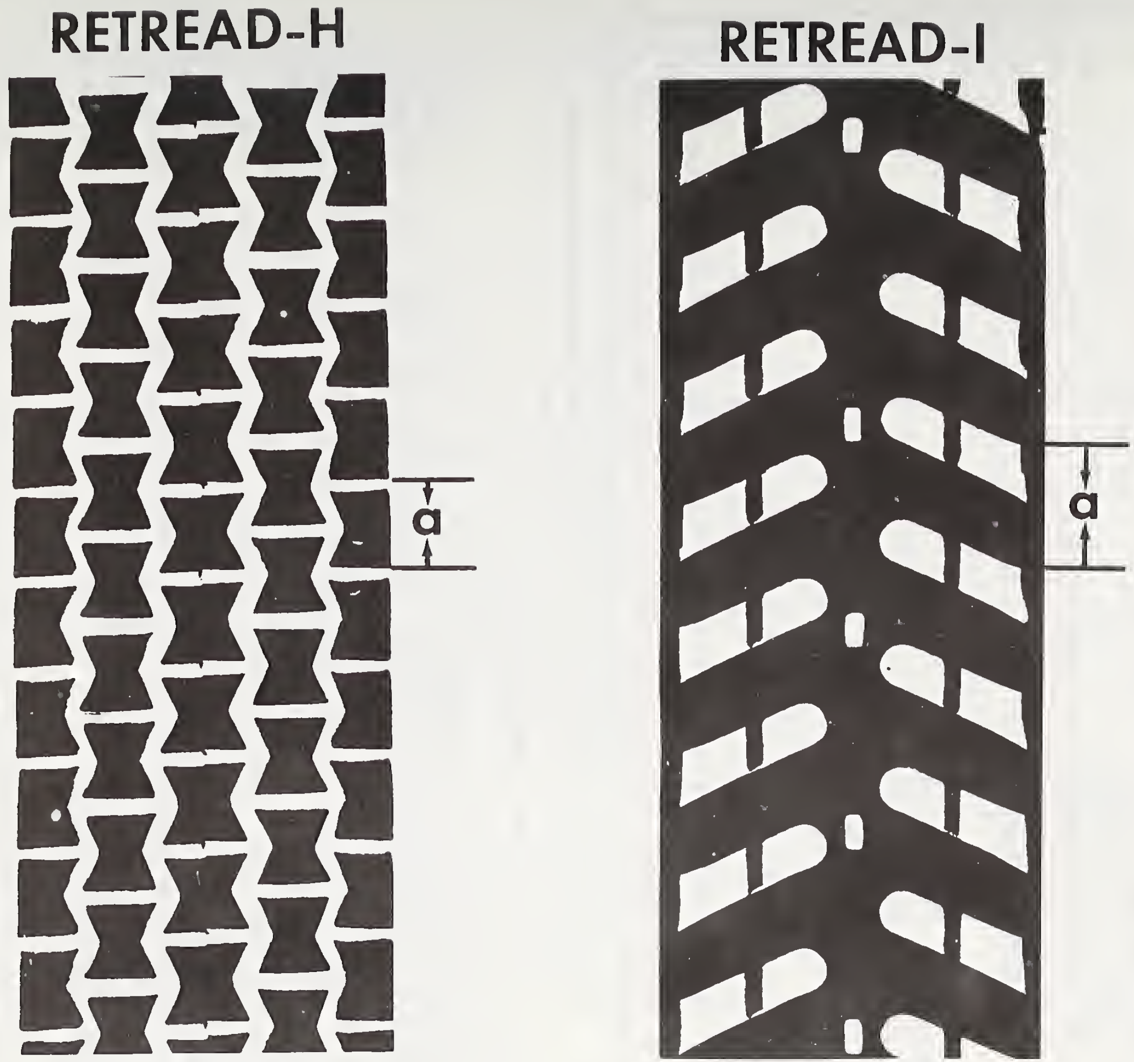


Figure 20. Test tires of retread (block and pocket) design with the major tread element spacing, designated as "a", identified. See Table 1 for the "a" values for these tires.

| Tire | Major Tread Spacing in. | Predicted Fundamental Frequency, Hz. | Band Limits Of One-Third Octave Band(s) Containing The Measured Fundamental Frequency, Hz |
|---|---|---|---|
| Rib-A | -- | -- | - |
| Rib-B | 2.01 - 2.28 | 386 - 438 | 354.0 - 446.0 |
| Rib-C | 1.93 - 2.95 | 298 - 456 | 278.5 - 446.0 |
| Cross-Bar-D | 3.35 | 263 | 221.0 - 279.0 |
| Cross-Bar-E | 2.76 | 319 | 278.5 - 351.5 |
| Cross-Bar-F | 2.44 - 2.91 | 302 - 361 | 278.5 - 351.5 |
| Retread-G | 1.56 | 564 | 442.0 - 558.0 |
| Retread-H | 1.89 | 466 | 354.0 - 558.0 |
| Retread-I | 2.48 | 355 | 278.5 - 351.5 |

Table 1. Predicted and measured fundamental tire noise frequencies based on major tread spacing considerations corresponding to a vehicle speed of 50 mph.

Each truck passby of interest, which had been recorded in the field in analog form, was previewed in order to determine the time delay between the second photocell (data start) and the occurrence of the maximum A-weighted sound level measured for that particular run. The software that was utilized to perform the analysis required an 0.5 second data sample and this sample was selected such that the maximum A-weighted sound level observed was approximately centered within the sample. The analog data were then digitized to produce a digital voltage versus time array. This array was Fourier transformed, utilizing software in the computer, into 512 channels, each of 2 Hz bandwidth, covering the frequency range from 0 - 1054 Hz. The computer utilized was a Varian 620/i. 6/ The plots in this report are for those data covering the frequency range 0-1000 Hz only.

6/ Commercial instruments are identified in this report in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards nor does it imply that the equipment identified is necessarily the best available for the purpose.

It is important to provide an indication of the statistical significance of these narrow-band spectra; that is, how much error is incurred by using practical analysis equipment with finite band widths and finite averaging times. As stated earlier, the analysis utilized a bandwidth (B) of 2 Hz and a sample record (T) of 0.5 seconds; therefore, the statistical uncertainty associated with the narrow band spectra is 3dB ($\varepsilon = 1/2\sqrt{BT}$). Aliasing errors are estimated to be less than 0.6 dB.

To provide an indication of the results, the narrow band spectra for rib-A, cross-bar-F and retread-H are shown in Figures 21-26. These data are for new tires mounted in dual pairs on the loaded (4430 lbs/tire), single-chassis vehicle for a nominal speed of 50 mph. The pavement surface was concrete. The narrow-band spectra for the remaining twenty-two runs which were investigated are presented in Appendix C.

The one-third octave band data for rib-A (Figure A-1 of Appendix A) are rather broad band in nature with no pronounced spectral peaks. This tire has a tread pattern consisting of straight circumferential grooves that run parallel to each other around the circumference of the tire. This tire was originally chosen for this test program since it was felt that due to the total absense of sipes and cross-bars this tire would provide a lower bound on truck tire noise level among current production tires. It has been reported [6] that circumferentially grooved treads exhibit slightly higher noise levels than smooth treads and that the sound levels generated by both smooth and circumferentially grooved treads depend heavily on the road surface. The narrow band spectra (Figures 21 and 22) 7/ are also broad band in nature as expected.

In the case of cross-bar-F (Figure A-21 of Appendix A), the one-third octave band data show a fundamental at 315 Hz and a secondary plateau ranging from 630 - 1000 Hz which includes the apparent second and third harmonics. This tire, which has a circumferential tread face centers (central rib) with shoulders of laterally aligned bars with sipes, possesses a randomized tread pattern with the major tread spacing ranging from 2.44 - 2.91 in. For this spacing, with a vehicle speed of 50 mph, equation 2 would predict a fundamental between 302 and 361 Hz. These frequencies are contained in the one-third octave bands centered at 315 and 400 Hz. The narrow band data (Figures 23 and 24) show seven major peaks -- 270, 308, 348, 386, 582, 656 and 894 Hz. The maximum in the narrow band spectrum at 308 Hz is in the range of the predicted fundamental. Although evident in the spectrum, the second and third harmonics of this peak -- 616 and 924 Hz -- are not prominent (more than 20 dB below the fundamental). The maxima at 348 Hz (which is 17 dB down from the level at 308 Hz) is also in the range of the predicted fundamental. The remaining peaks, whose influence is visible in the one-third octave band data, are not accounted for by major tread spacing considerations. A review of the narrow band data seems to indicate that the more randomization evident in the tread pattern the more likely one is to see numerous

7/ All frequency components below 40 Hz in the narrow-band spectra are neglected since comparable data do not exist for the one-third octave spectra.

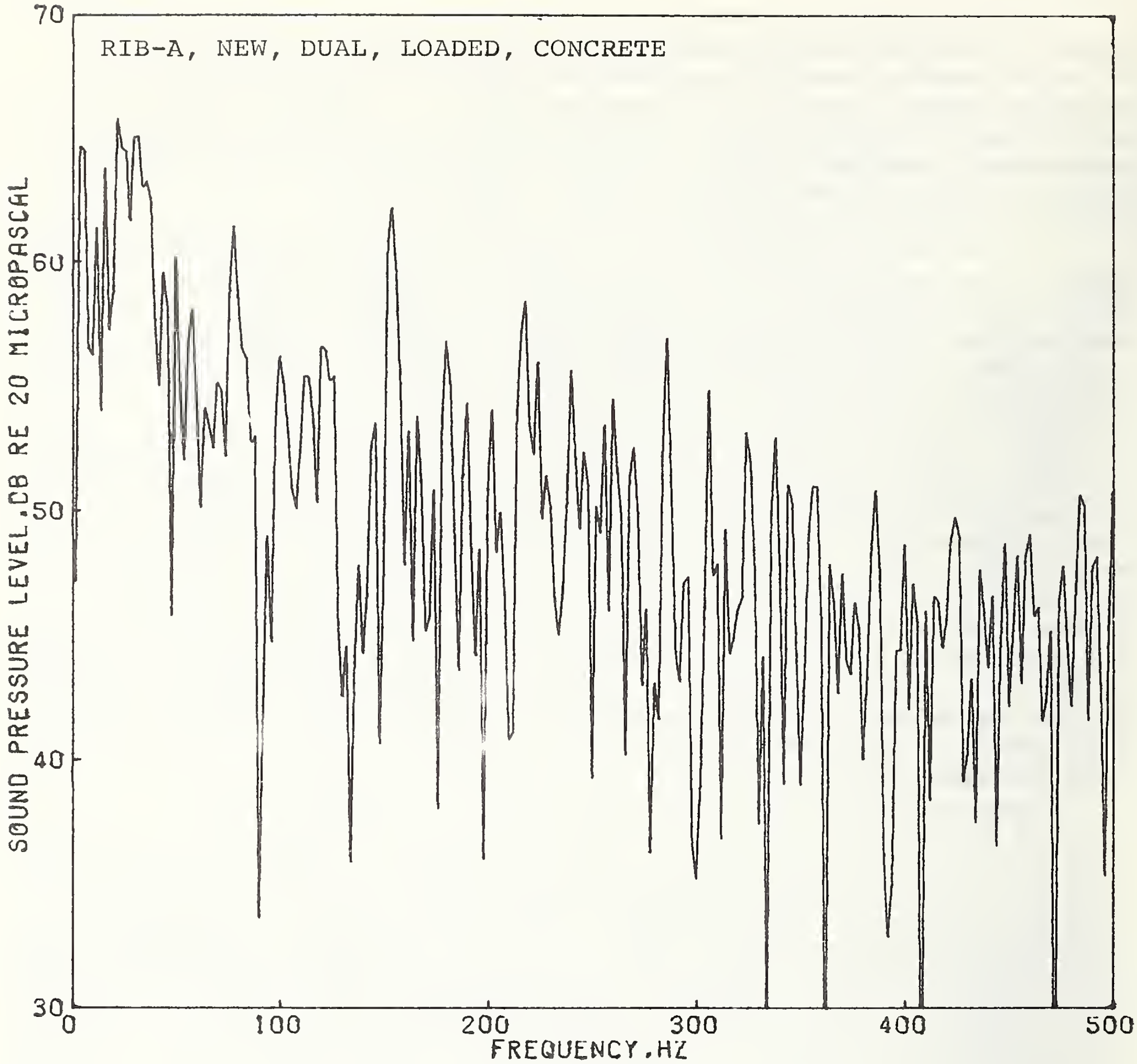


Figure 21. Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and dual, new, rib-A tires on the drive axle. The 50 mph coastby was on a concrete surface.

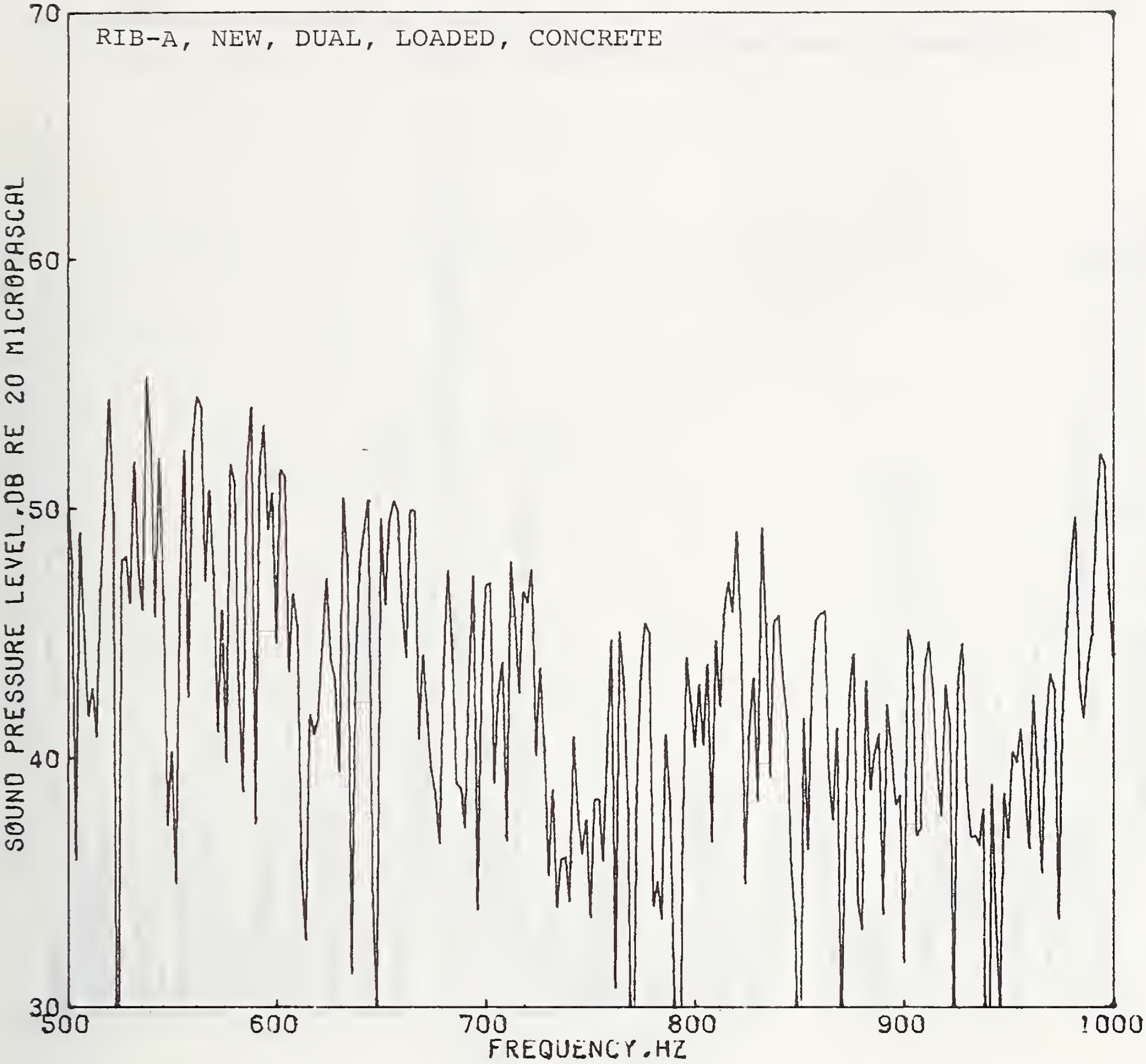


Figure 22. Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and dual, new, rib-A tires on the drive axle. The 50 mph coastby was on a concrete surface.

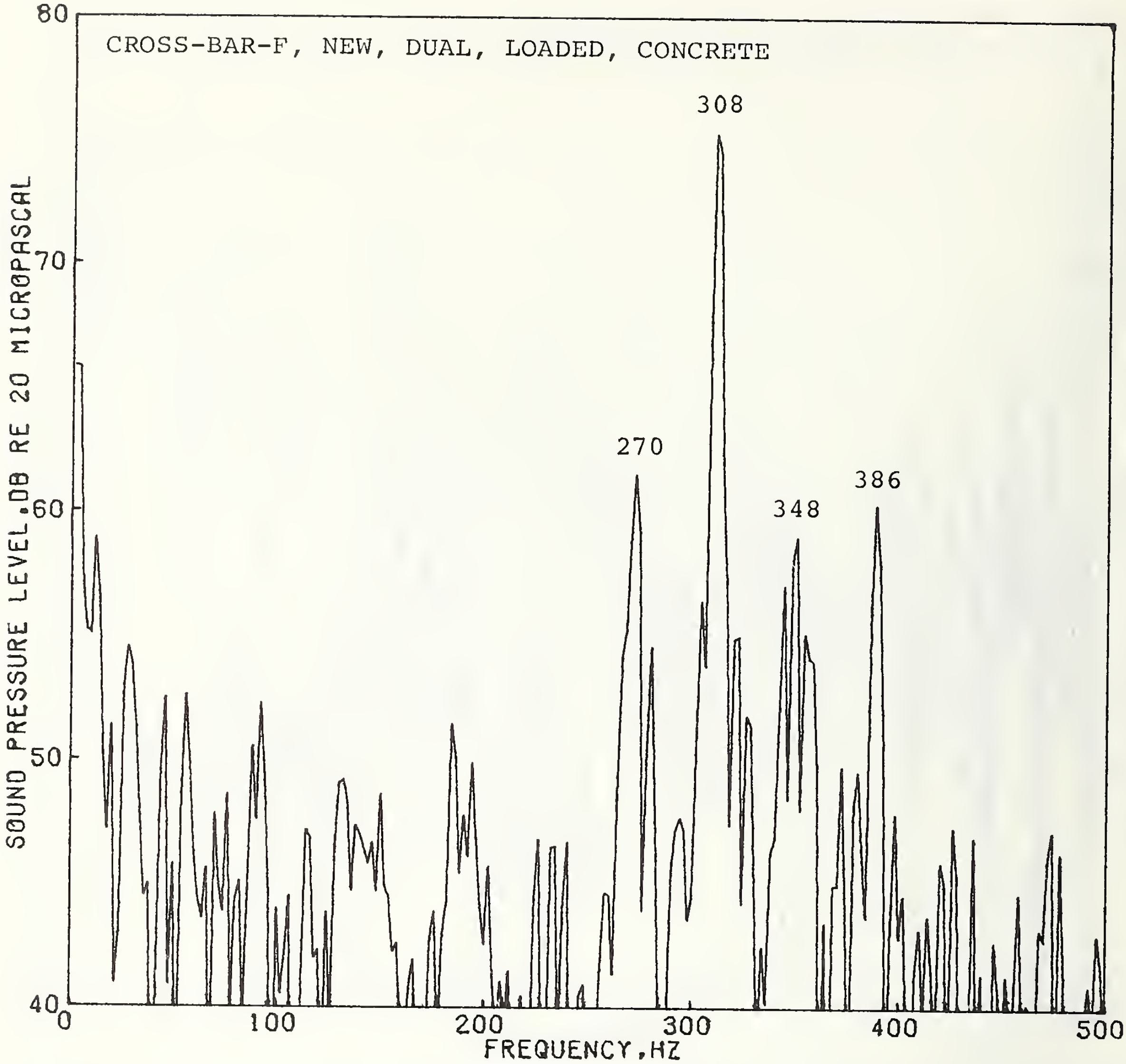


Figure 23. Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and dual, new, cross-bar-F tires on the drive axle. The 50 mph coastby was on a concrete surface.

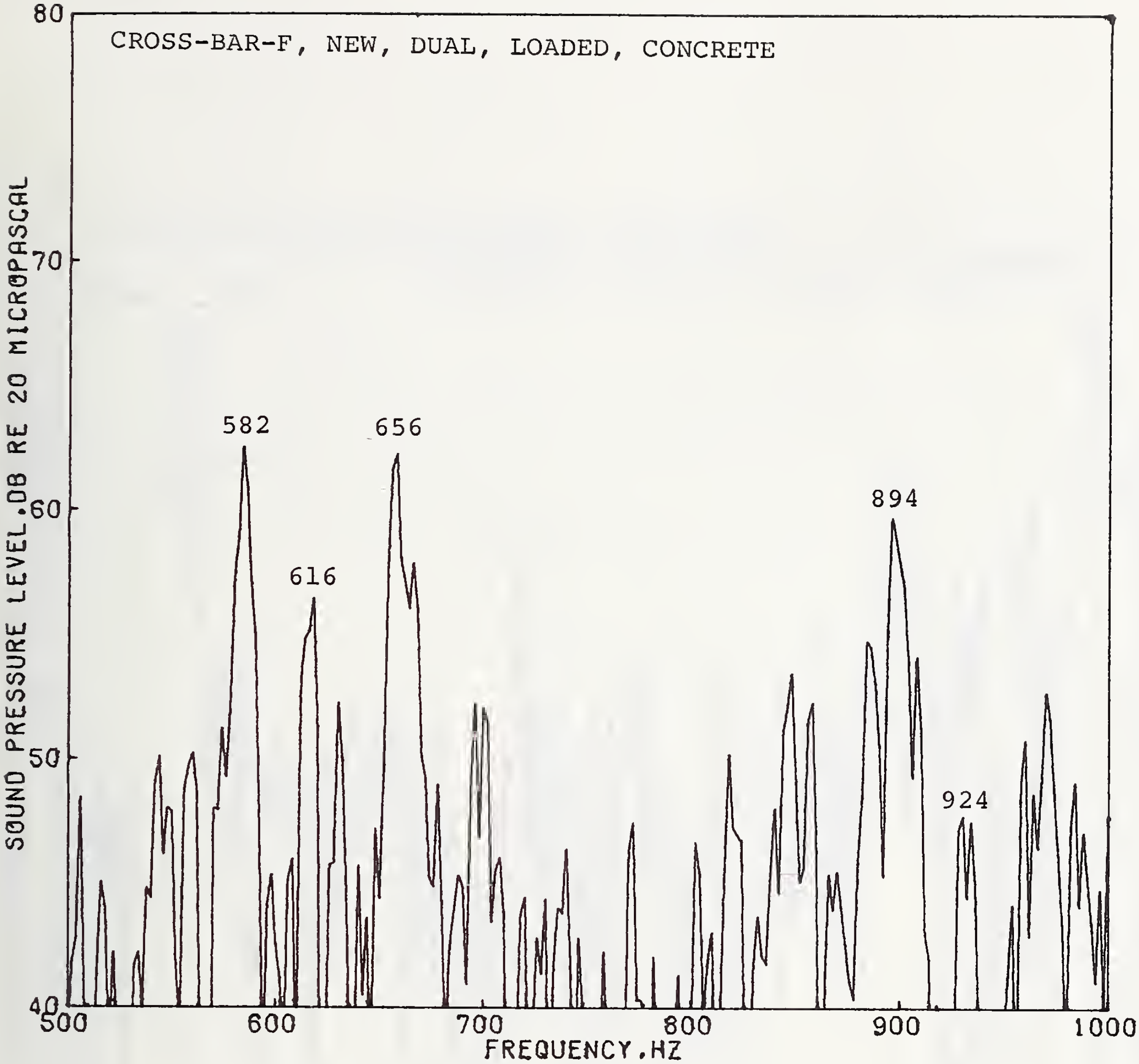


Figure 24. Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and dual, new, cross-bar-F tires on the drive axle. The 50 mph coastby was on a concrete surface.

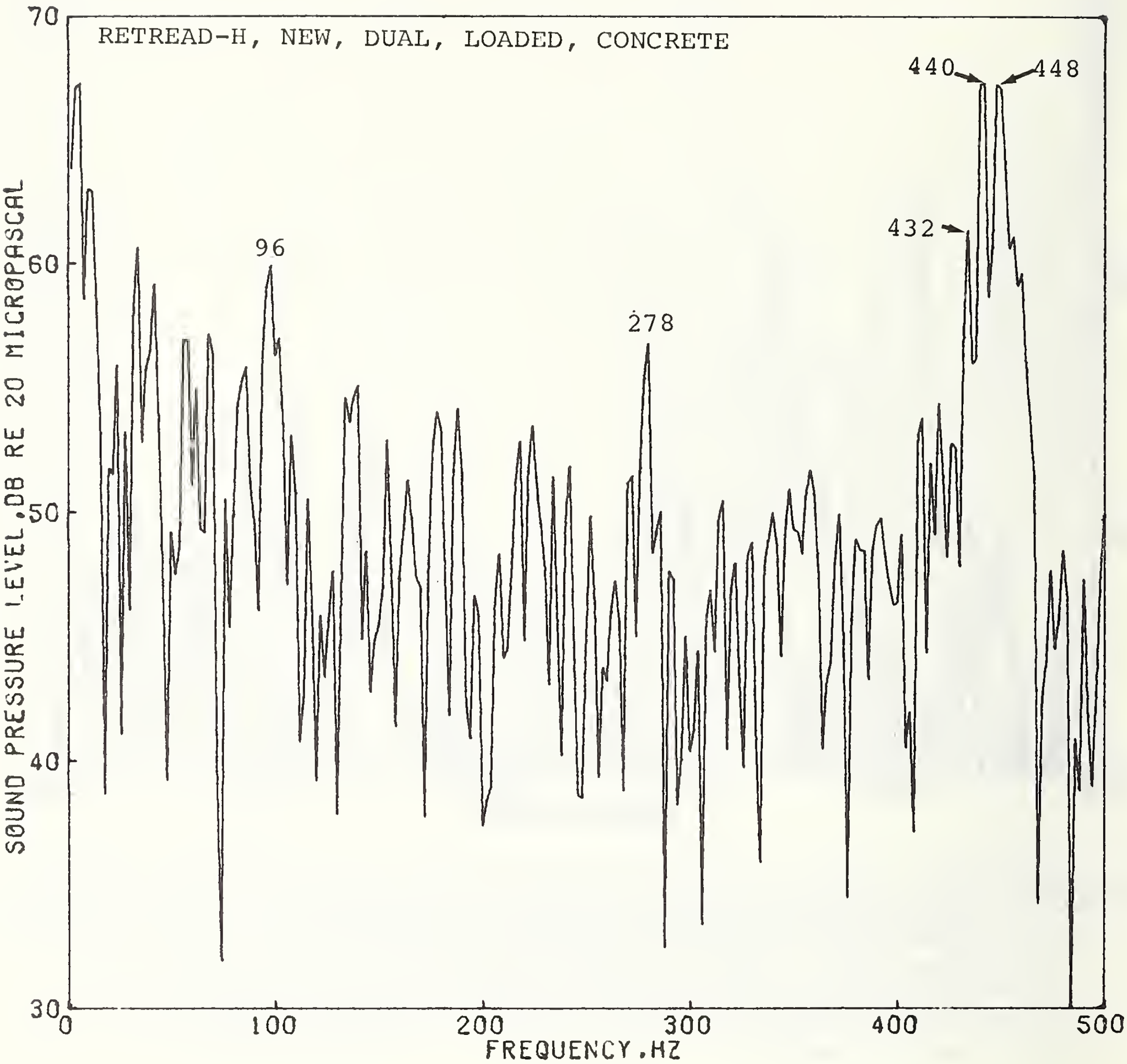


Figure 25. Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and dual, new, retread-H tires on the drive axle. The 50 mph coastby was on a concrete surface.

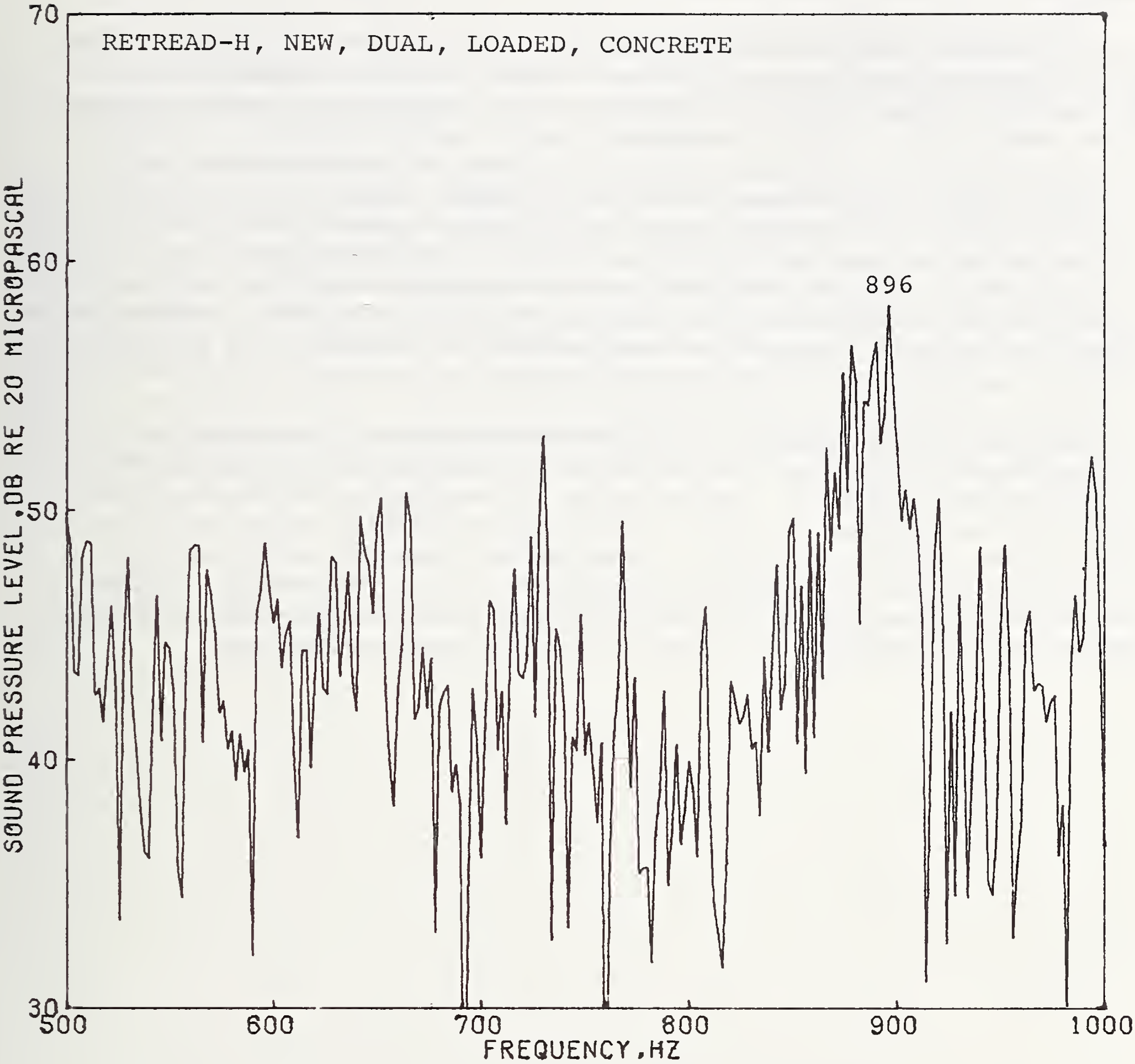


Figure 26. Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and dual, new, retread-H tires on the drive axle. The 50 mph coastby was on a concrete surface.

lower level peaks in the narrow band spectrum rather than a few higher level ones. This seems logical since the purpose of tread randomization is the breakup of the noise energy that would be concentrated in a few single frequency bands (if the tread pattern was repetitive) and distribution of this energy at lower levels over a broader frequency range. The characteristic of the tire noise appears to depend on the lengths and distribution of lengths of the tread elements.

Retread-H, the final tire to be considered, does not possess a randomized tread element pattern but has a major tread spacing of 1.89 in. The one-third octave band data (Figure A-32 of Appendix A) show a maximum in the spectrum at 500 Hz (fundamental) and a second harmonic at 1000 Hz. For a vehicle speed of 50 mph, one would predict a fundamental at 466 Hz. The narrow band data (Figures 25 and 26) clearly indicate a double peak in this region -- 440 and 448 Hz -- and the second harmonic at 896 Hz. Other major peaks occur at 96, 278 and 432 Hz. A comparison of the data for cross-bar-F with the data for retread-H clearly shows the spectral differences that can be expected when a narrow band frequency spectra for a tire with a fixed, repetitive tread pattern is compared with another tire with a randomized tread element pattern.

Since our knowledge of tire noise mechanisms is limited, it is difficult to evaluate the total significance of the data resulting from the narrow-band analysis. The situation is complicated by the fact that the data being analyzed are for a set of six tires (two steering, four drive) rather than a single tire. Narrow-band analysis will, however, be a necessity when we reach the point where we are evaluating a single tire and are attempting to pinpoint frequencies associated with specific vibrational, air pumping, or other tire noise source mechanism.

## 3. Conclusions

Many of the phenomena exhibited by the data presented in this report are not fully explainable at present due to our limited knowledge of the mechanisms of tire noise generation. However, it is important that such data be placed into the public domain since: (1) further evaluation of these data may lead eventually to explanations of the presently unexplainable phenomena and, thus, to an understanding of tire noise generation mechanisms, and (2) on-going and future experimental and analytical research in tire noise must account for such experimentally observed phenomena, e.g., the double-peaked sideward lobe observed in the directionality patterns.

In reviewing the data, one could easily be mislead into thinking that the mechanism question is simply one associated with tread design alone, however, the apparent attainable "limit" with present structural design - a blank tire (full tread depth but no tread pattern) on a smooth surface - is only a few decibels lower than current original equipment rib tires of quiet design. Therefore, to accomplish significant levels of tire noise reduction it is necessary first to evaluate thoroughly the presently postulated tire noise source mechanisms -- aerodynamic, air pumping and vibration -- and others that may evolve through appropriate research. By combining the results of such research with other aspects of tire performance, it is expected that tires may be designed for safety, longevity and quiet.

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# 4. Appendix A. Parametric Study Results

This appendix contains the expanded data base on the noise generated by rib, cross-bar and retread truck tires tested during the field efforts conducted at Wallops Station, Virginia in 1970 and 1971.

Test results for the single-chassis vehicle are presented in a series of figures comprised of two separate facing pages. One page contains (1) a computer generated plot of one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level and (2) a tire footprint of one of the actual test tires utilized (scale 1:4) showing the characteristic tread element pattern in its given state of wear.[8/] The accompanying pages present directionality information in the form of equal A-weighted sound level contours. The zero point on the contour plots correspond to the center line of the drive (rear) axle of the test vehicle. These plots correspond to a vehicle coastby at 50 mph on both a concrete and an asphalt surface. The specific tread design and associated degree of wear are defined in the title at the top of the page. Also identified are the loading condition and information as to whether the tires were mounted in dual pairs or singly. Tires with identical tread designs were mounted at each position on the drive axle of the test vehicle. These were the test tires. New neutral rib (rib-A) control tires were mounted on the steering axle for all tests.

Pertinent tire data such as tread depth and Shore hardness (rubber hardness), which were taken for each test tire, were tabulated and reported in the previous reports [1,2].

It should be noted that on several occasions one or more microphones were inoperative during the truck passby and therefore, data are not available in these instances. Also, data for retread-G should be used with caution. Note the difference in tread patterns shown for the new and half-worn tires. Examination of the tire footprints for retread-G tires showed that one of the half-worn tires had a different tread pattern than the other tire (footprints were made for a dual pair of identical tread designs). The different tread patterns resulted from a misaligned tire mold. A discussion of the problem was presented in an earlier report [2]. No knowledge exists as to how many of the retread-G tires had these tread variations.

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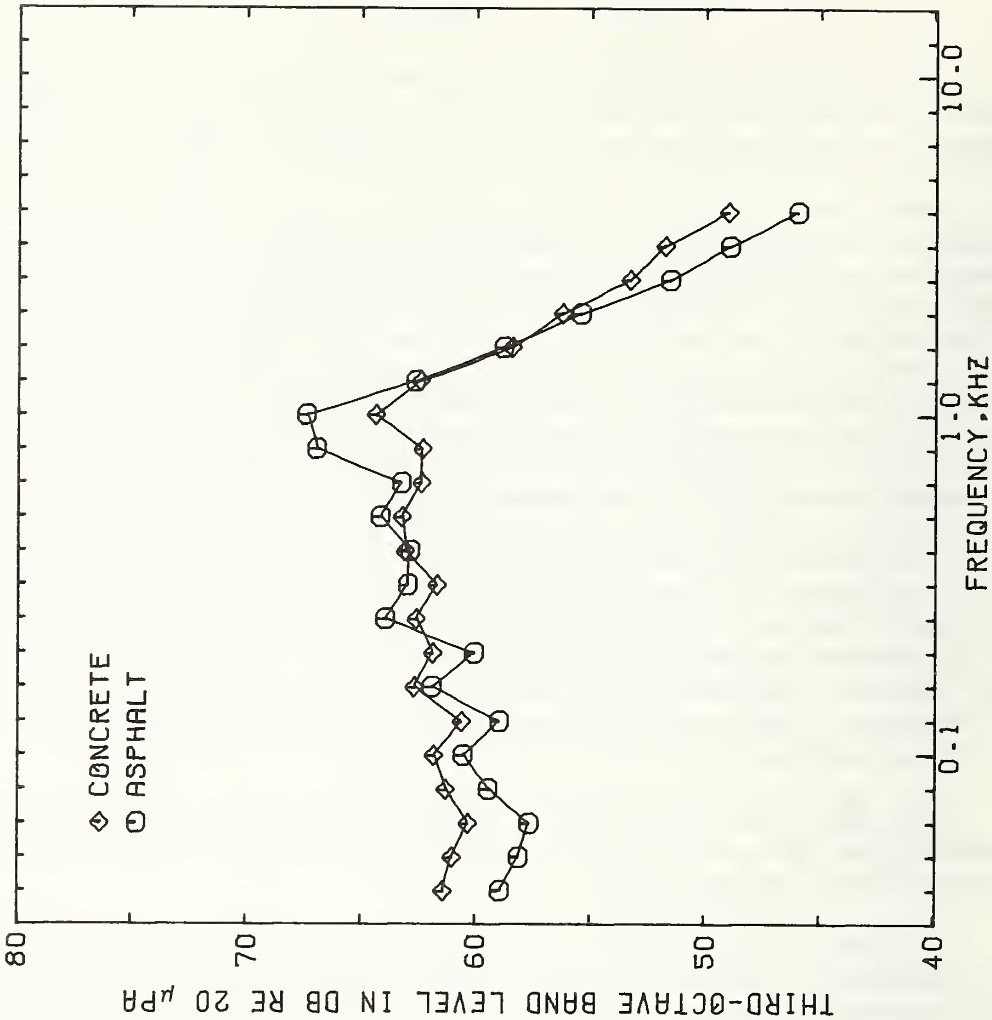
8/ No footprint was made of the tread element pattern for rib-C in a fully-worn state. The footprint which is shown with data corresponding to the fully-worn tires is that for a half-worn rib-C.

RIB-A, NEW, DUAL, LOADED



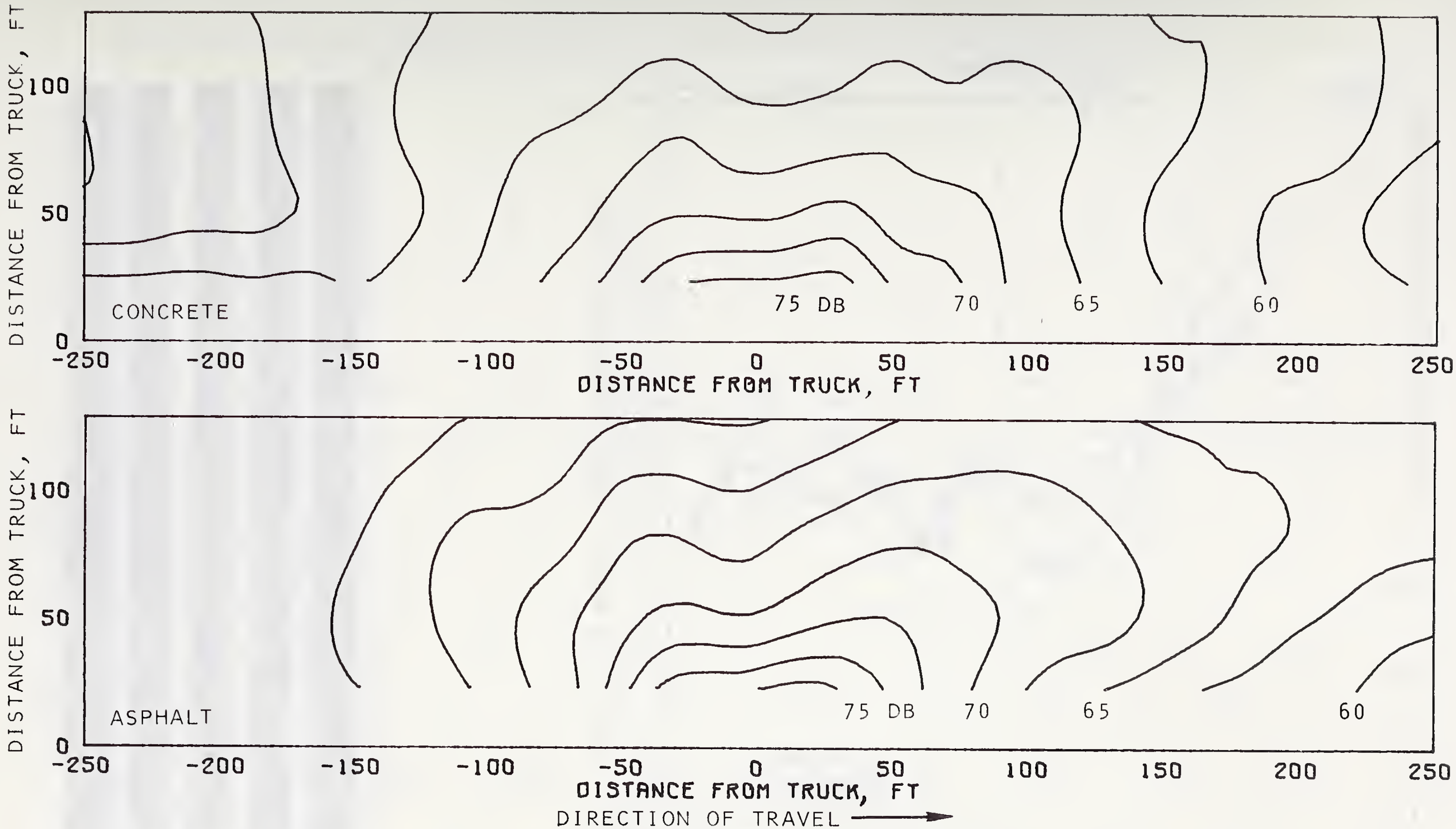
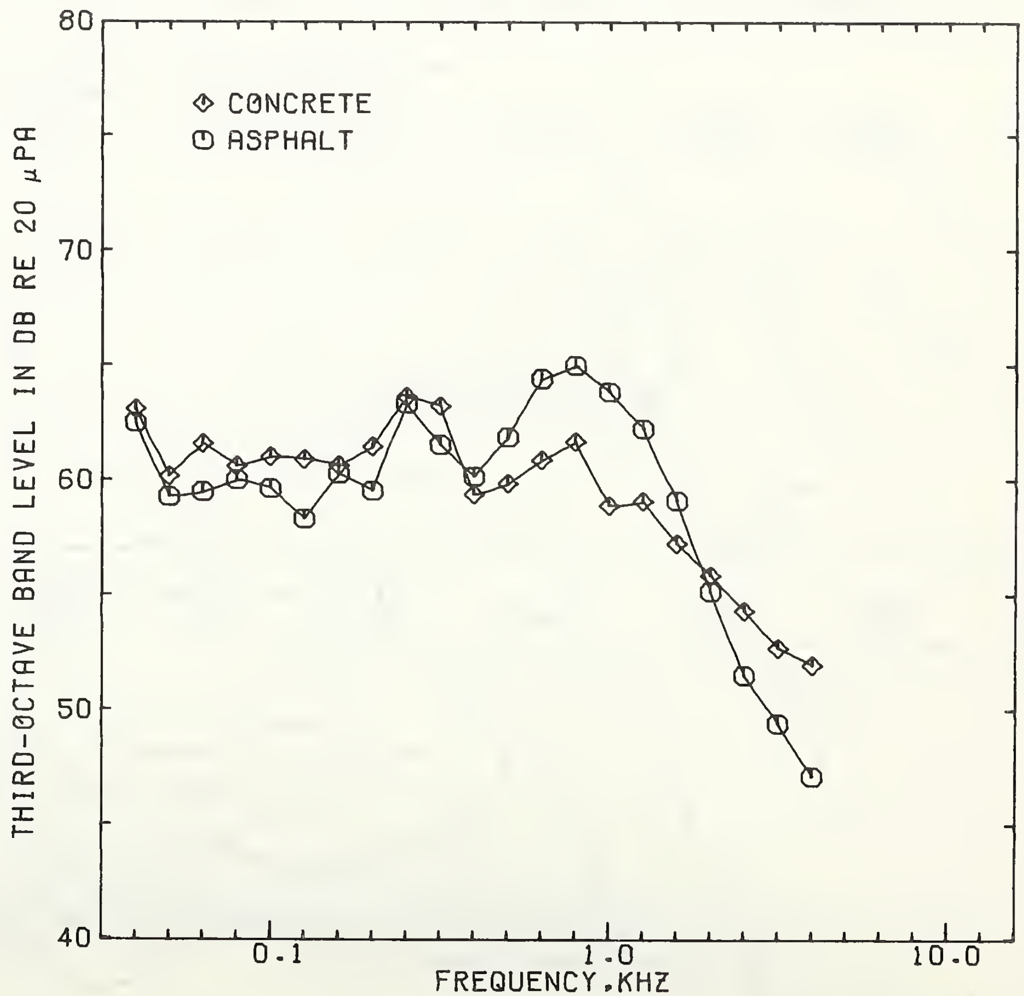




Figure A-1. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, rib-A tires on the drive axle.

RIB-A, NEW, DUAL, UNLOADED



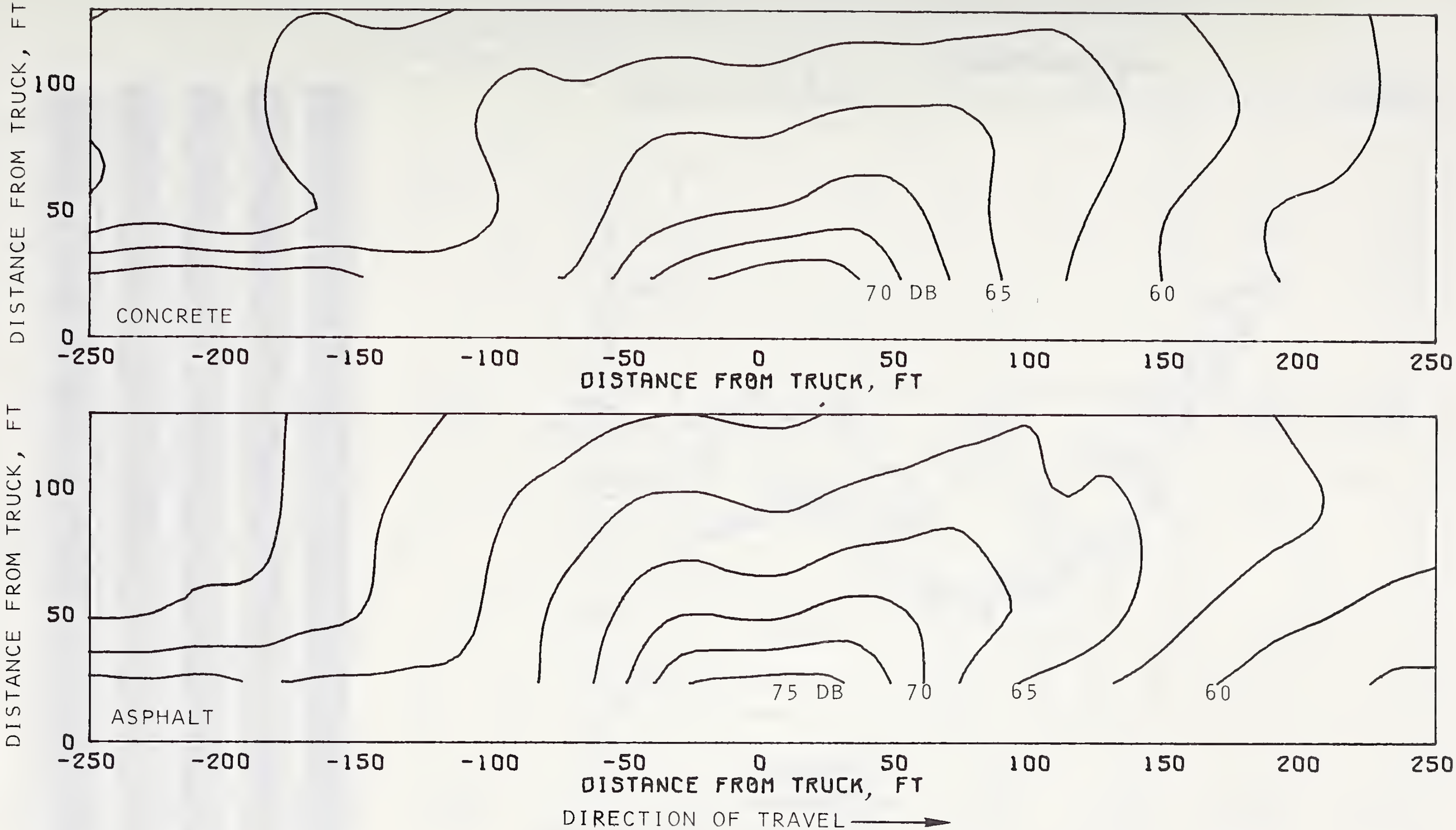
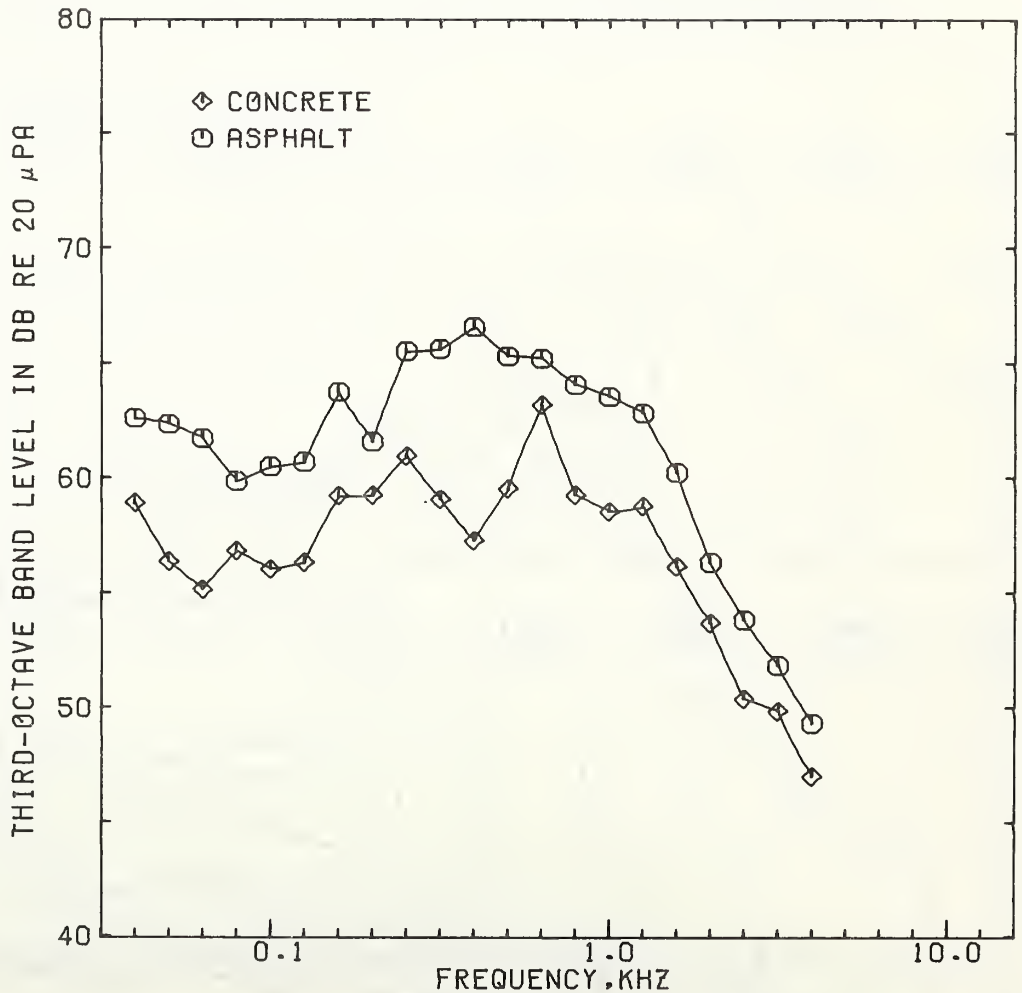



Figure A-2. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, rib-A tires on the drive axle.

RIB-A, NEW, SINGLE, UNLOADED



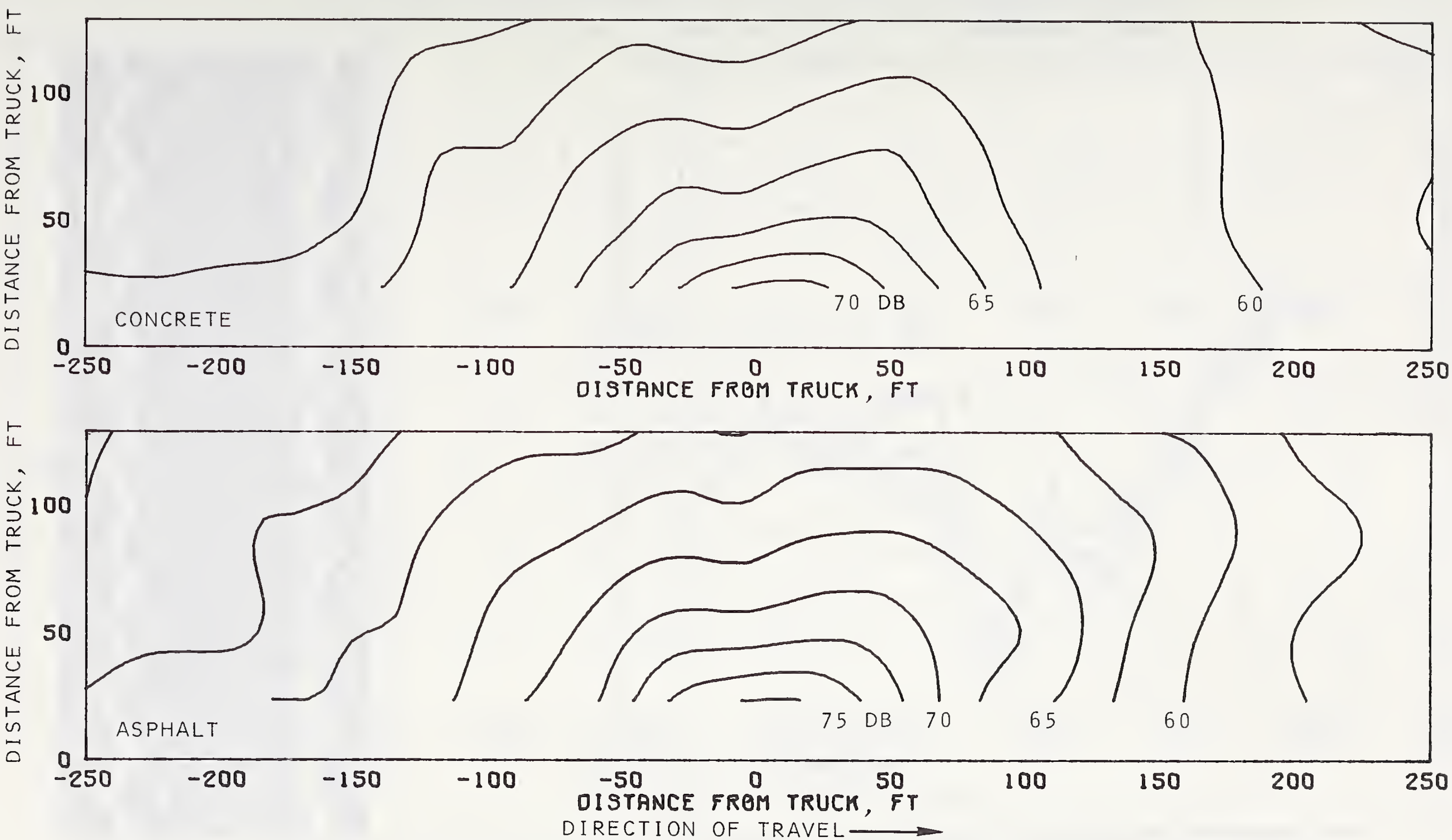
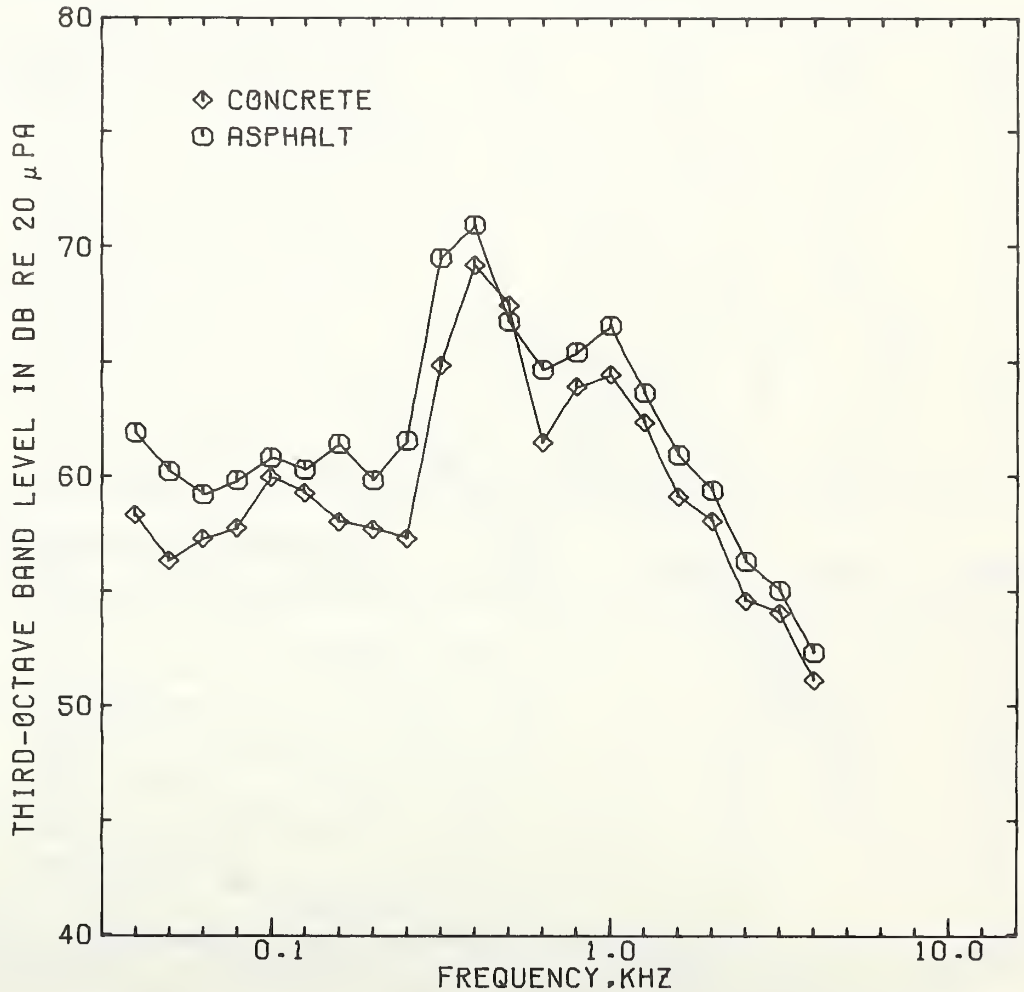



Figure A-3. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and single, new, rib-A tires on the drive axle.

## RIB-B, NEW, DUAL, LOADED



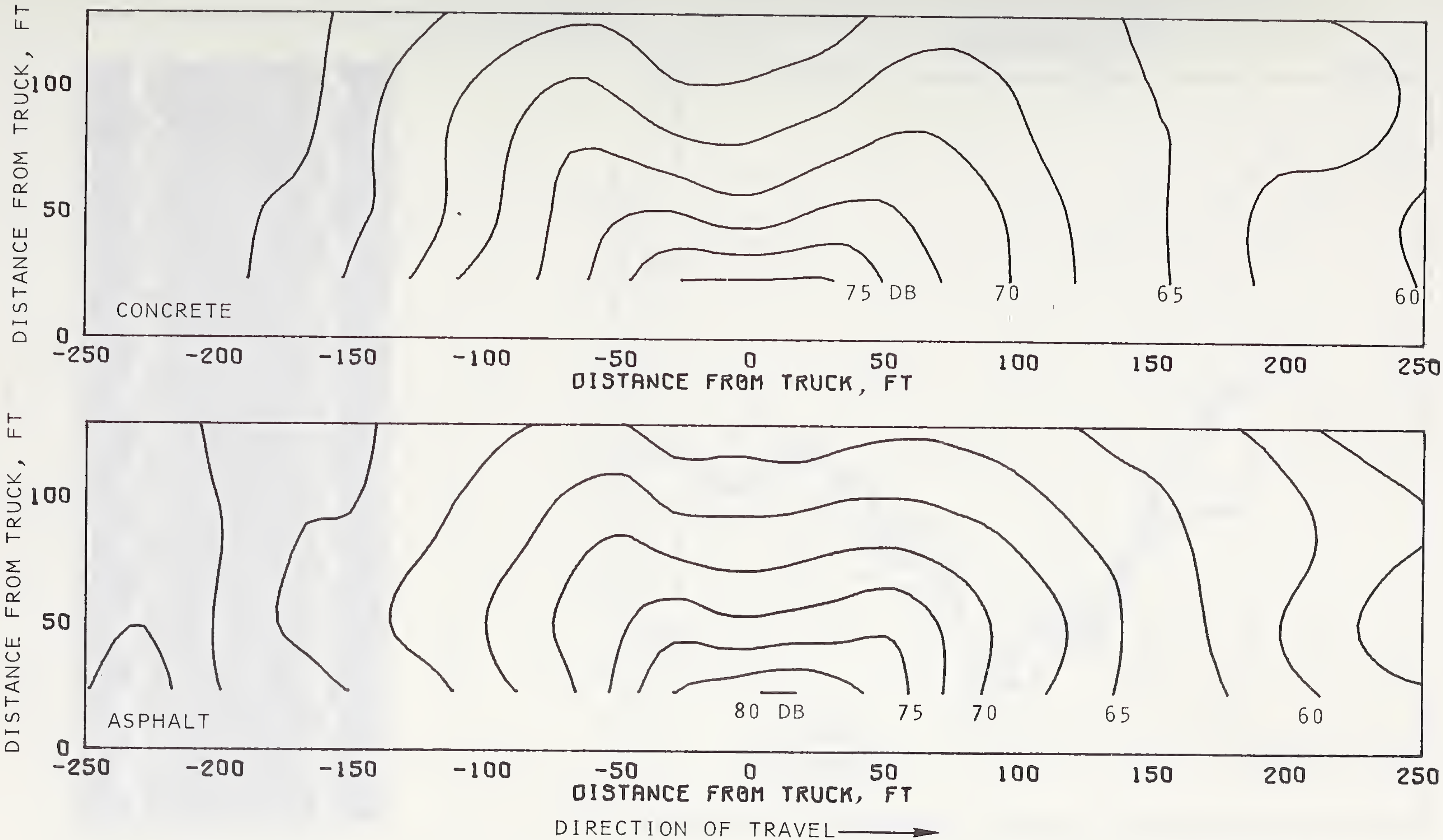
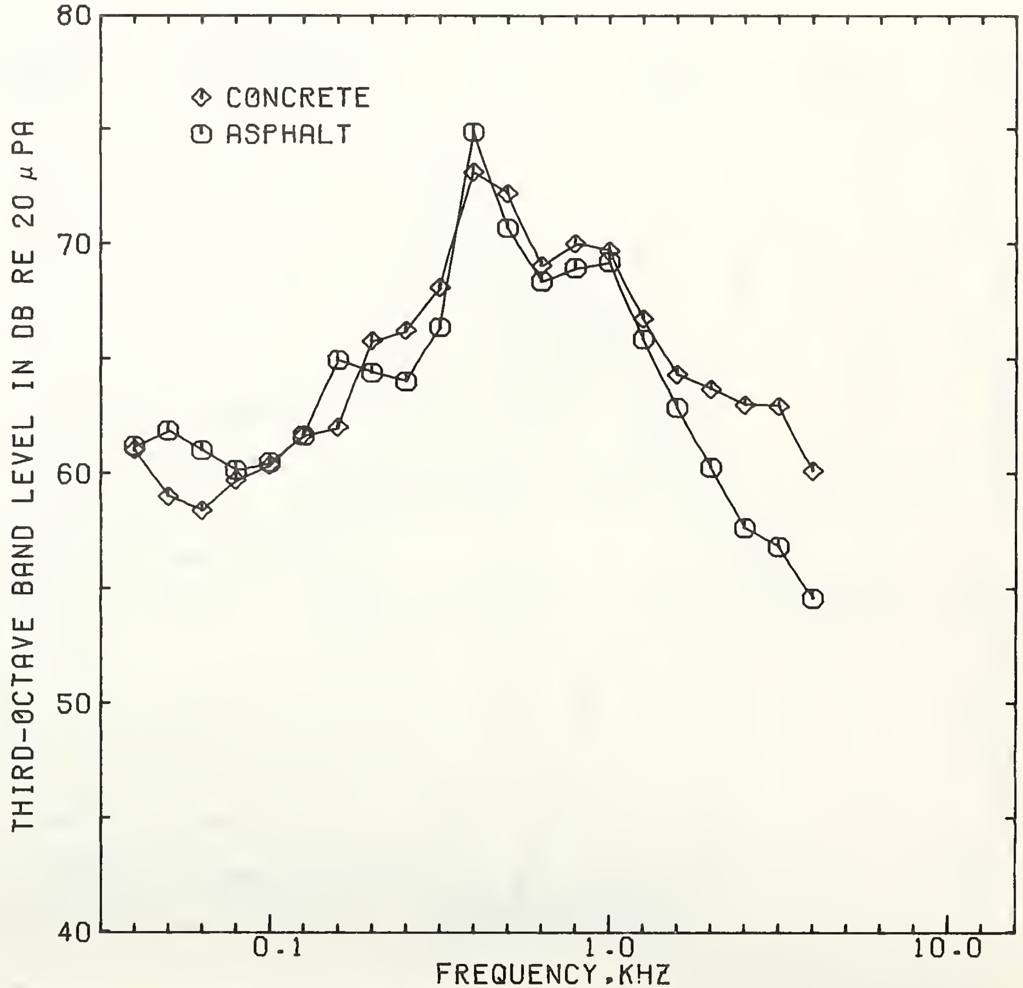



Figure A-4. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, rib-B tires on the drive axle.

## RIB-B, HALF-WORN, DUAL, LOADED



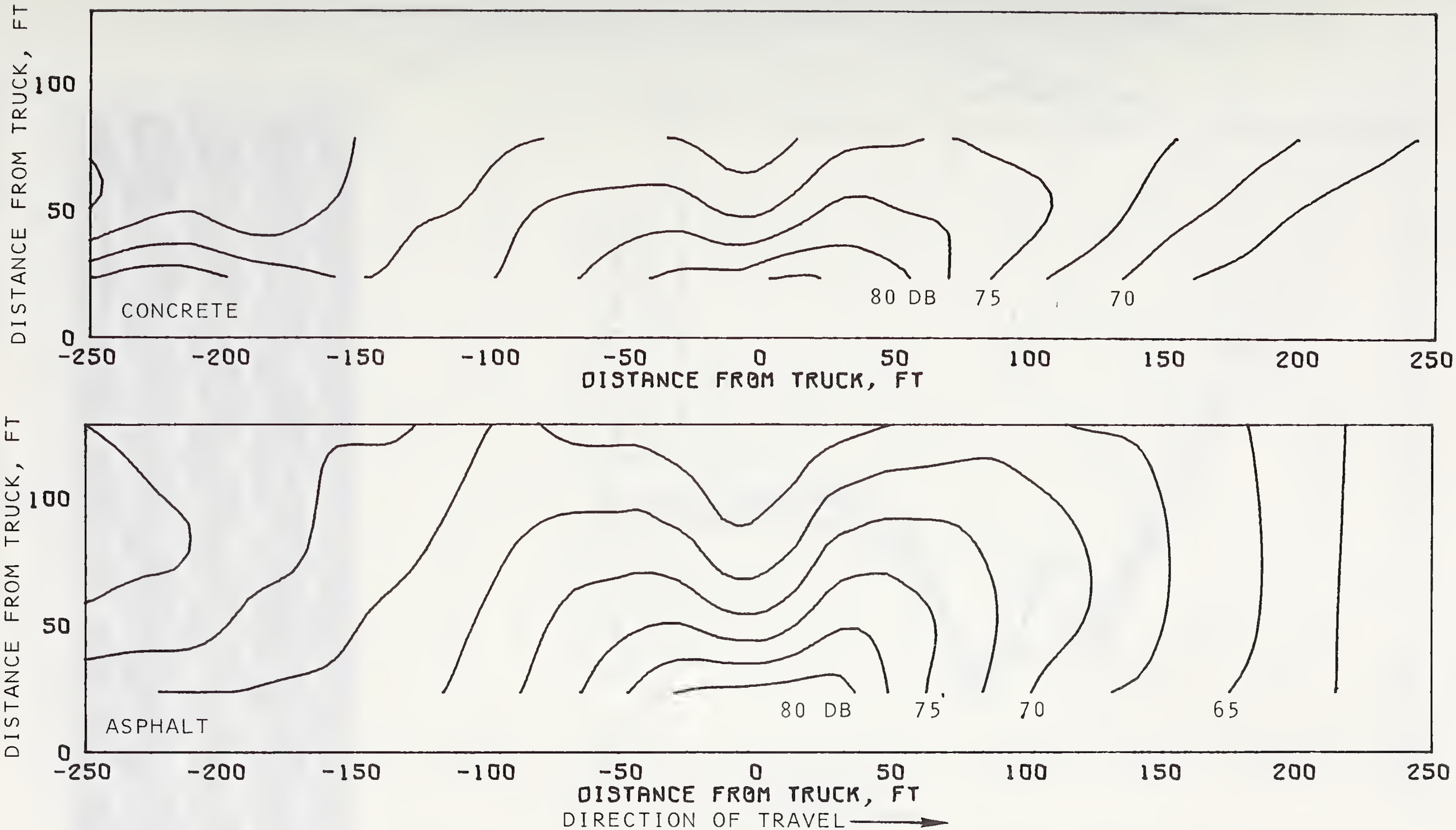
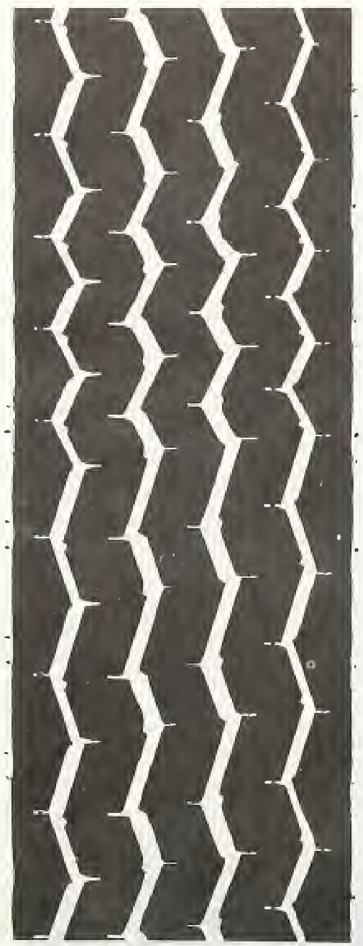
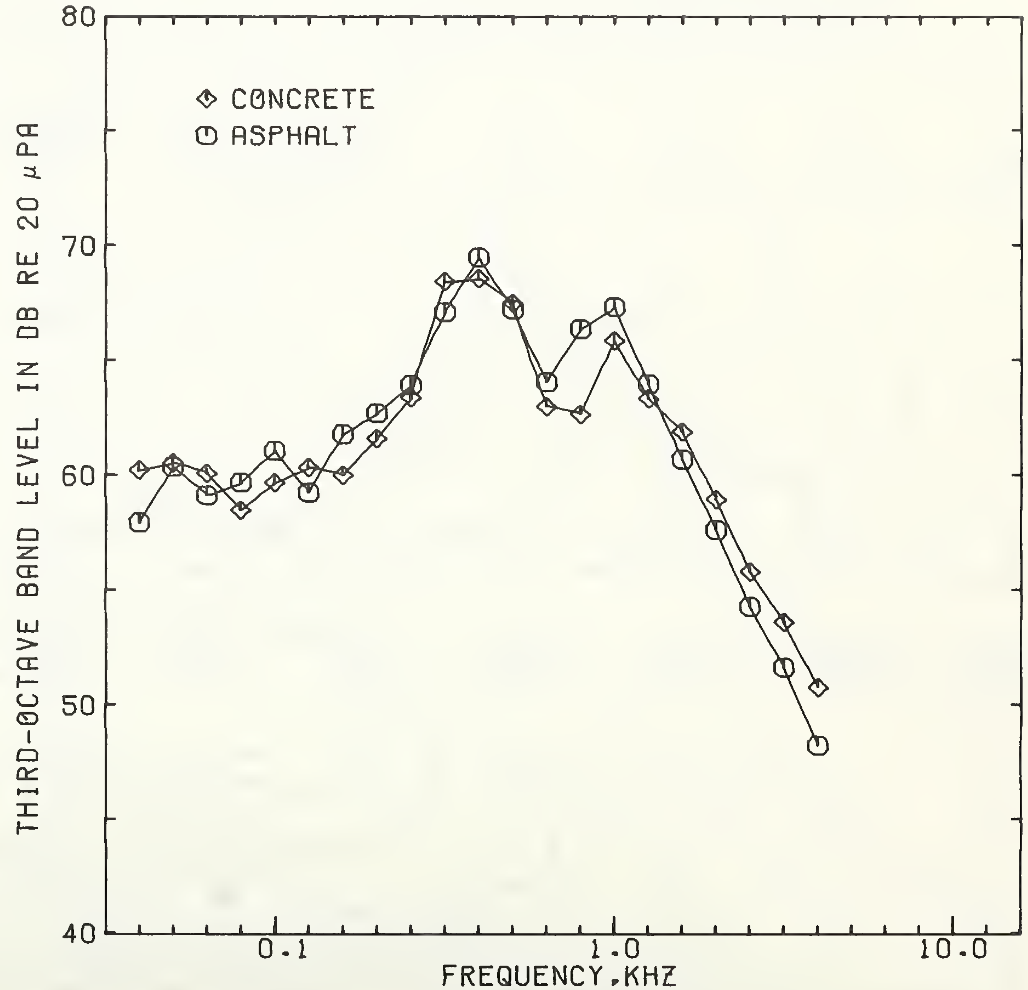



Figure A-5. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, rib-B tires on the drive axle.

RIB-C, NEW, DUAL, LOADED





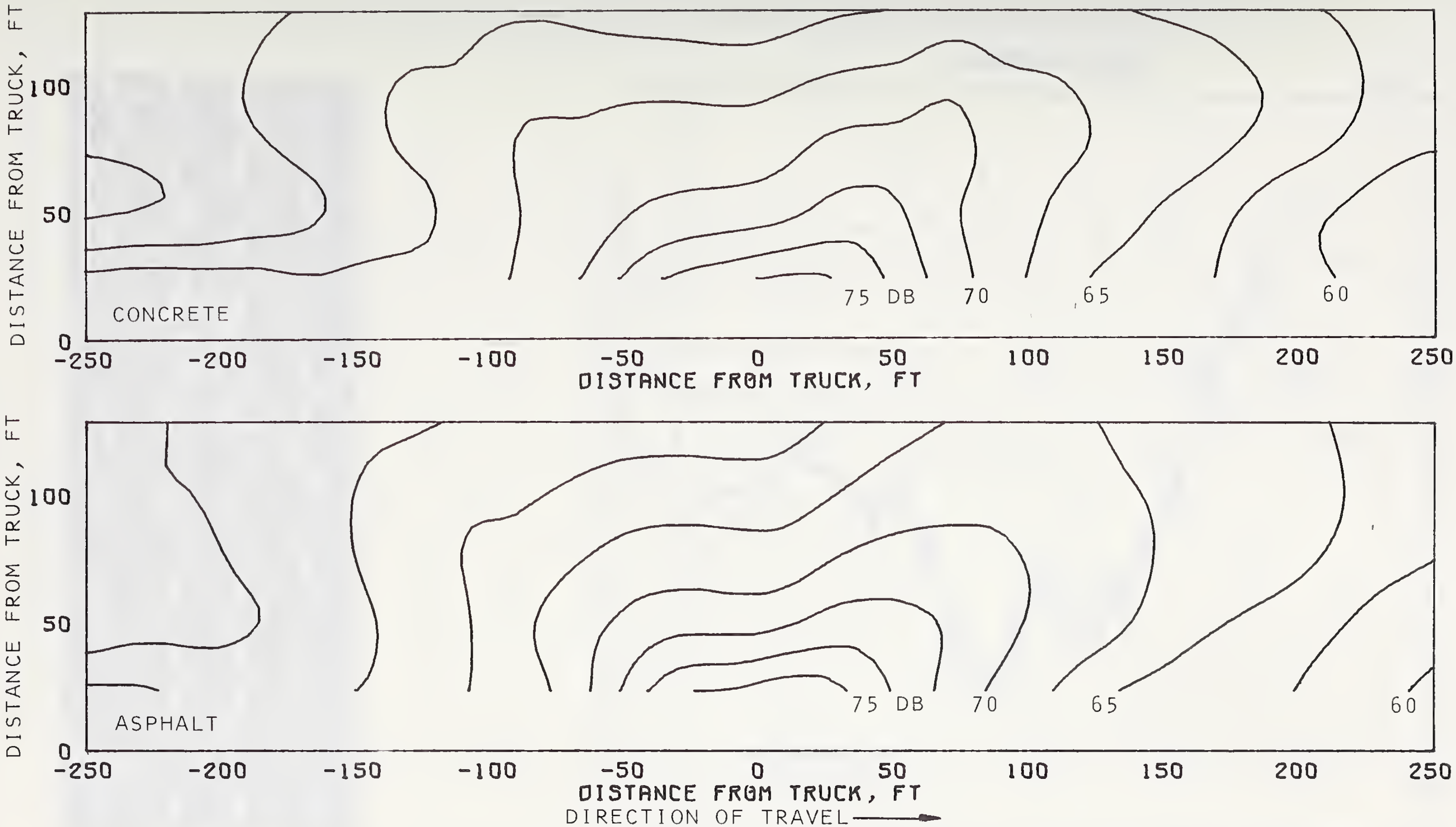
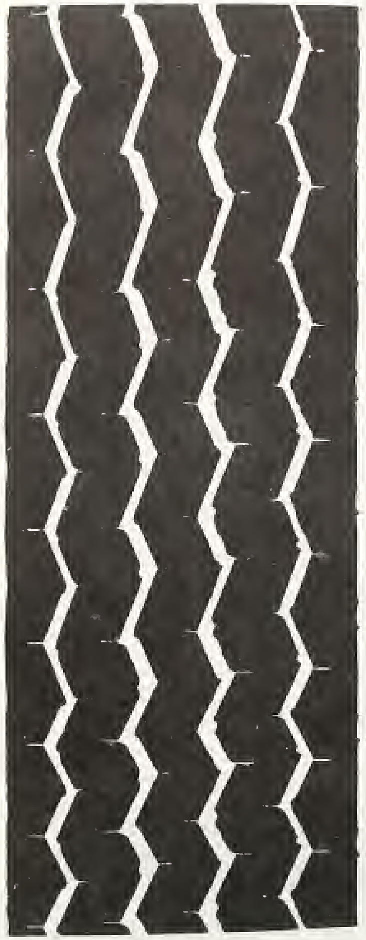
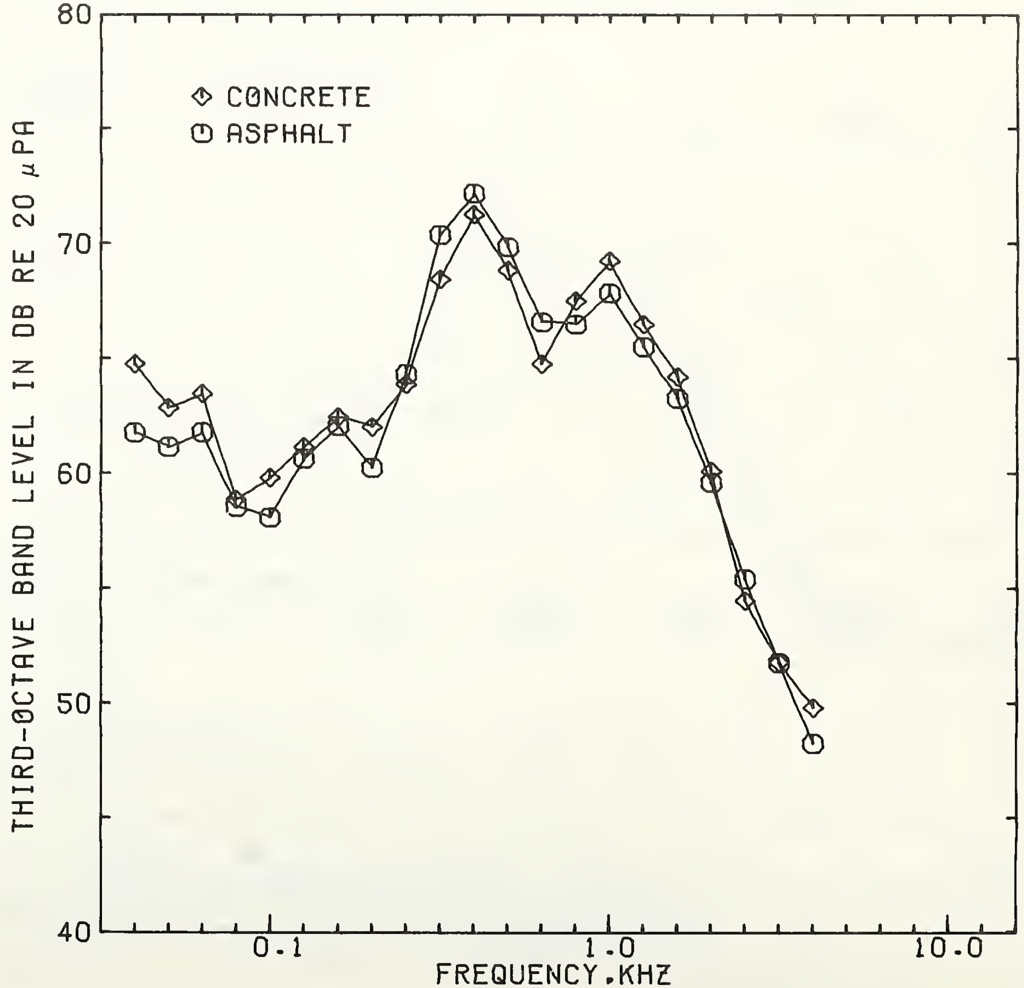



Figure A-6. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, rib-C tires on the drive axle.

RIB-C, HALF-WORN, DUAL, LOADED





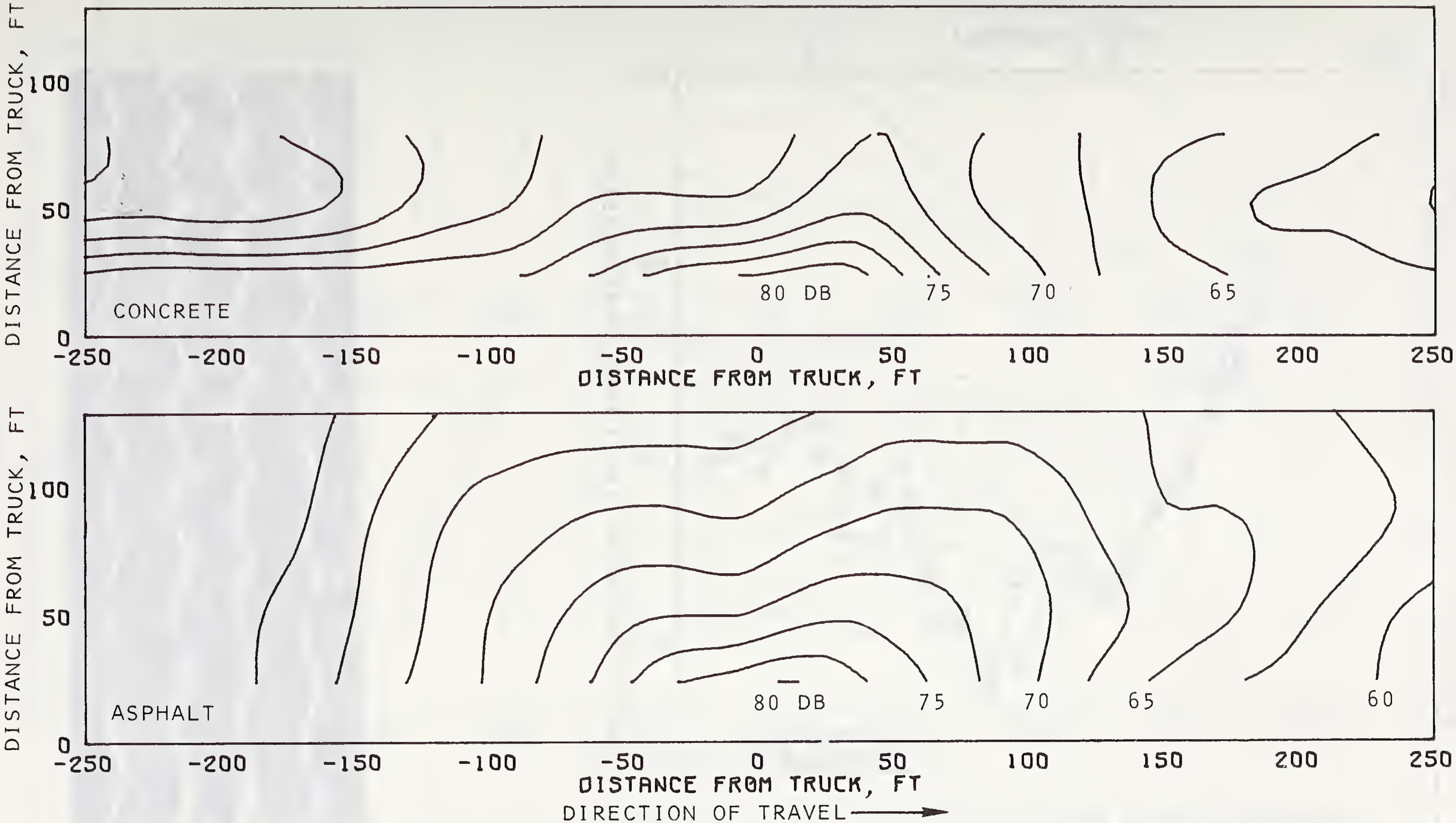
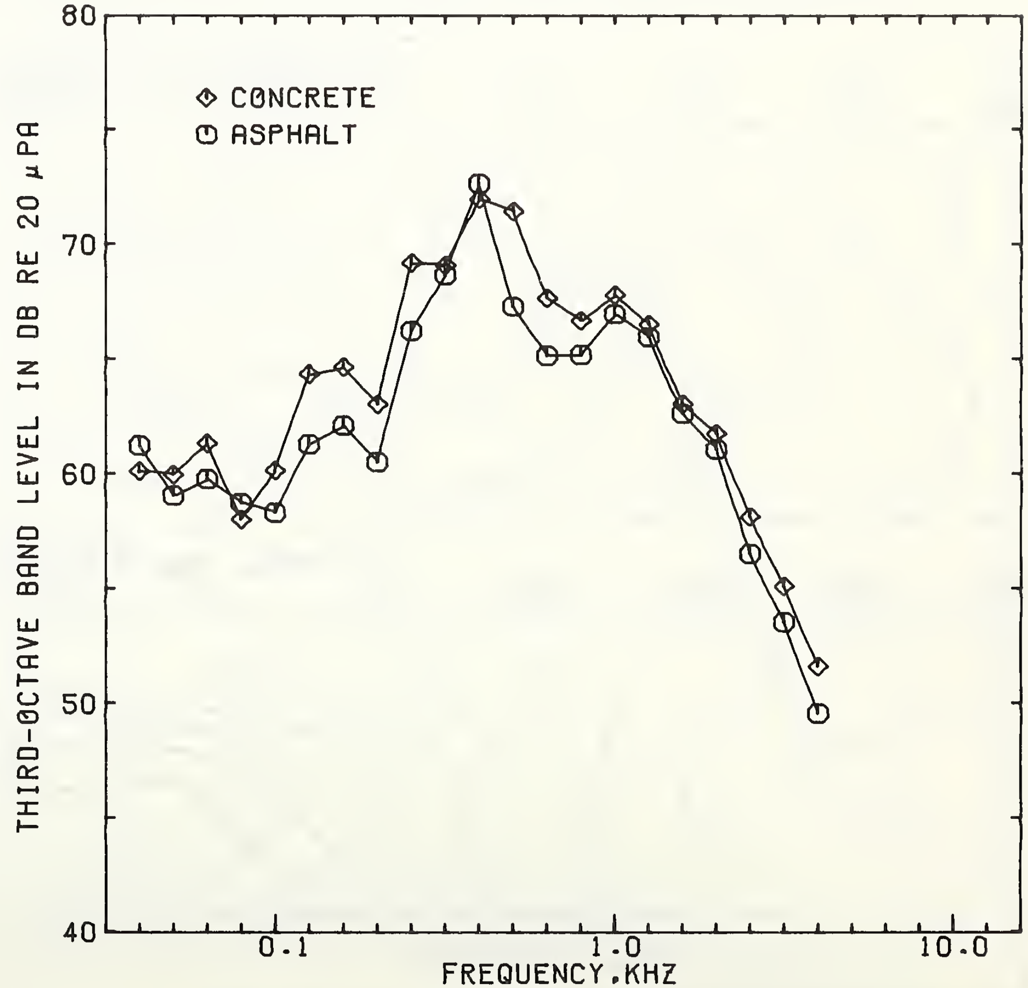



Figure A-7. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, rib-C tires on the drive axle.

RIB-C, FULLY-WORN, DUAL, LOADED



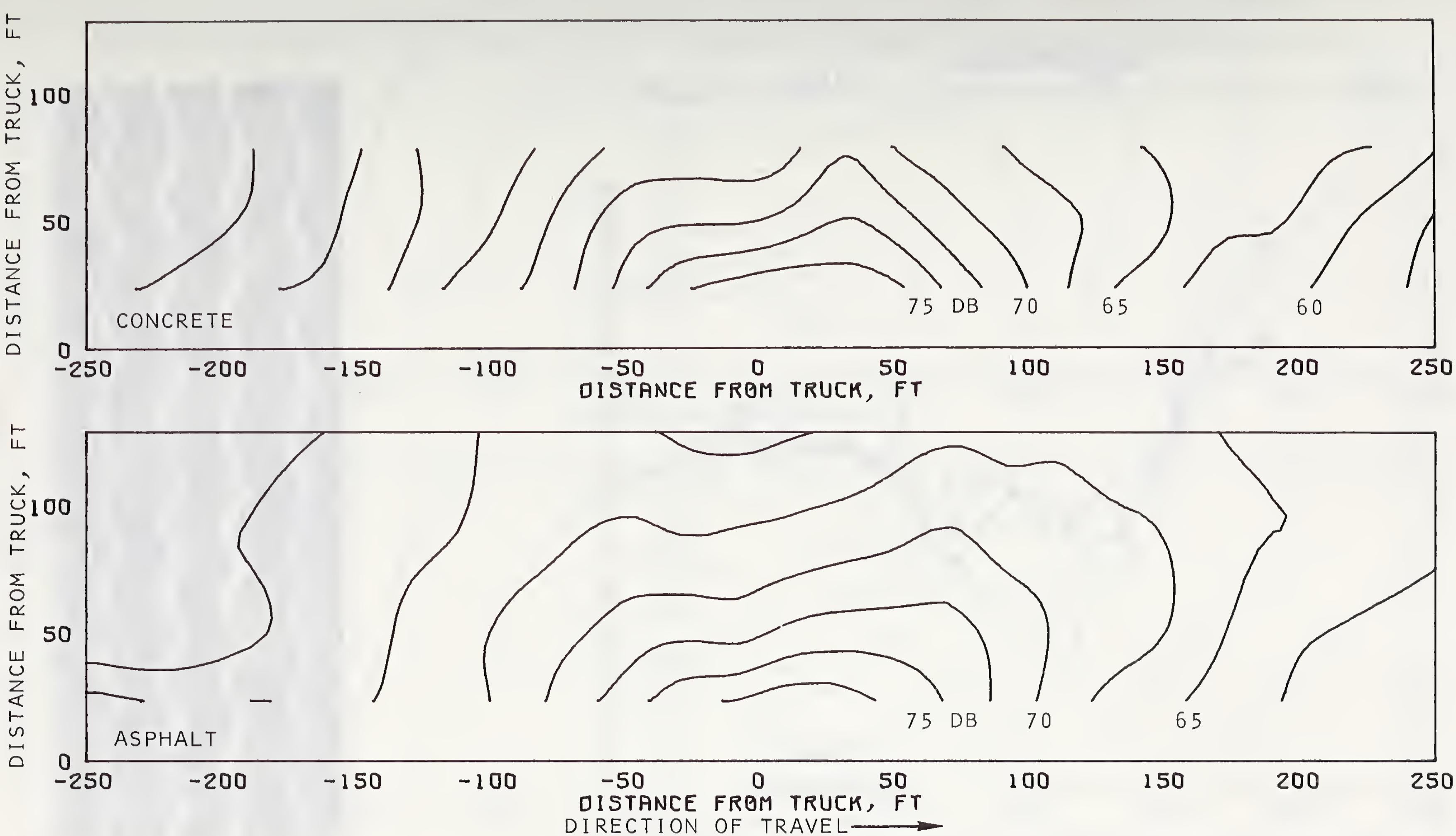
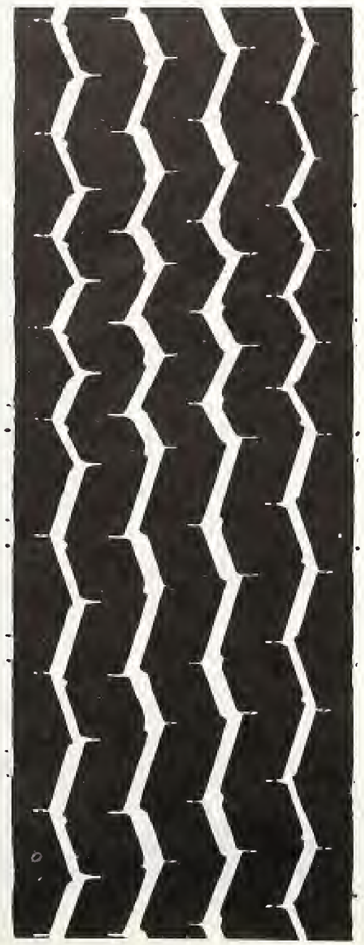
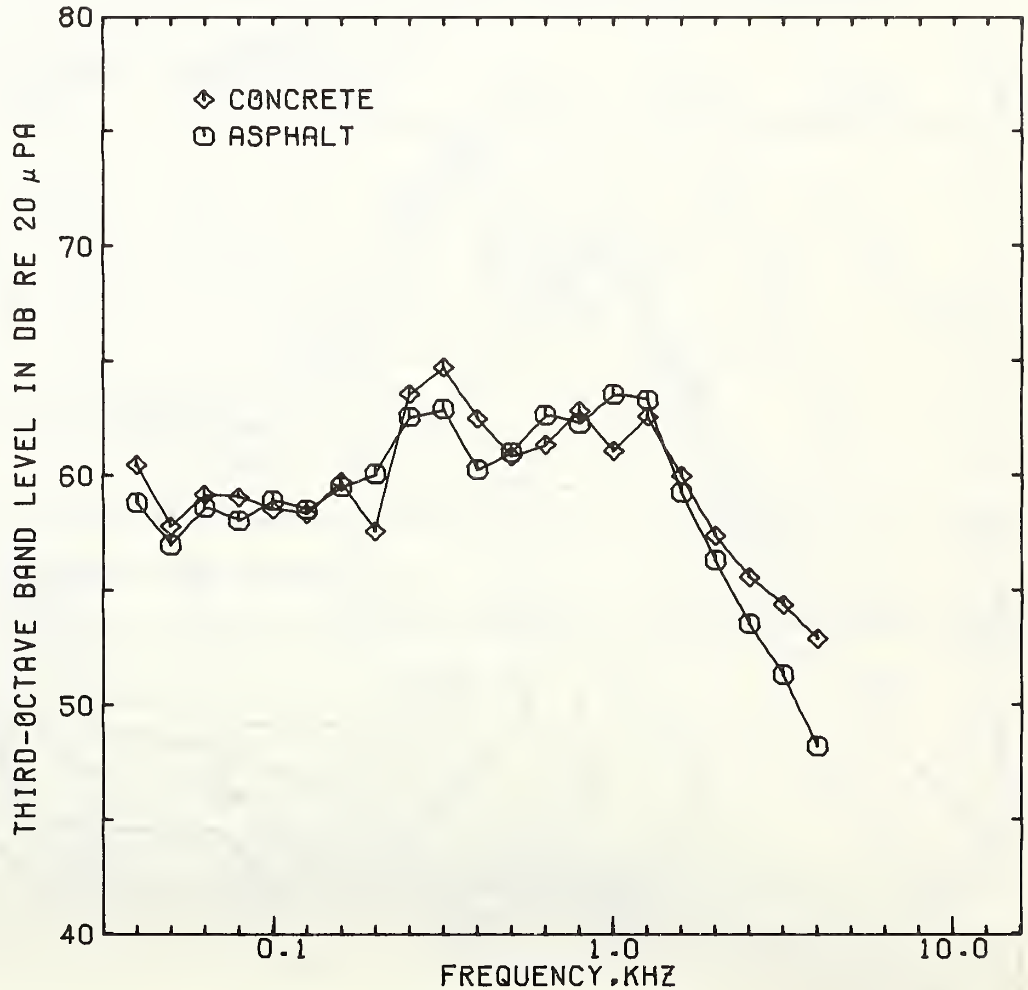



Figure A-8. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, fully-worn, rib-C tires on the drive axle.

RIB-C, NEW, DUAL, UNLOADED





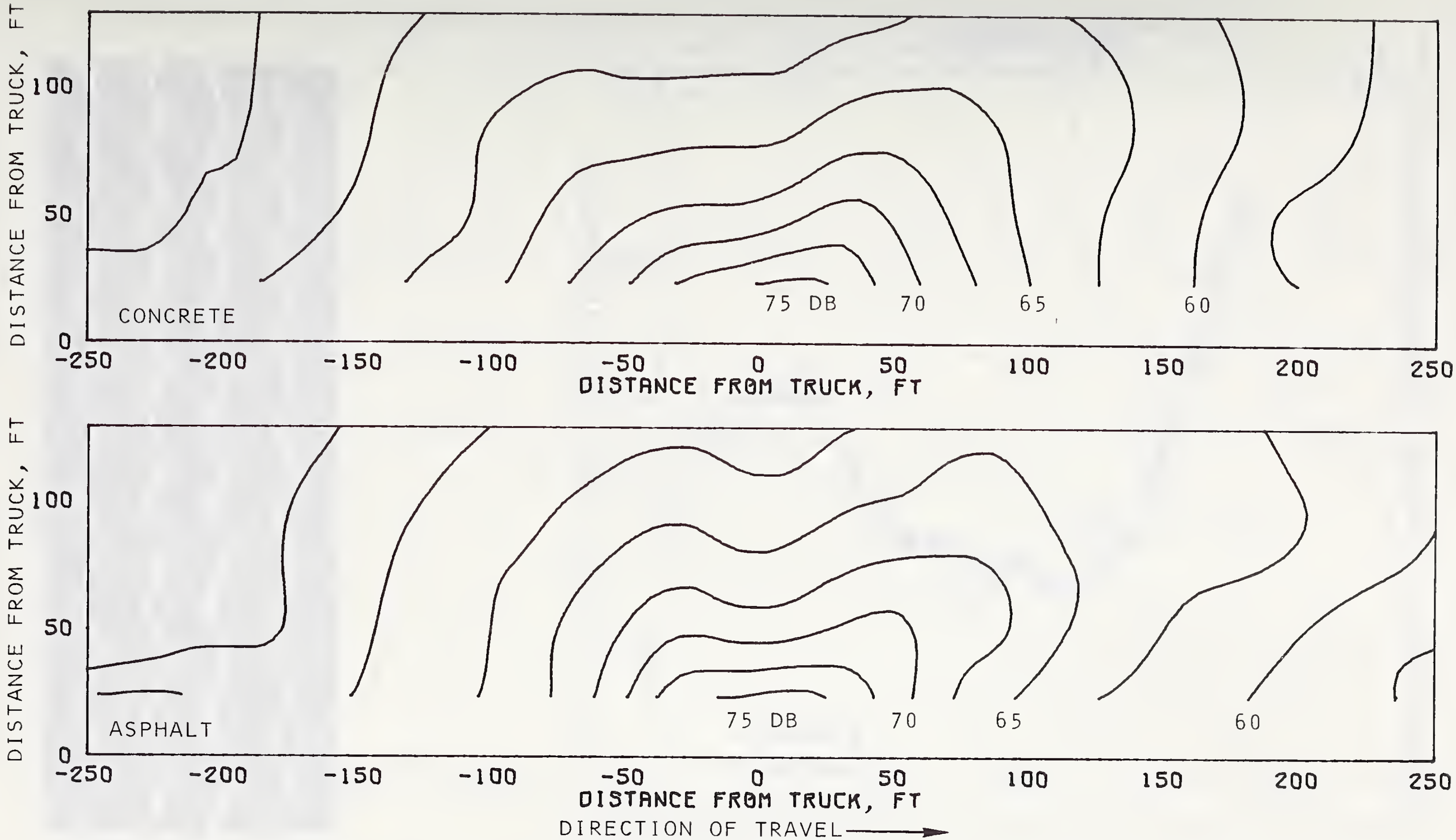
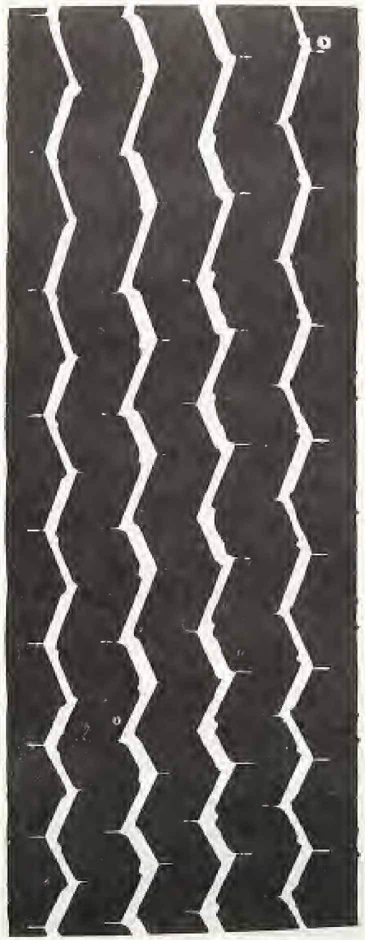
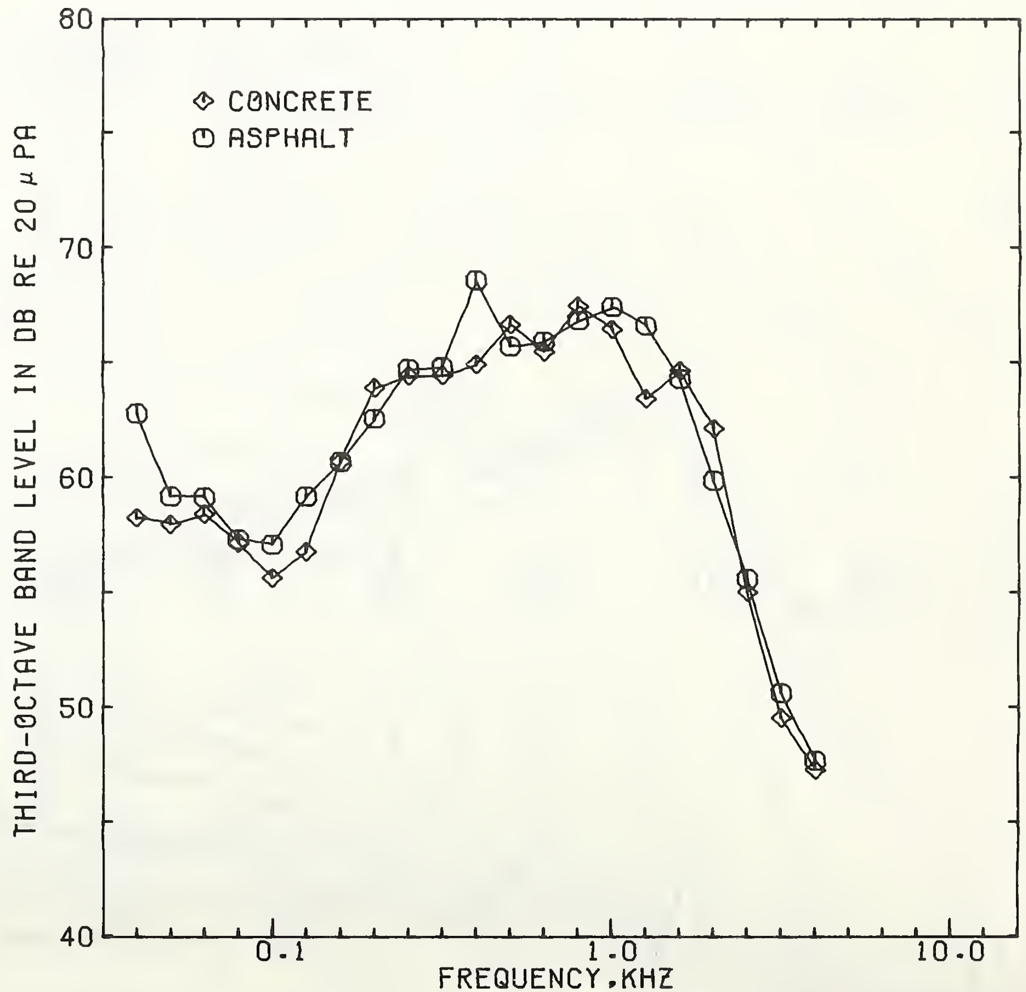



Figure A-9. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, rib-C tires on the drive axle.

## RIB-C, HALF-WORN, DUAL, UNLOADED





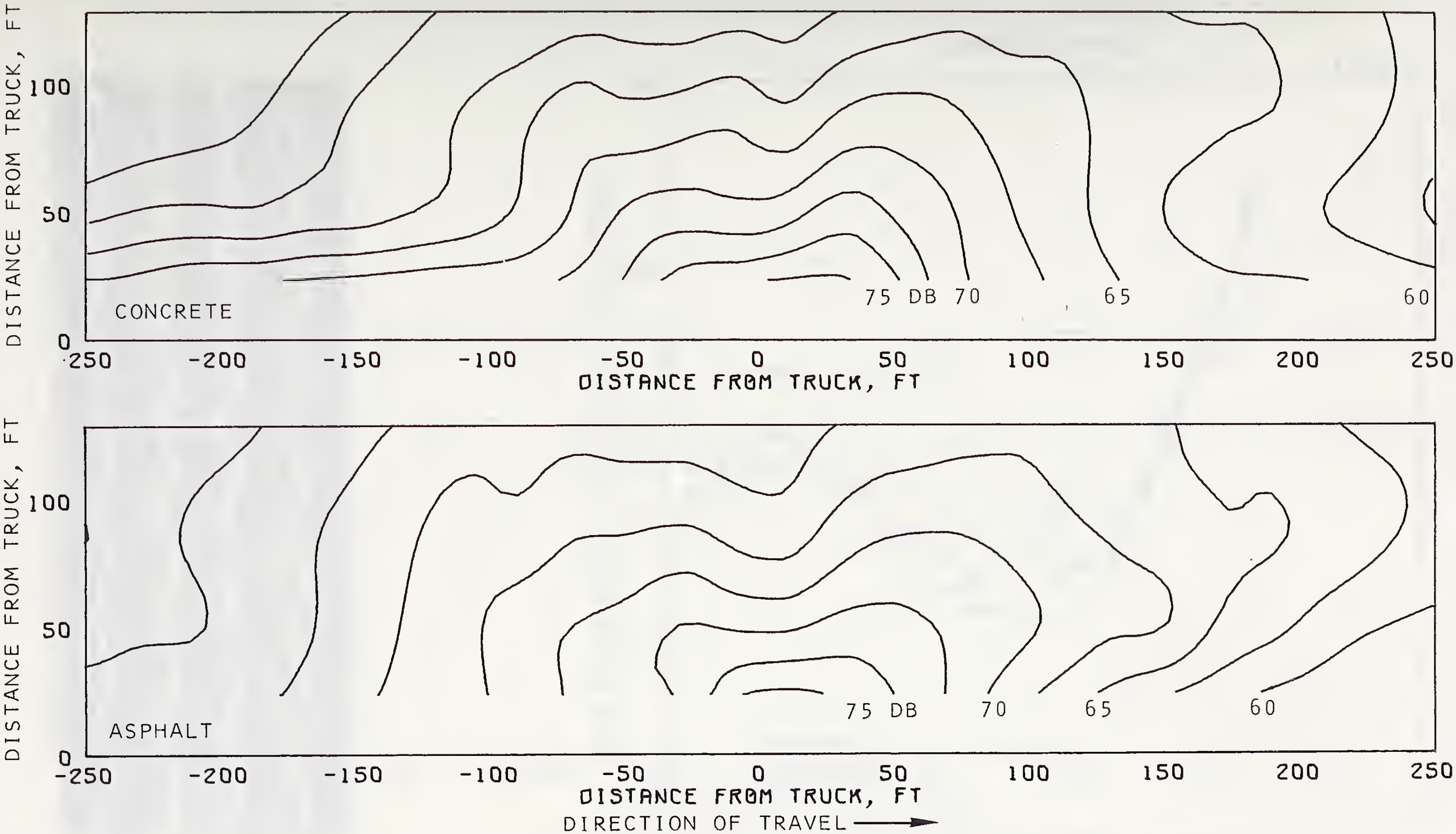
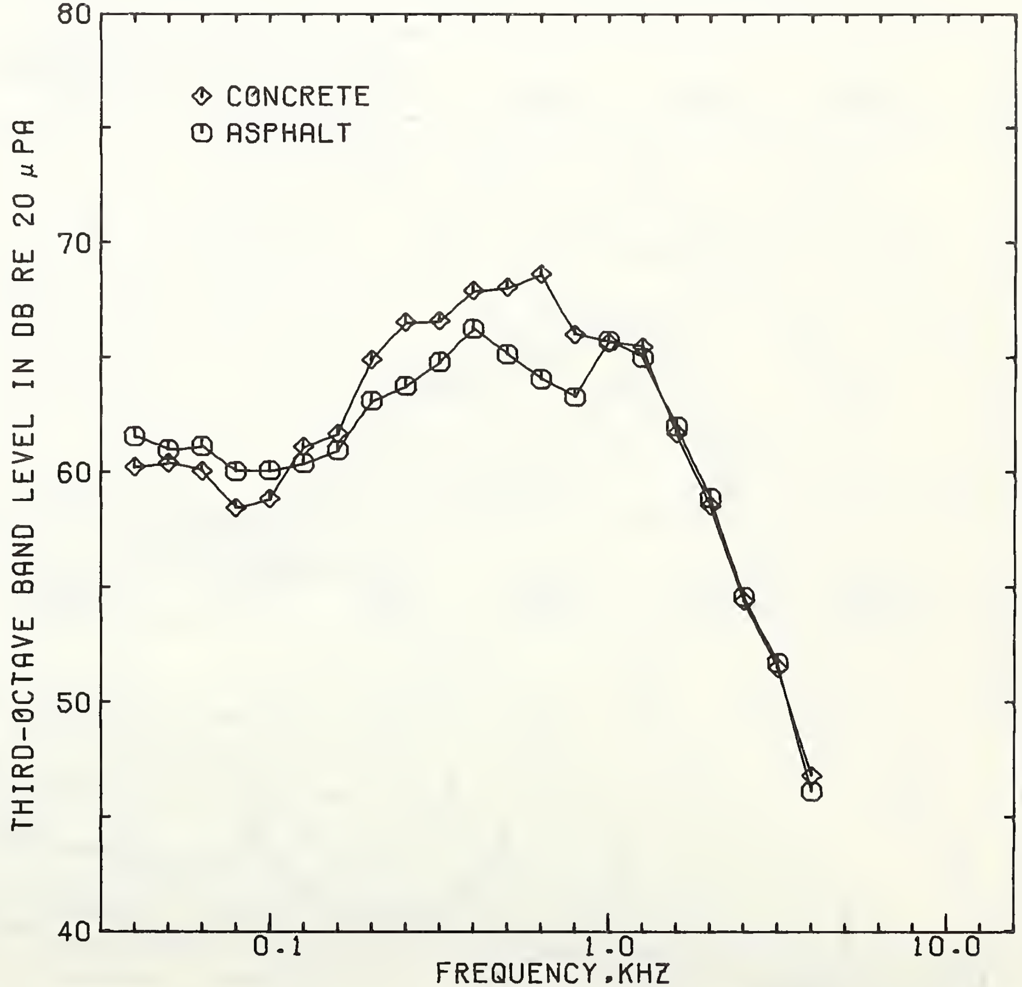



Figure A-10. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, rib-C tires on the drive axle.

## RIB-C, FULLY-WORN, DUAL, UNLOADED



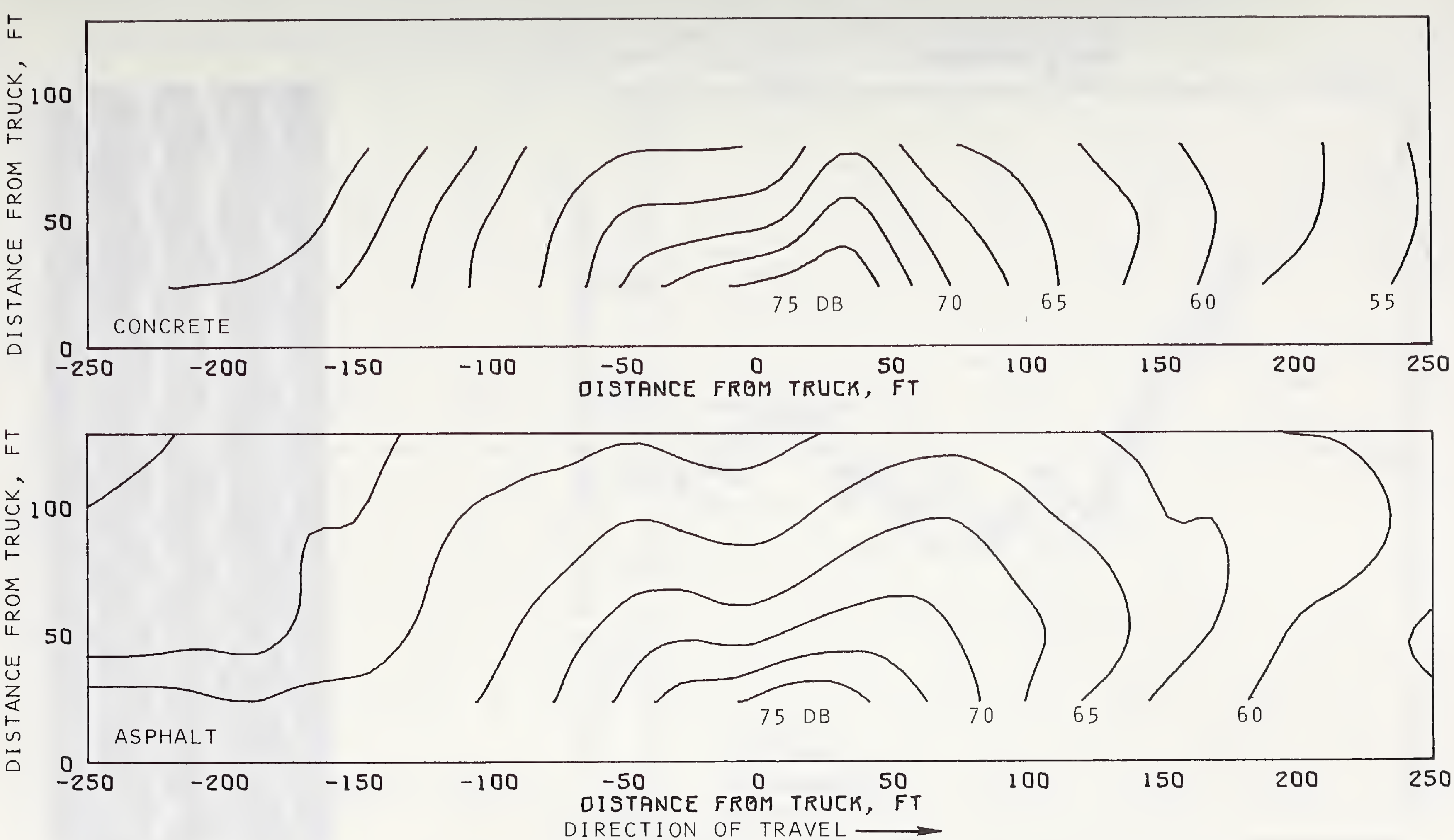
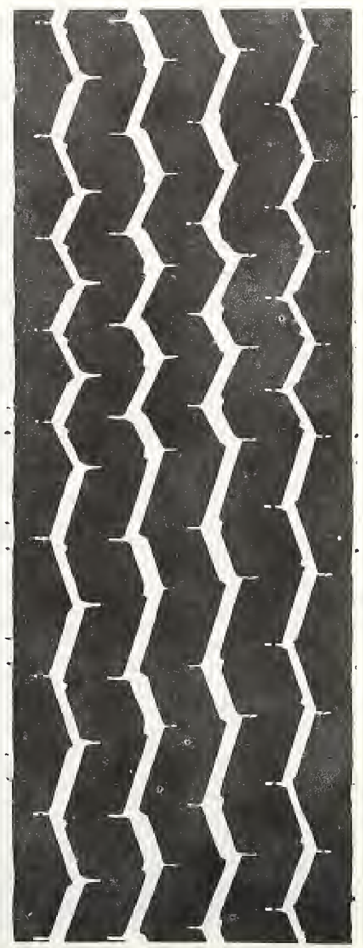
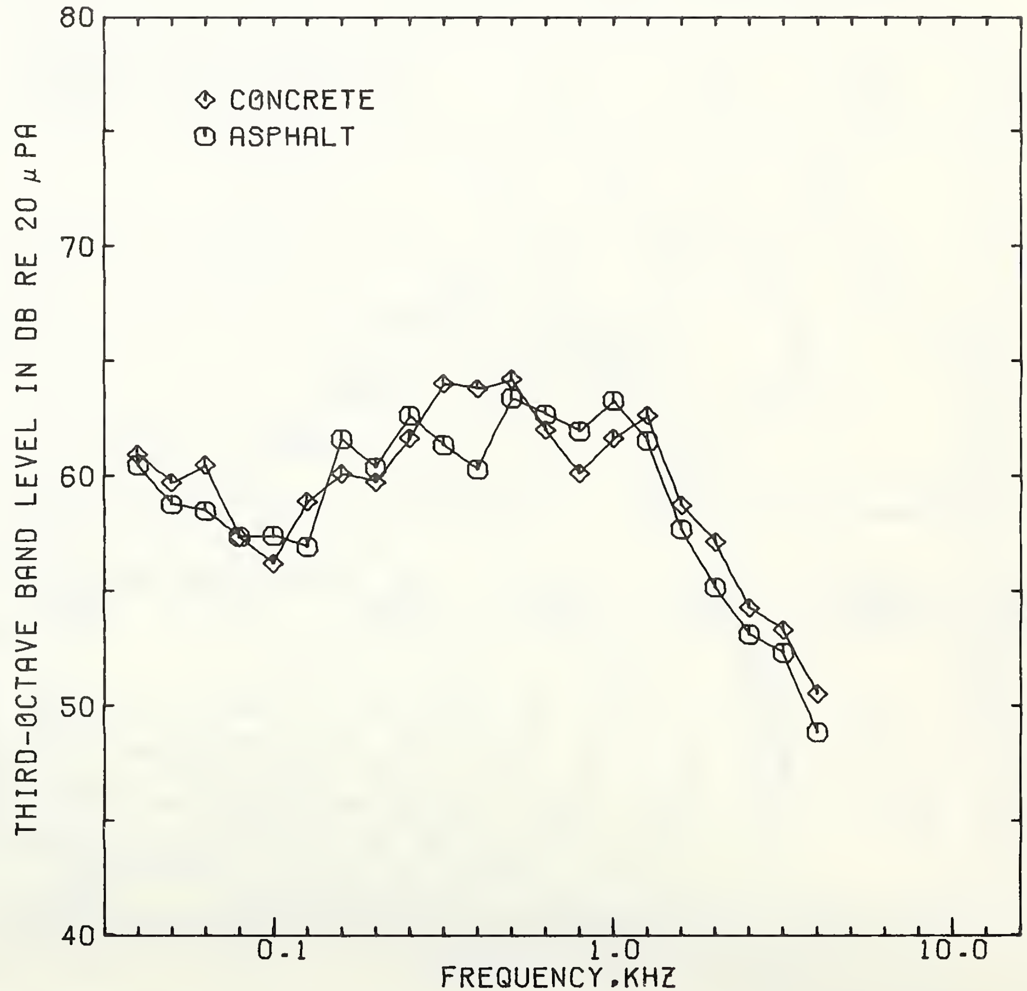



Figure A-11. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, fully-worn, rib-C tires on the drive axle.

RIB-C, NEW, SINGLE, UNLOADED





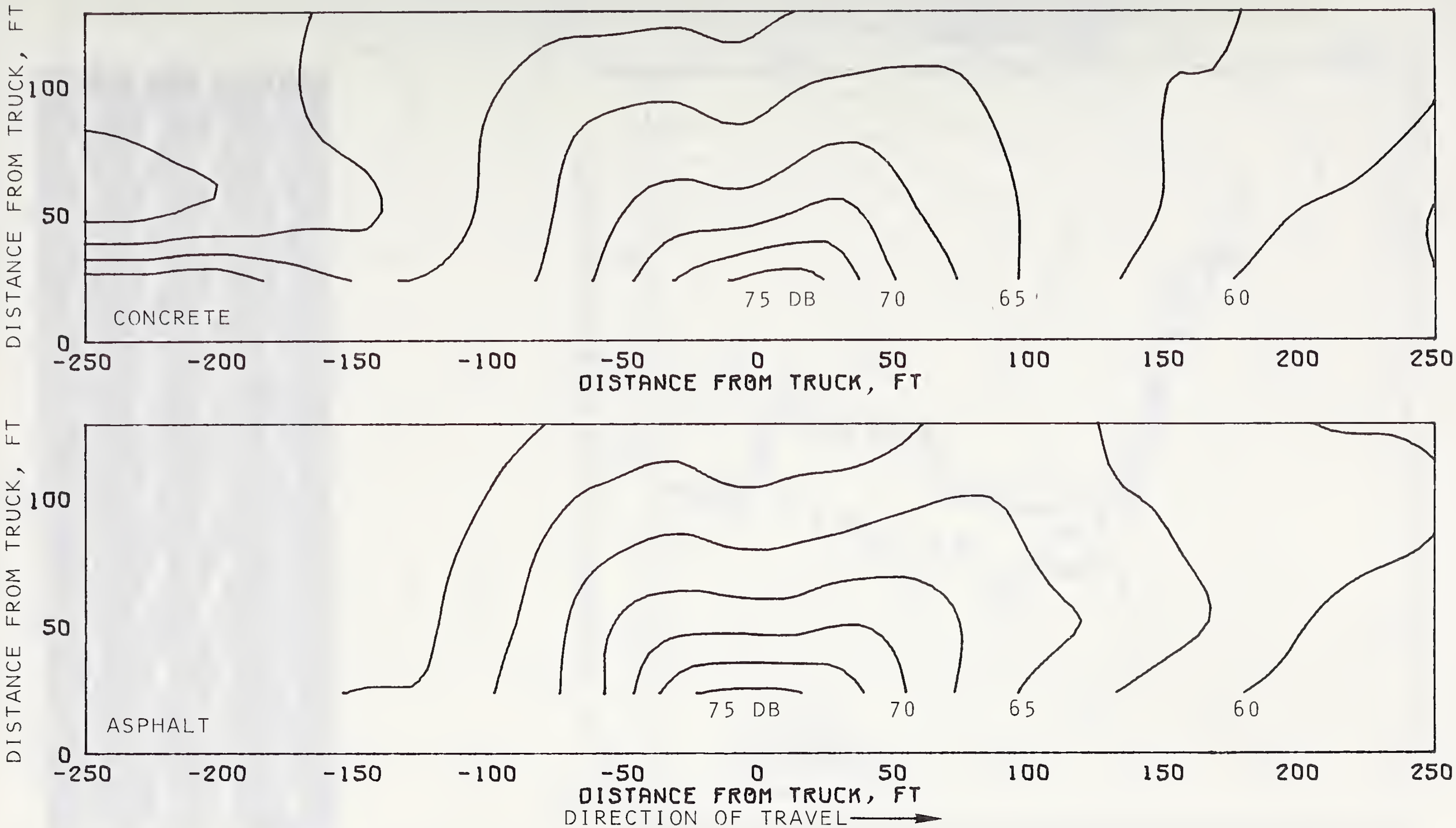
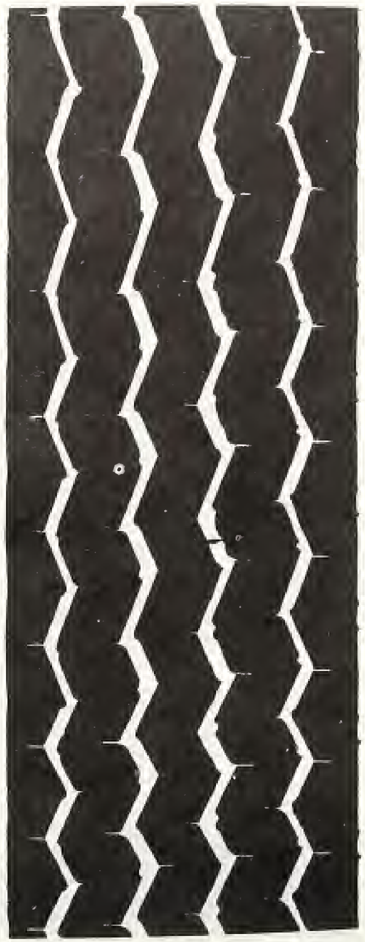
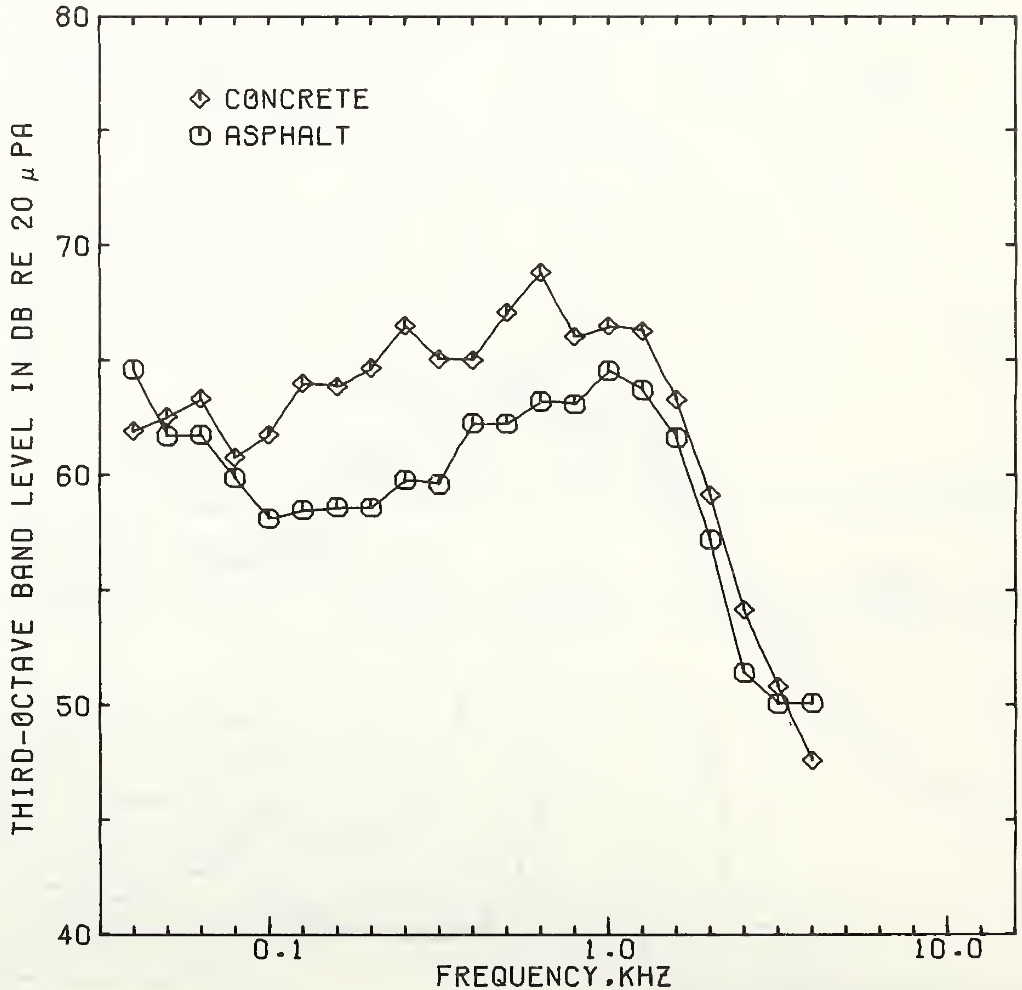



Figure A-12. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and single, new, rib-C tires on the drive axle.

## RIB-C, HALF-WORN, SINGLE, UNLOADED





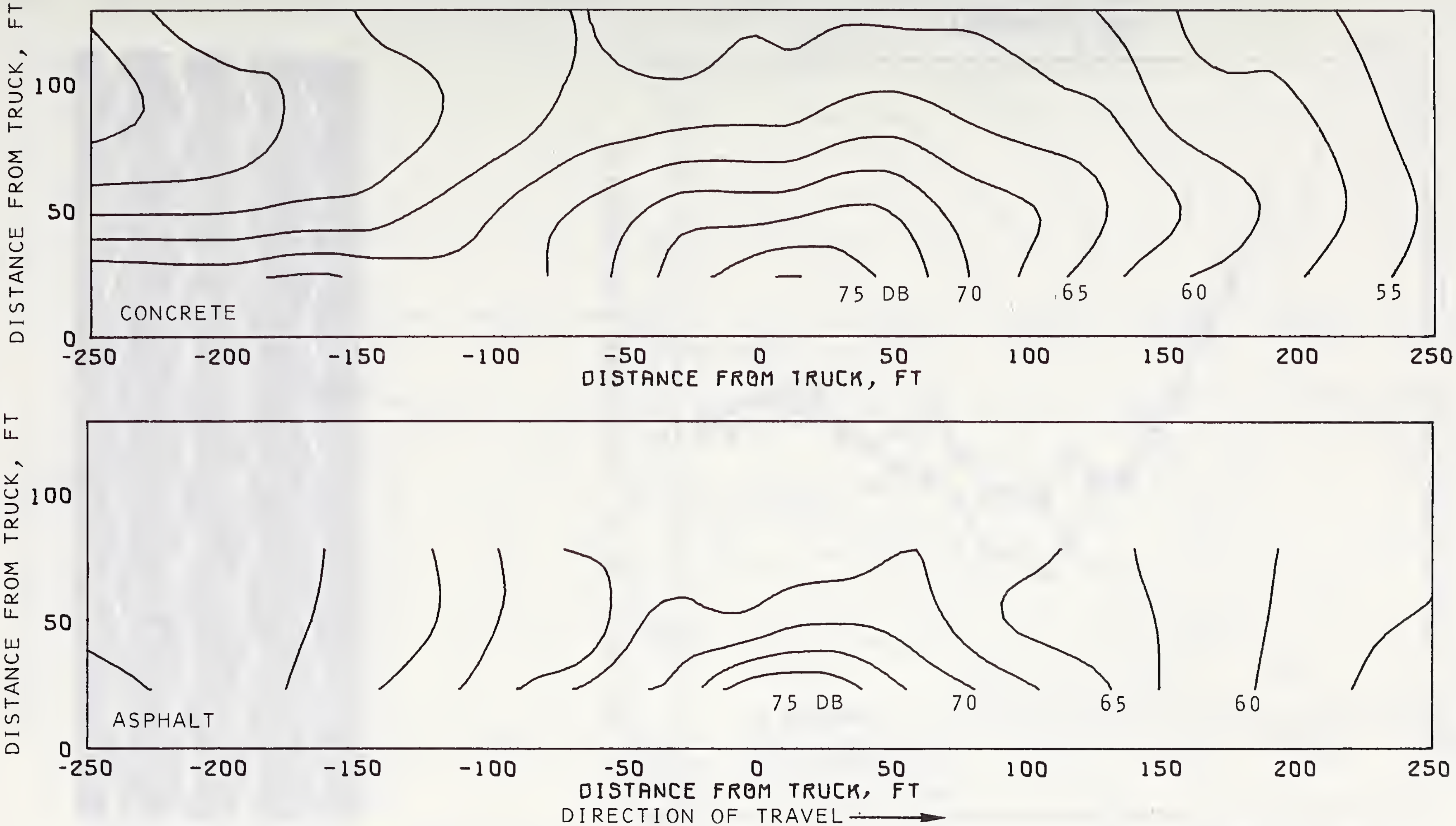
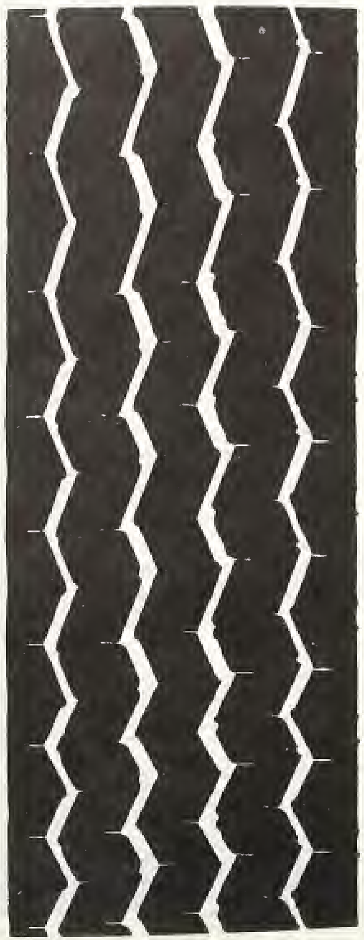
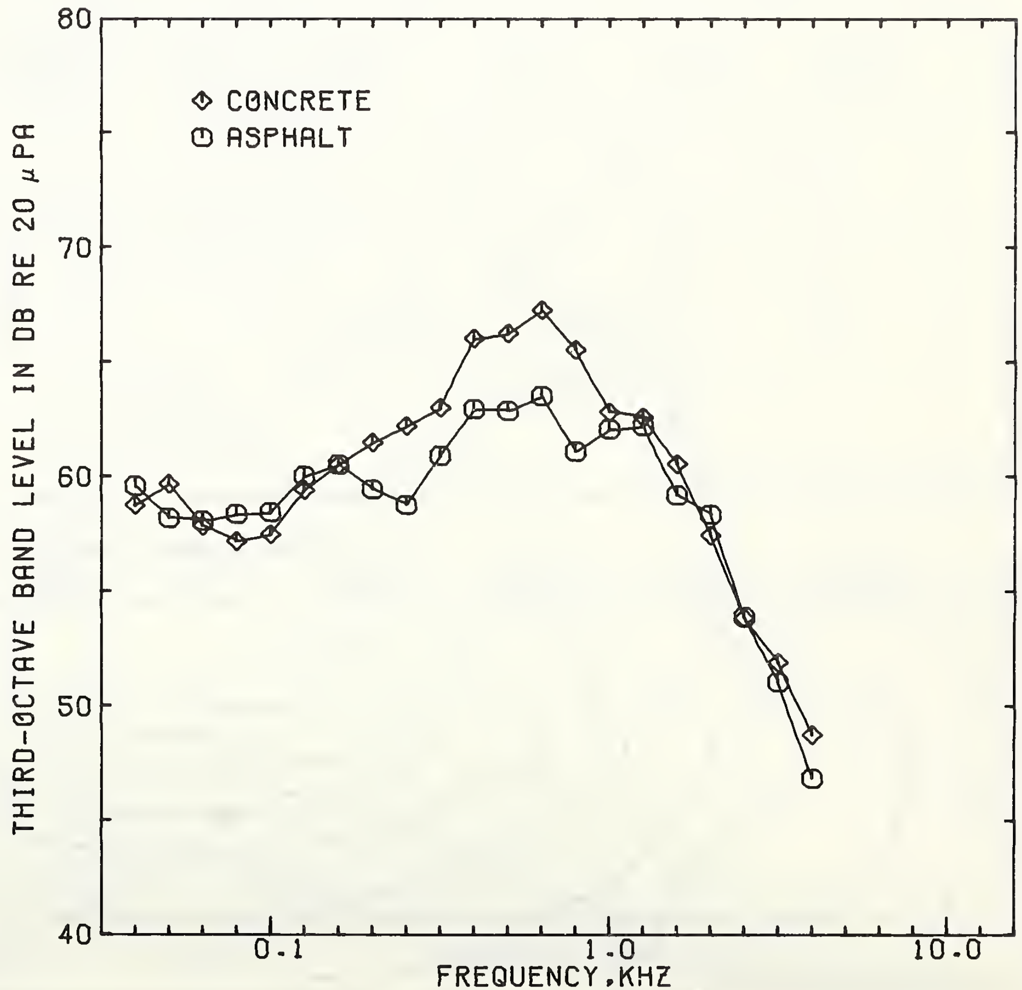



Figure A-13. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and single, half-worn, rib-C tires on the drive axle.

RIB-C, FULLY-WORN, SINGLE, UNLOADED





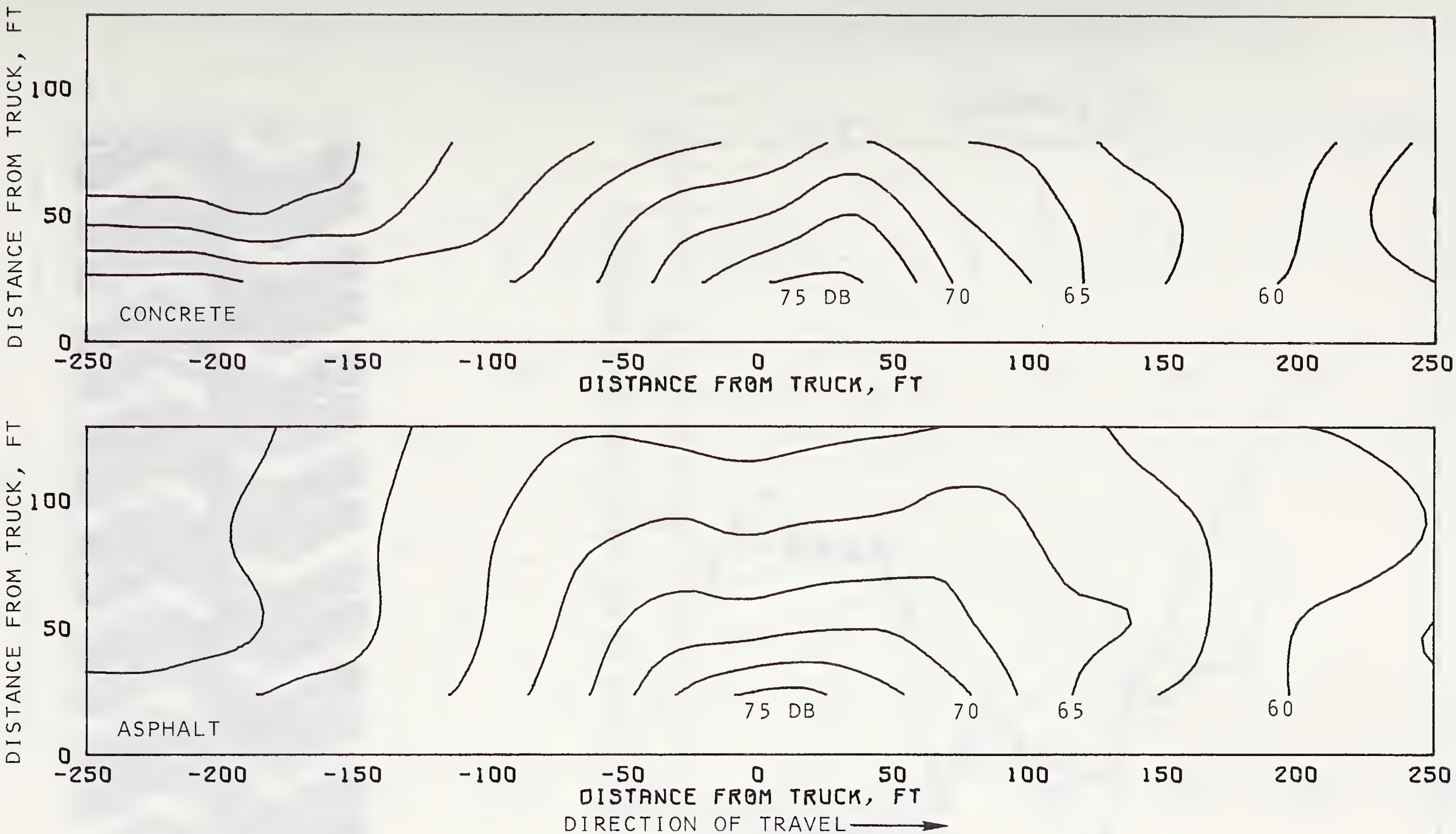
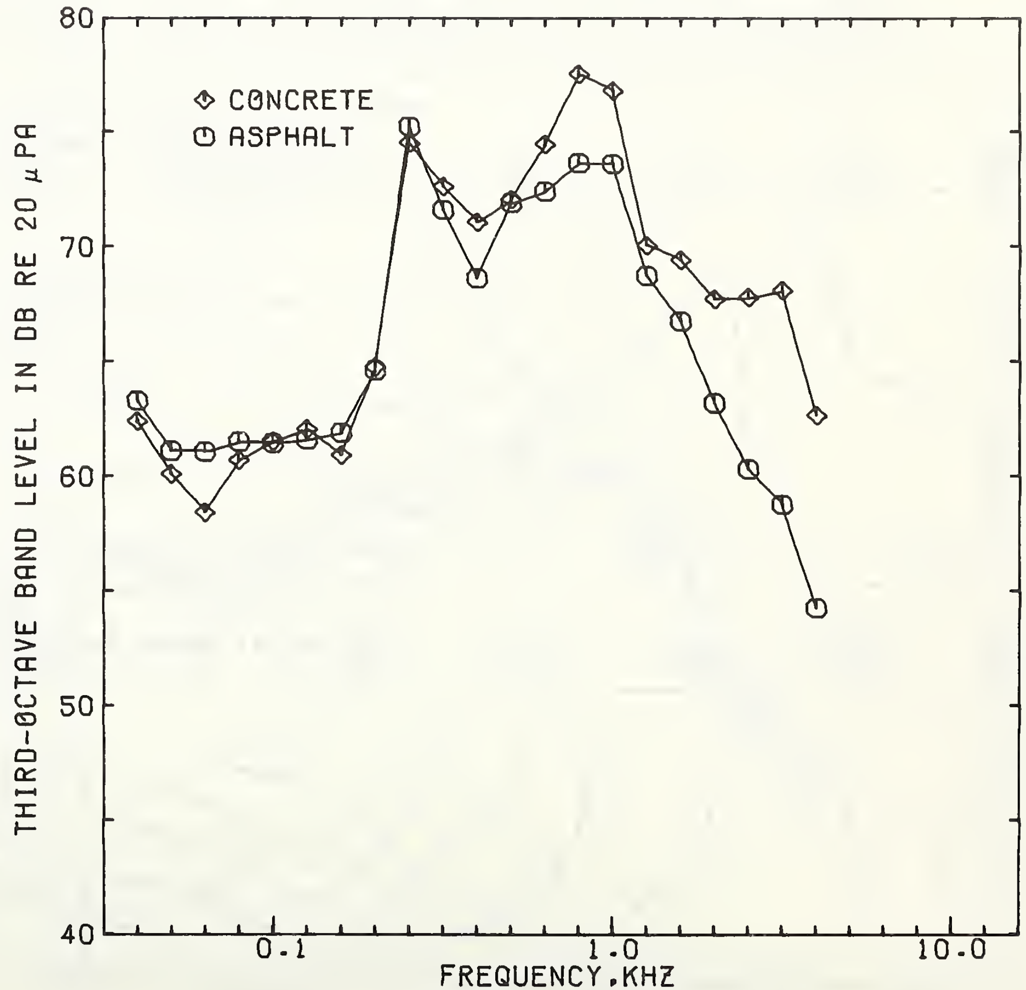



Figure A-14. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and single, fully-worn, rib-C tires on the drive axle.

## CROSS-BAR-D, NEW, DUAL, LOADED



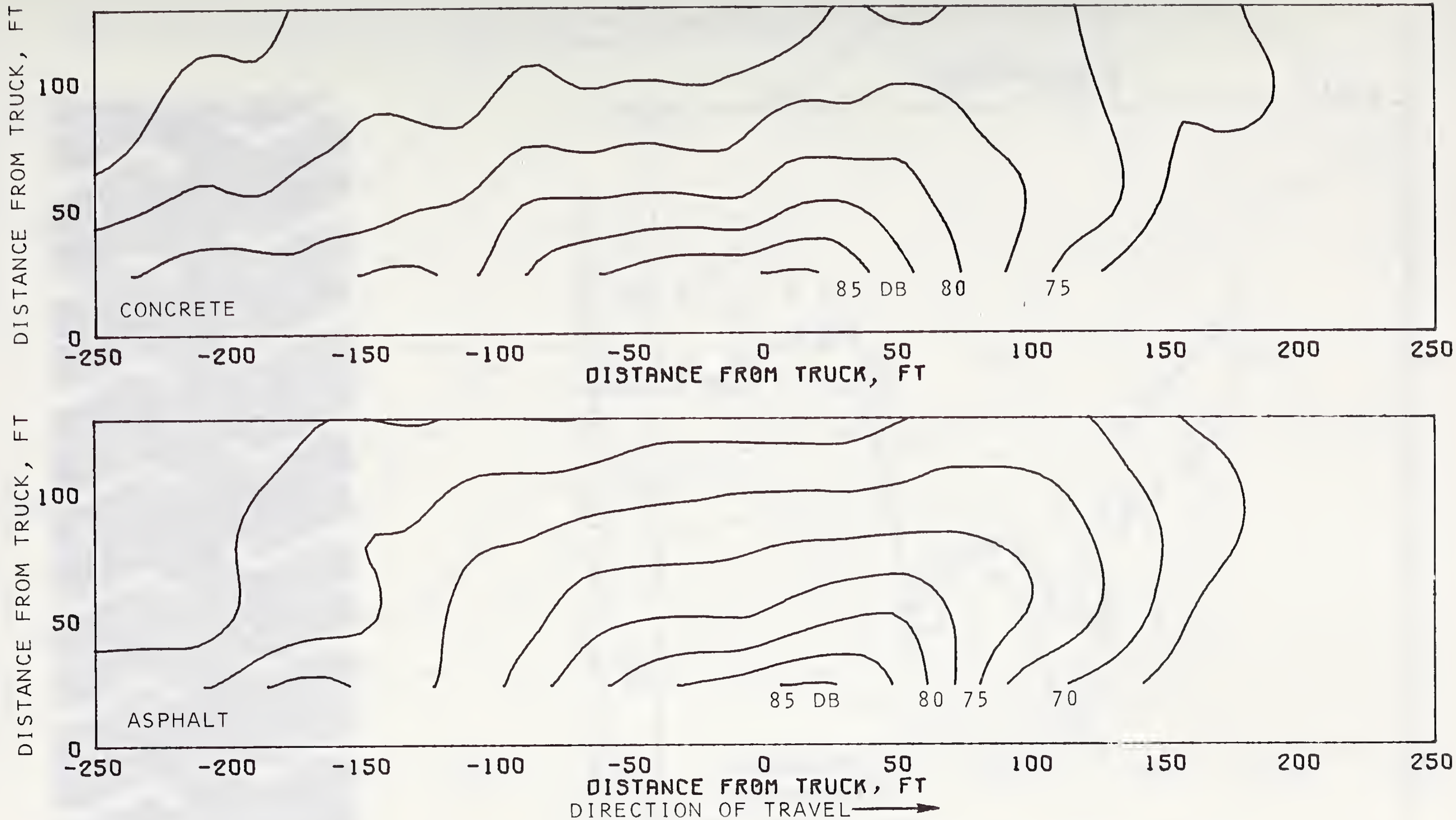
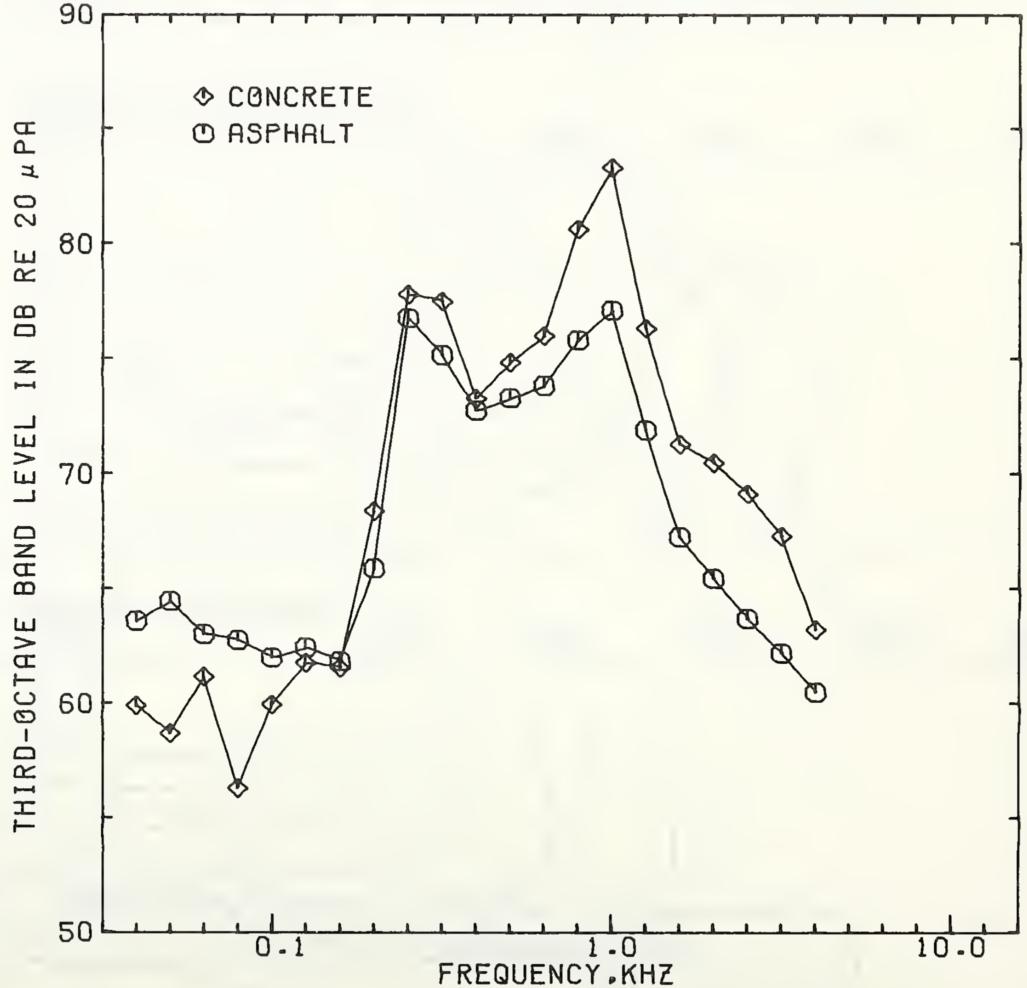



Figure A-15. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, cross-bar-D tires on the drive axle.

## CROSS-BAR-D, HALF-WORN, DUAL, LOADED



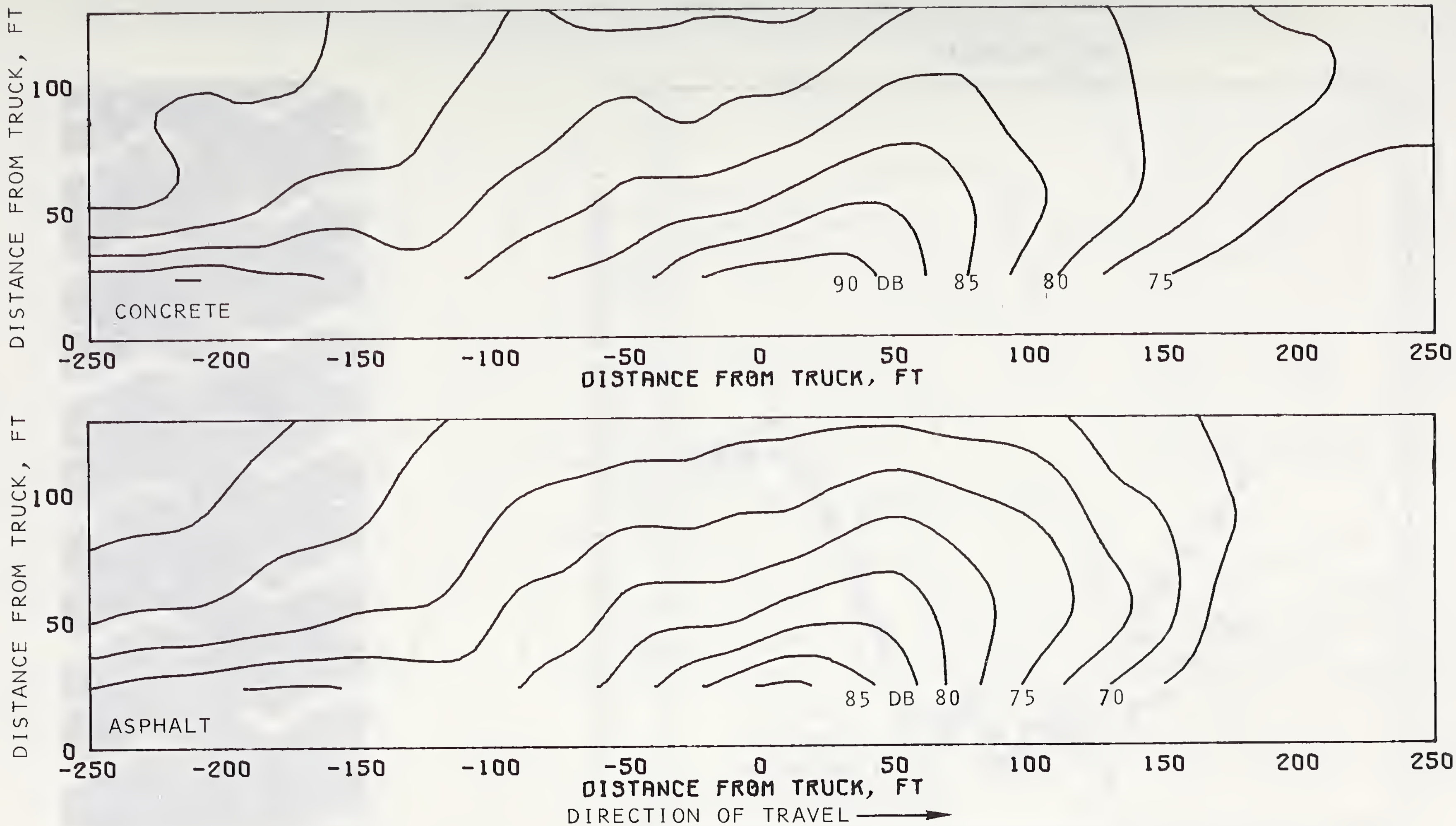
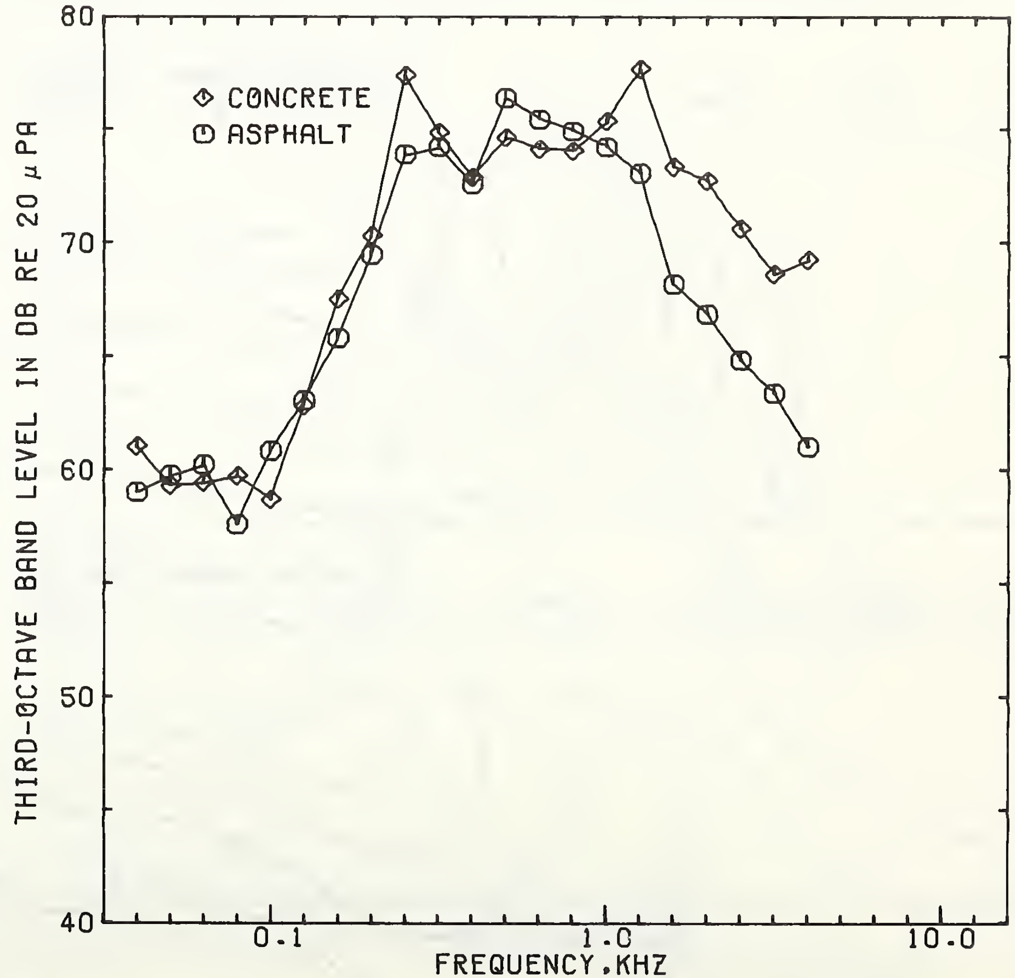



Figure A-16. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, cross-bar-D tires on the drive axle.

CROSS-BAR-D, FULLY-WORN, DUAL, LOADED



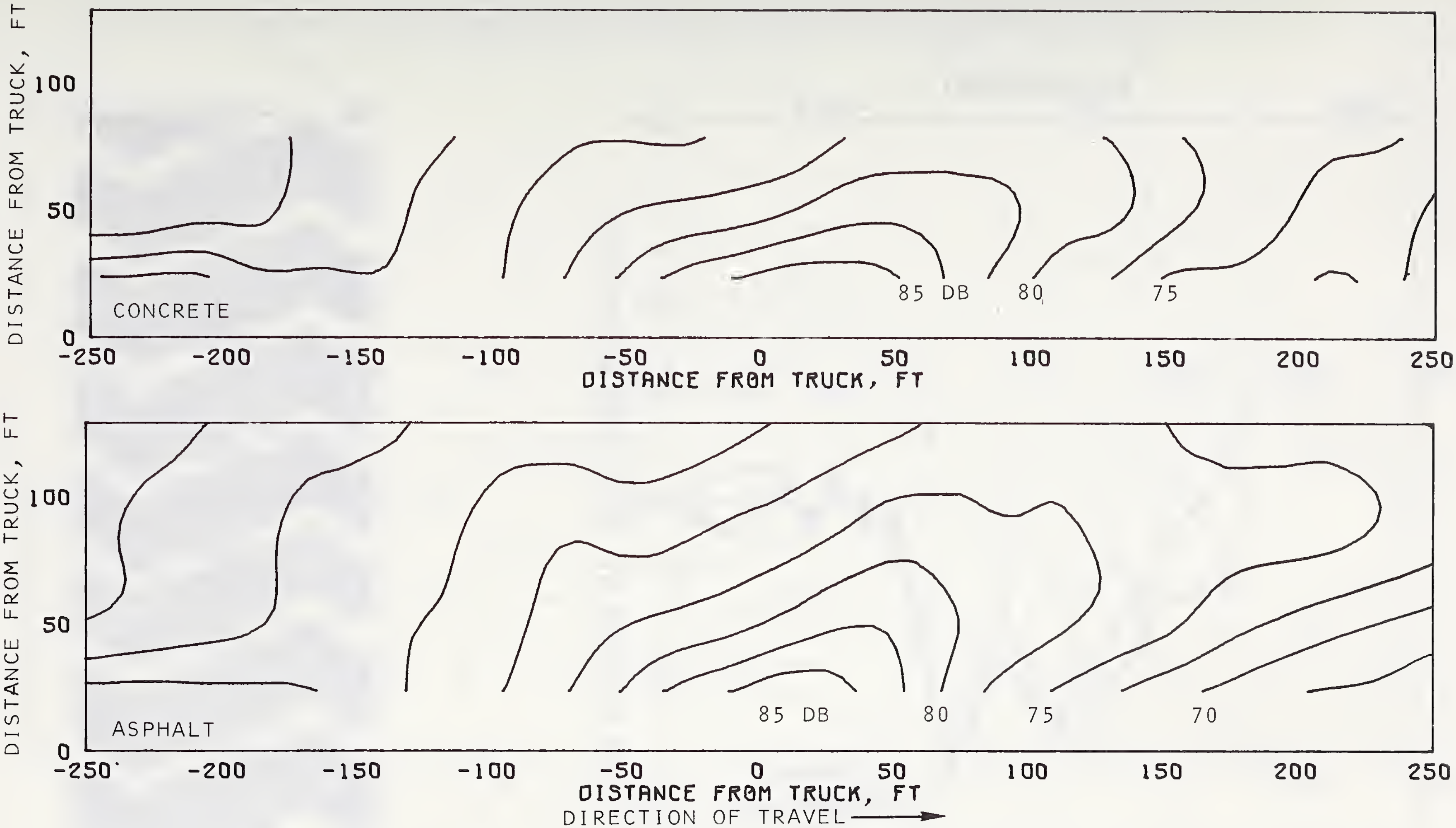
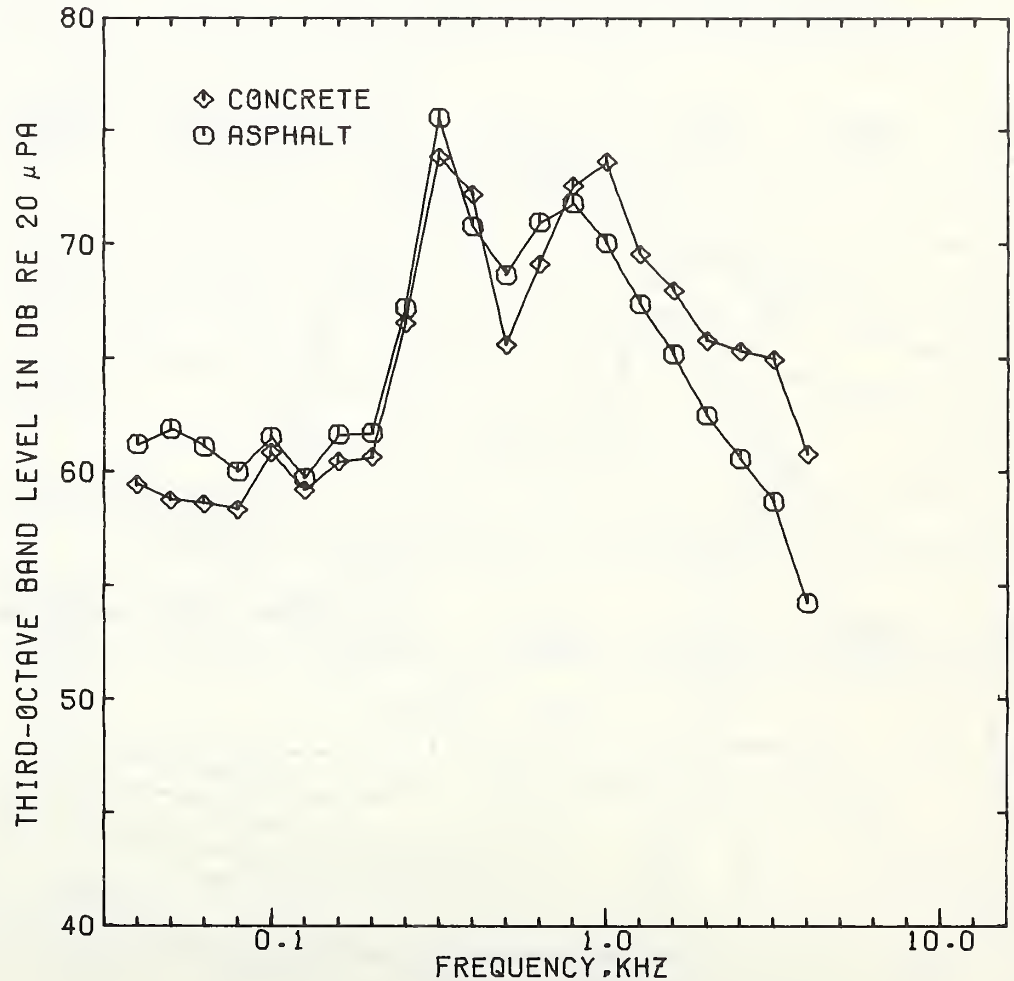



Figure A-17. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, fully-worn, cross-bar-D tires on the drive axle.

CROSS-BAR-E, NEW, DUAL, LOADED



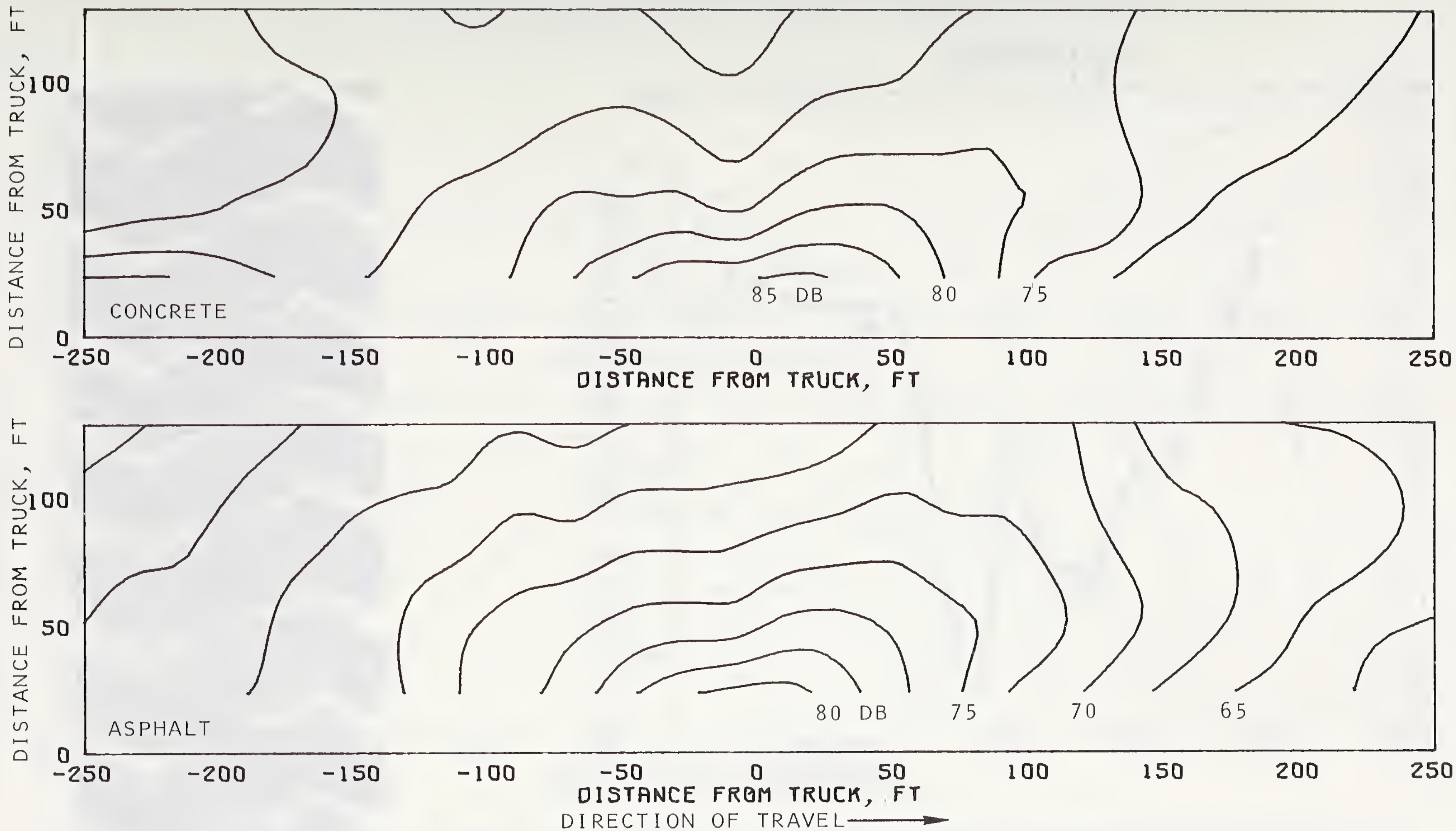
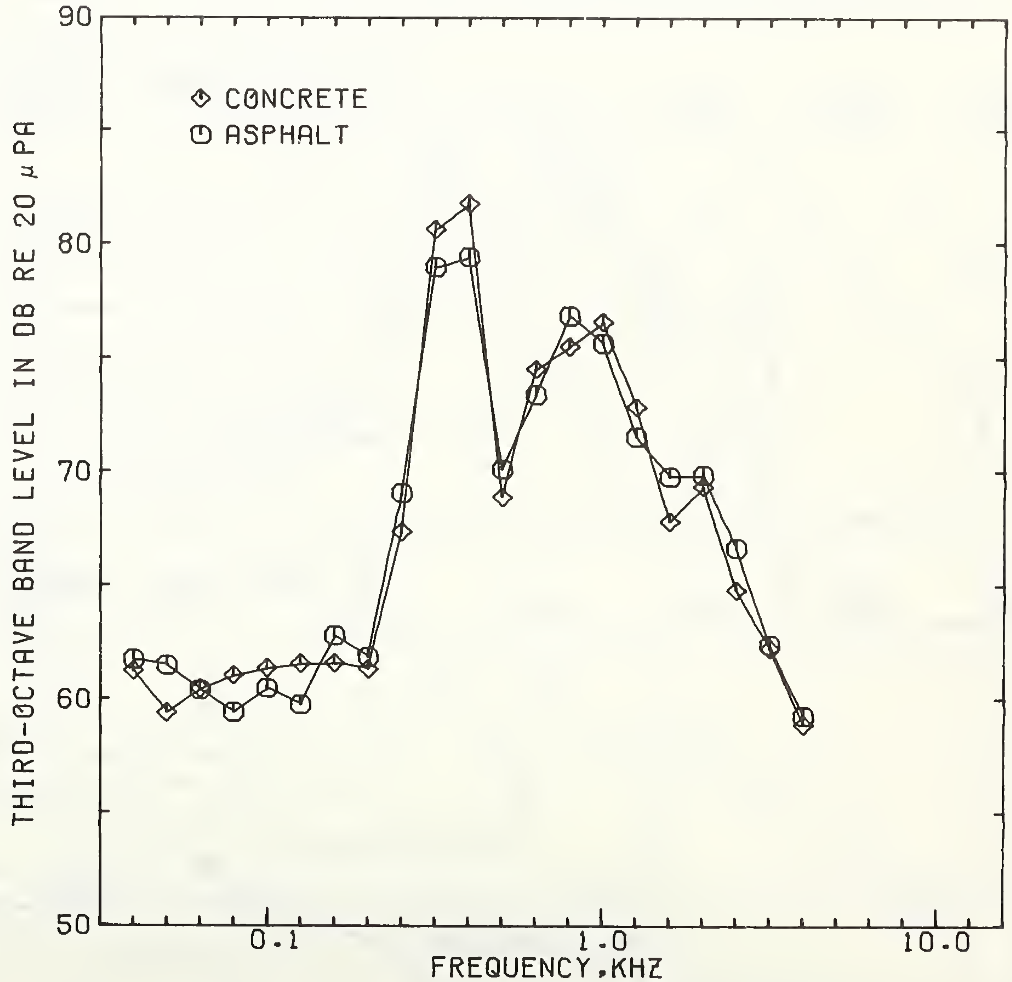



Figure A-18. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, cross-bar-E tires on the drive axle.

## CROSS-BAR-E, HALF-WORN, DUAL, LOADED



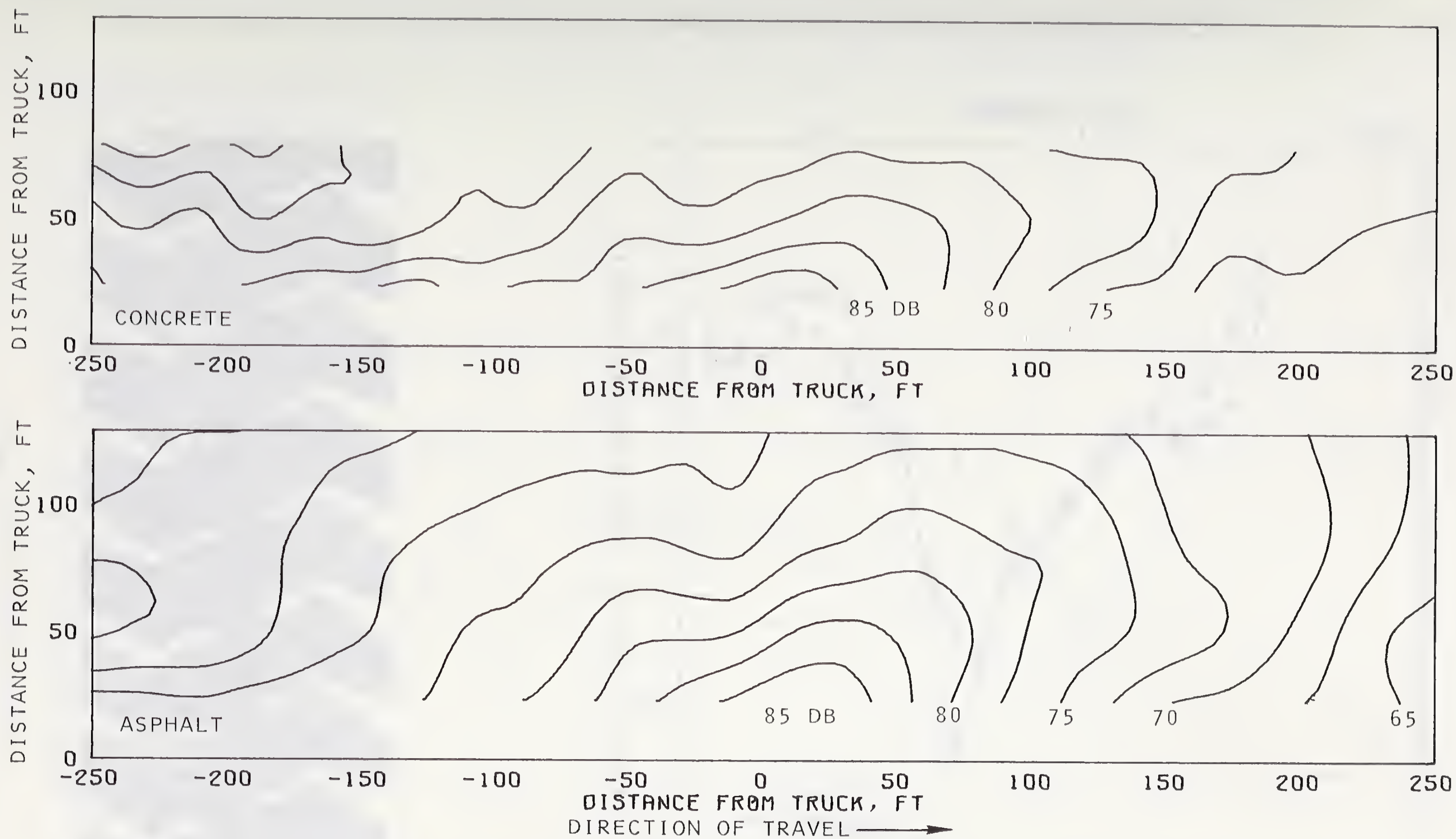
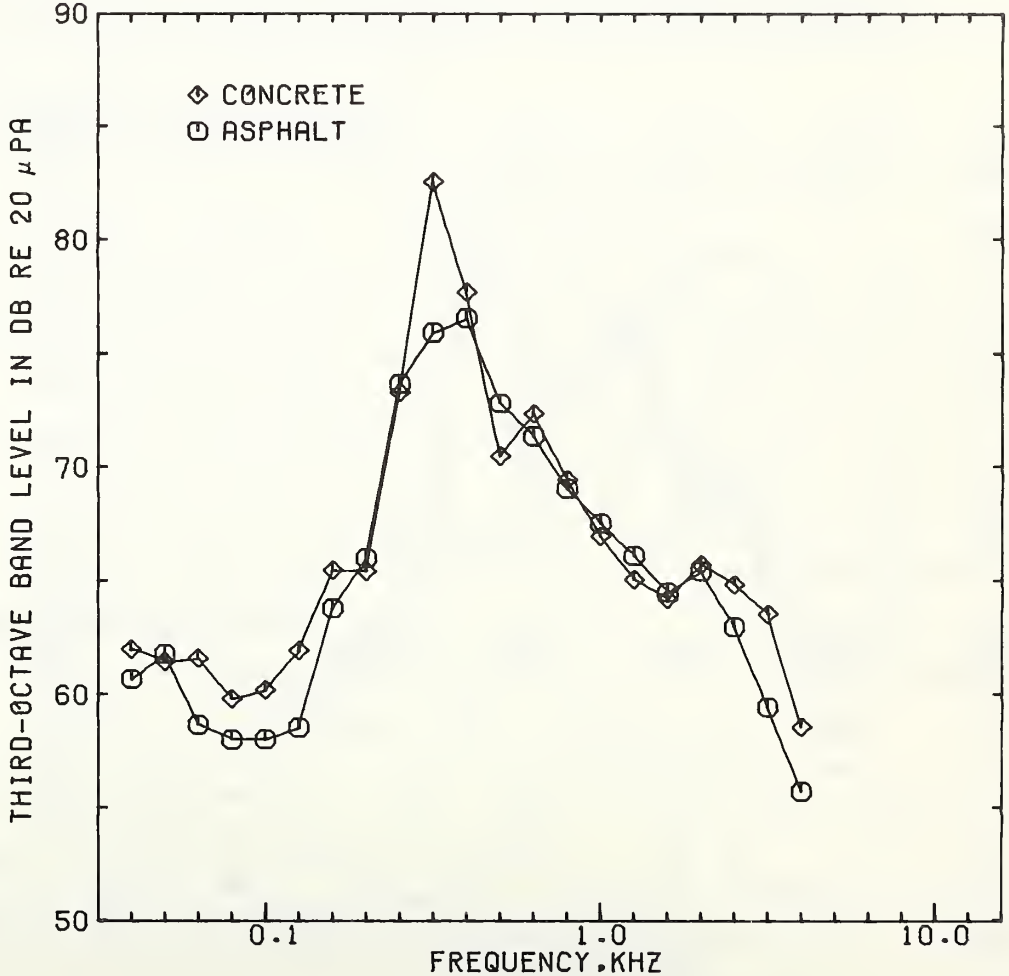



Figure A-19. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, cross-bar-E tires on the drive axle.

## CROSS-BAR-E, FULLY-WORN, DUAL, LOADED



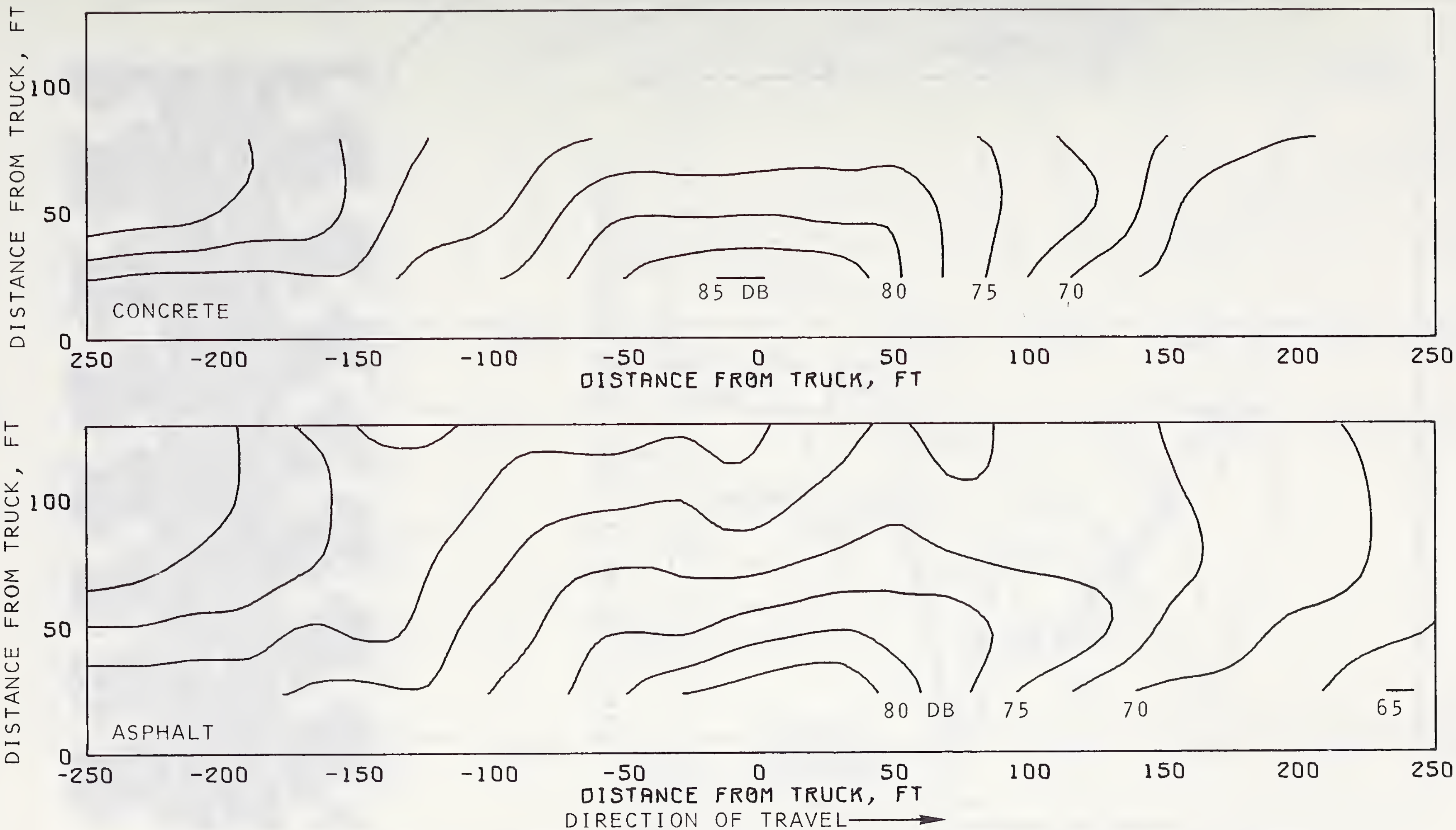
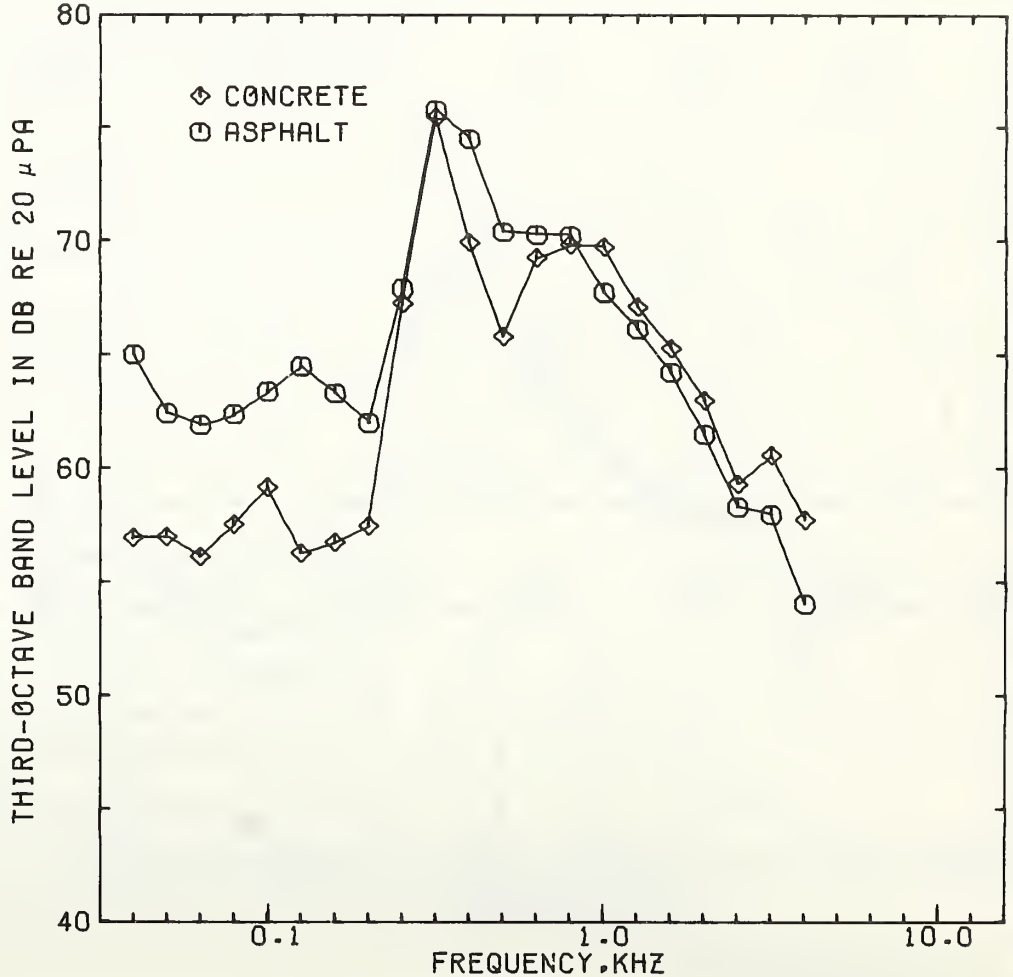



Figure A-20. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, fully-worn, cross-bar-E tires on the drive axle.

CROSS-BAR-F, NEW, DUAL, LOADED



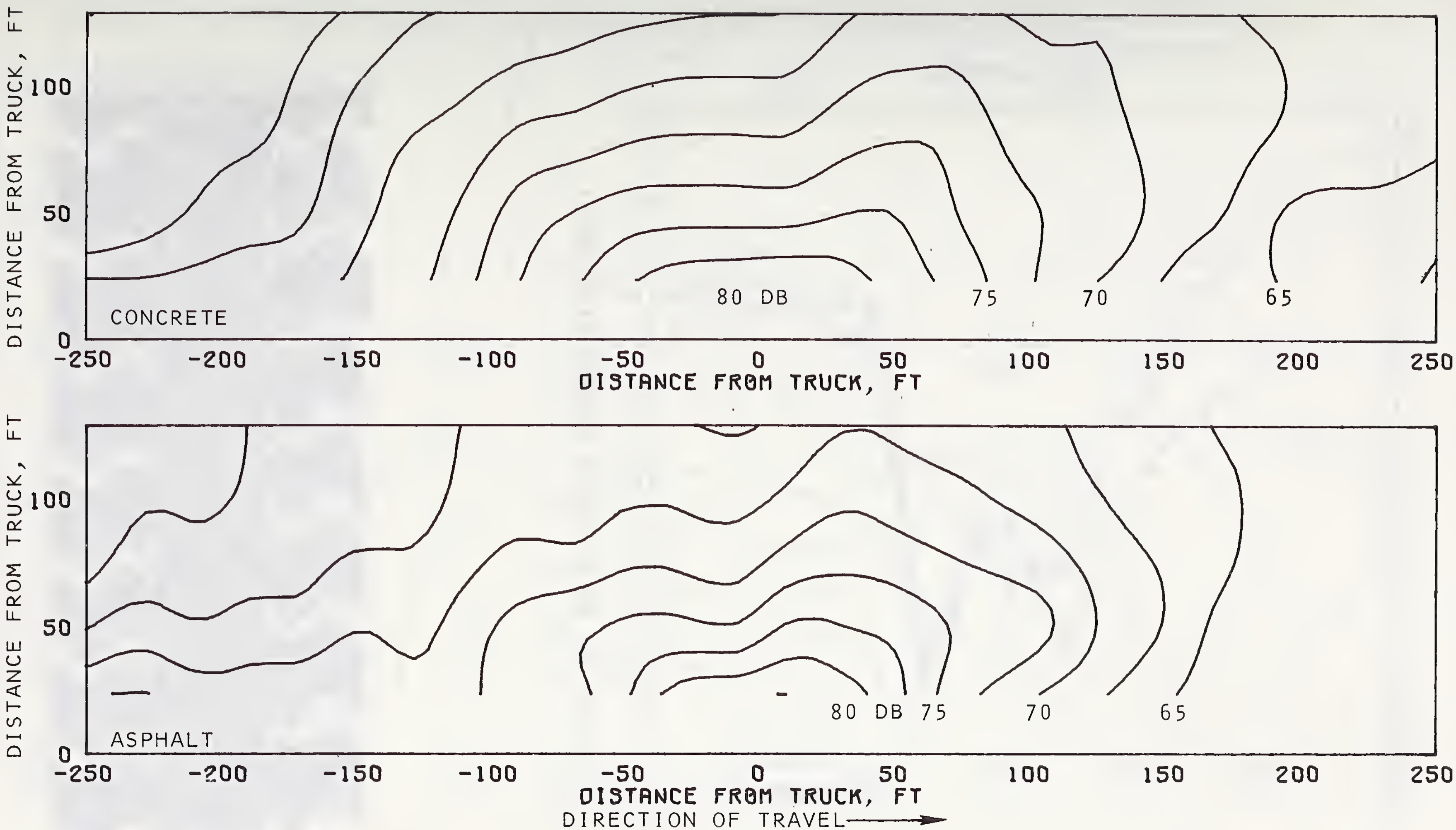
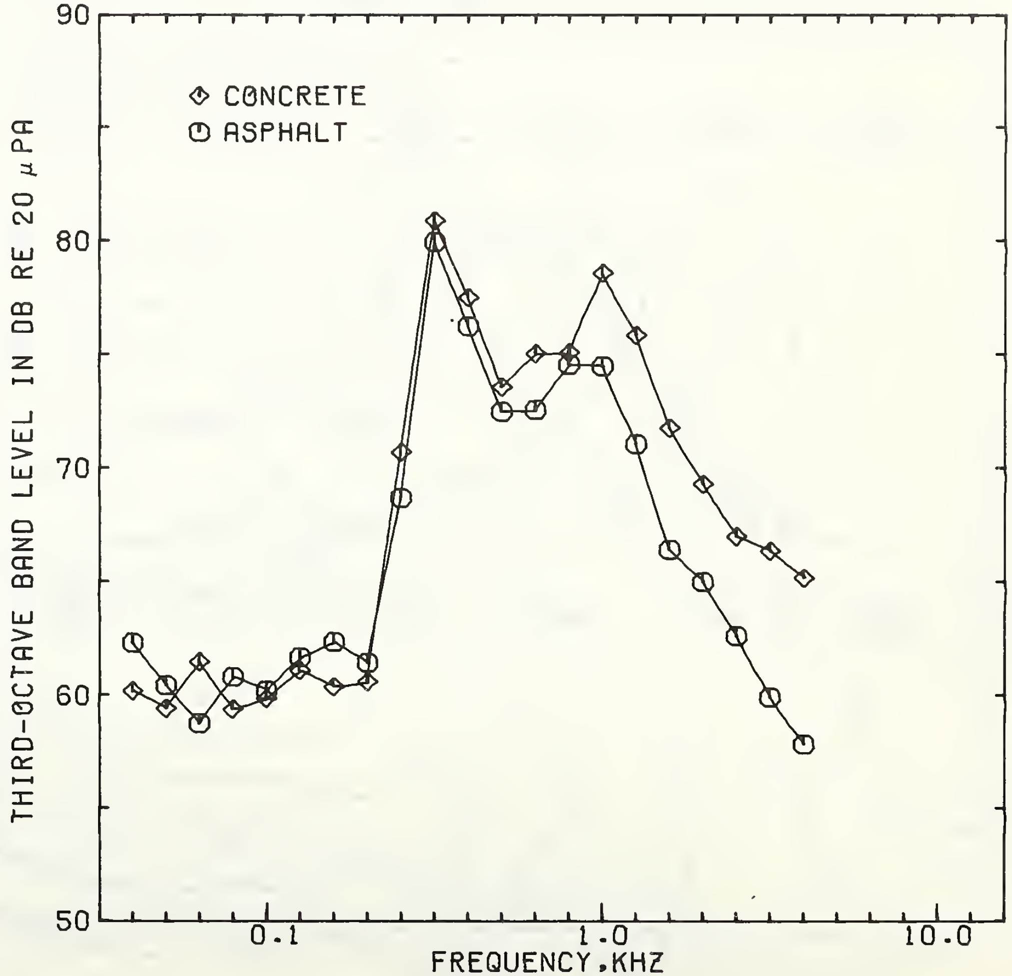



Figure A-21. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, cross-bar-F tires on the drive axle.

## CROSS-BAR-F, HALF-WORN, DUAL, LOADED



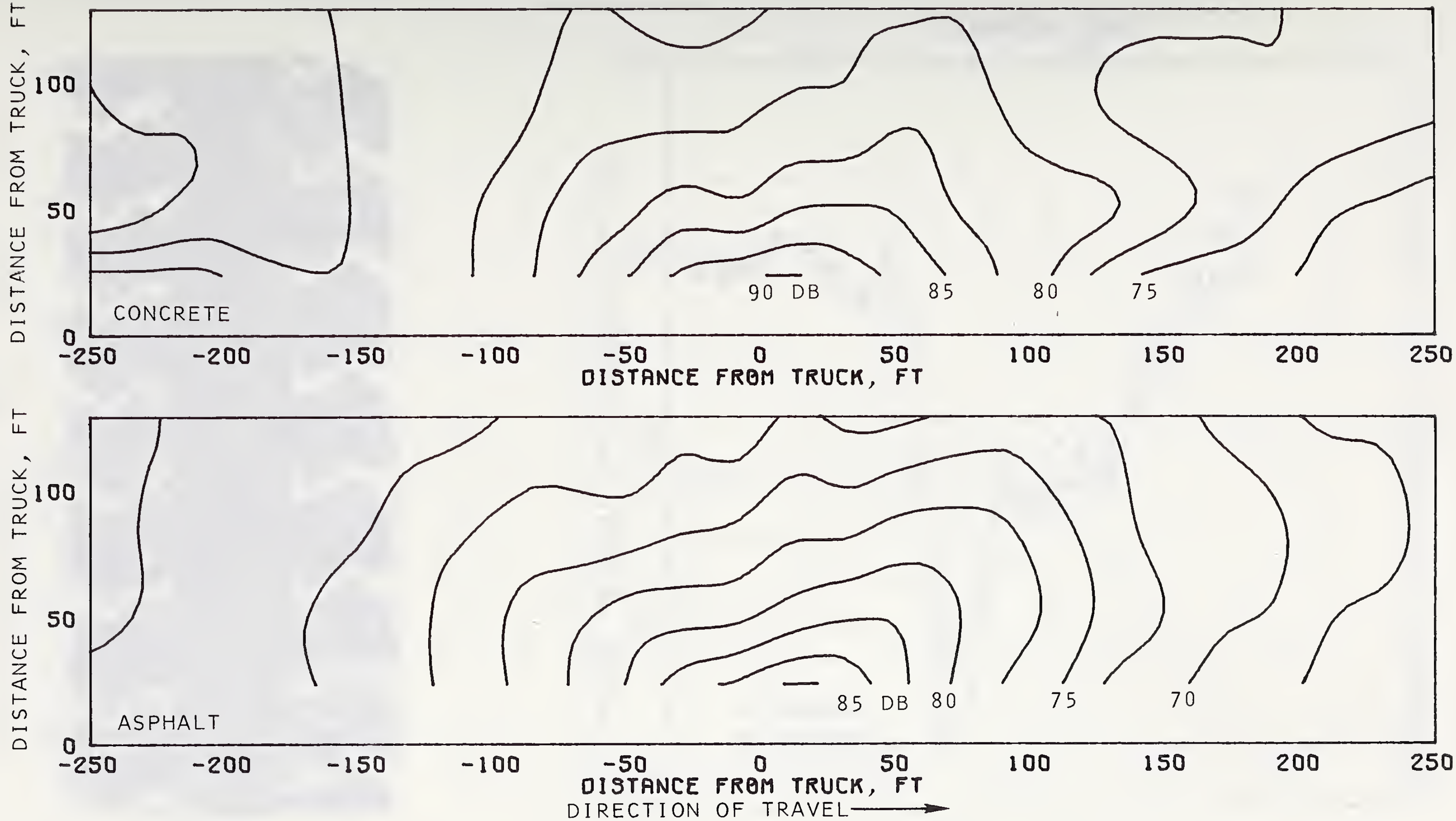
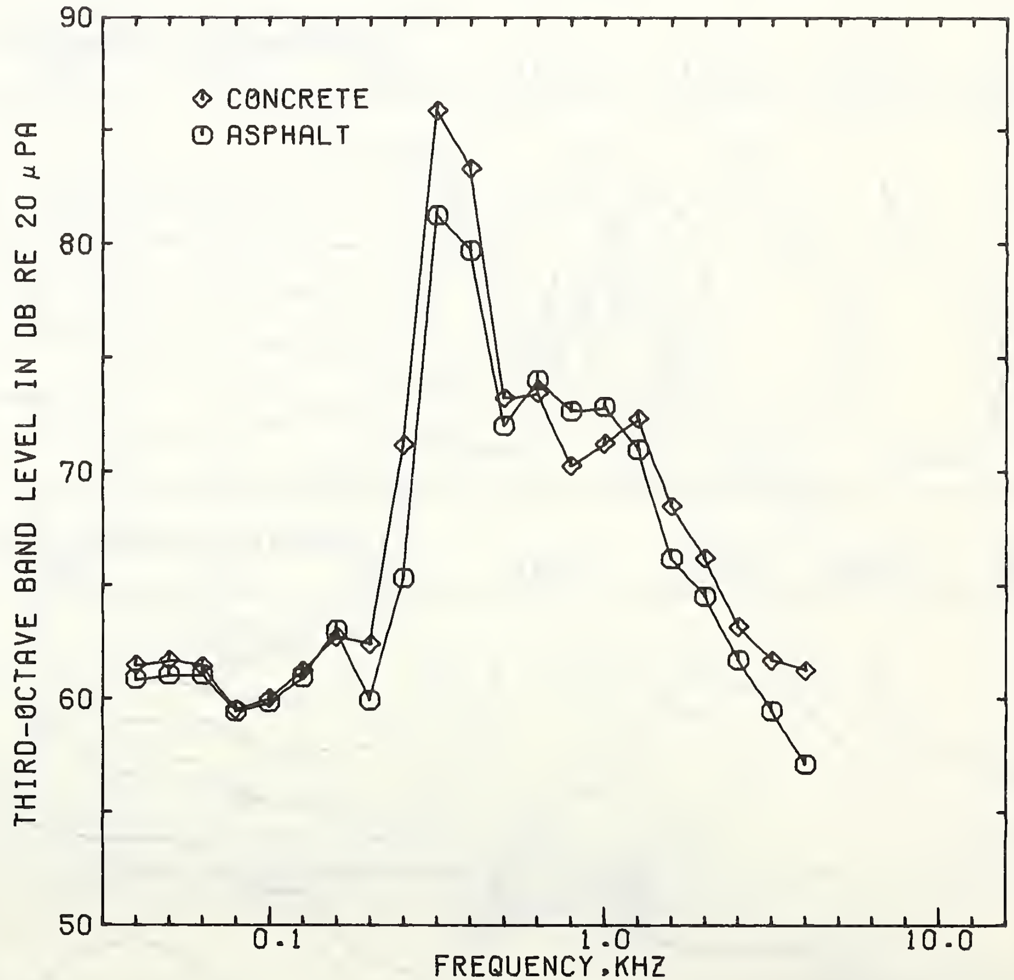



Figure A-22. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, cross-bar-F tires on the drive axle.

CROSS-BAR-F, FULLY-WORN, DUAL, LOADED



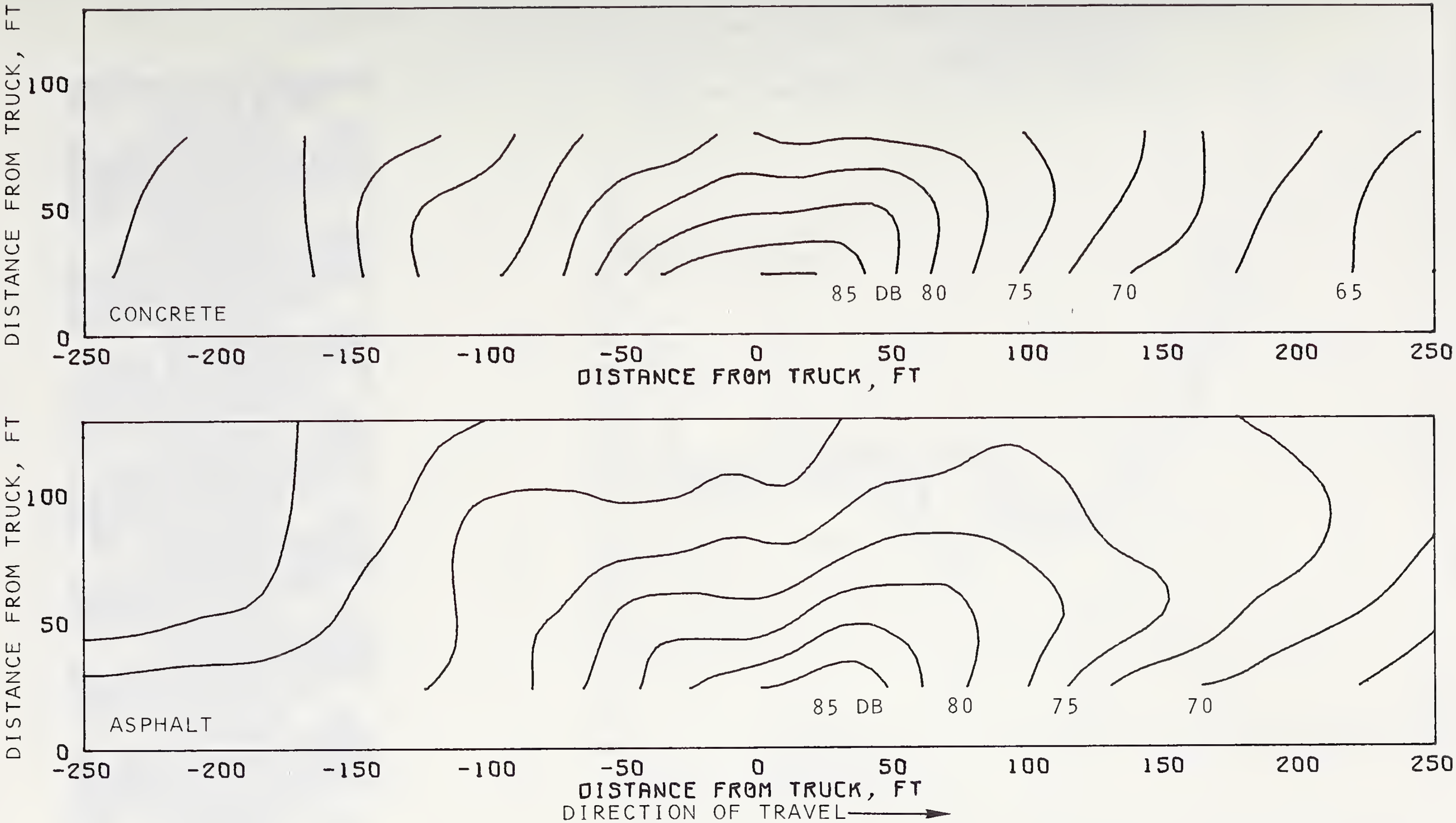
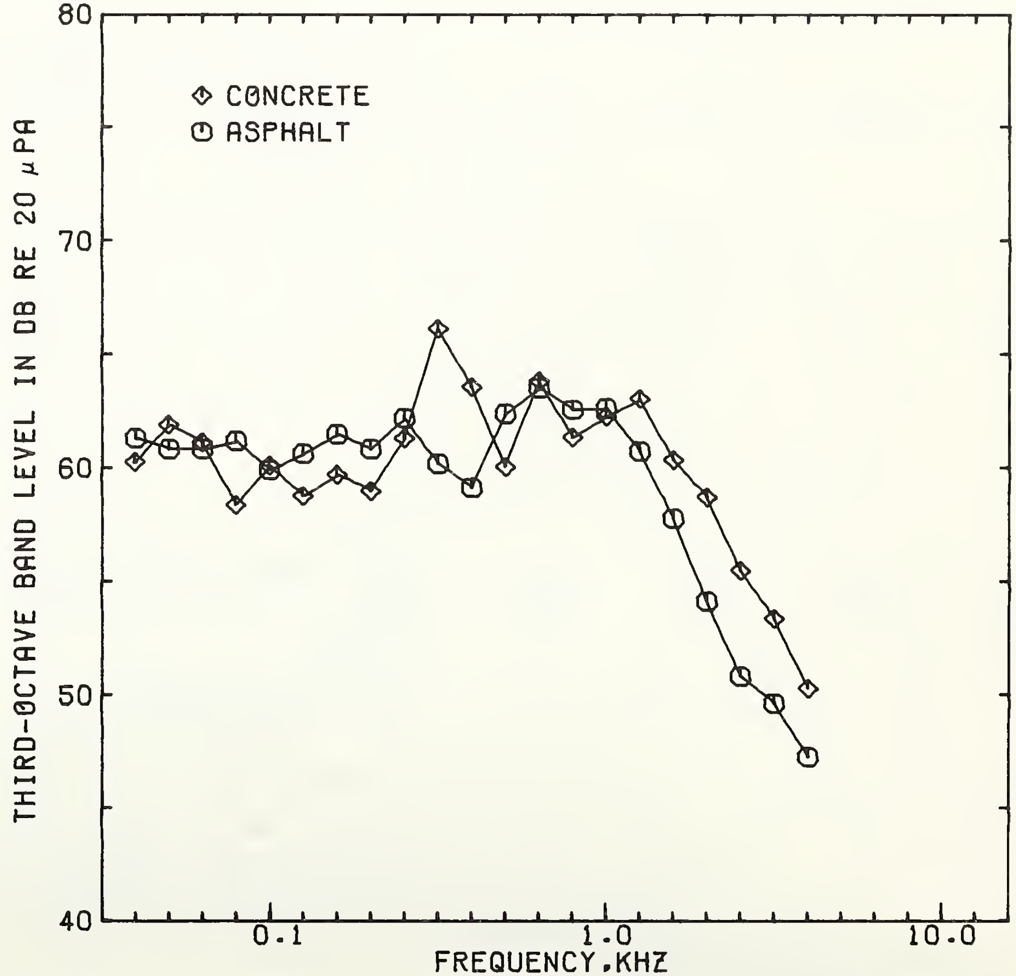



Figure A-23. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, fully-worn, cross-bar-F tires on the drive axle.

## CROSS-BAR-F, NEW, DUAL, UNLOADED



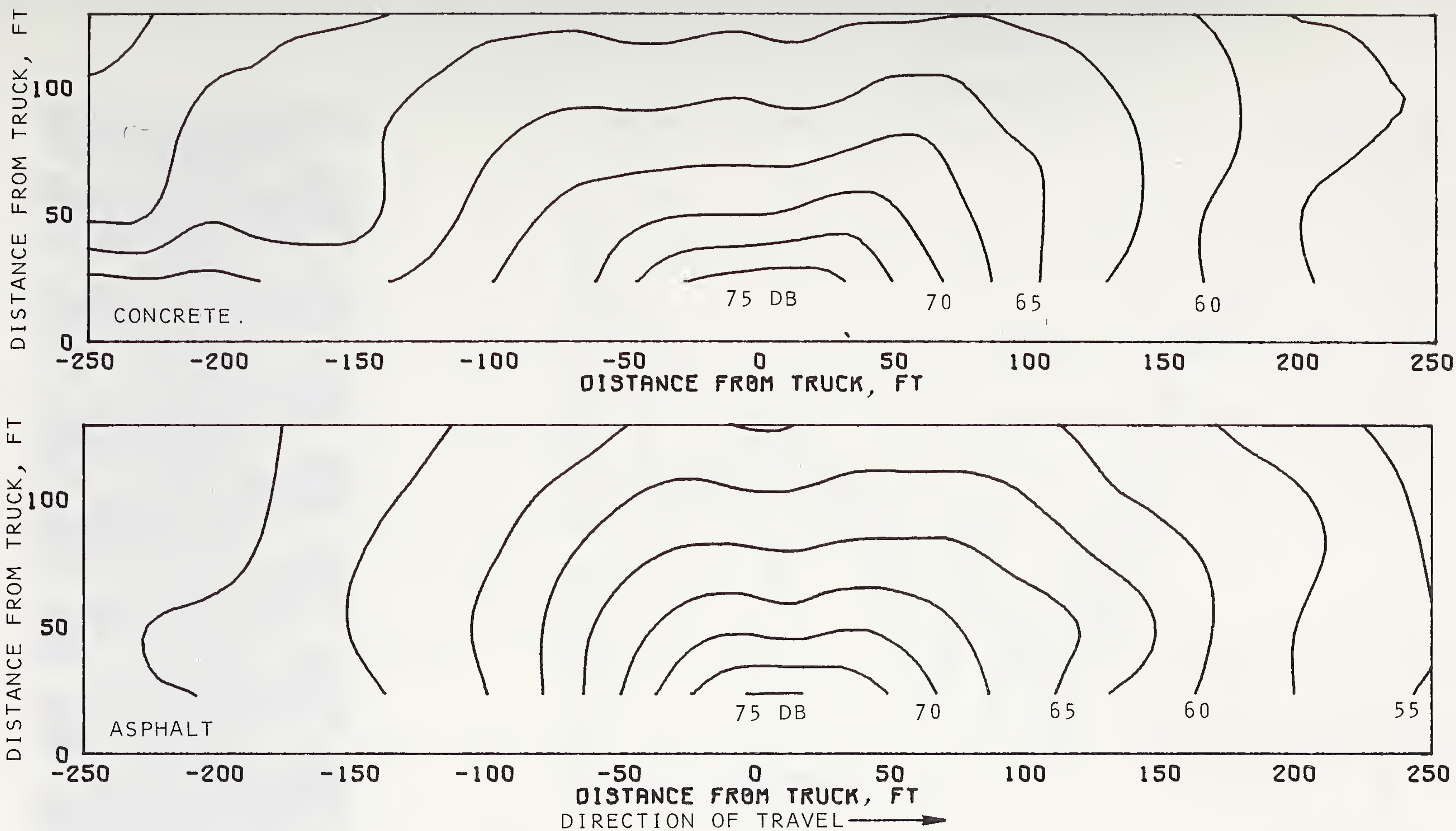
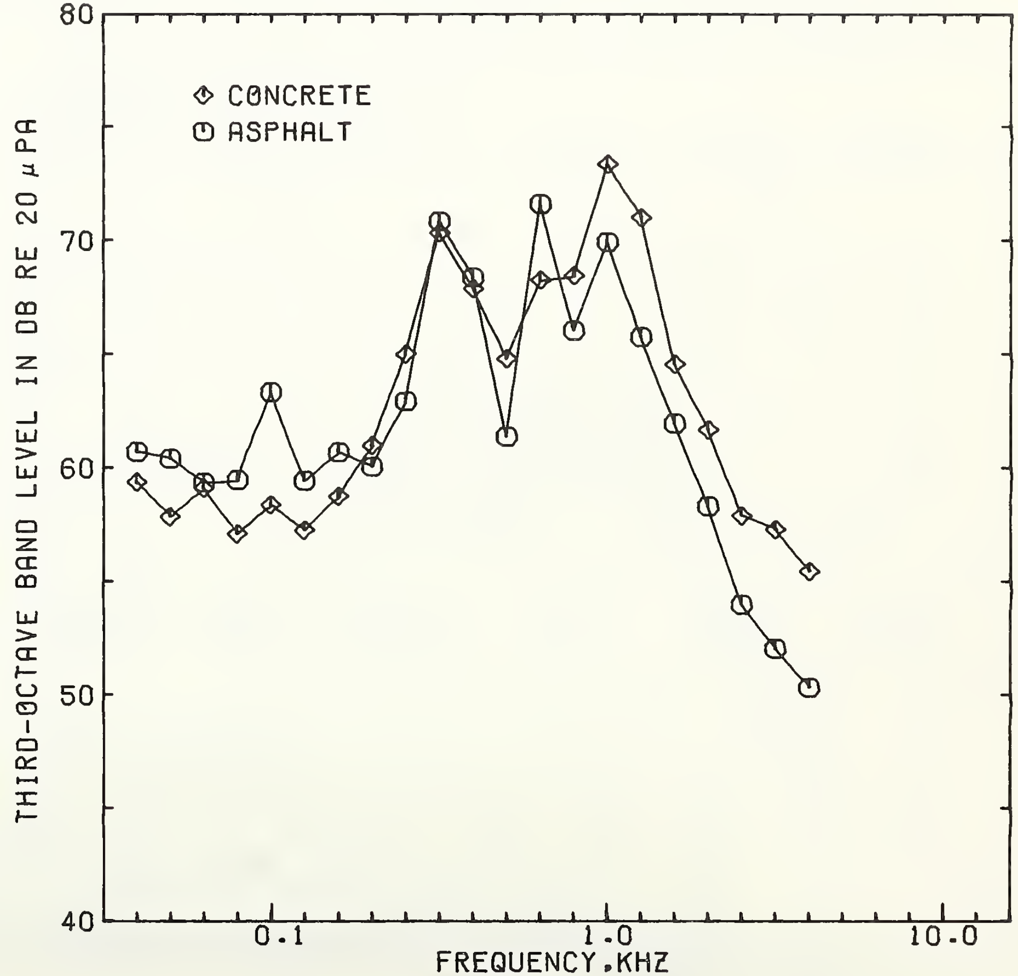



Figure A-24. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, cross-bar-F tires on the drive axle.

## CROSS-BAR-F, HALF-WORN, DUAL, UNLOADED



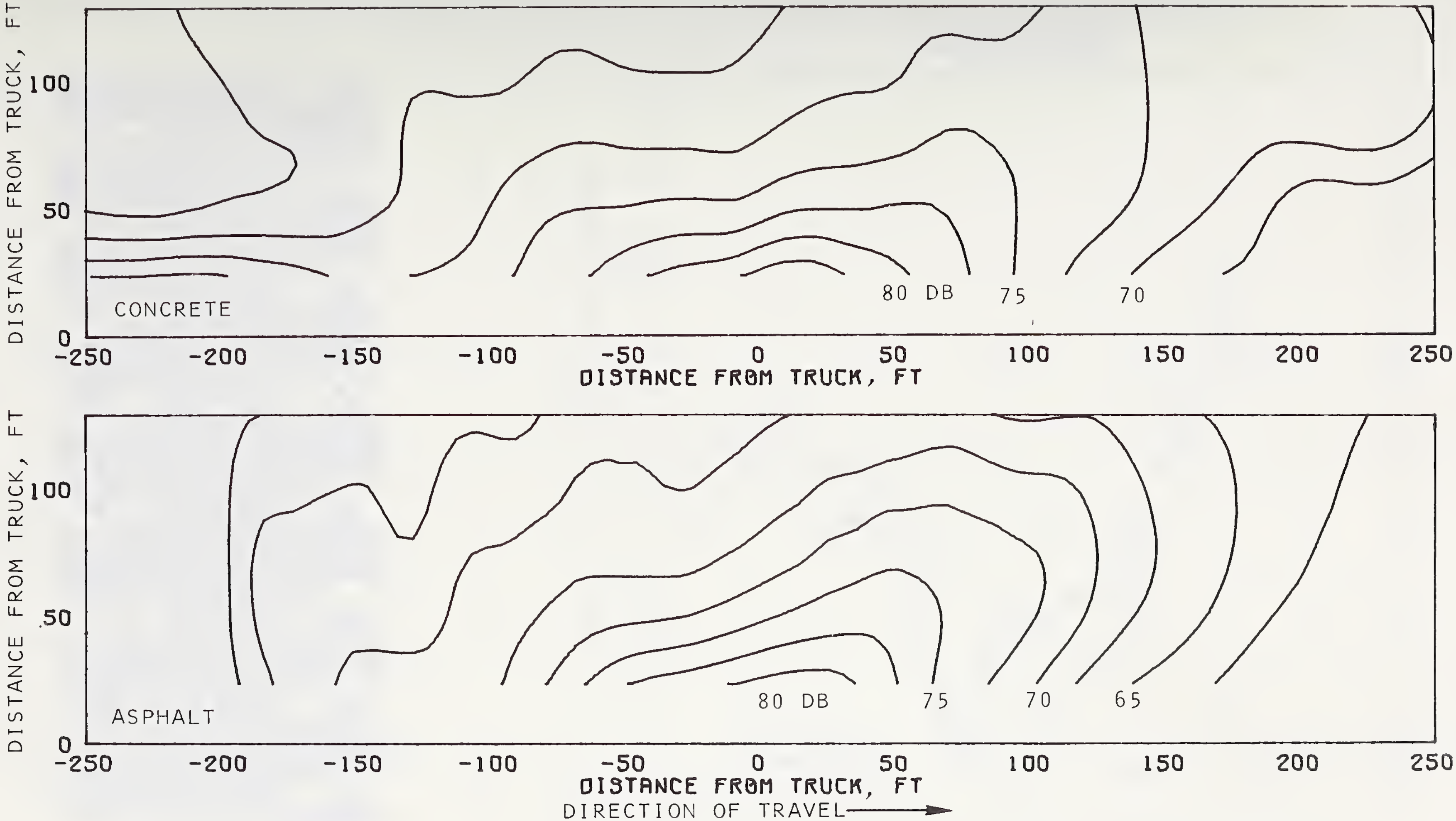
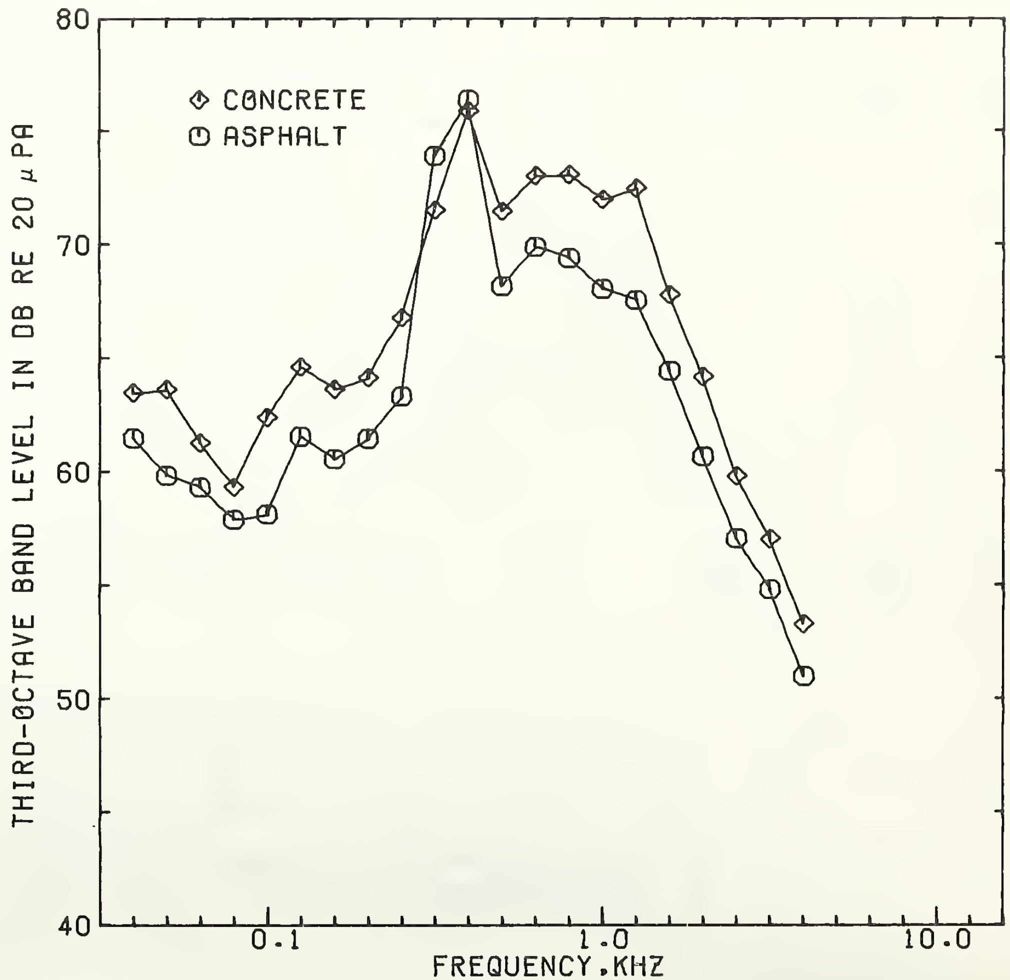



Figure A-25. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, cross-bar-F tires on the drive axle.

## CROSS-BAR-F, FULLY-WORN, DUAL, UNLOADED



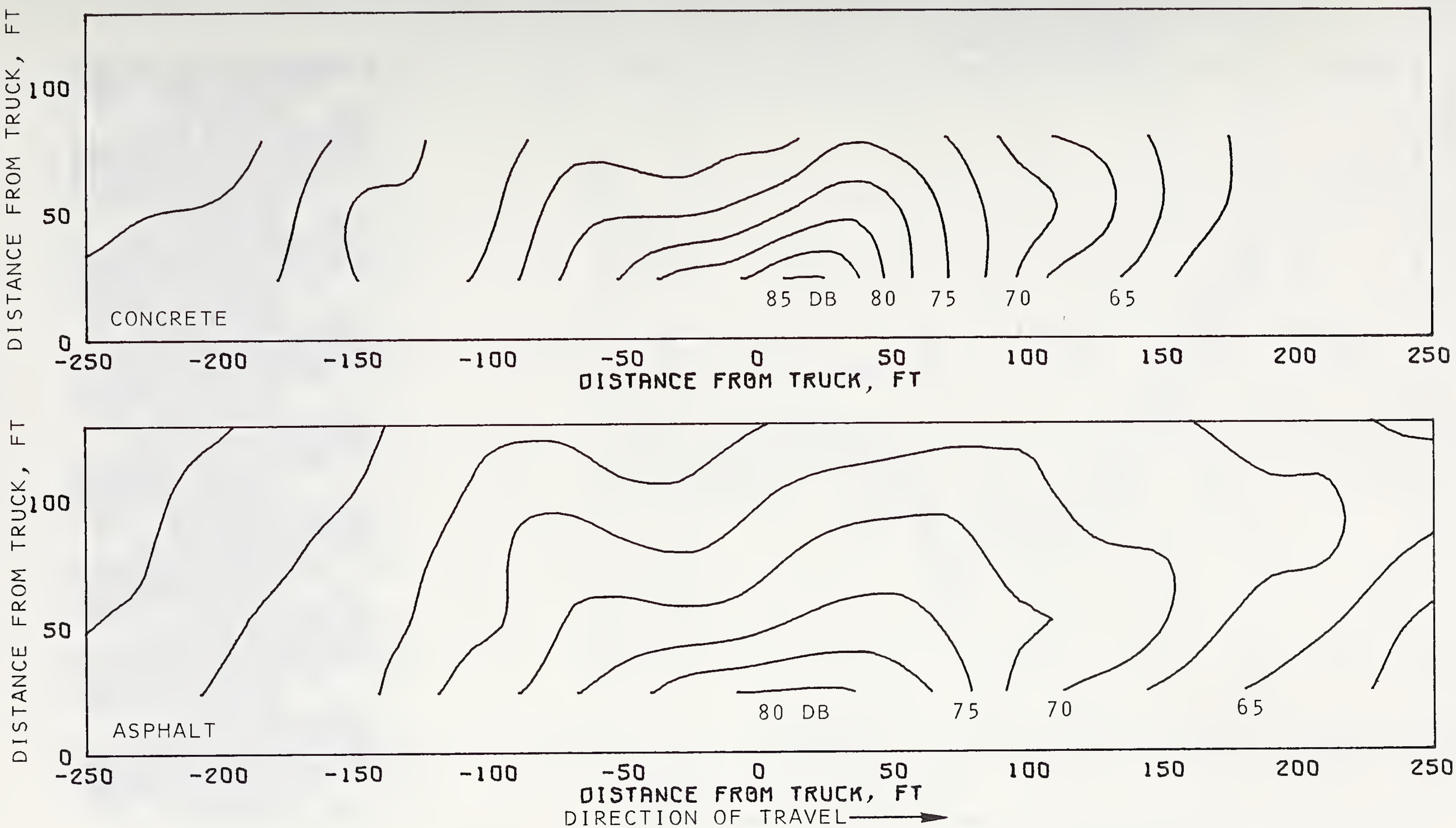
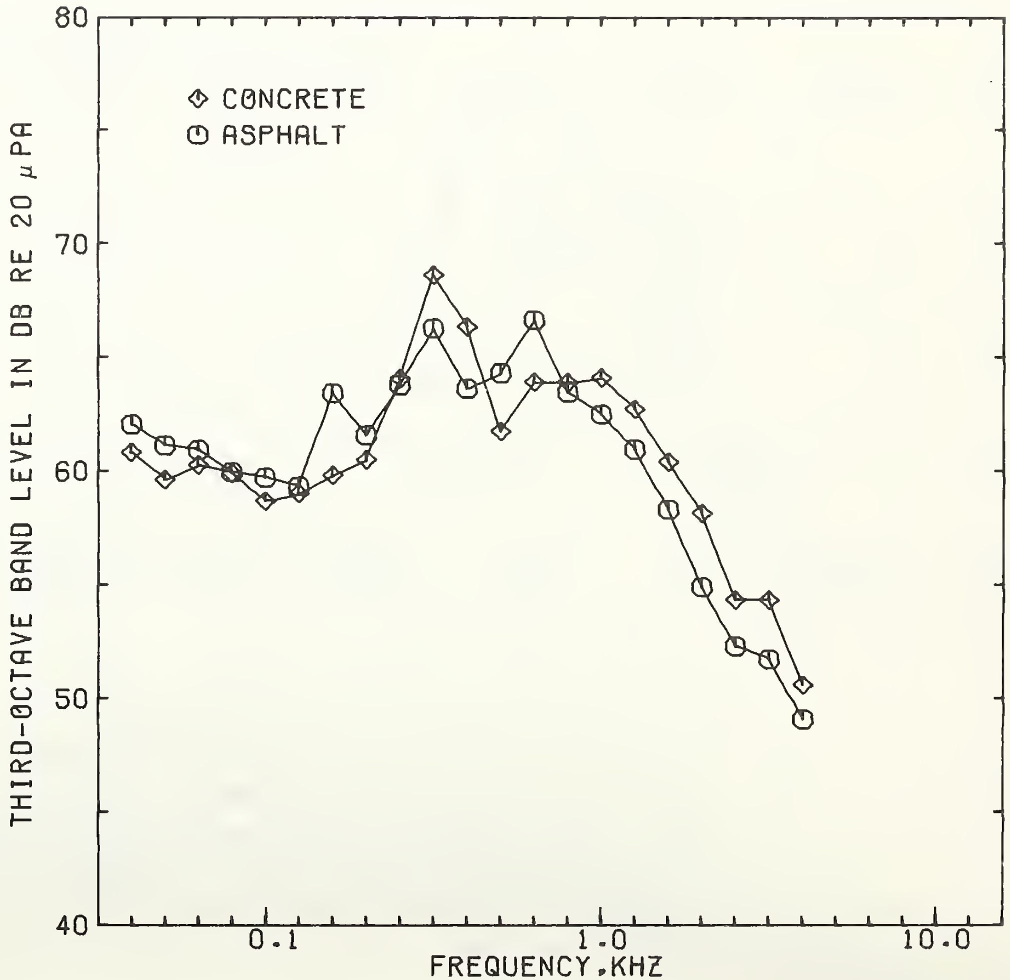



Figure A-26. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, fully-worn, cross-bar-F tires on the drive axle.

## CROSS-BAR-F, NEW, SINGLE, UNLOADED



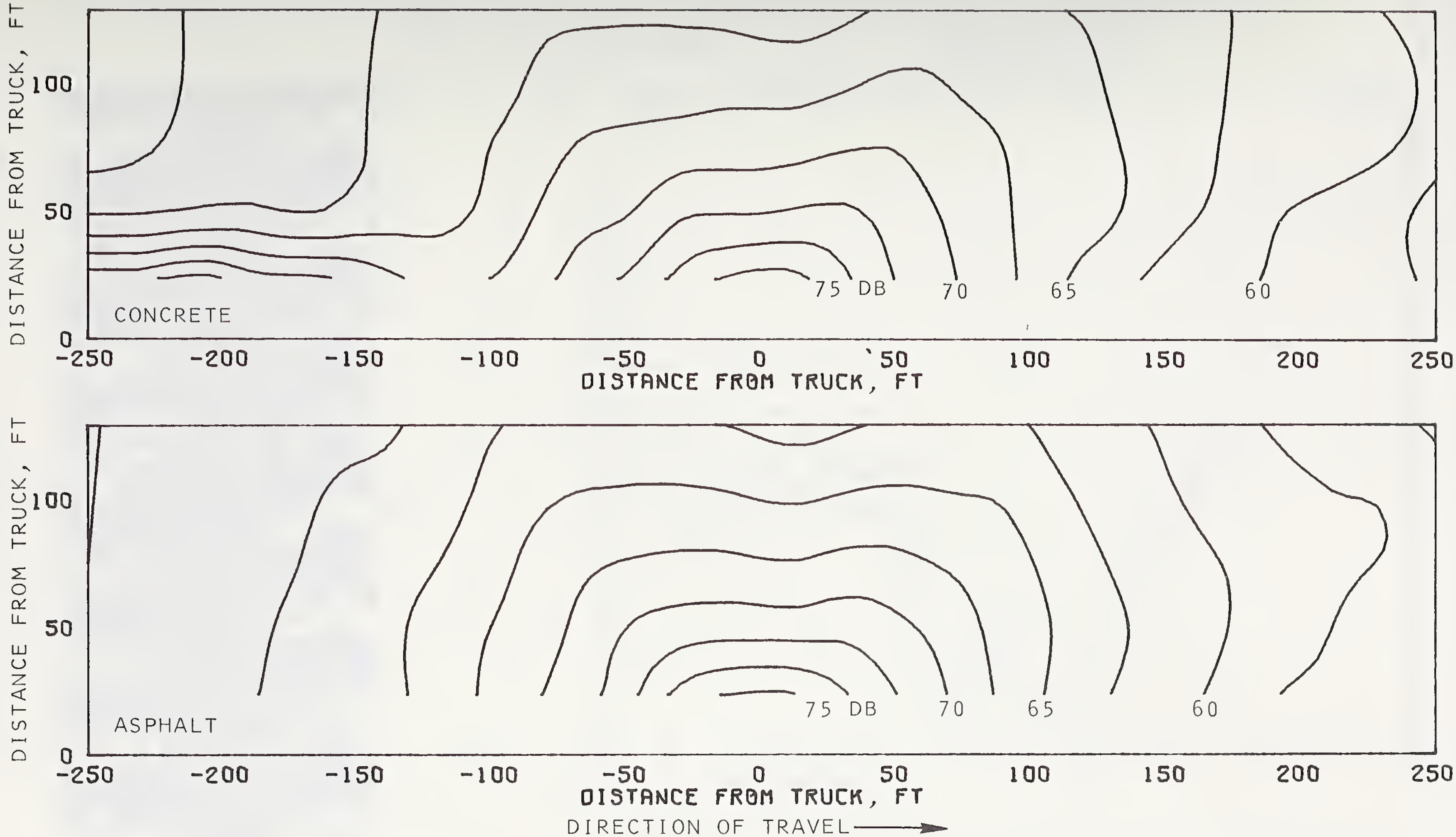
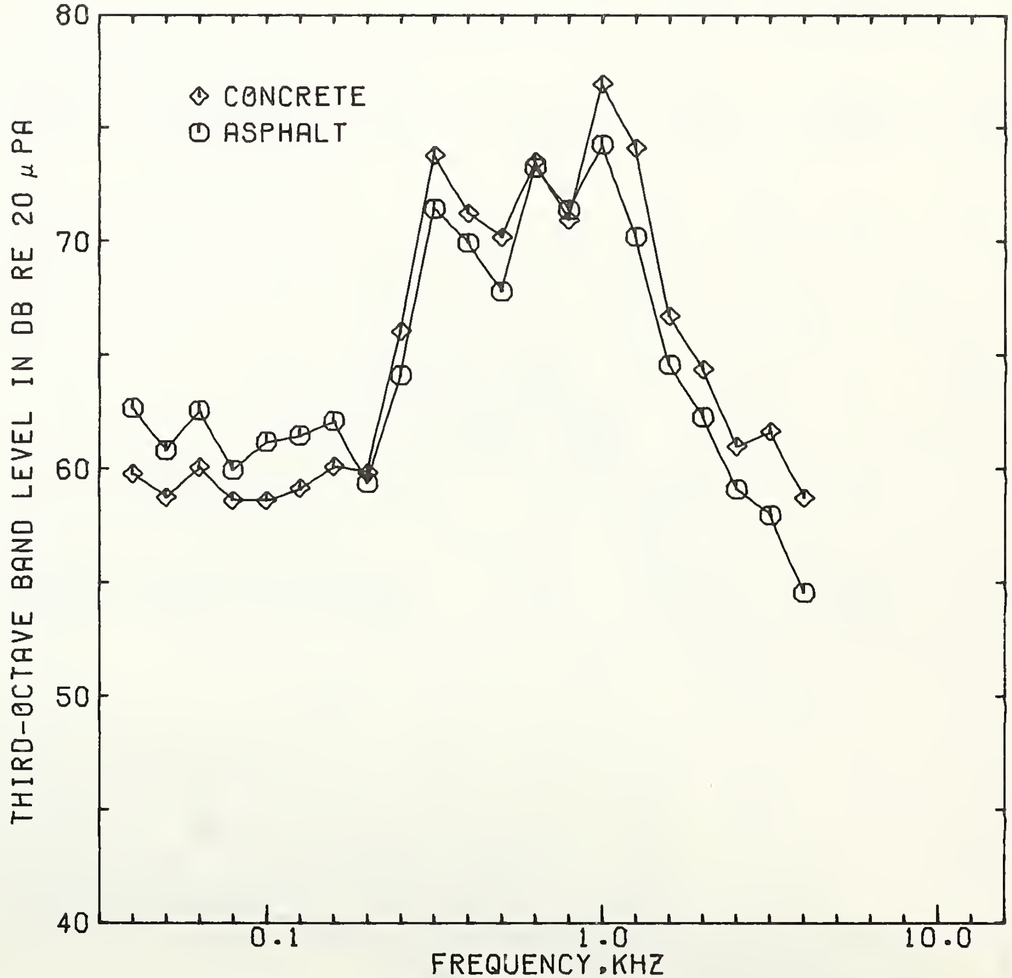



Figure A-27. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and single, new, cross-bar-F tires on the drive axle.

## CROSS-BAR-F, HALF-WORN, SINGLE, UNLOADED



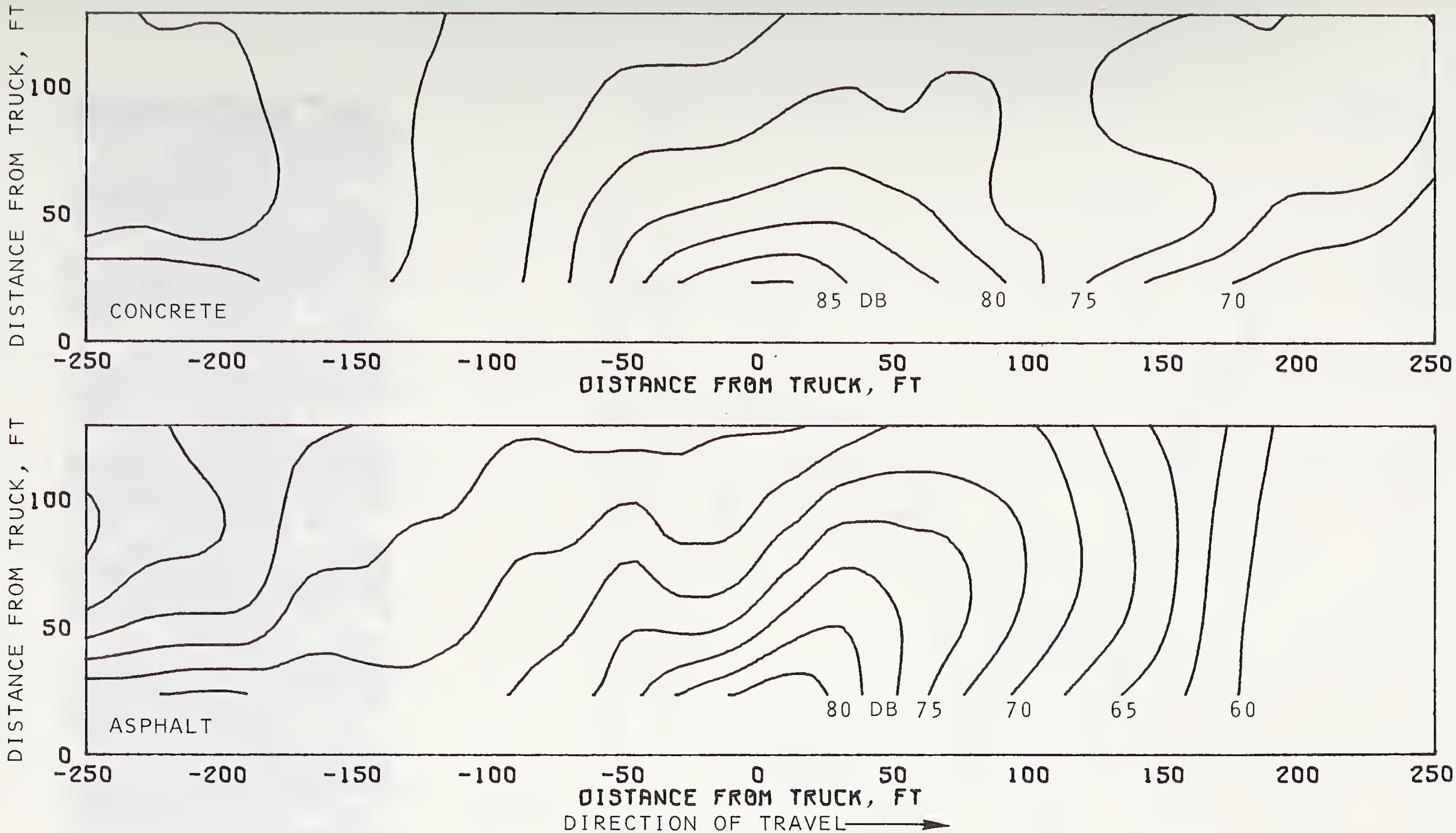
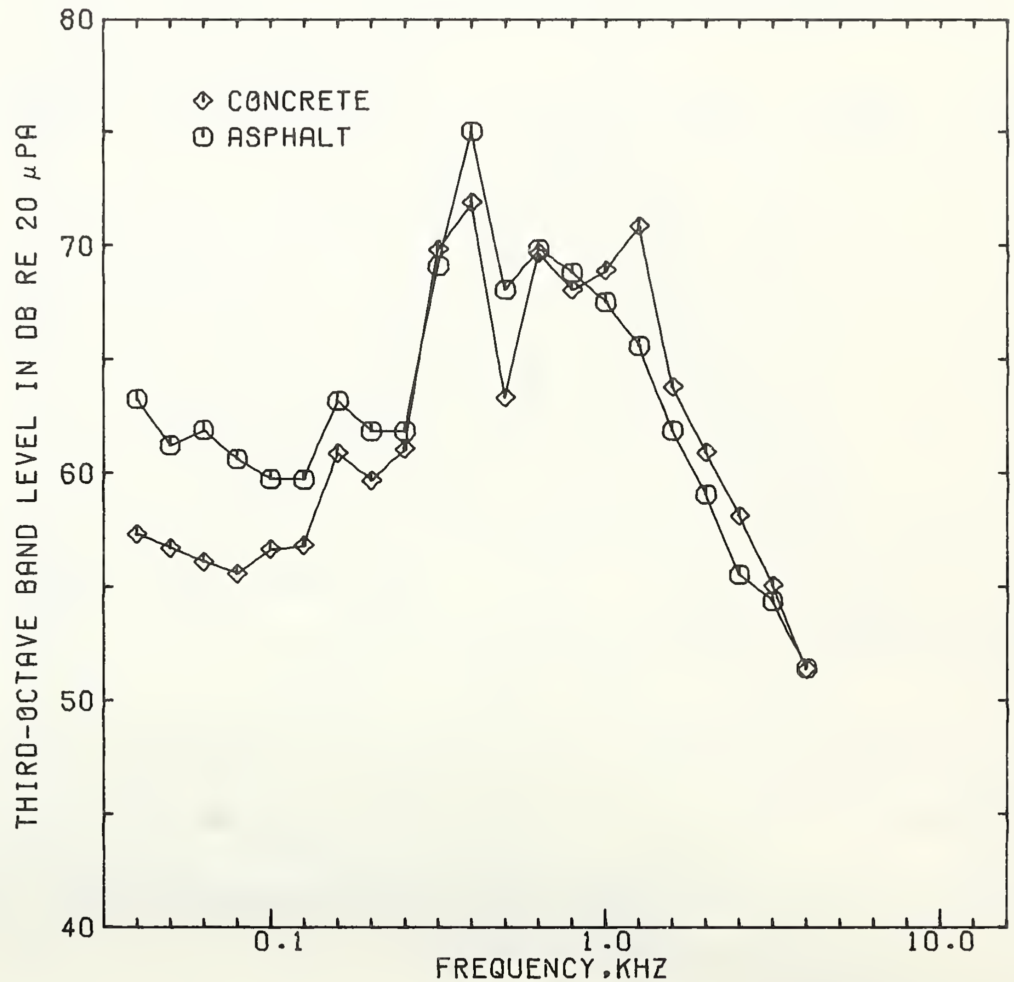



Figure A-28. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and single, half-worn, cross-bar-F tires on the drive axle.

## CROSS-BAR-F, FULLY-WORN, SINGLE, UNLOADED



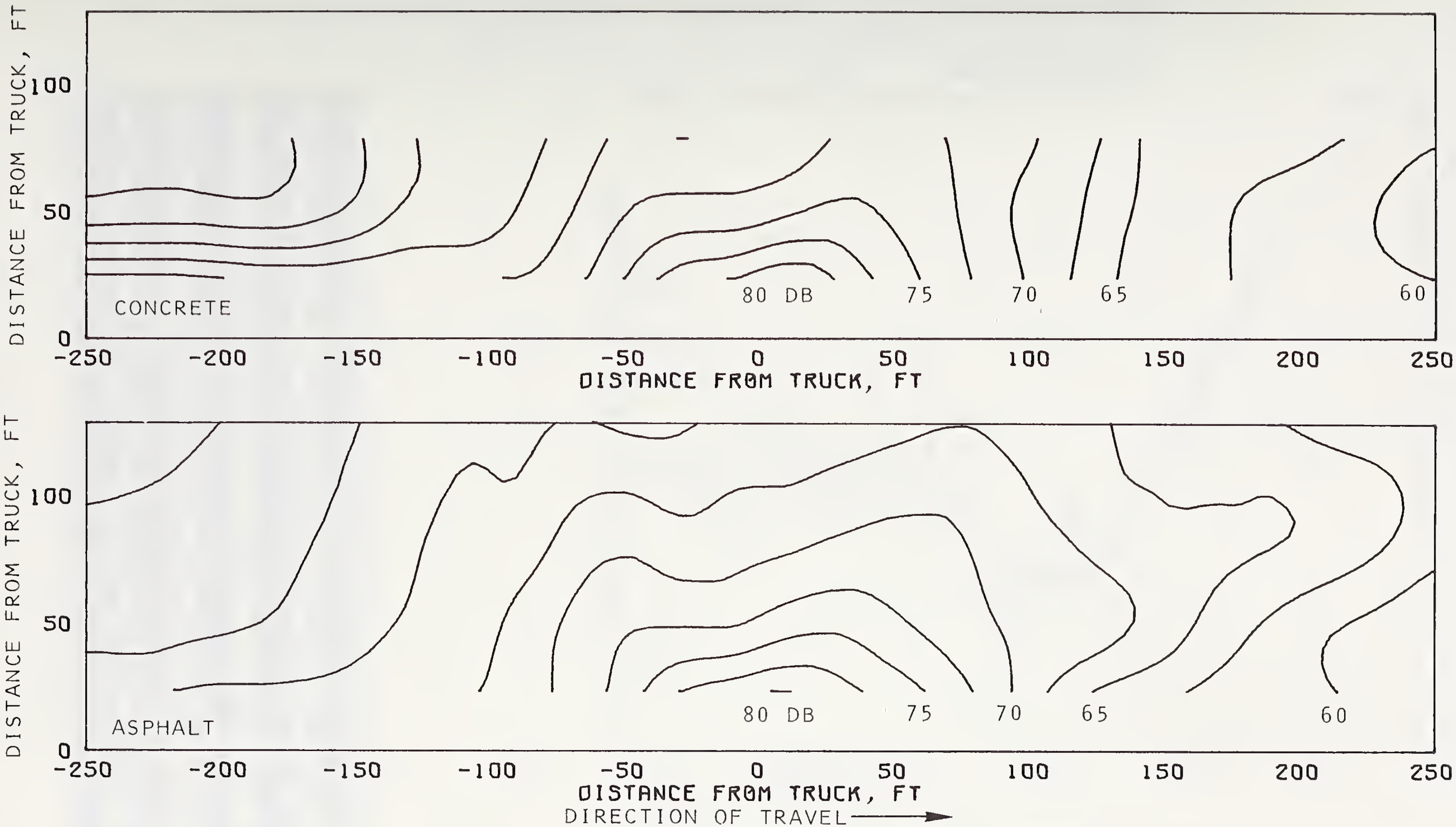
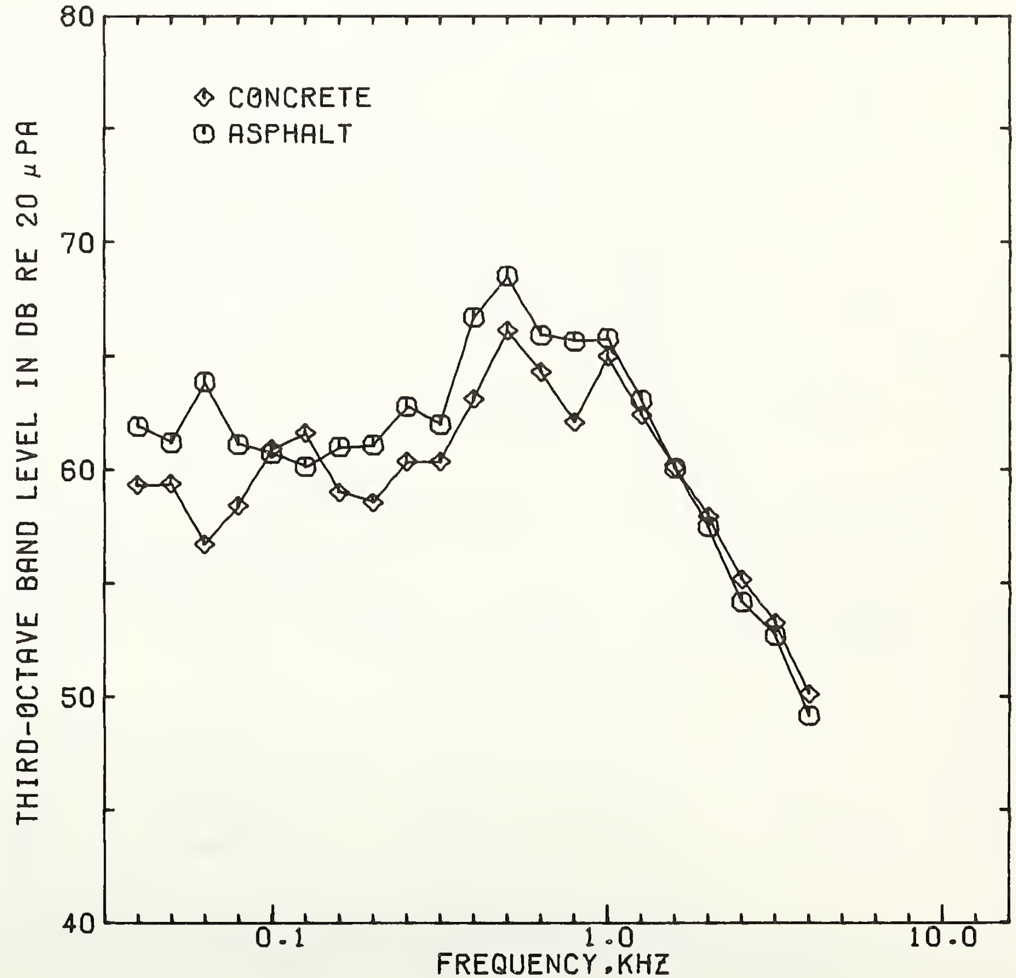



Figure A-29. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and single, fully-worn, cross-bar-F tires on the drive axle.

RETREAD-G, NEW, DUAL, LOADED



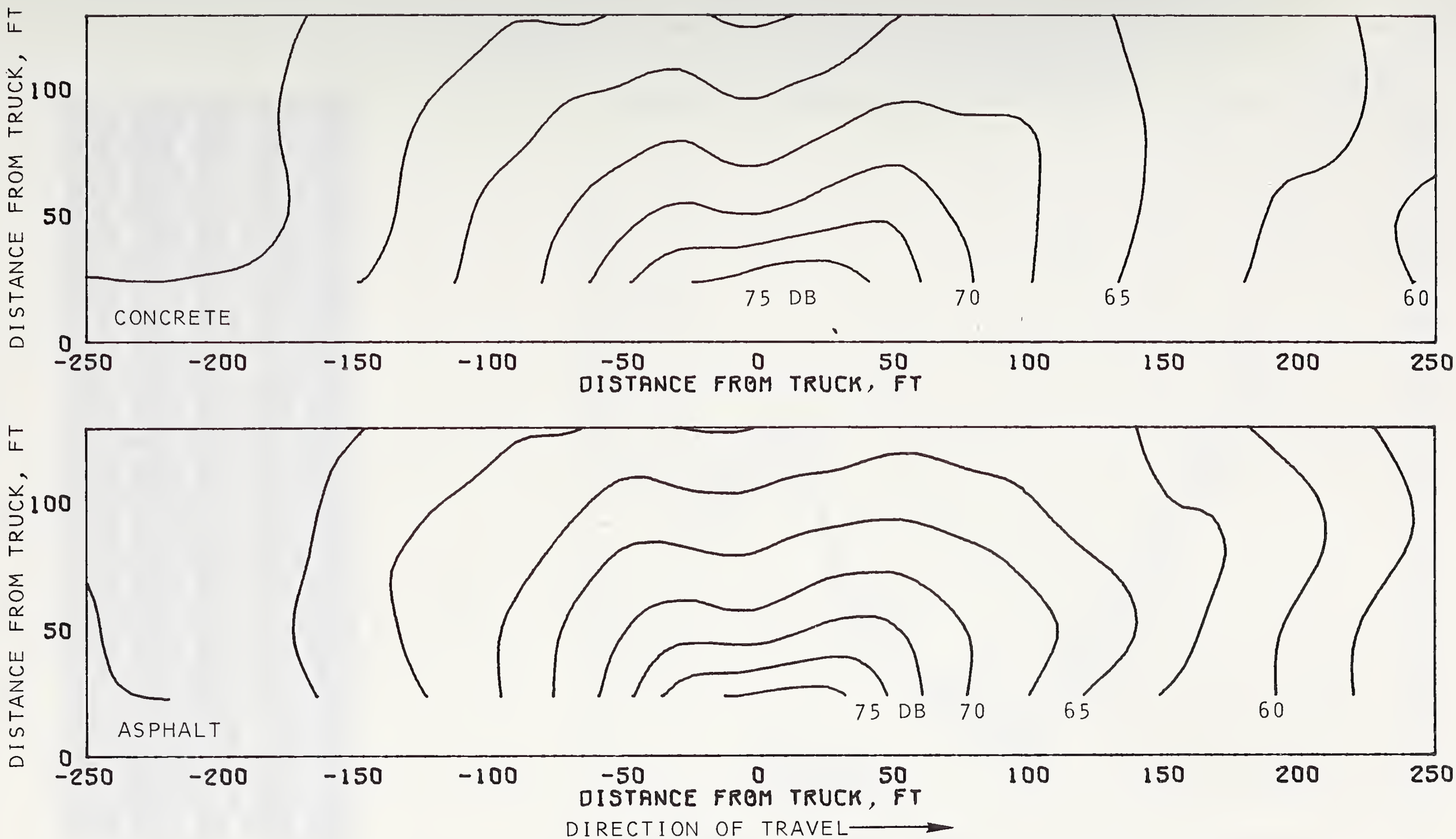
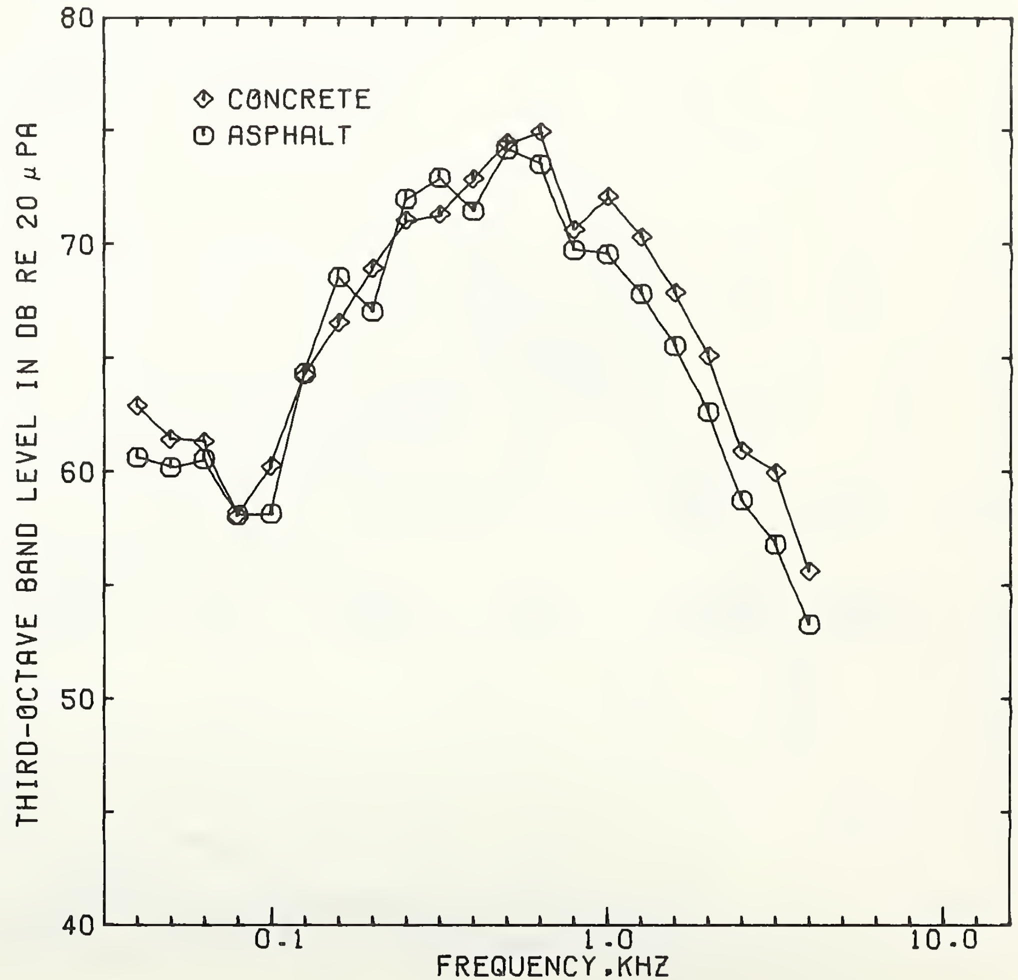



Figure A-30. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, retread-G tires on the drive axle.

RETREAD-G, HALF-WORN, DUAL, LOADED



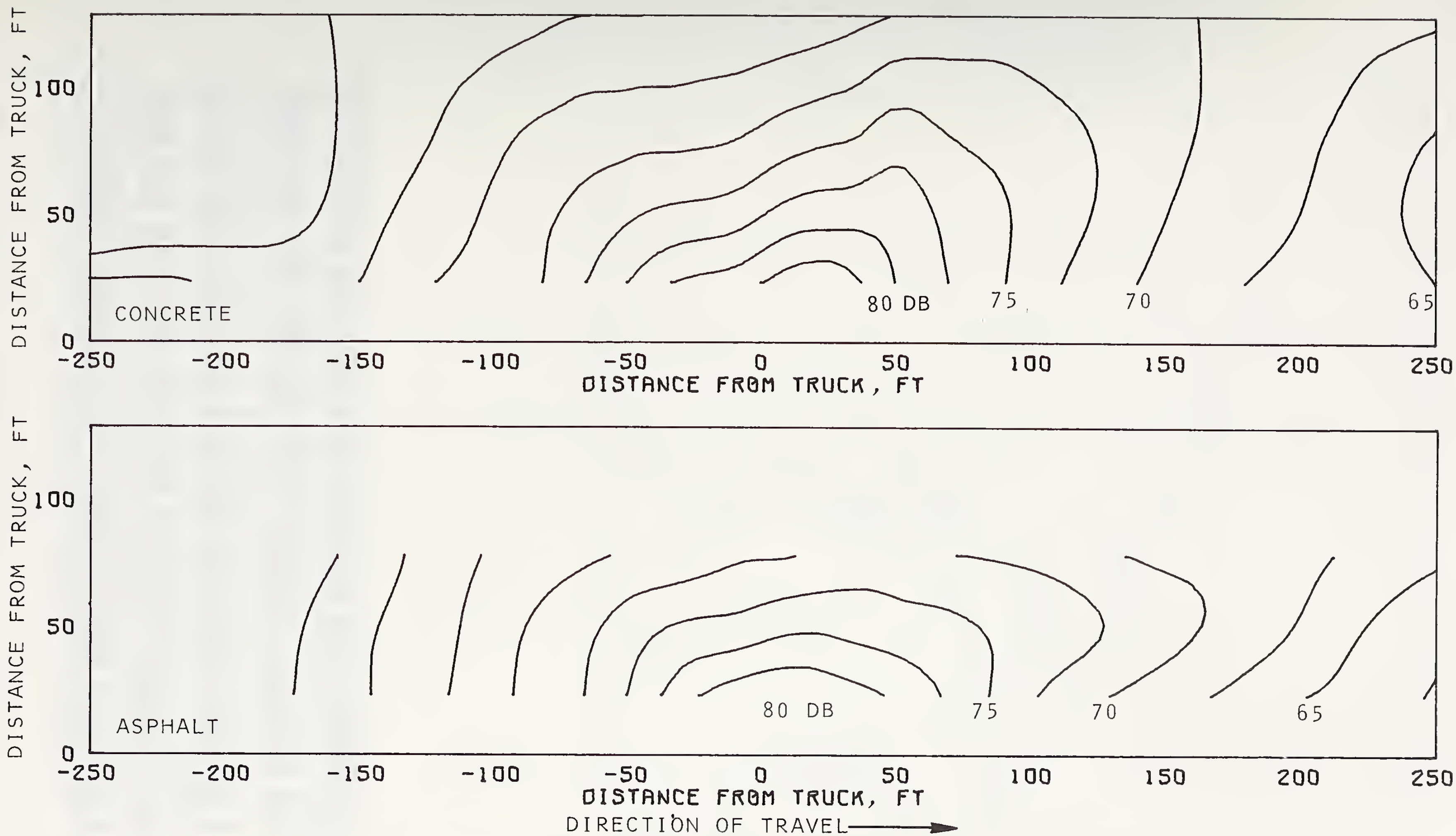
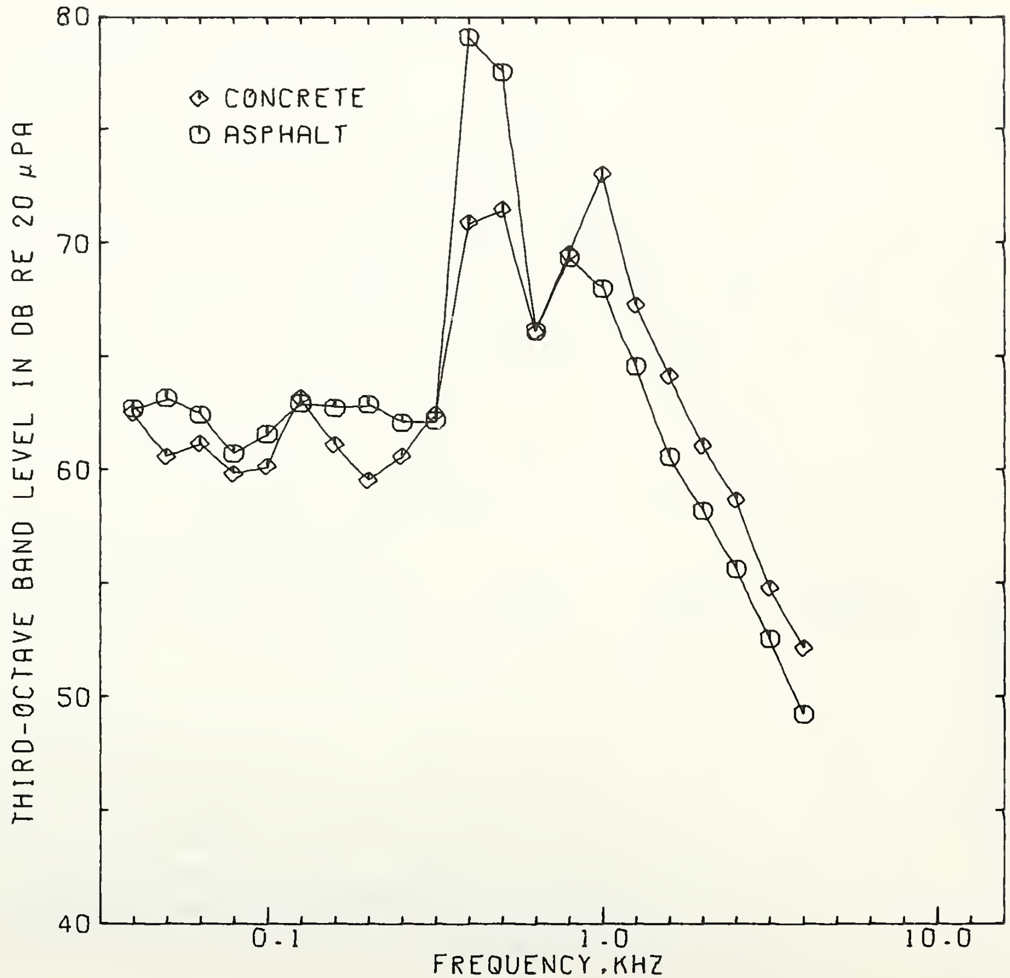



Figure A-31. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, retread-G tires on the drive axle.

RETREAD-H, NEW, DUAL, LOADED



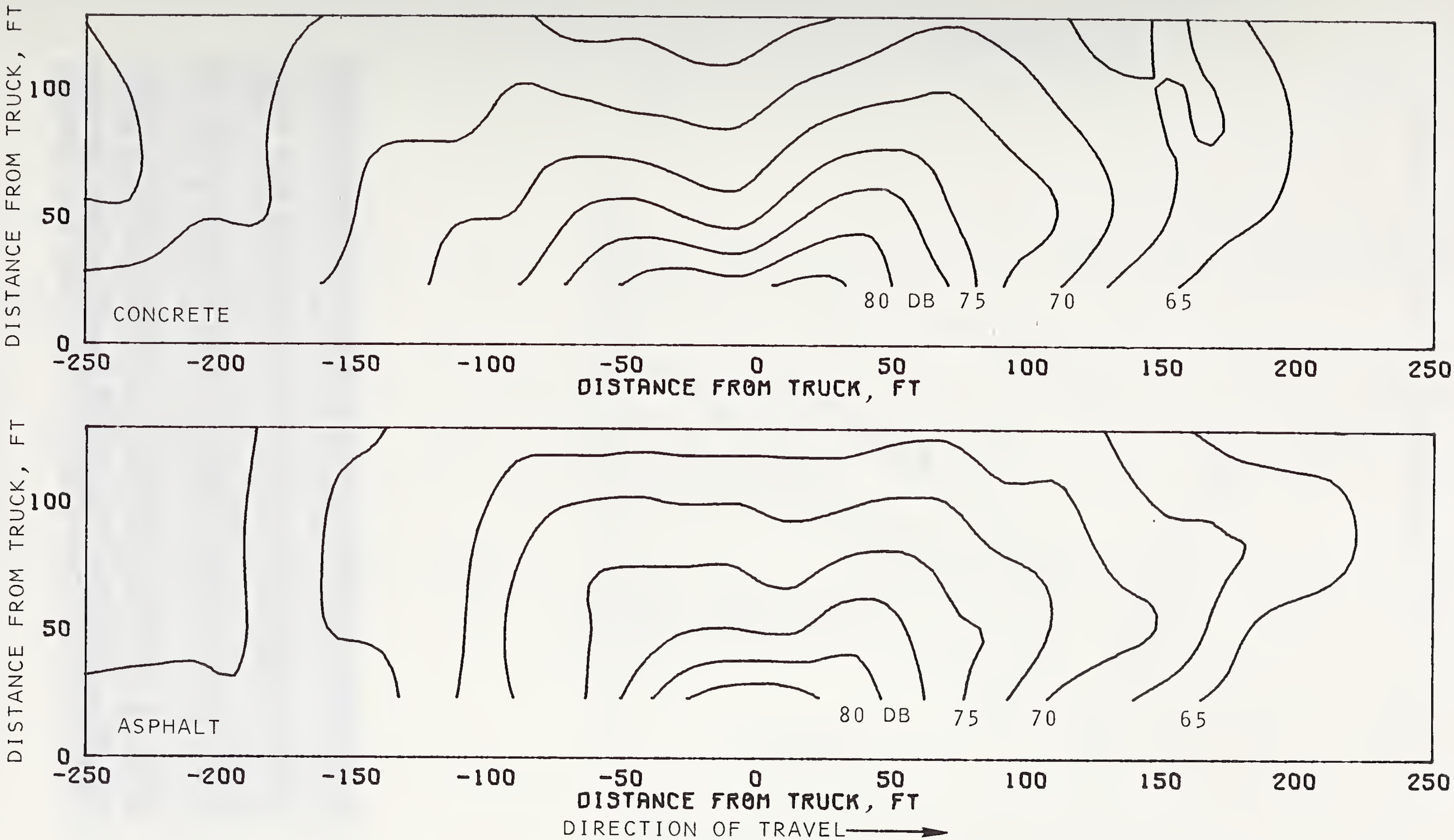
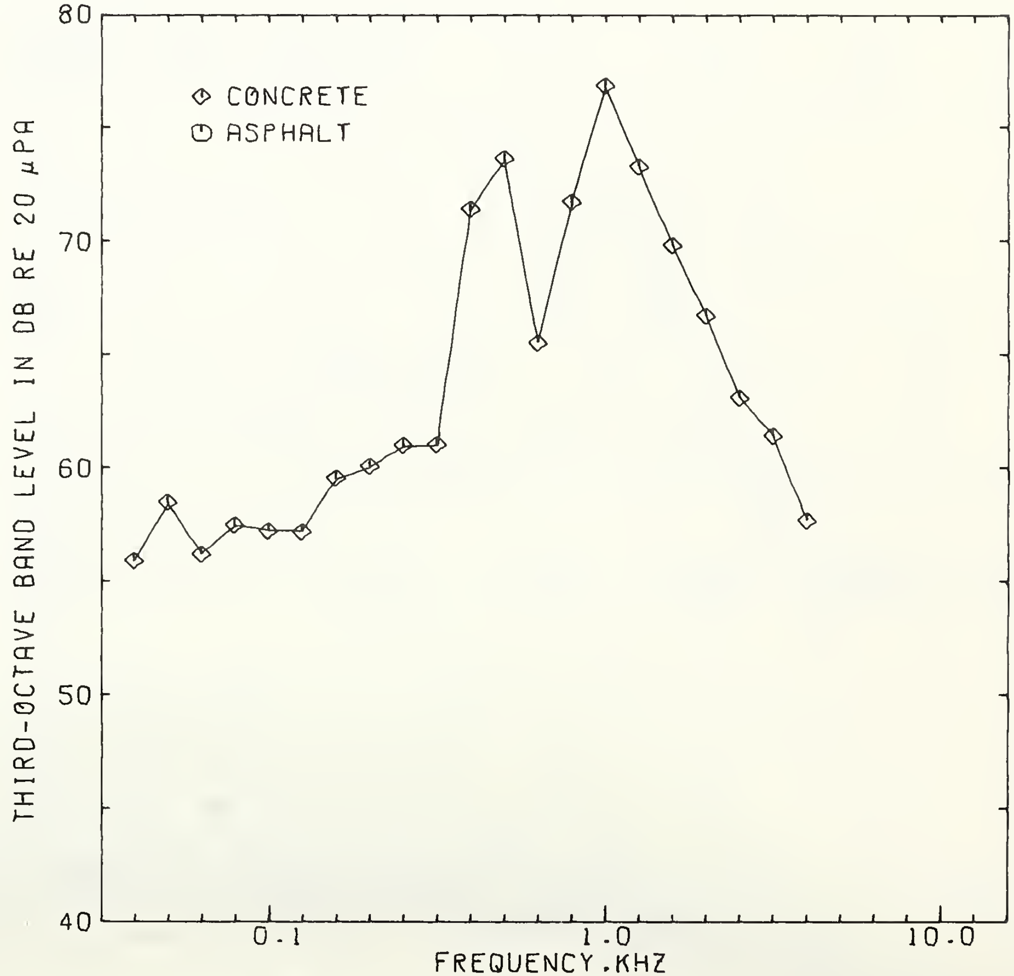



Figure A-32. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, retread-H tires on the drive axle.

## RETREAD-H, HALF-WORN, DUAL, LOADED



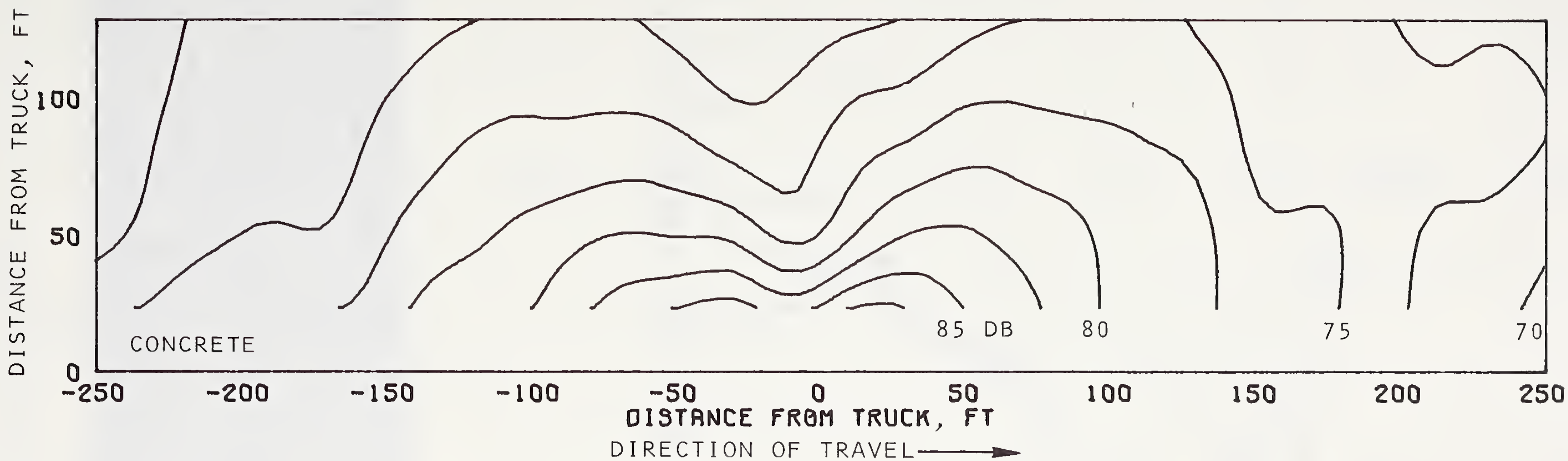
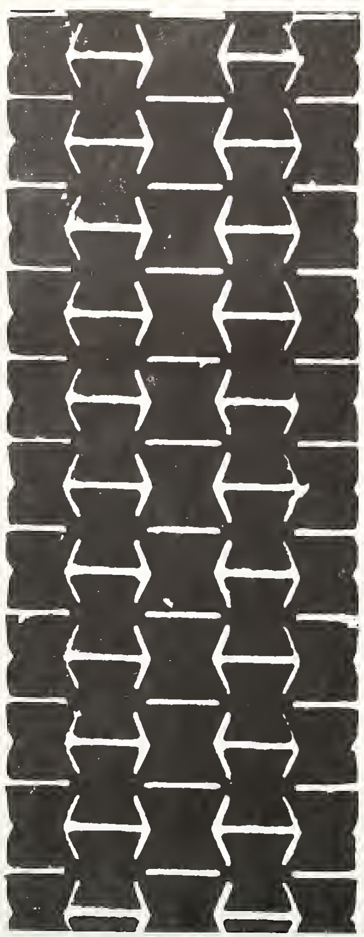
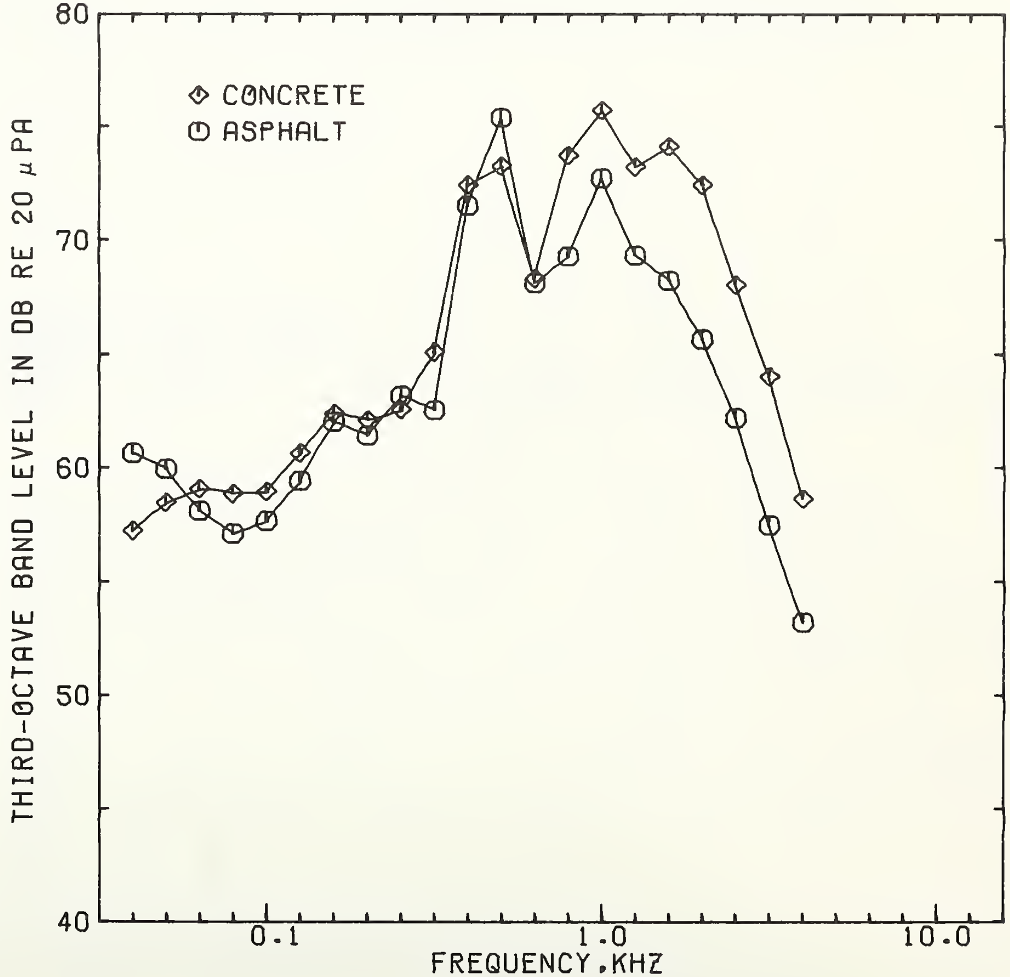



Figure A-33. The upper plot presents one-third octave bands sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plot shows equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on a concrete surface. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, retread-H tires on the drive axle.

RETREAD-H, FULLY-WORN, DUAL, LOADED





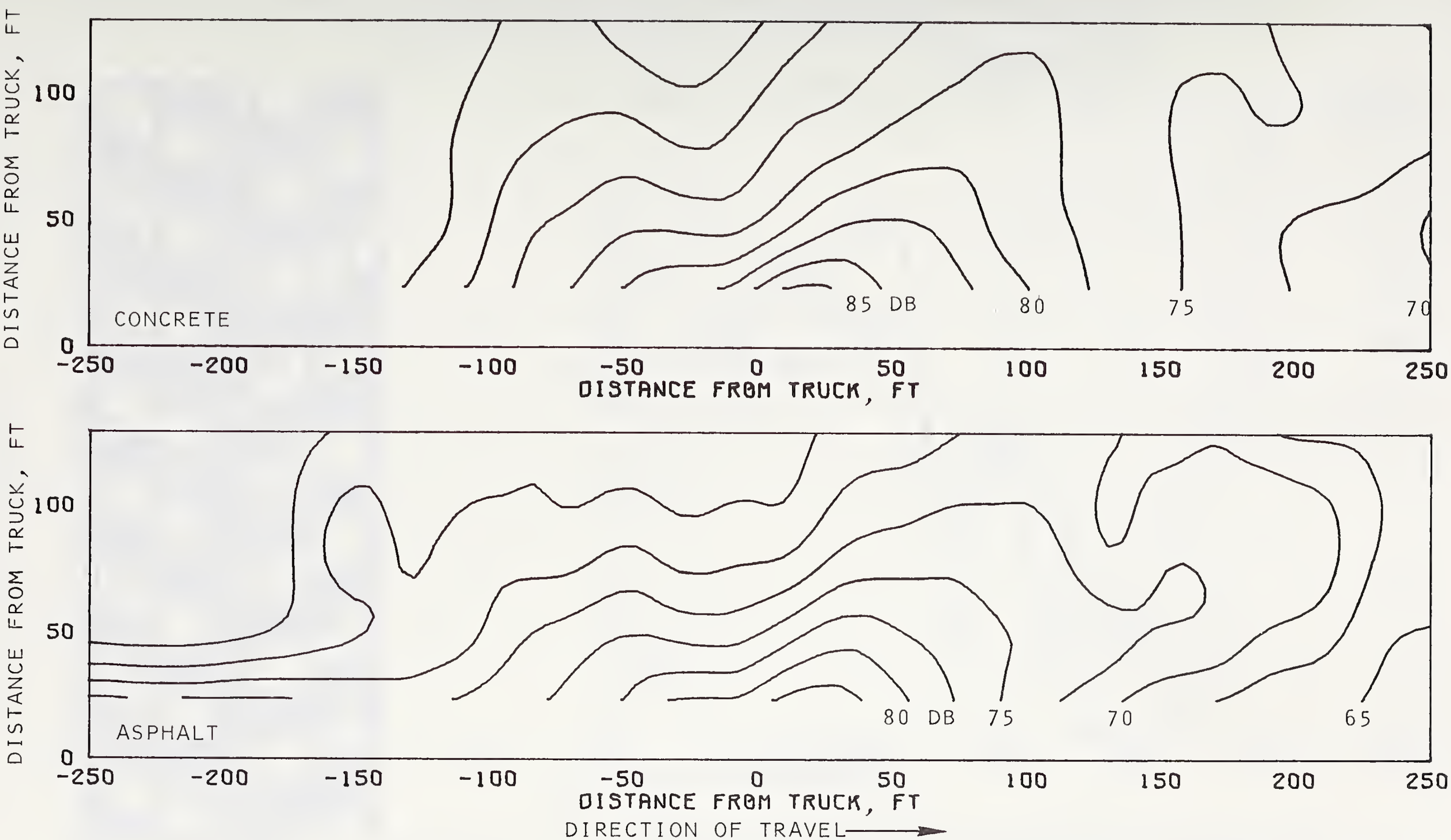
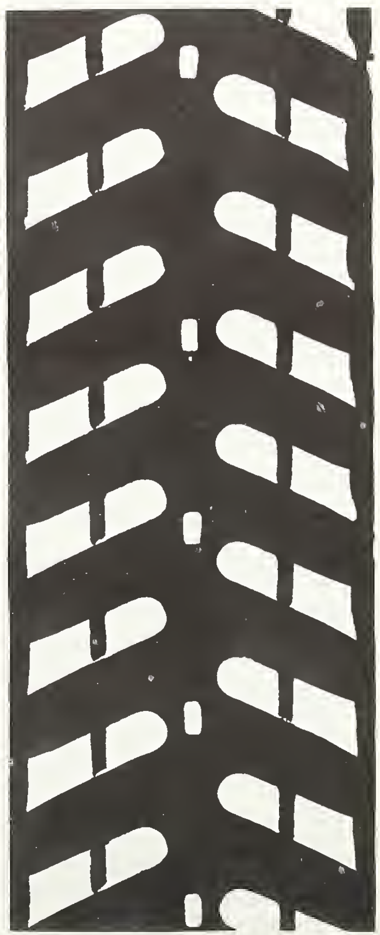
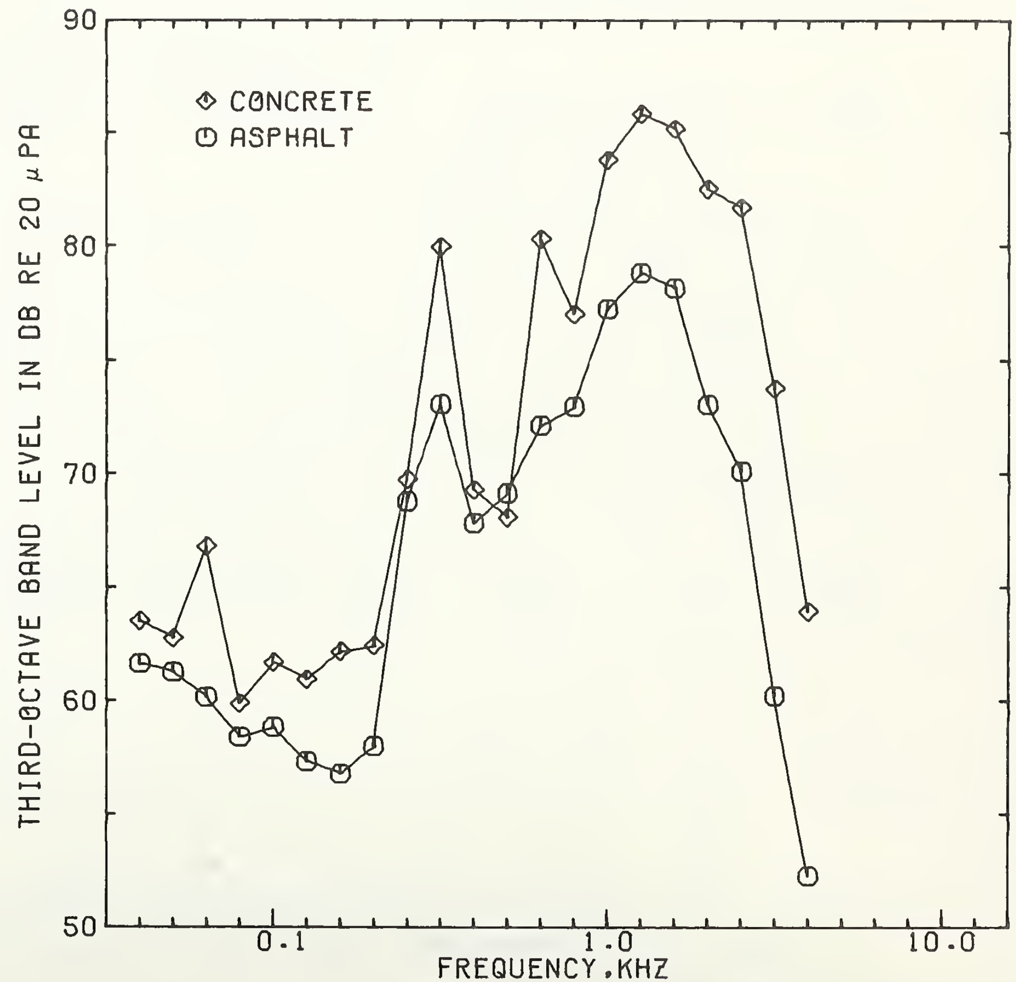



Figure A-34. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, fully-worn, retread-H tires on the drive axle.

RETREAD-I, NEW, DUAL, LOADED





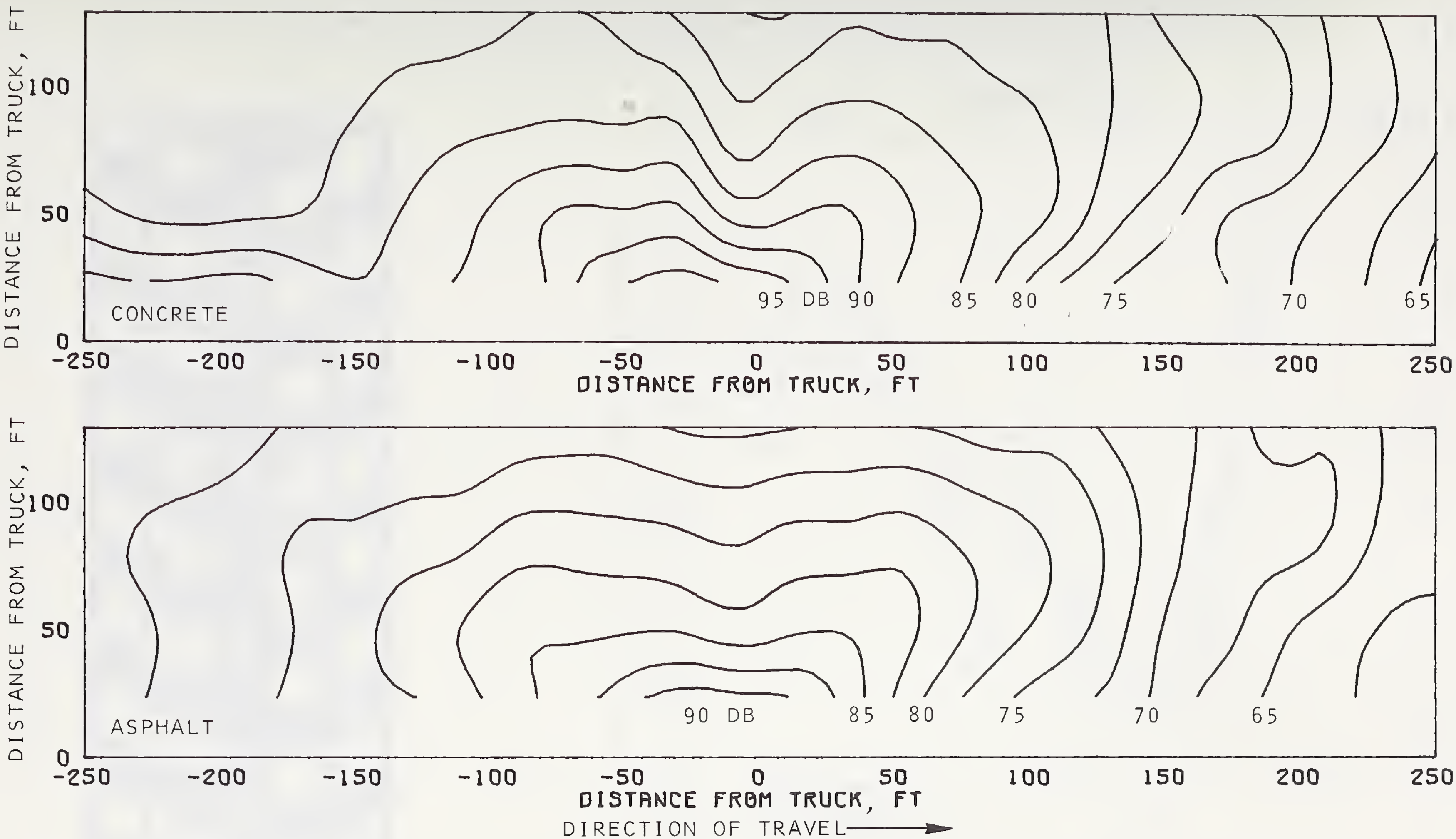
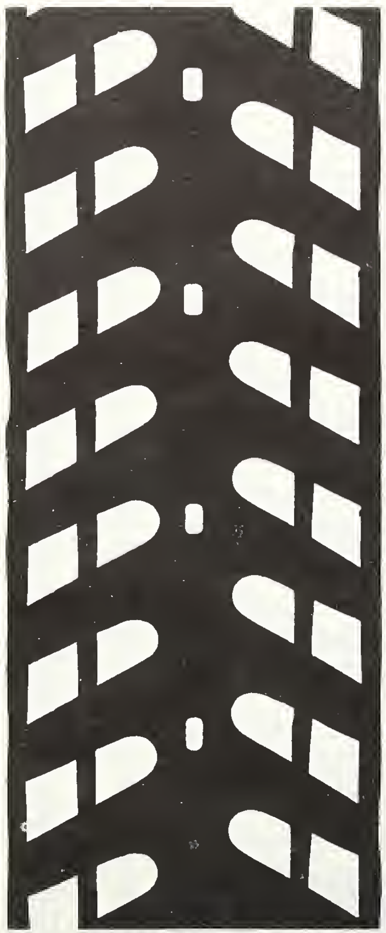
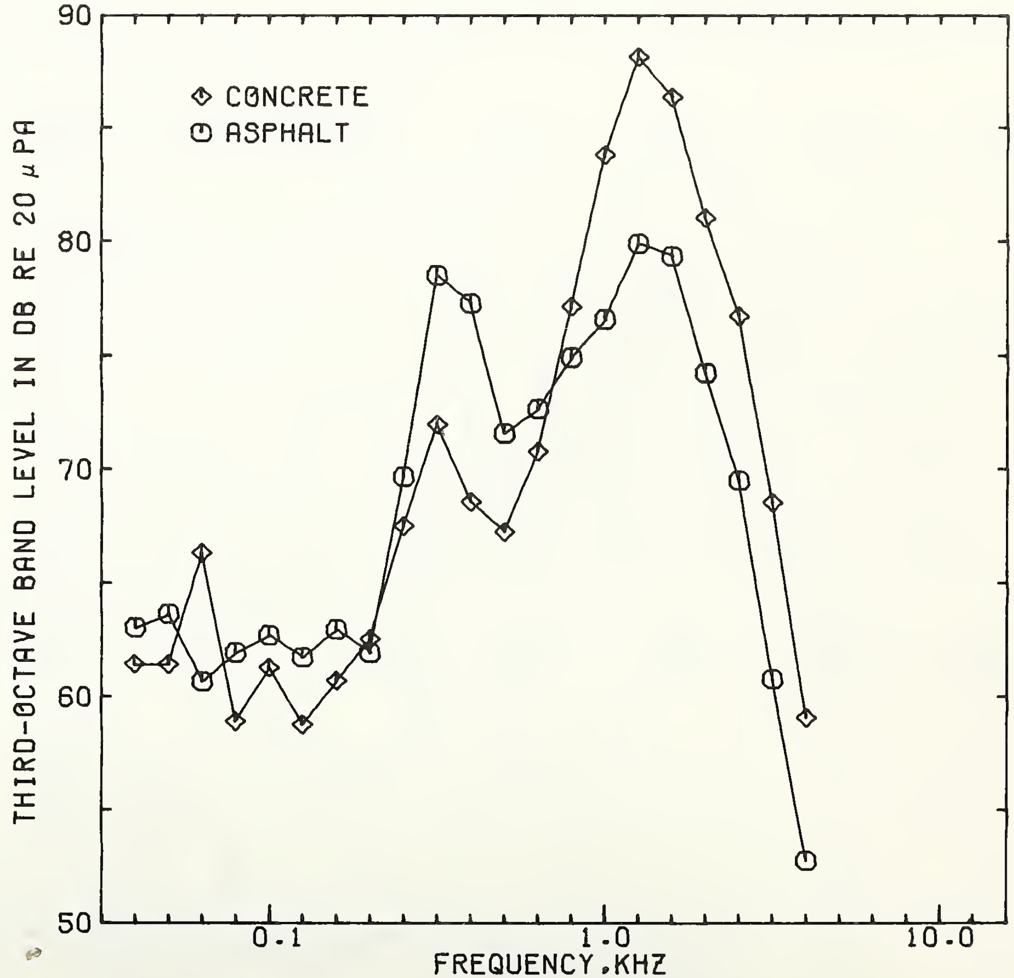



Figure A-35. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, retread-I tires on the drive axle.

RETREAD-I, HALF-WORN, DUAL, LOADED





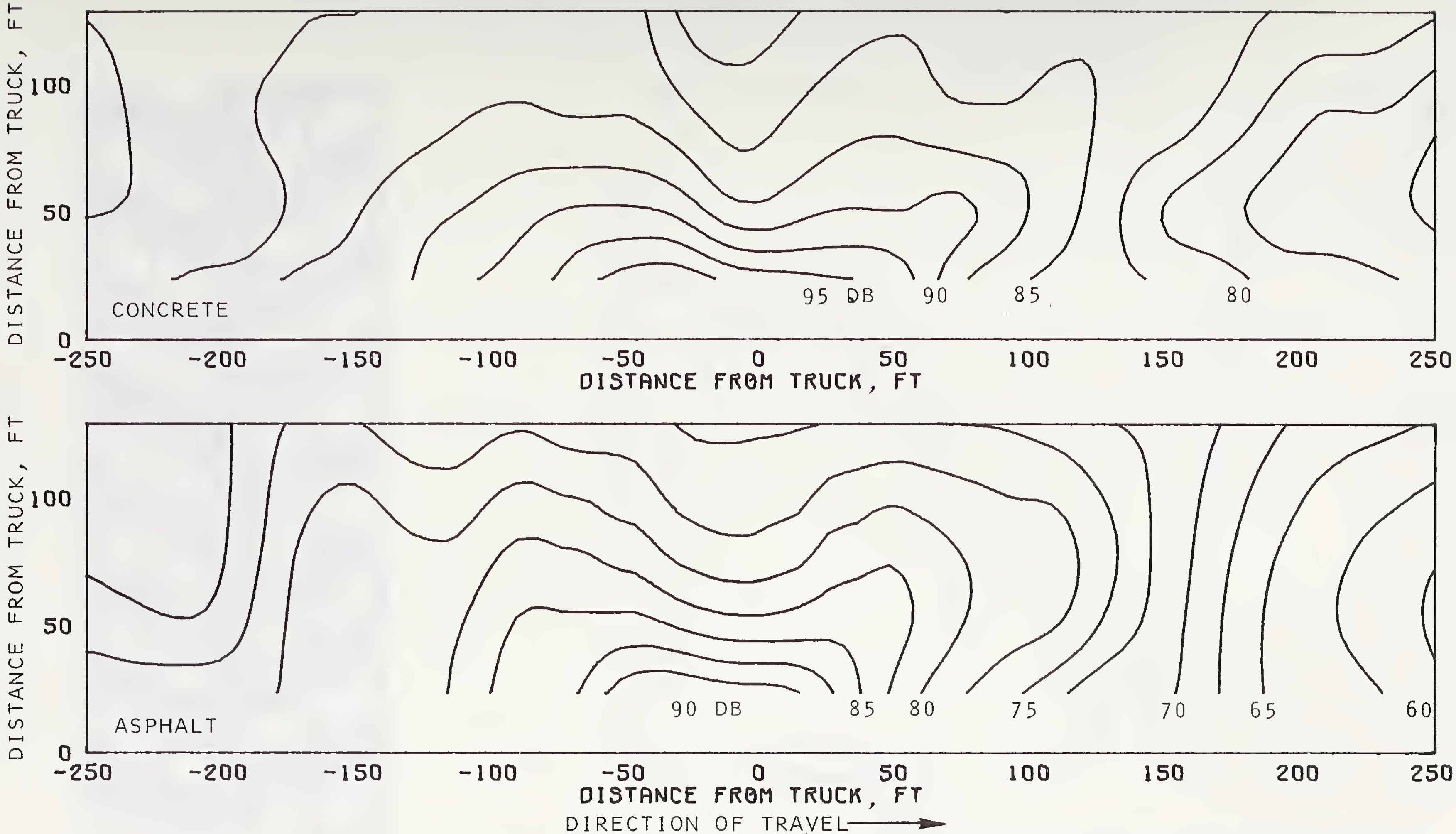
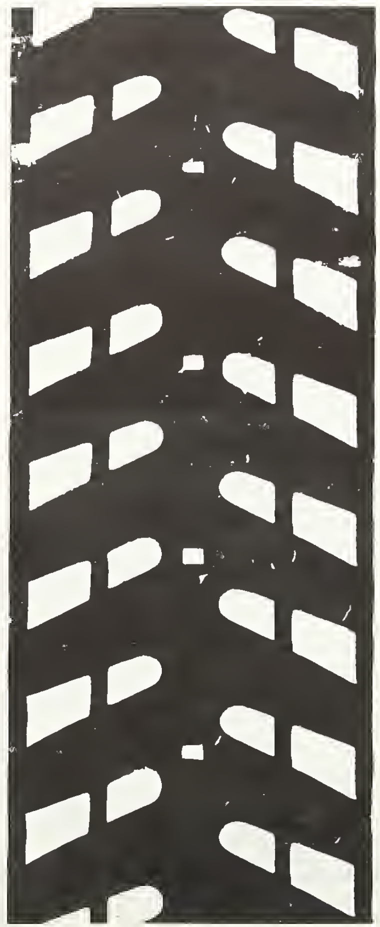
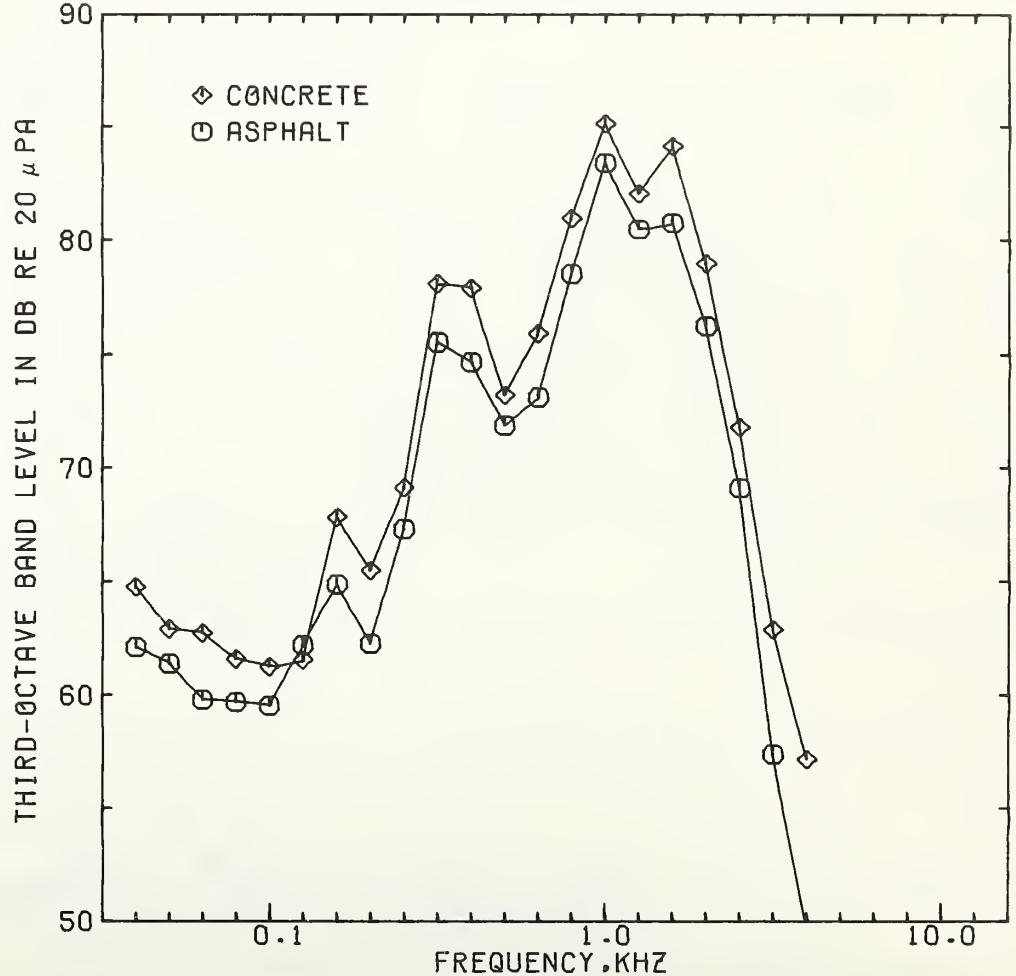



Figure A-36. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, retread-I tires on the drive axle.

# RETREAD-I, FULLY-WORN, DUAL, LOADED





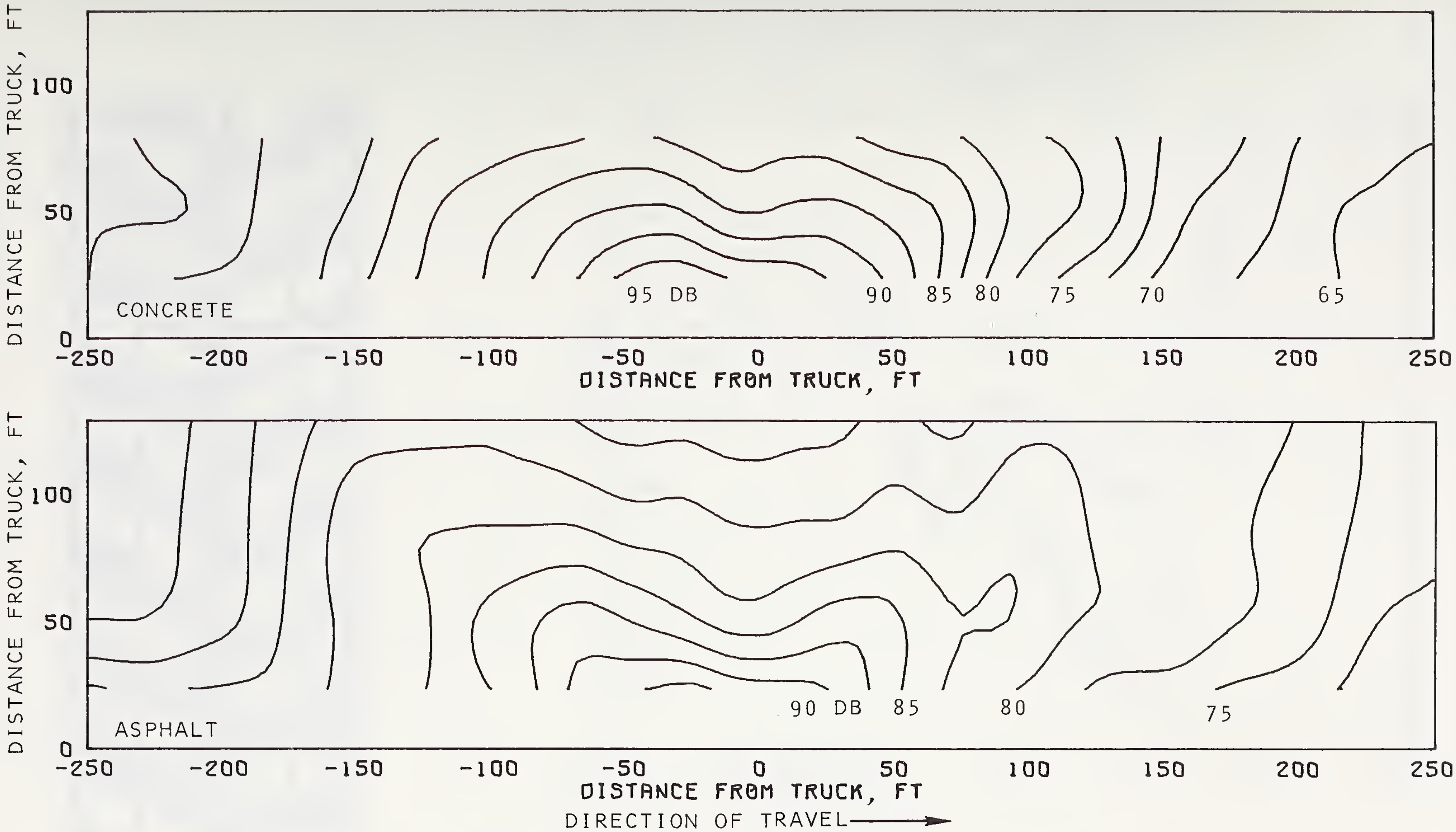
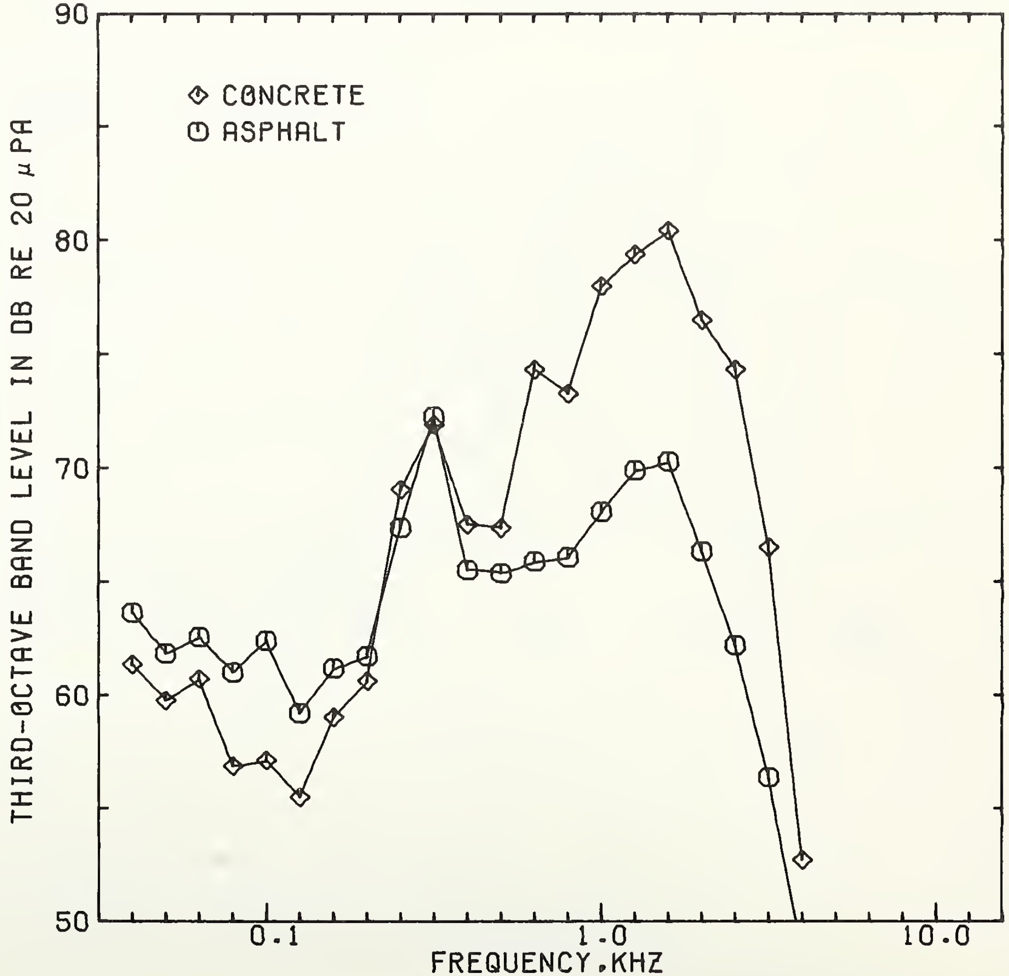



Figure A-37. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to a loaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, fully-worn, retread-I tires on the drive axle.

RETREAD-I, NEW, DUAL, UNLOADED



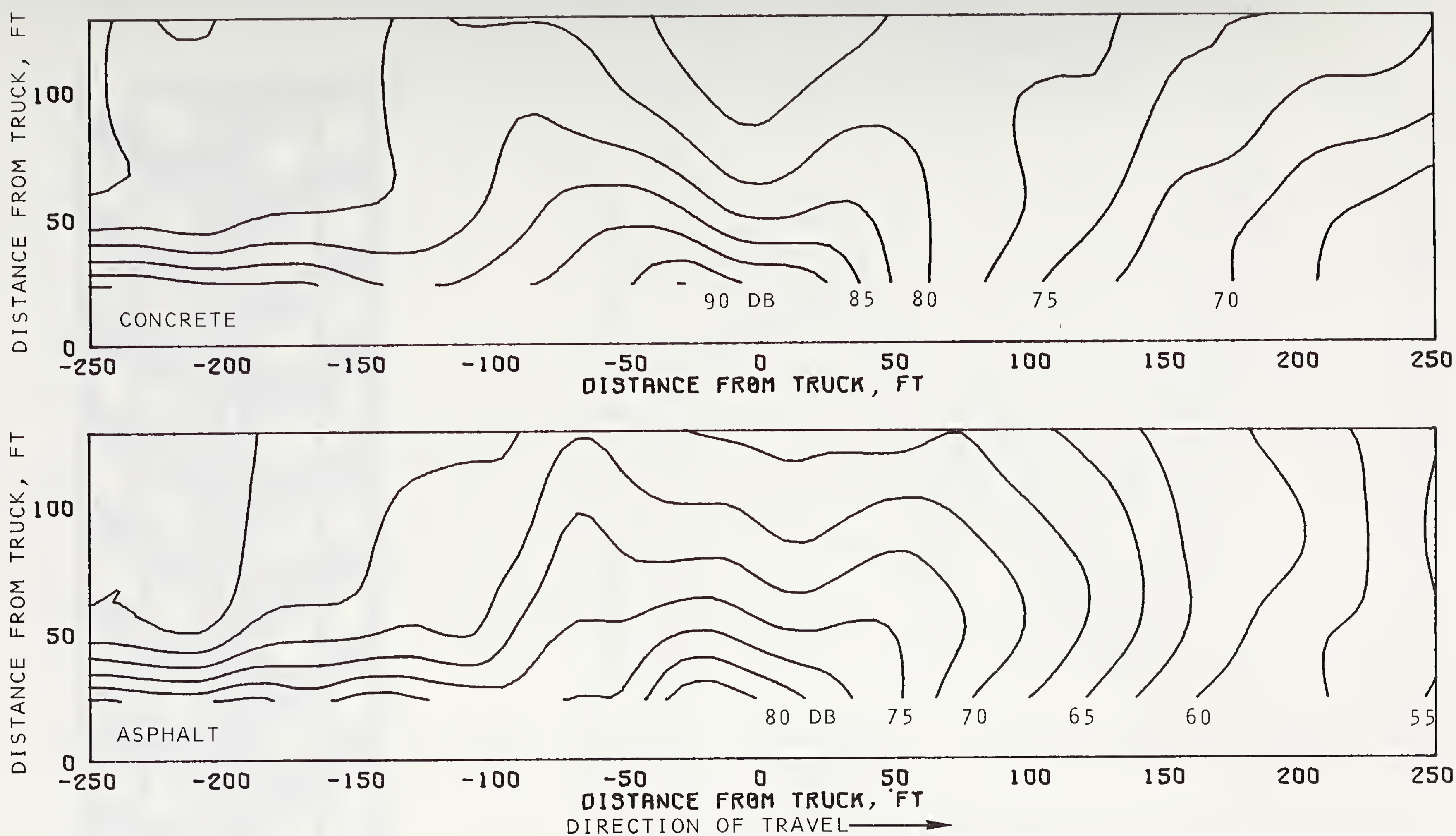
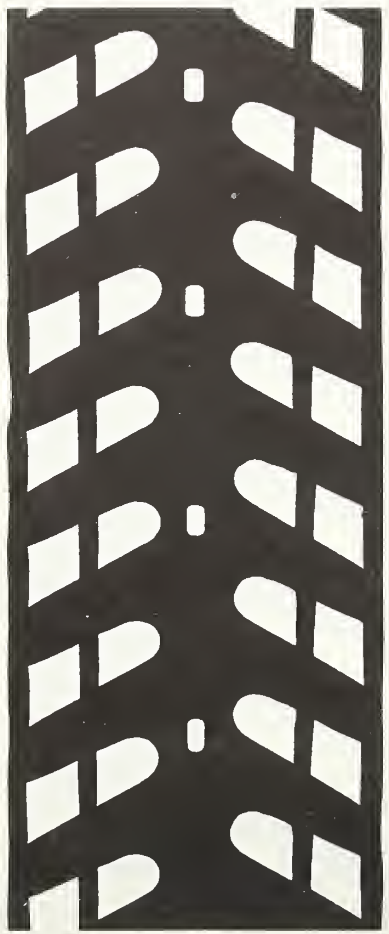
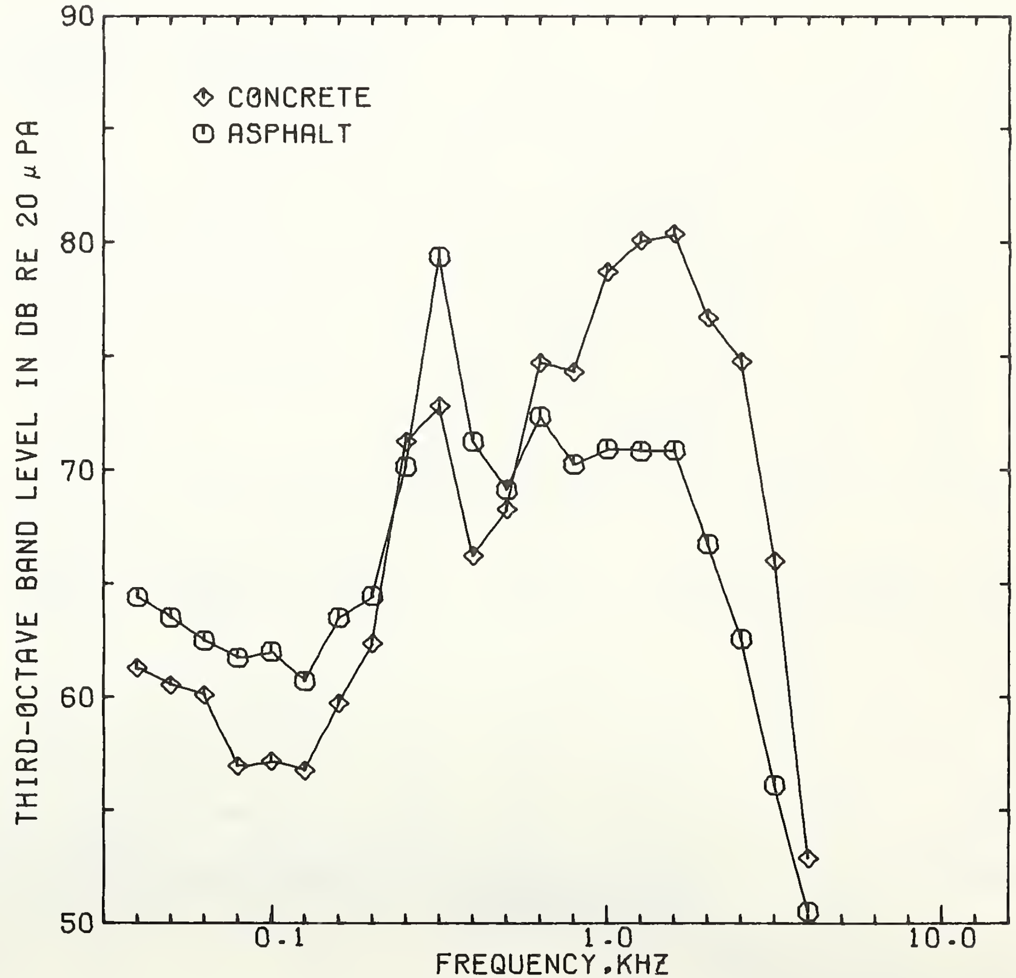



Figure A-38. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, new, retread-I tires on the drive axle.

## RETREAD-I, HALF-WORN, DUAL, UNLOADED





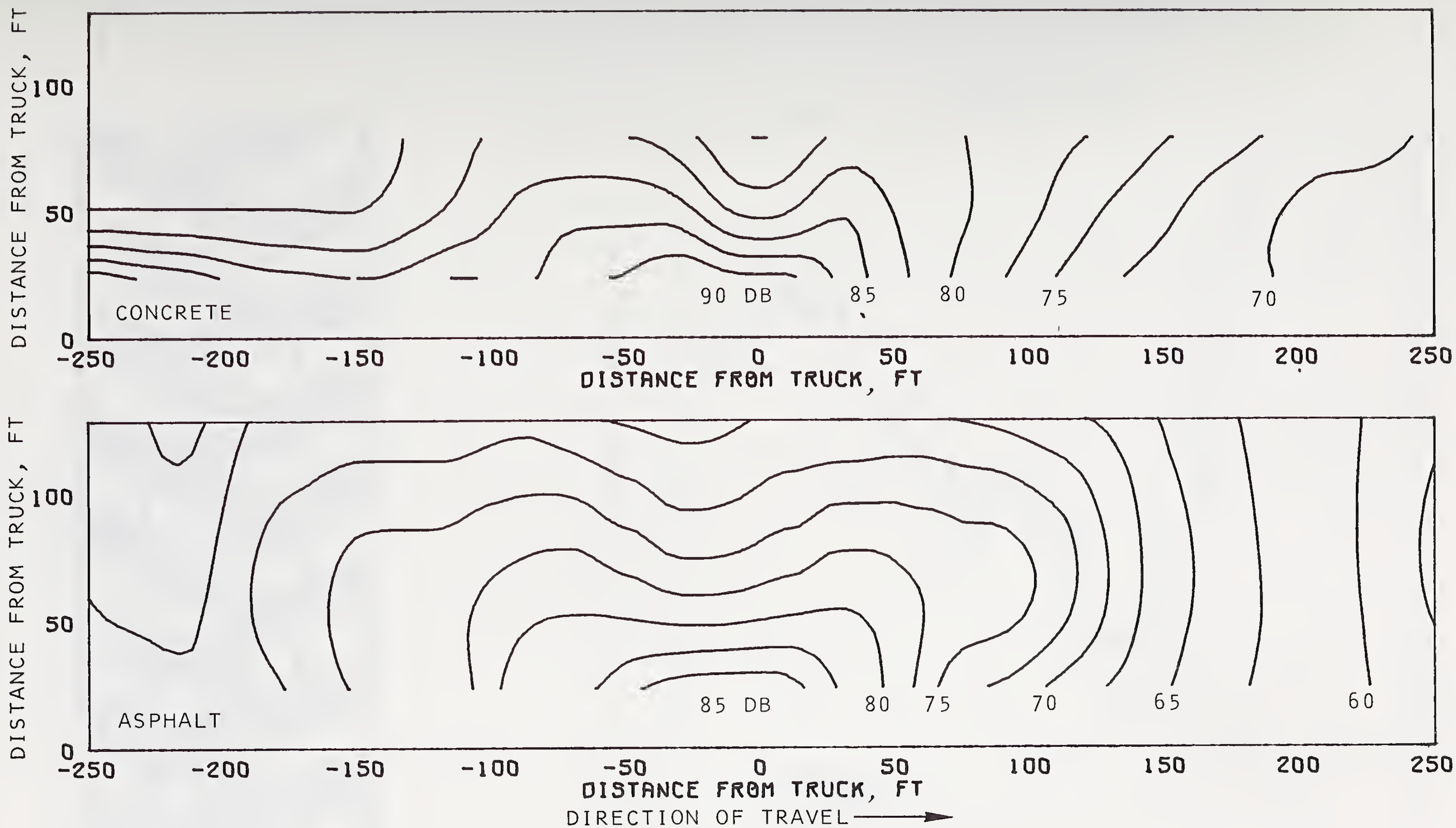
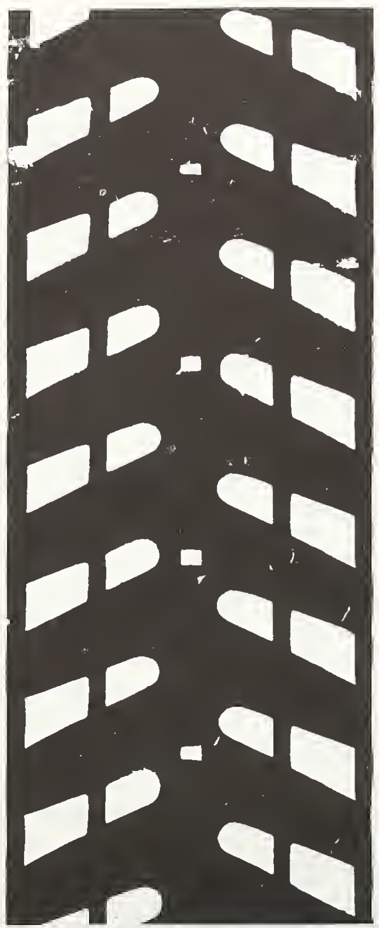
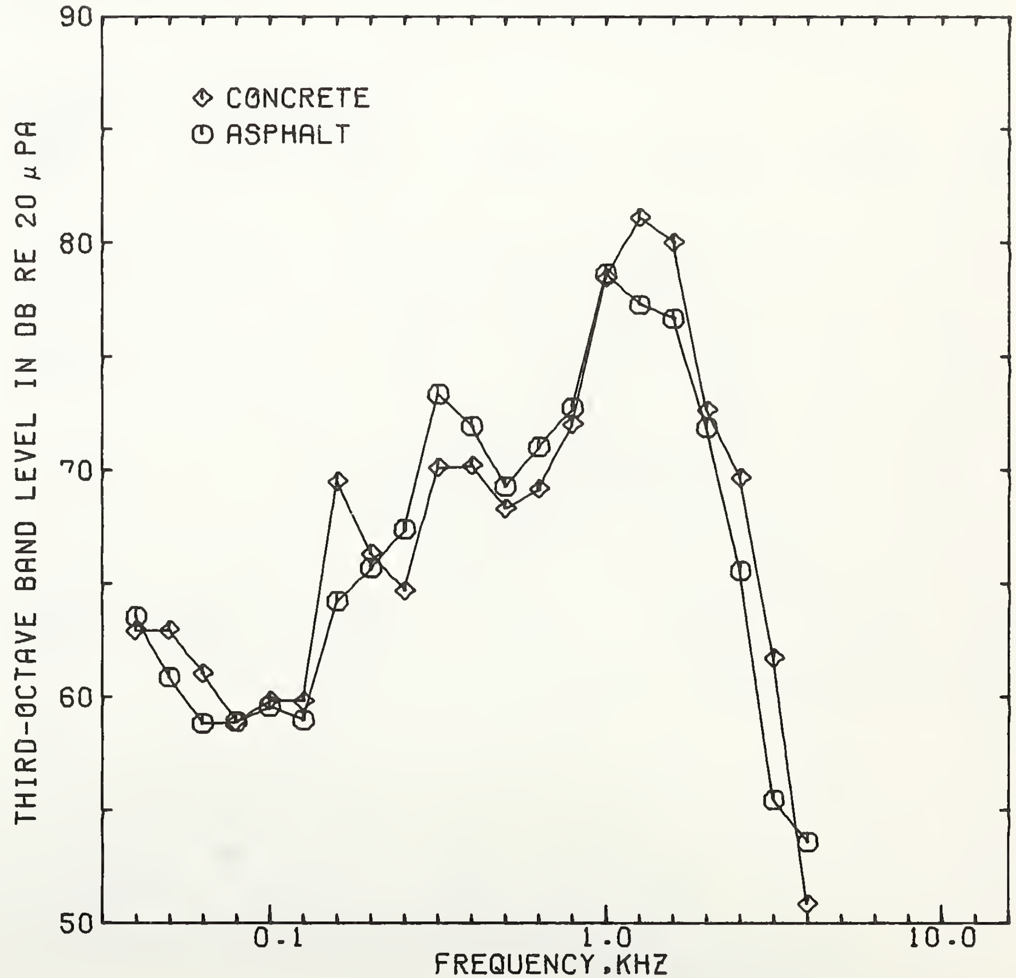



Figure A-39. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, half-worn, retread-I tires on the drive axle.

## RETREAD-I, FULLY-WORN, DUAL, UNLOADED





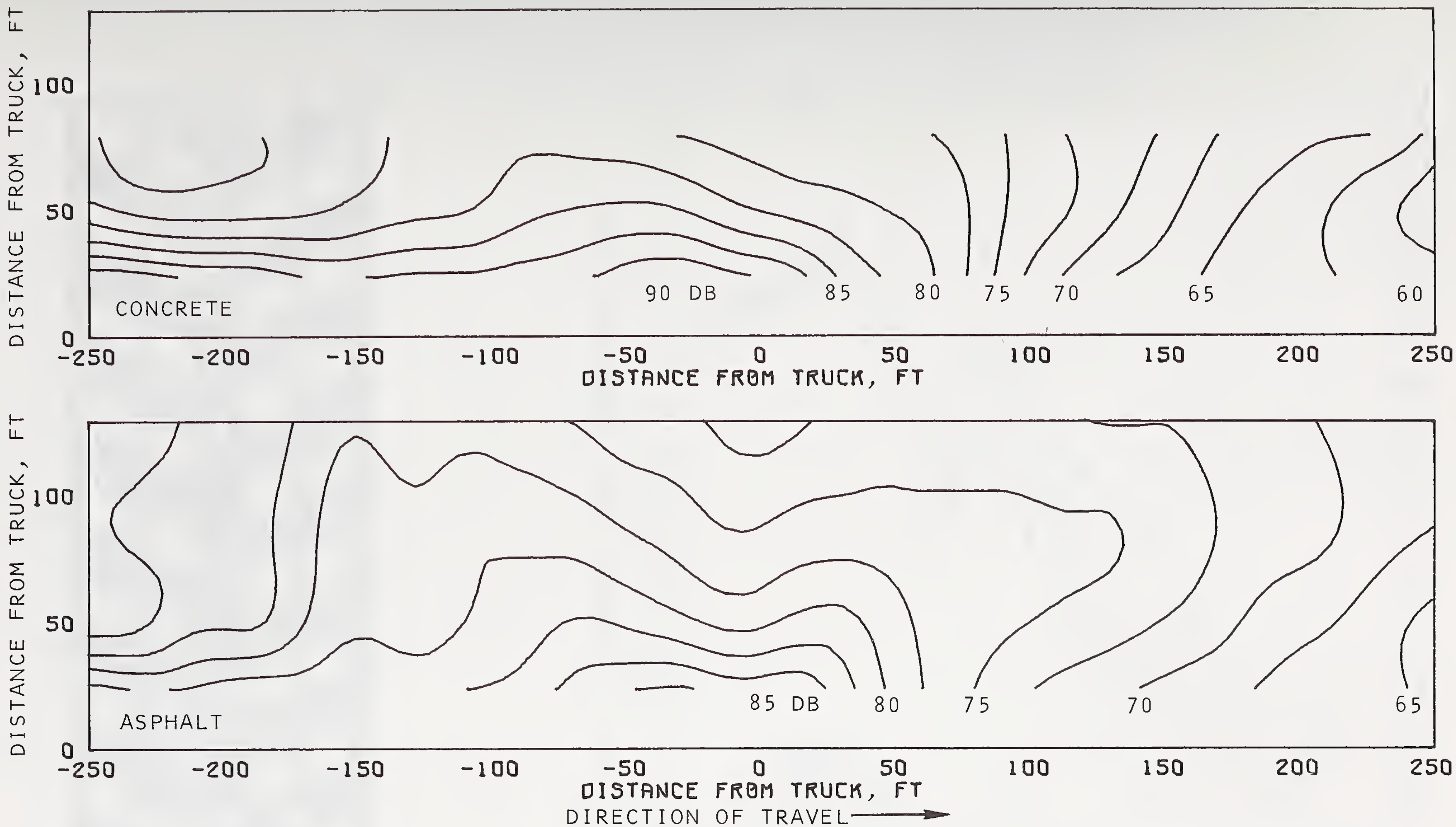
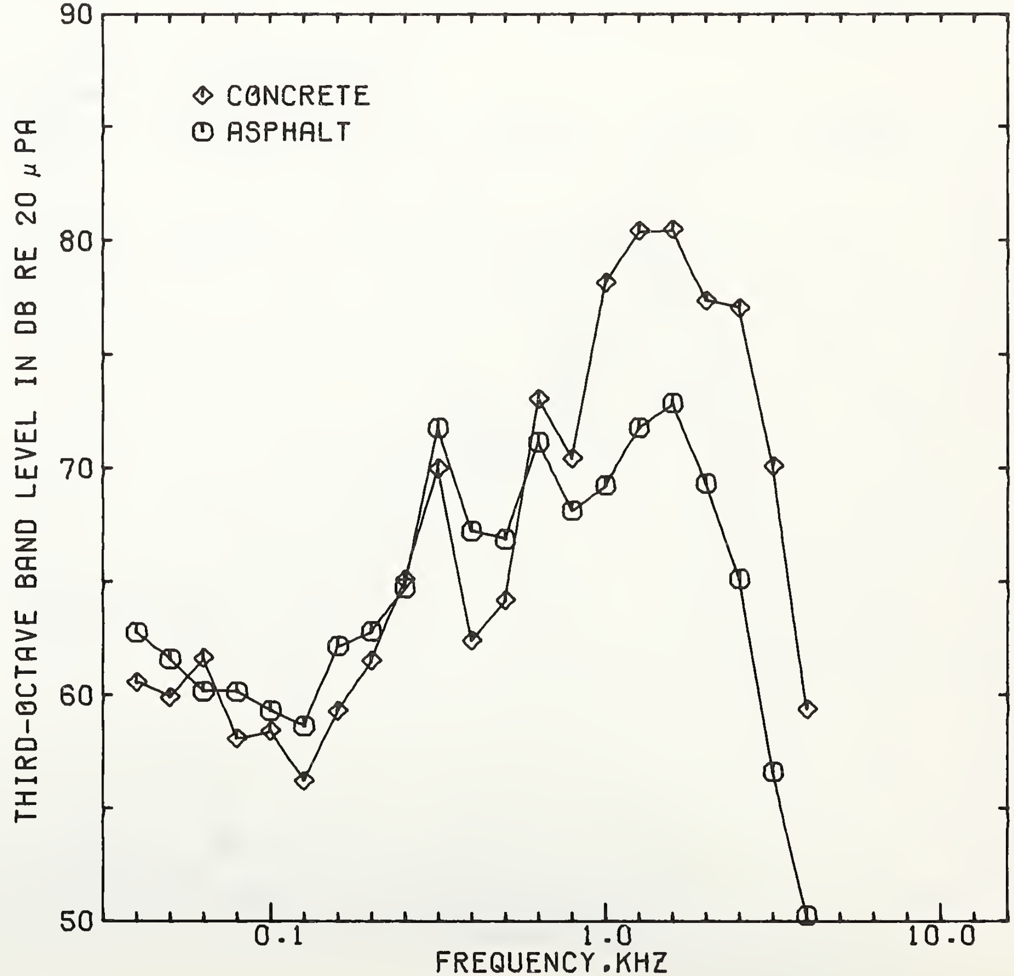



Figure A-40. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and dual, fully-worn, retread-I tires on the drive axle.

RETREAD-I, NEW, SINGLE, UNLOADED



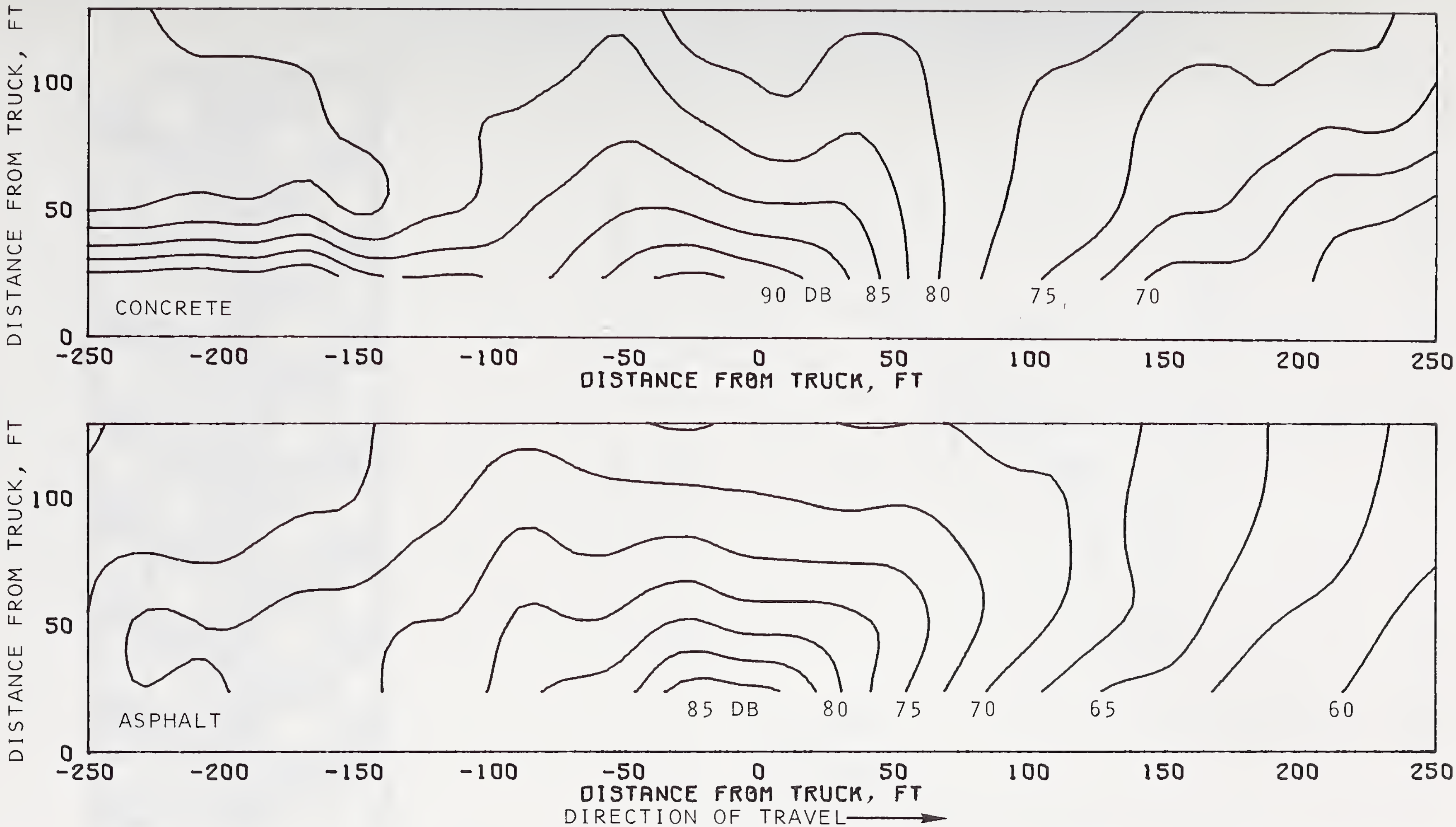
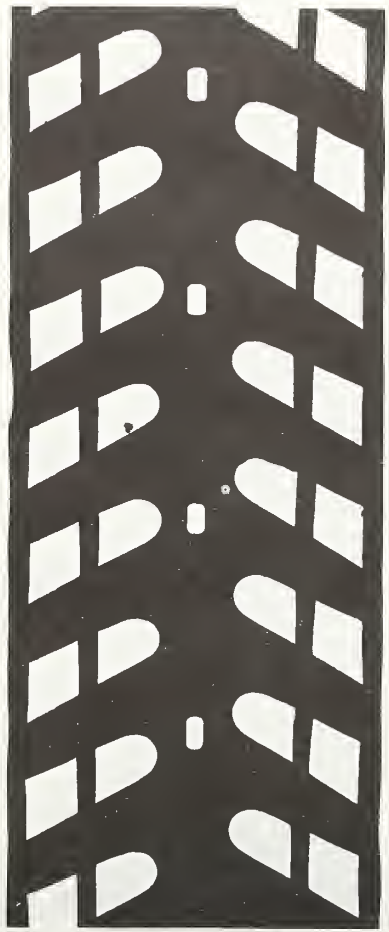
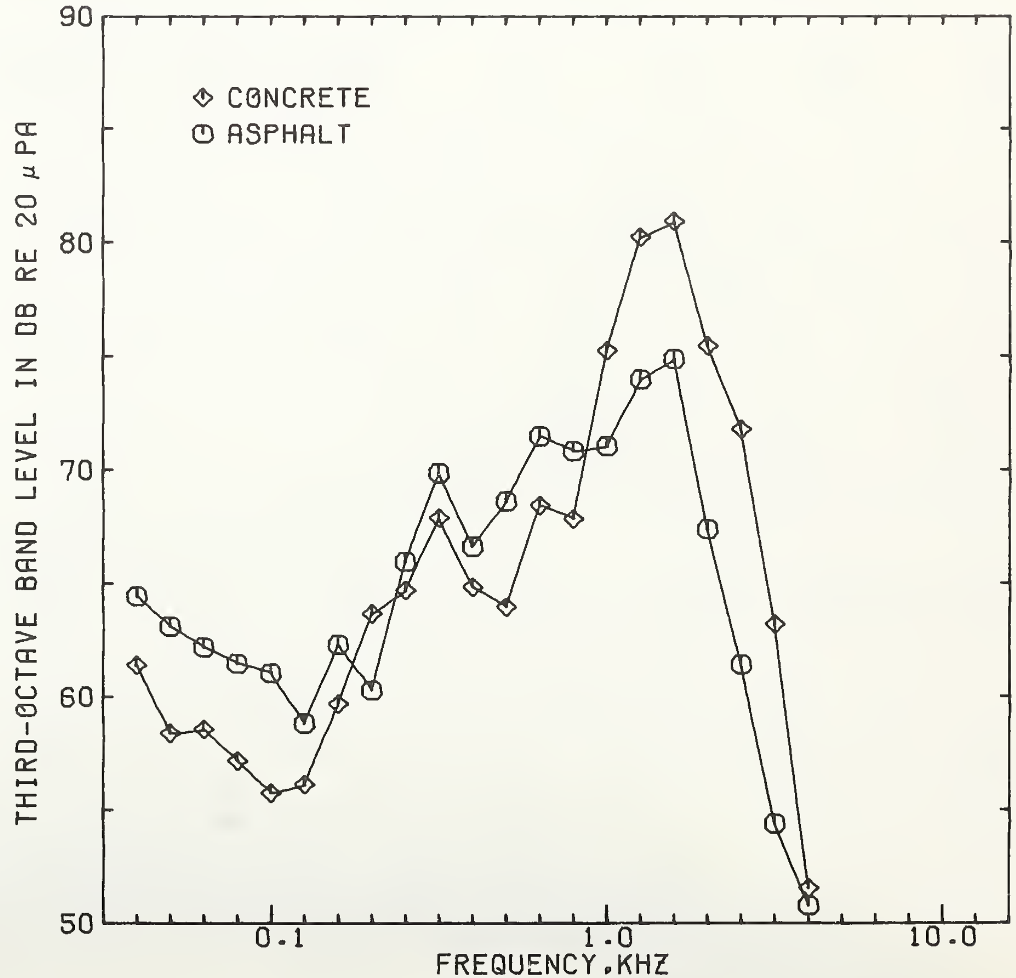



Figure A-41. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and single, new, retread-I tires on the drive axle.

## RETREAD-I, HALF-WORN, SINGLE, UNLOADED





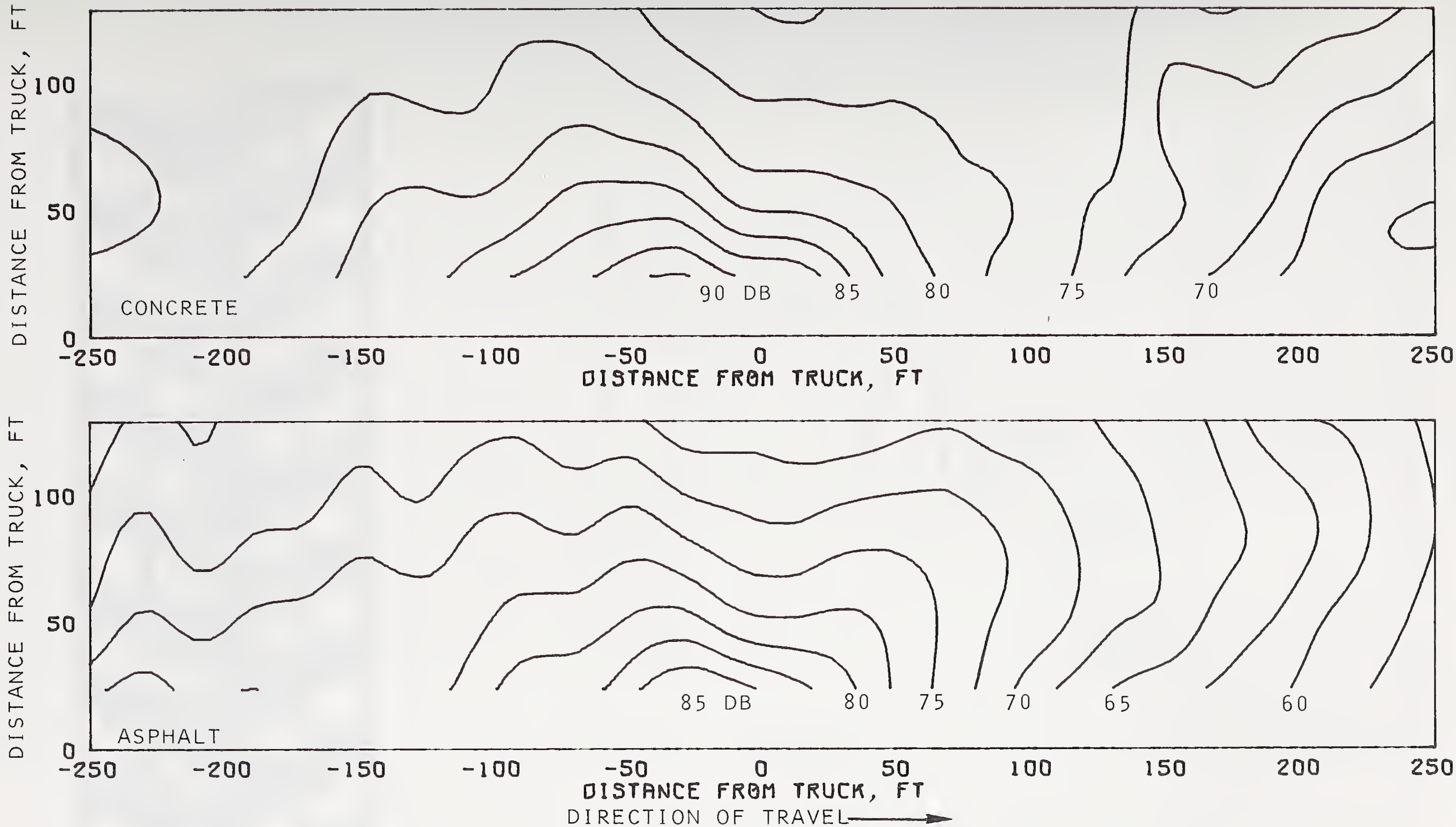
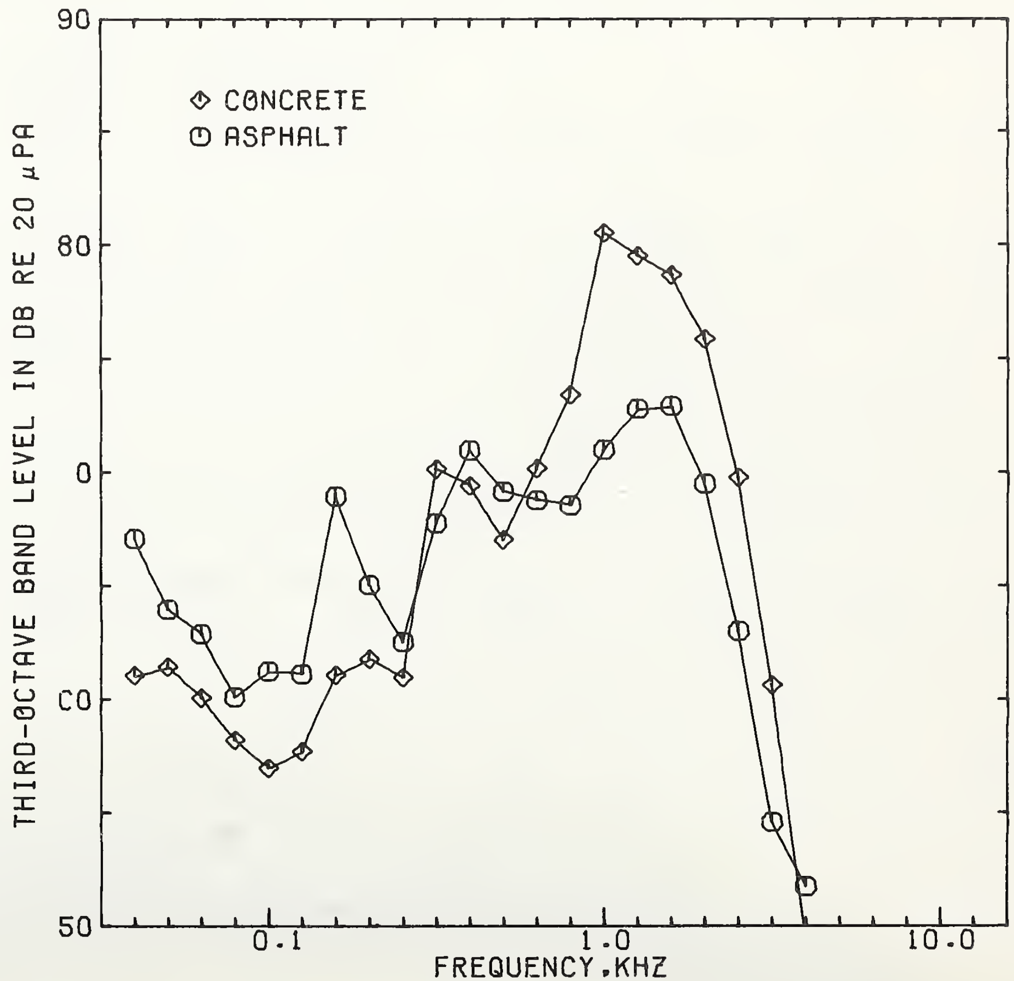



Figure A-42. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and single, half-worn, retread-I tires on the drive axle.

## RETREAD-I, FULLY-WORN, SINGLE, UNLOADED



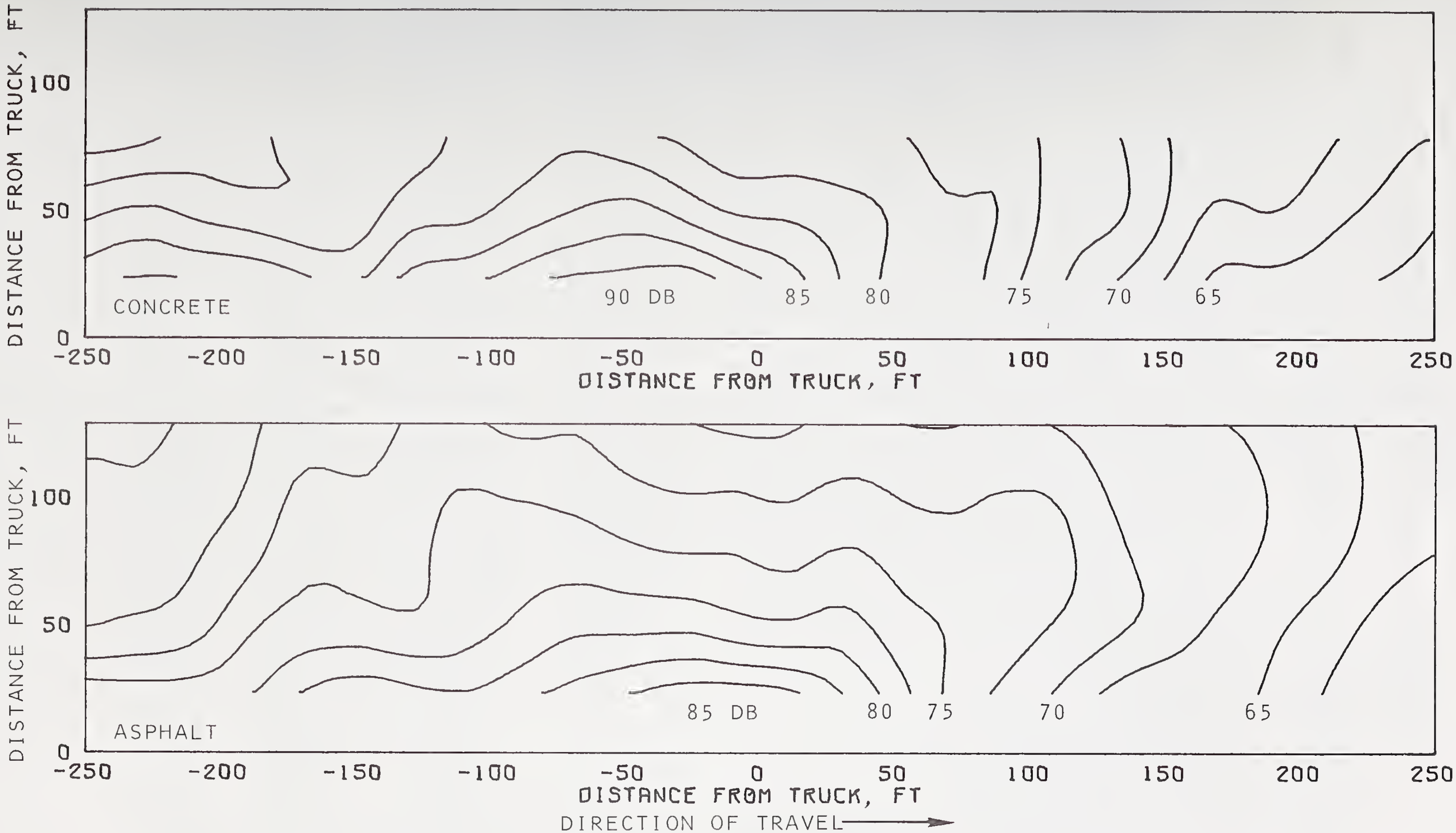



Figure A-43. The upper plot presents one-third octave band sound pressure levels versus frequency as measured at the 50 foot microphone at the time corresponding to the occurrence of the maximum A-weighted sound level while the lower plots show equal A-weighted sound level contours. These plots correspond to an unloaded single-chassis vehicle coastby at 50 mph on both asphalt and concrete surfaces. New neutral rib (rib-A) tires were mounted on the steering axle and single, fully-worn, retread-I tires on the drive axle.

## 5. Appendix B
## Description of the Procedure for the Development of the Directionality Contours

The equal A-weighted sound level contours presented in this report were generated according to the following procedure.

An array of six microphones, which were placed along a line perpendicular to the line of travel of the test vehicle, was utilized in the data acquisition portion of the program to record tire noise levels as the test truck coasted through a 1000 foot test section. Five photosensors, activated by a light beam produced by a spotlight mounted on the truck, were located 250 feet apart along the test lane parallel to the path of the vehicle. The photosensors provided information on truck position versus time. (See Appendix D for a summary description of the test section, instrumentation placement and test procedure.) During analysis, each analog tape was played back a channel at a time through a one-third octave band real-time-analyzer interfaced to a mini-computer. One-third octave band sound pressure levels and A-weighted sound levels were digitized and stored on magnetic tape. Analysis was initiated at the first photosensor -- when the truck was 500 feet from the microphone array -- and the analog data were sampled approximately every 20 feet throughout the 1000 foot test section. The time constant utilized for one-third octave analysis was 0.2 second above 200 Hz; below 200 Hz the time constant increased with decreasing frequency to 2 second at 20 Hz. The time constant for the weighting networks was 70 milliseconds. For nominal speeds from 30-60 mph, this was accomplished by increasing the sampling rate as vehicle speed increased. The sampling rates utilized were: (1) 400 milliseconds at vehicle speeds of 30, 35 and 40 mph, (2) 300 milliseconds at 45 and 50 mph, and (3) 200 milliseconds at 55 and 60 mph. As an example, for a vehicle speed of 30 mph (44 ft./sec.), data were sampled every 0.4 seconds after the initial photosensor or approximately every 18 feet during the passby. In this manner, A-weighted sound level versus time data were generated for each microphone location for each passby.

A major goal of the program was the measurement and tabulation of the maximum A-weighted sound level at each microphone position. This goal conflicted somewhat with the requirements for developing directionality contours, especially for the two near-field microphone locations at 6 and 12 feet. For these two locations, the dynamic range available in state-of-the-art instrumentation did not allow for the recording of both the maximum sound level and the sound level data as the truck approached and receded from the microphone array; therefore, only the data from the remaining four microphones were utilized for the generation of the directionality plots.

The A-weighted sound-level-versus-time data for each microphone of interest were then transformed to A-weighted sound level versus distance data utilizing the information provided by the photosensor system. The five photosensor placements plus the time of arrival at each microphone location gave four measurements of distance versus time, plus the zero point, to which a cubic polynomial in time of form $X=A+Bt+Ct^2+Dt^3$ was fitted by the method of least squares. The reason for the choice of the cubic polynomial was the fact that the velocity versus time data obtained by differentiation of the distance versus time data deviates from a straight line, although only slightly. The speed of the truck at any given time t is calculated as follows: $v = B + 2Ct + 3Dt^2$ where B, C, and D are the constants found above in the fitted distance versus time data.

A typical set of data now consisted of A-weighted sound level versus distance for four microphones at seven different nominal speeds from 30 to 60 mph in 5 mph increments. It is desirable to compare directionality contours at identical truck speeds, e.g., 50 mph; therefore, for each speed from 30 to 60 mph, an interpolation scheme was utilized to find A-weighted sound level versus distance data every 20 feet along the 1000 foot test section for each microphone of interest. Thus for each microphone at 51 locations along the line of travel we have 7 data points of A-weighted sound level versus speed. A parabolic interpolation of A-weighted sound level versus speed was performed to obtain 51 data points all at a constant speed of 50 mph. The parabolic fit was chosen because it was utilized previously [1,2] in fitting A-weighted sound level data versus speed. We now have a 4 x 51 dimensional matrix -- the 4 columns representing the 4 microphone locations at 25, 50, 80 and 130 feet and the 51 rows representing the 51 locations every 20 feet along the line of travel. These data showed that the majority of the information was contained around the microphone array location; therefore, for the purposes of this report, contours were drawn from -250 to +250 feet rather than the total distance of -500 to +500 feet.

All that remained was to draw the desired equal A-weighted sound level contours. This involved two steps. First, in order to generate a contour map with the truck in the center and contour levels surrounding it, the distance scale had to be reinterpreted. When the truck was at -250 feet, the microphone was in front of the truck and vice versa at +250 feet. Therefore, the scale must be reversed if we wish to draw the contours properly, e.g., the direction of travel of the test vehicle was from -250 feet to +250 feet. Second, to draw the actual contours a bi-variate spline contouring routine available at NBS on the Univac [9/] 1108 Exec. VIII system was utilized. This routine essentially searches the data for equal values of A-weighted sound level and draws a smooth curve through the points.

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[9/] Commercial equipment are identified in this report in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the equipment identified is necessarily the best available for the purpose.

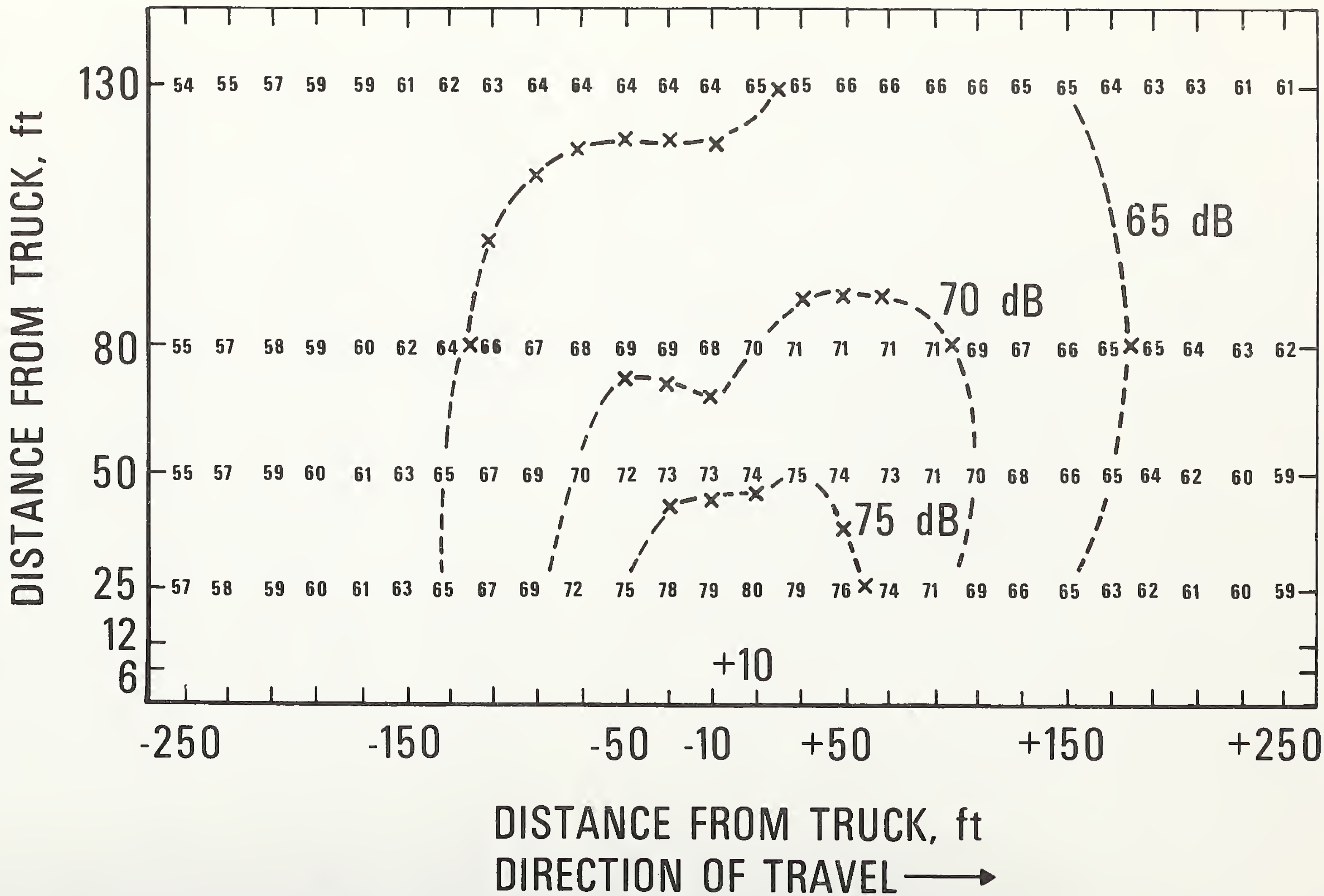


Figure B-1 A graphical representation of the 4x26 dimensional matrix [4 microphone locations at 25, 50, 80 and 130 feet and 26 data samples every 20 feet along the line of travel] from which the equal sound level directionality contour plots were generated.

# 6. Appendix C
## Results of Narrow-Band Spectral Analysis Investigation

As discussed earlier in this report, a limited number of runs was selected for narrow-band analysis. The purpose of this investigation was to address the question of whether one-third octave band analysis provides the discrimination necessary for identifying particular frequencies associated with noise generation mechanisms.

A total of twenty-five runs was selected. Data resulting from three of the runs were discussed in Section 2.2. The remainder of the data is presented in this Appendix. It should be noted that the choice of runs which were analyzed allows one to evaluate the effects of tread design, degree of tread wear, pavement surface, load and the number of tires on the drive axle. For example, a comparison among the spectra shown in Figures C11-12, C15-16 and C17-18 allows for the evaluation of wear as a parameter for rib-C tires. In these cases the speed, number of tires, load and pavement surface were held constant.

Since our present knowledge of tire noise source mechanisms is superficial at best, no in-depth analysis of the narrow-band spectral data shown in this appendix has been undertaken at this time. However, it is important that such data be placed into the public domain since the tire noise source models resulting from ongoing and future tire noise investigations should account for the phenomena shown by these data.

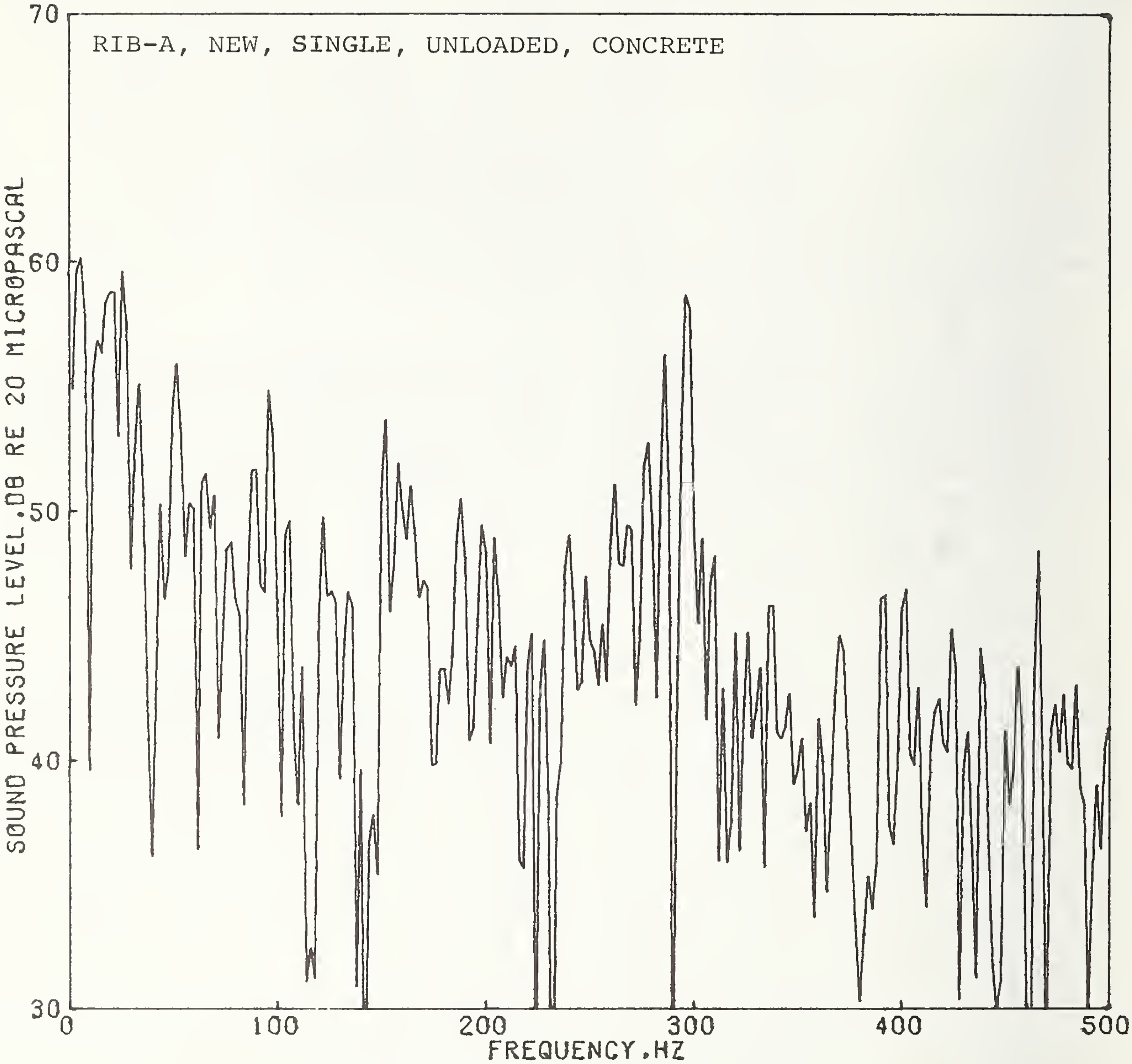


Figure C-1 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, rib-A tires on the drive axle. The 50 mph coastby was on a concrete surface.

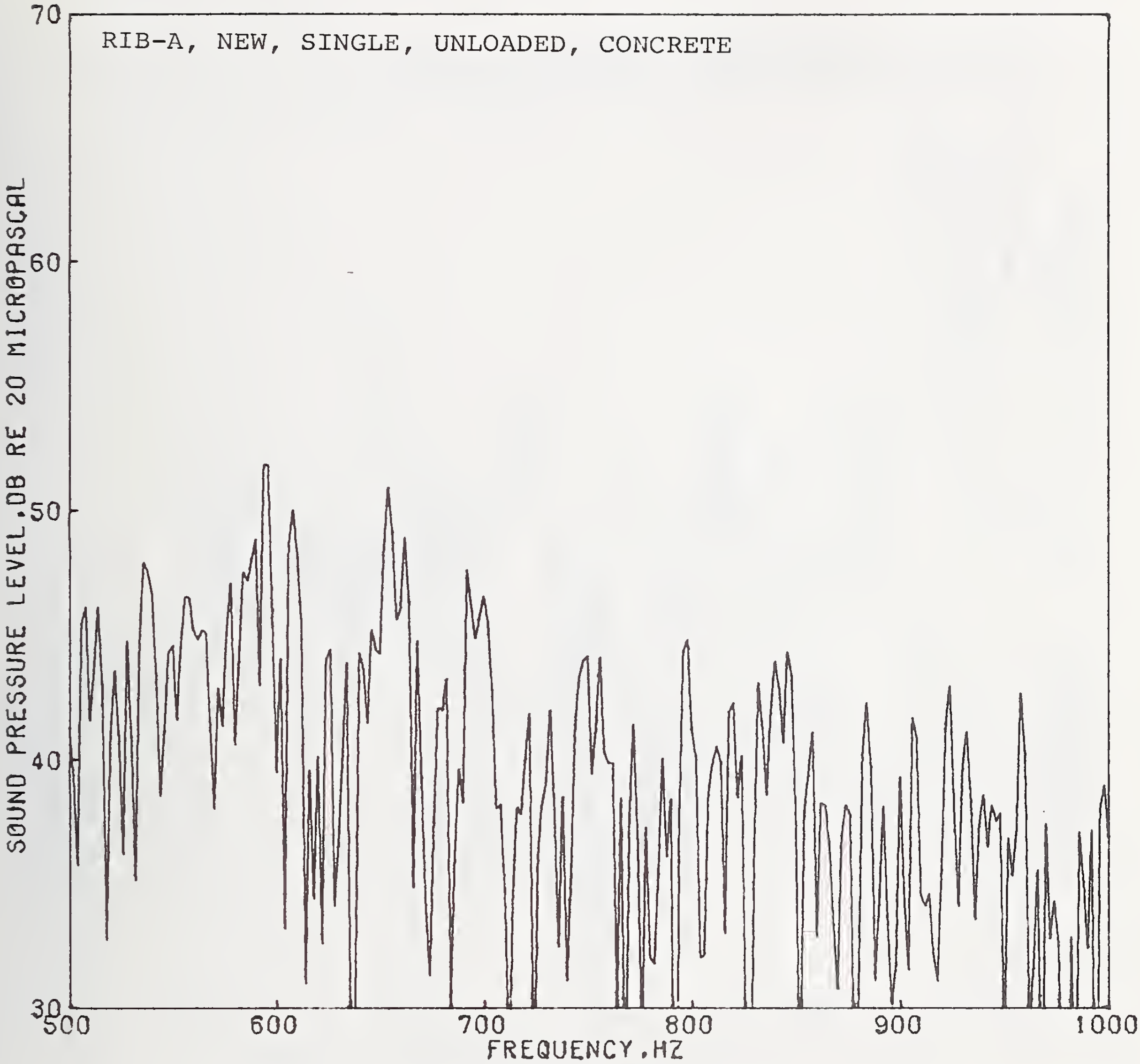


Figure C-2 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, rib-A tires on the drive axle. The 50 mph coastby was on a concrete surface.

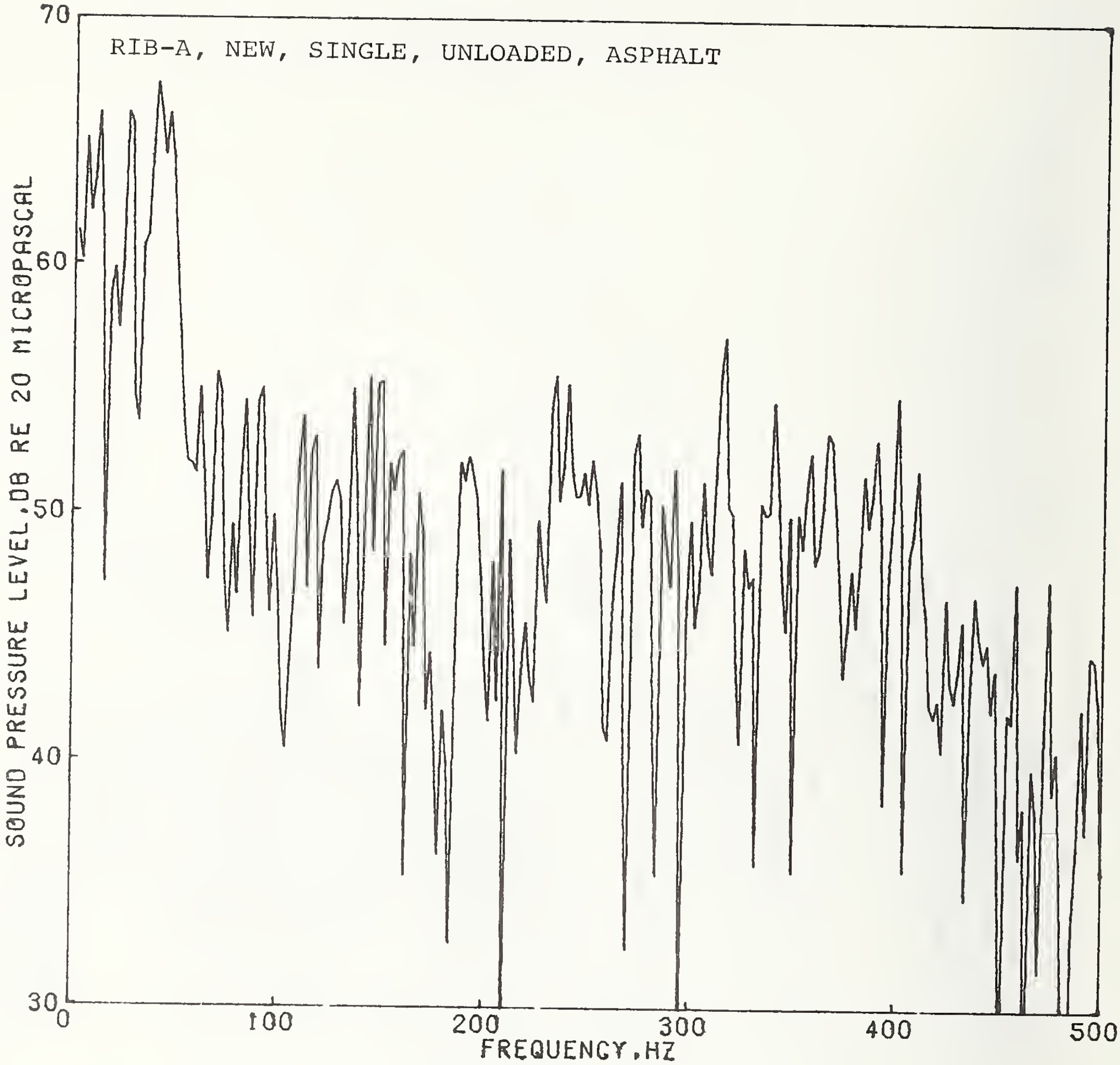


Figure C-3 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, rib-A tires on the drive axle. The 50 mph coastby was on an asphalt surface.

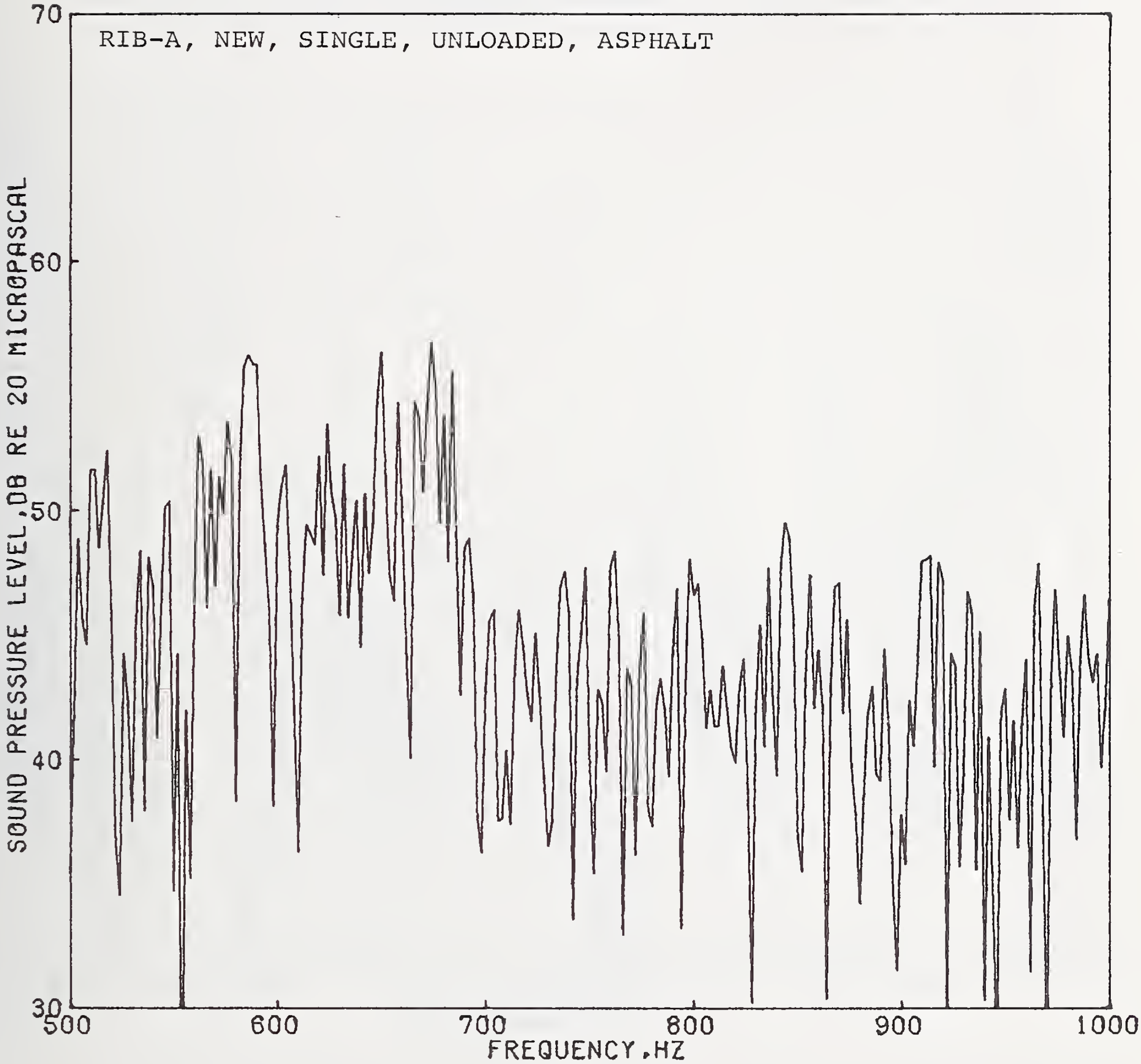


Figure C-4 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, rib-A tires on the drive axle. The 50 mph coastby was on an asphalt surface.

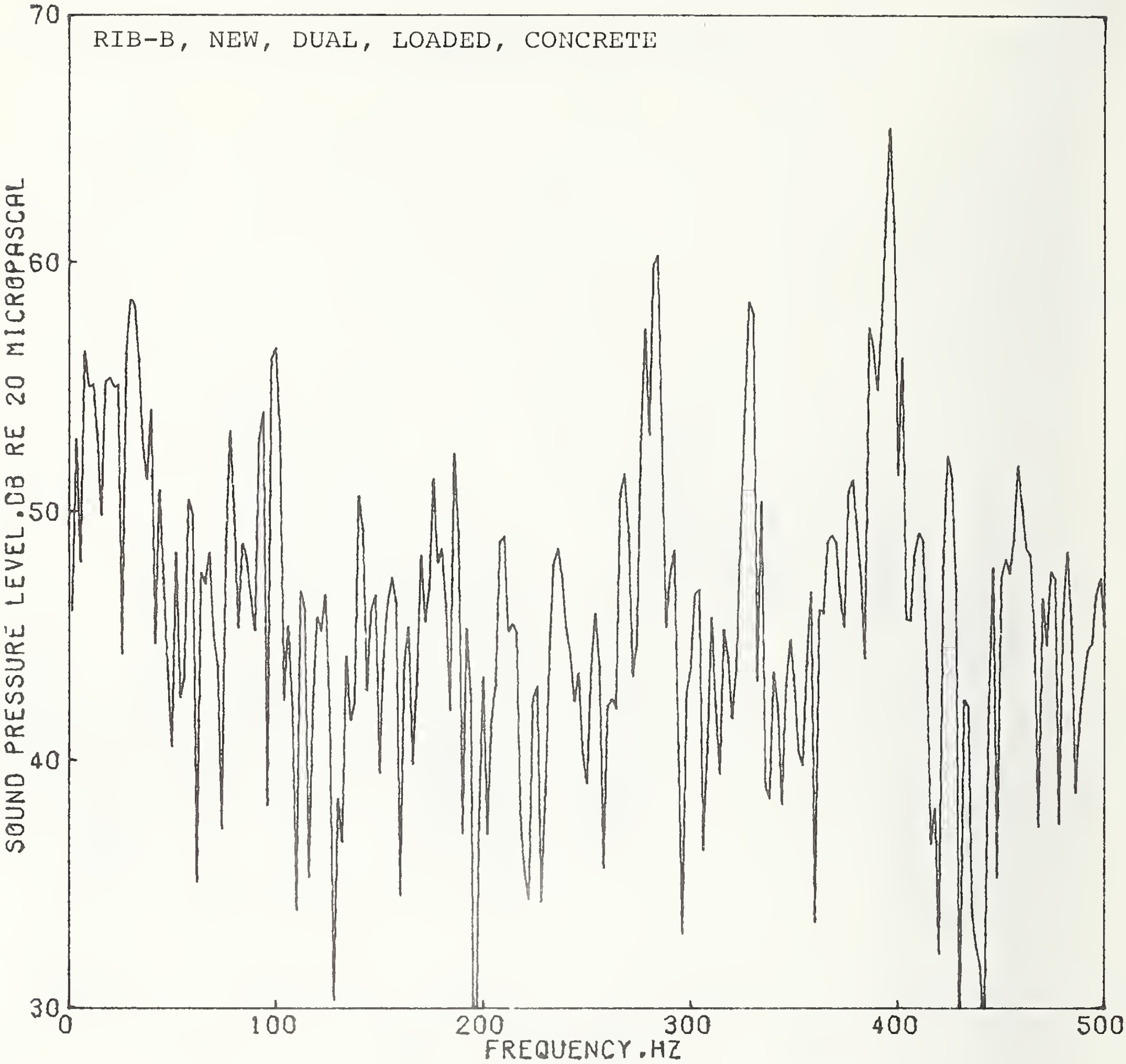


Figure C-5 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, rib-B tires on the drive axle. The 50 mph coastby was on a concrete surface.

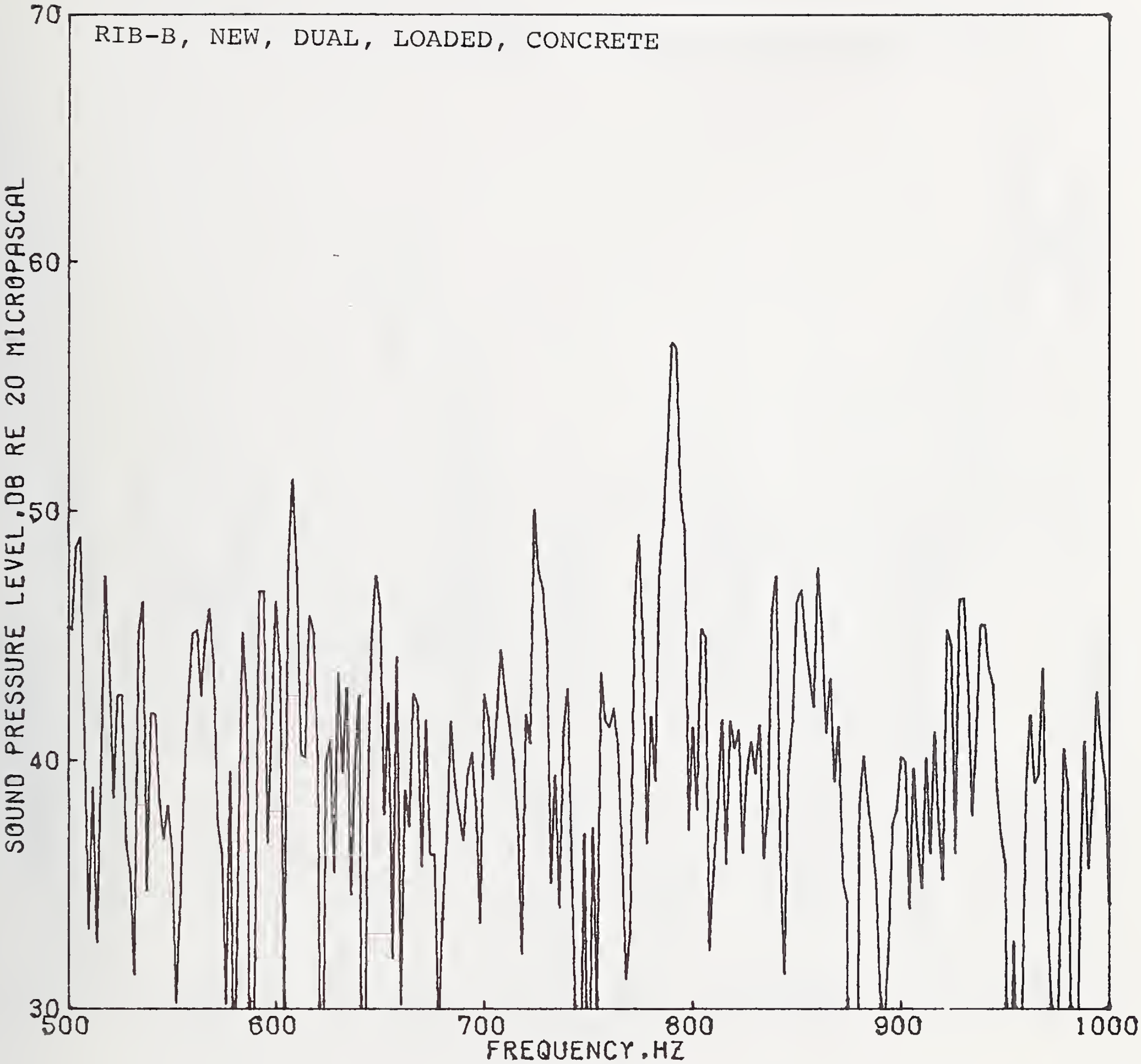


Figure C-6 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, rib-B tires on the drive axle. The 50 mph coastby was on a concrete surface.

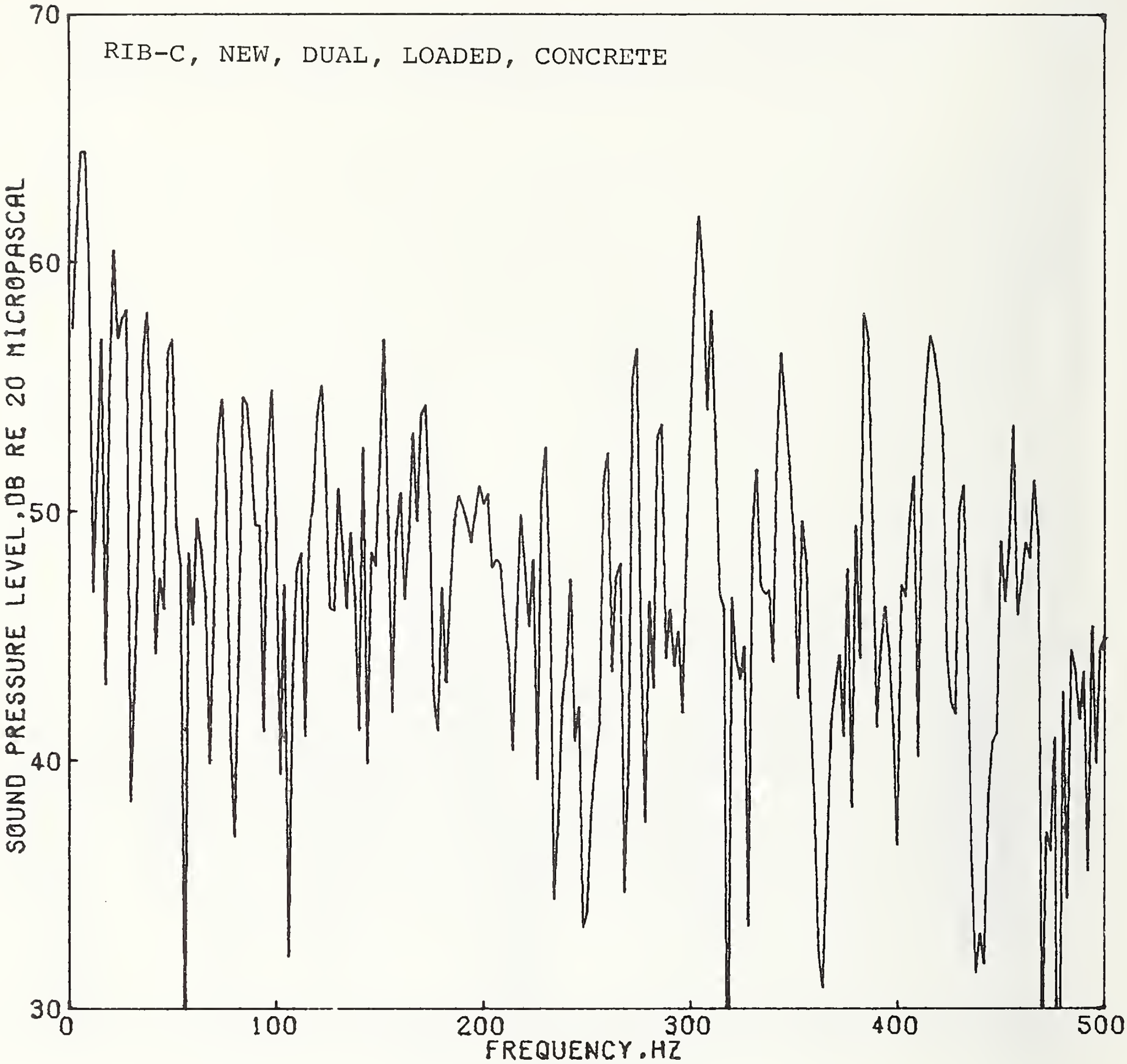


Figure C-7 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, rib-C tires on the drive axle. The 50 mph coastby was on a concrete surface.

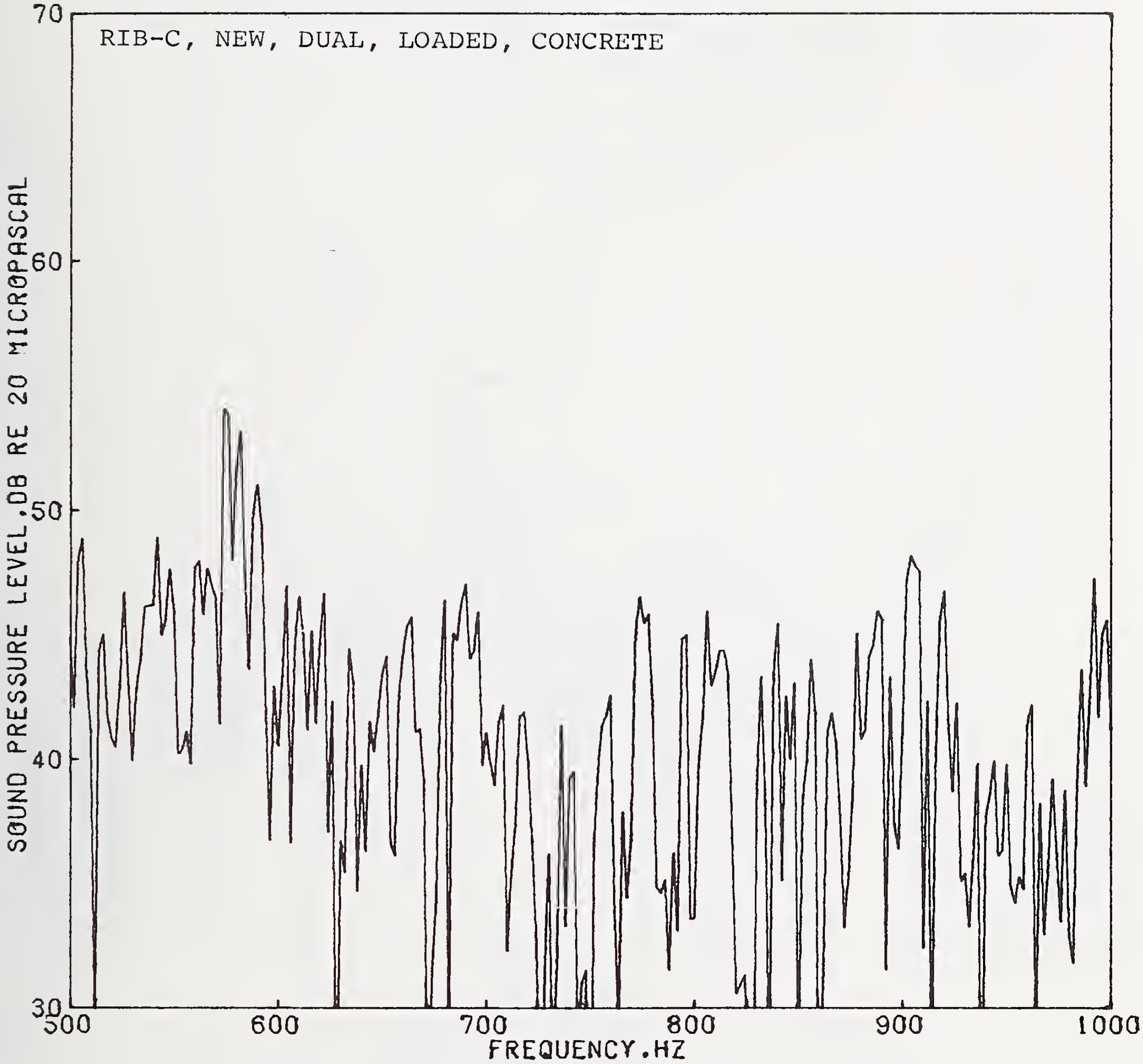


Figure C-8 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, rib-C tires on the drive axle. The 50 mph coastby was on a concrete surface.

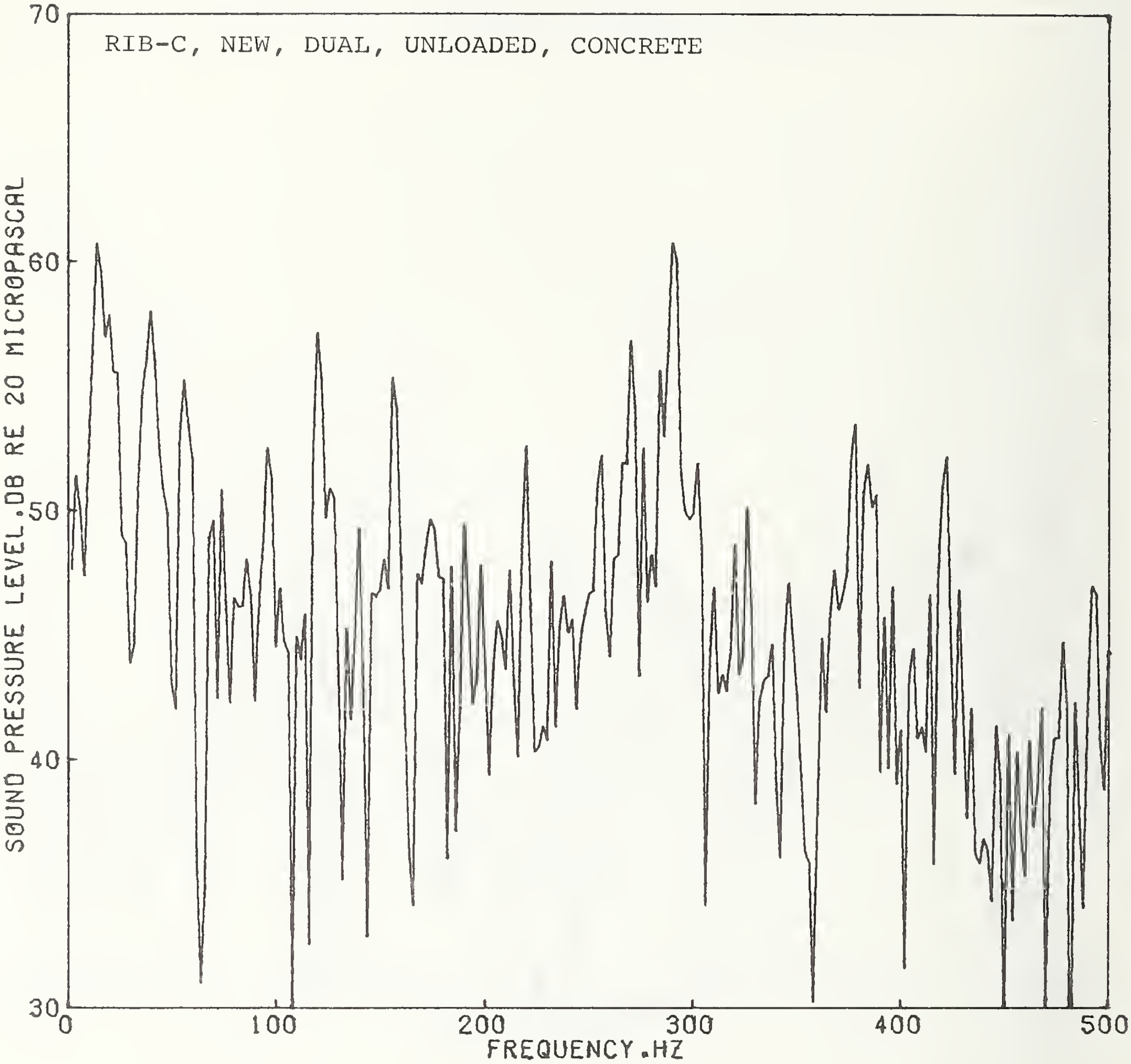


Figure C-9 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, rib-C tires on the drive axle. The 50 mph coastby was on a concrete surface.

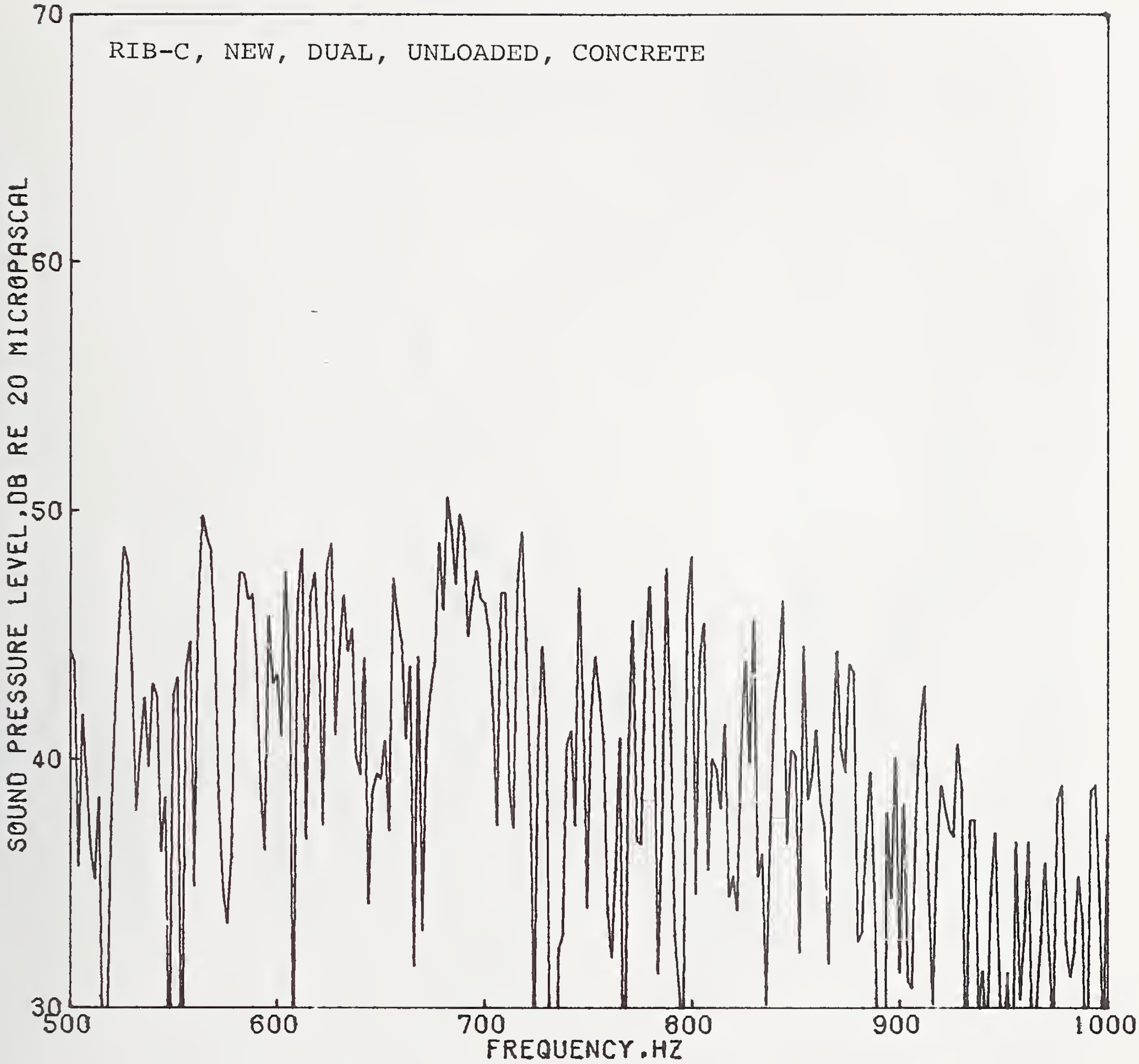


Figure C-10 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, rib-C tires on the drive axle. The 50 mph coastby was on a concrete surface.

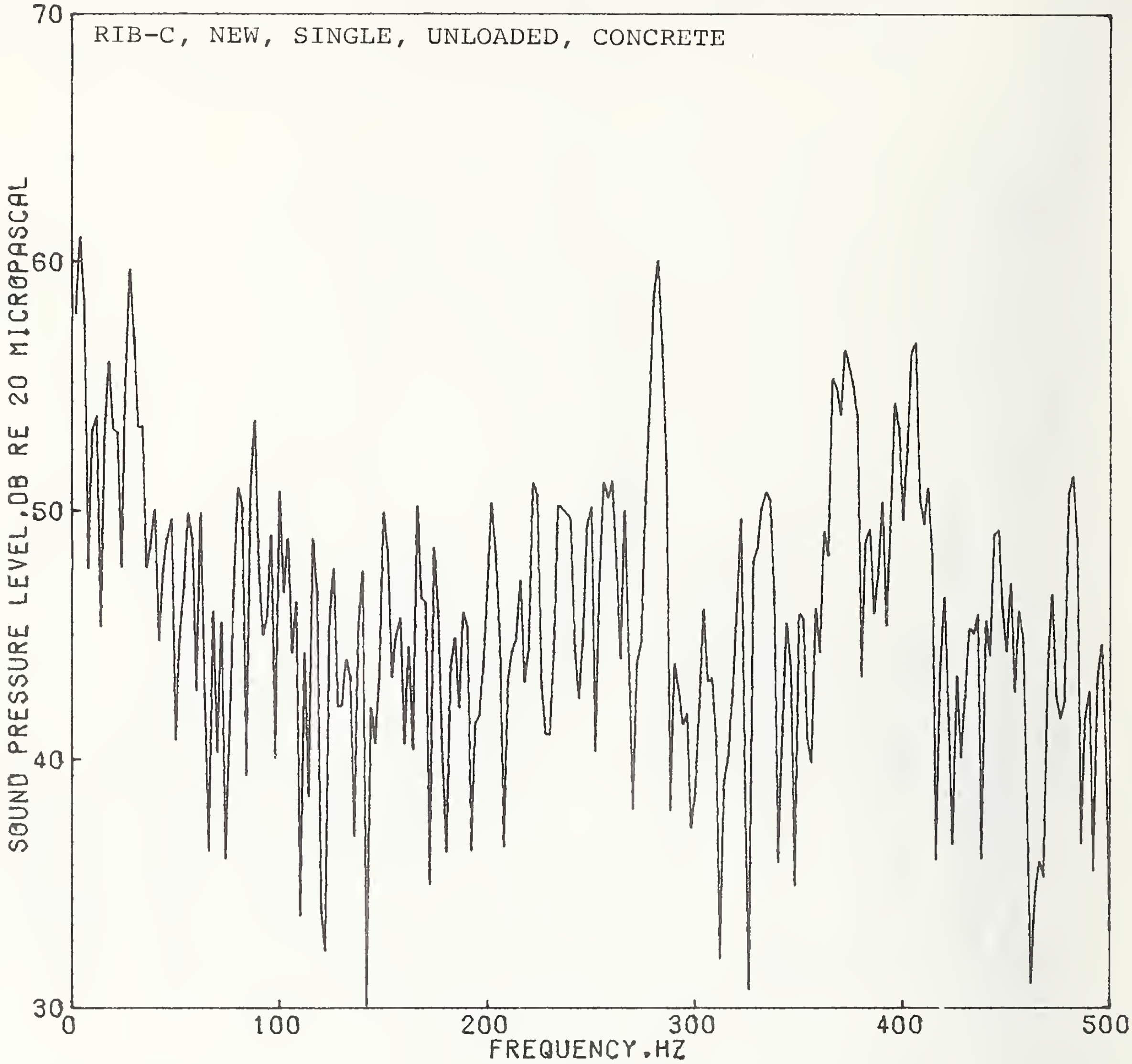


Figure C-11 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, rib-C tires on the drive axle. The 50 mph coastby was on a concrete surface.

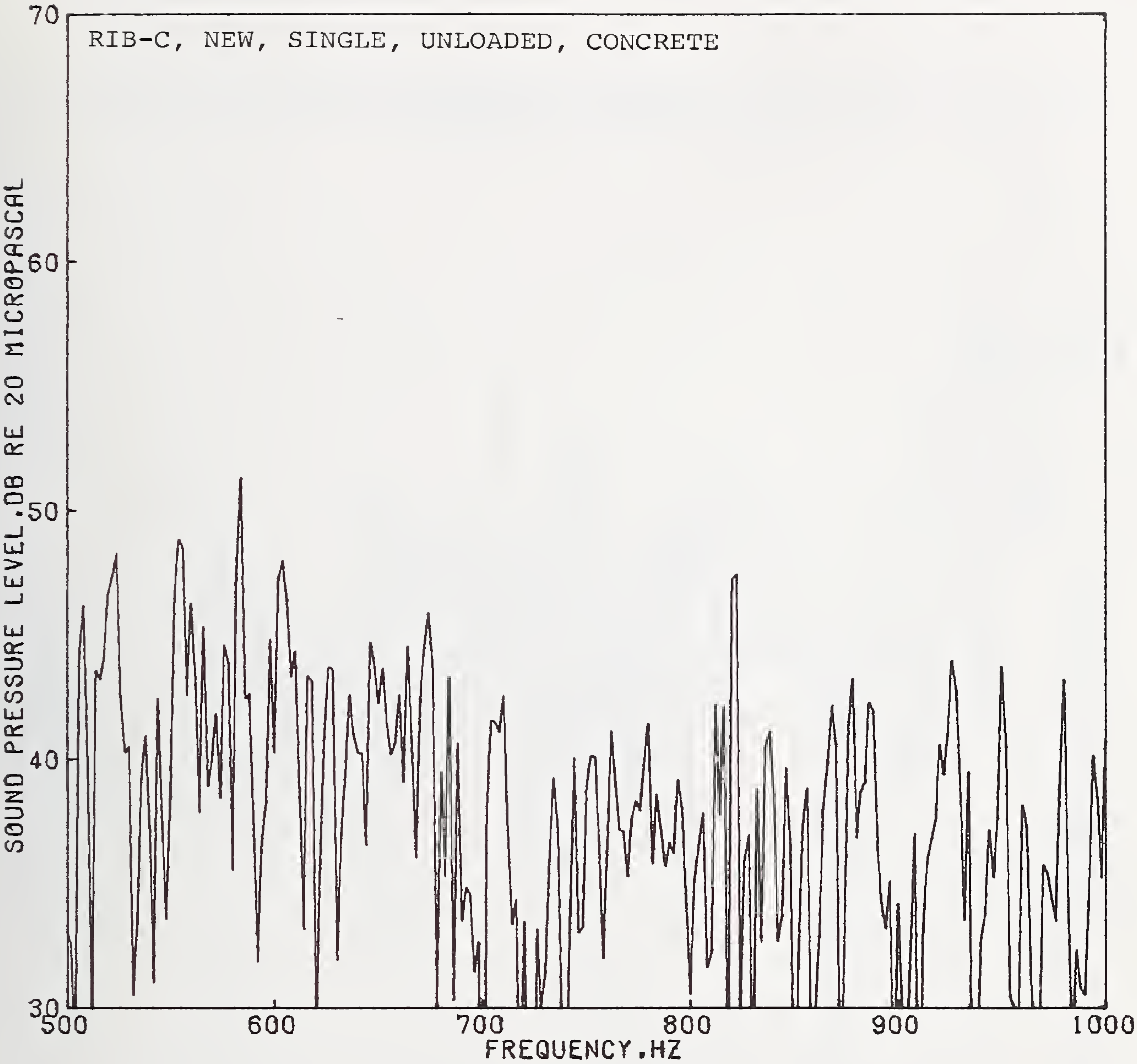


Figure C-12 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, rib-C tires on the drive axle. The 50 mph coastby was on a concrete surface.

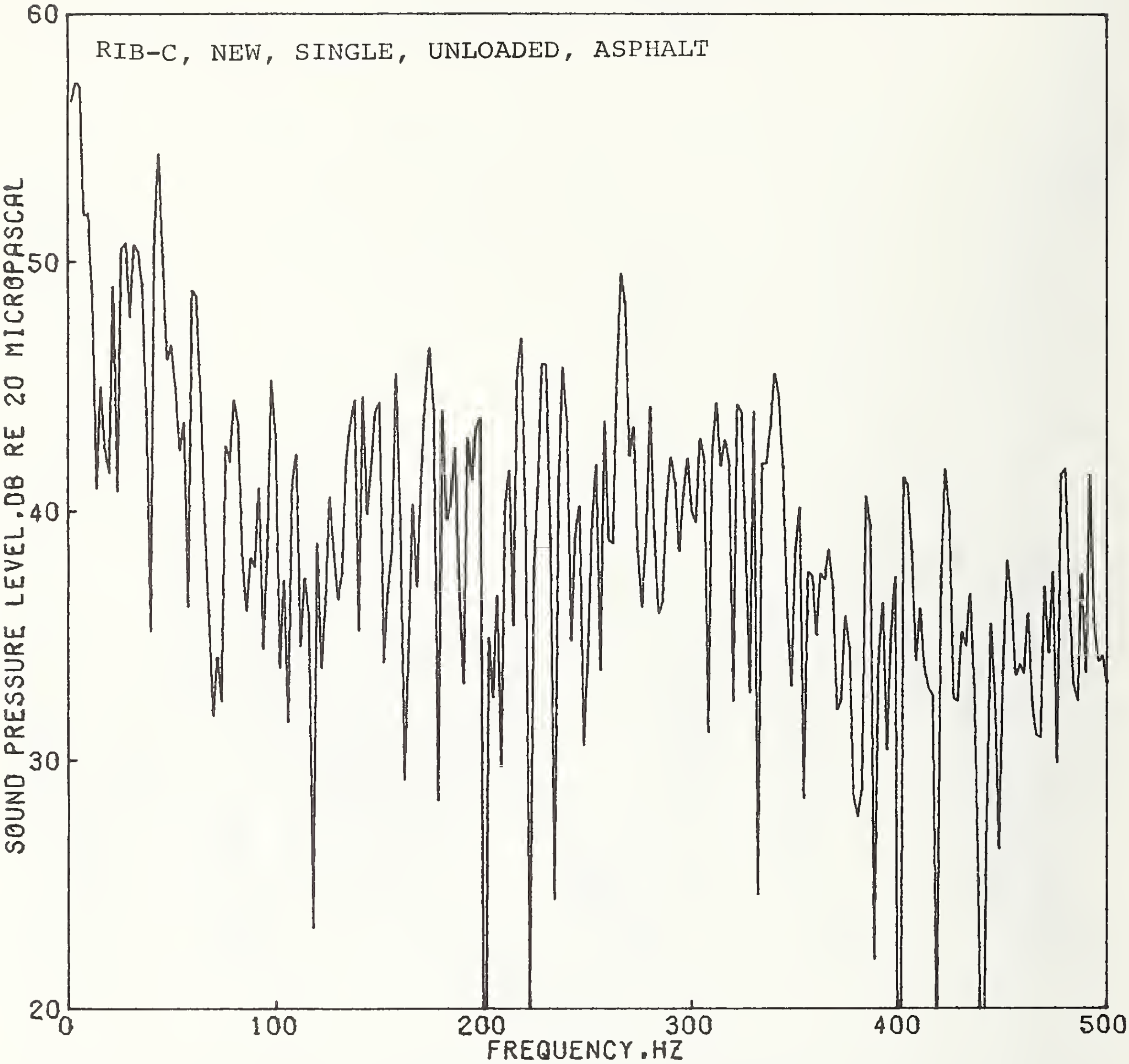


Figure C-13 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, rib-C tires on the drive axle. The 50 mph coastby was on an asphalt surface.

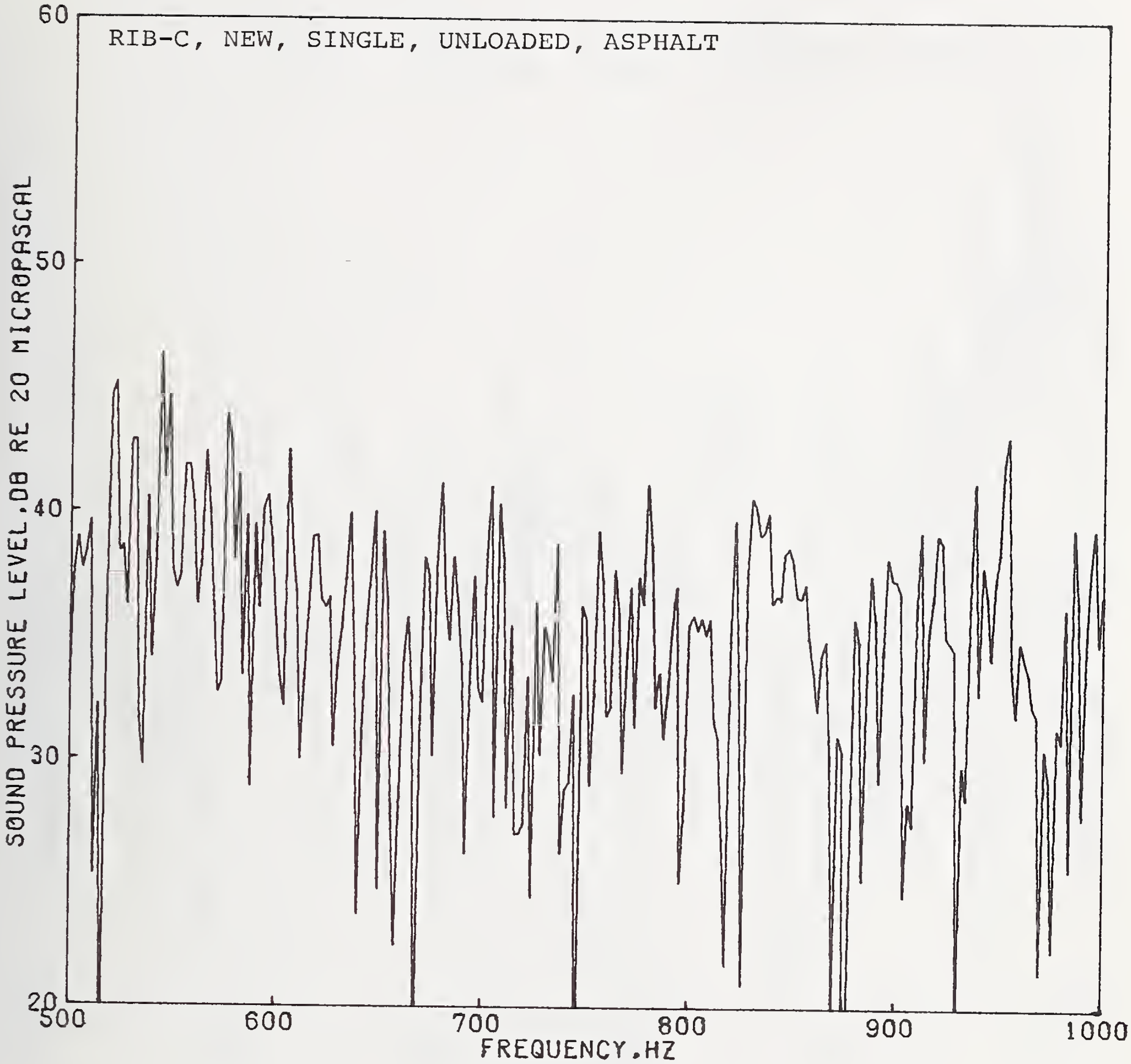


Figure C-14 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, rib-C tires on the drive axle. The 50 mph coastby was on an asphalt surface.

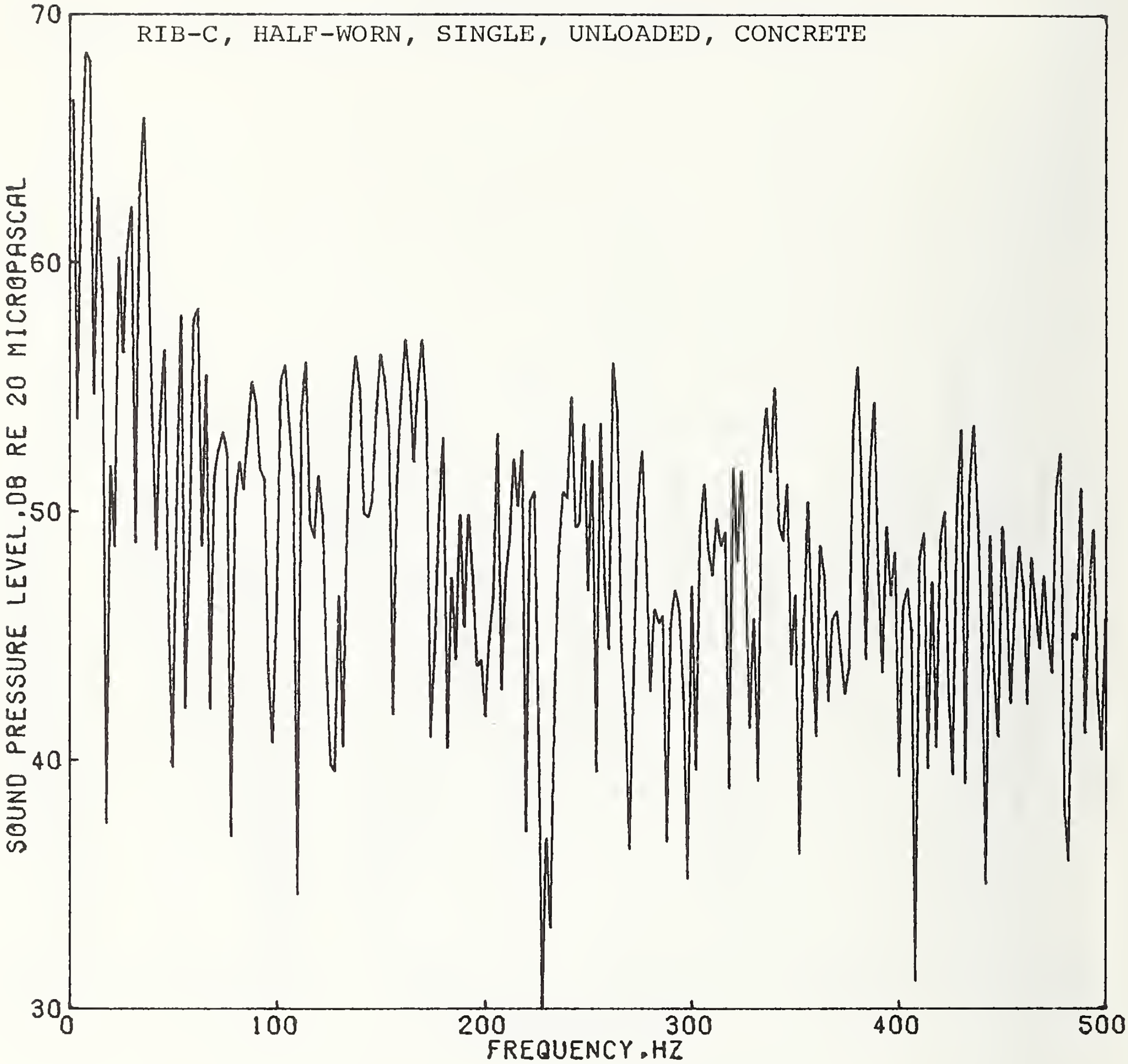


Figure C-15 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and half-worn, single, rib-C tires on the drive axle. The 50 mph coastby was on a concrete surface.

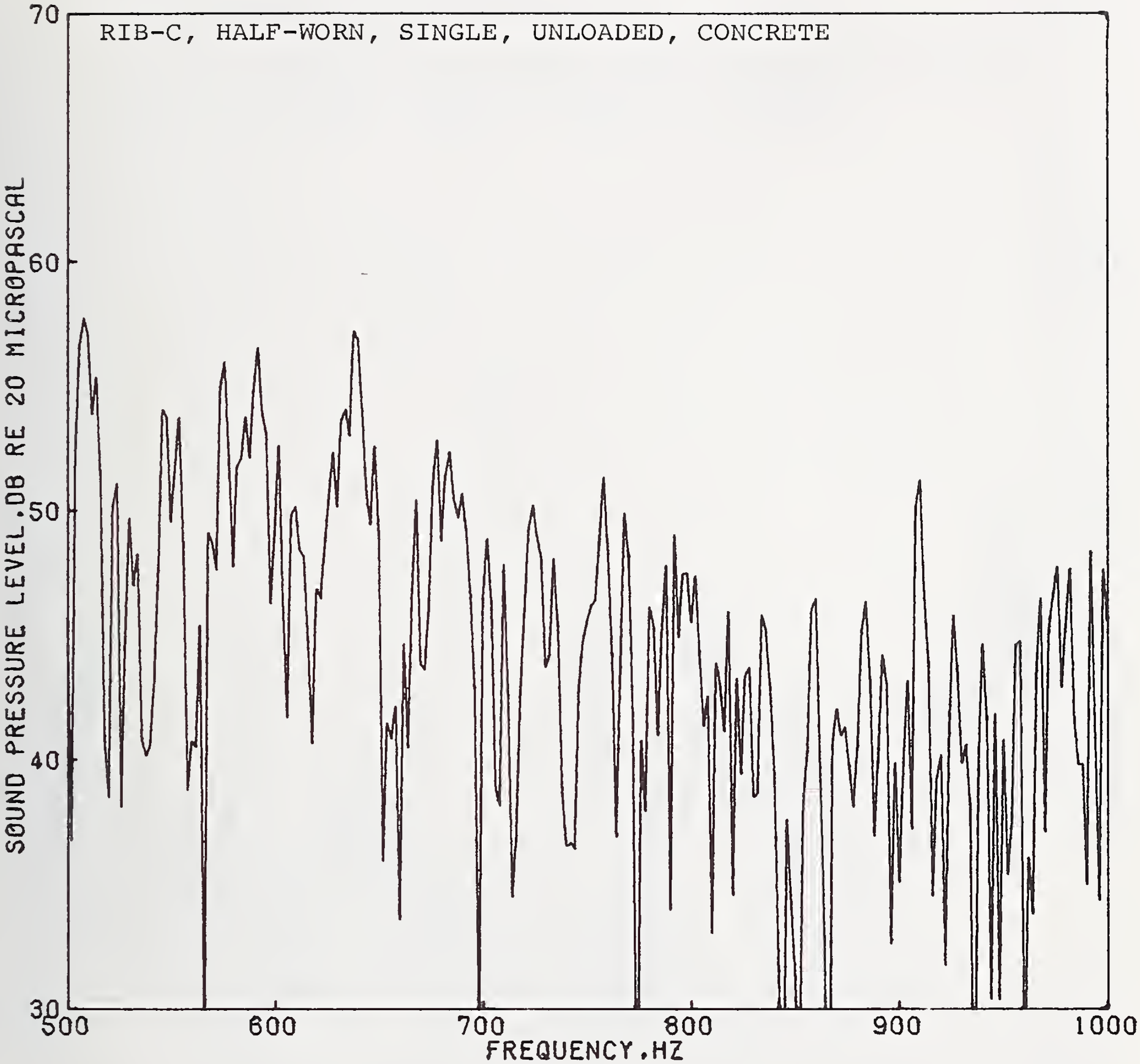


Figure C-16 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and half-worn, single, rib-C tires on the drive axle. The 50 mph coastby was on a concrete surface.

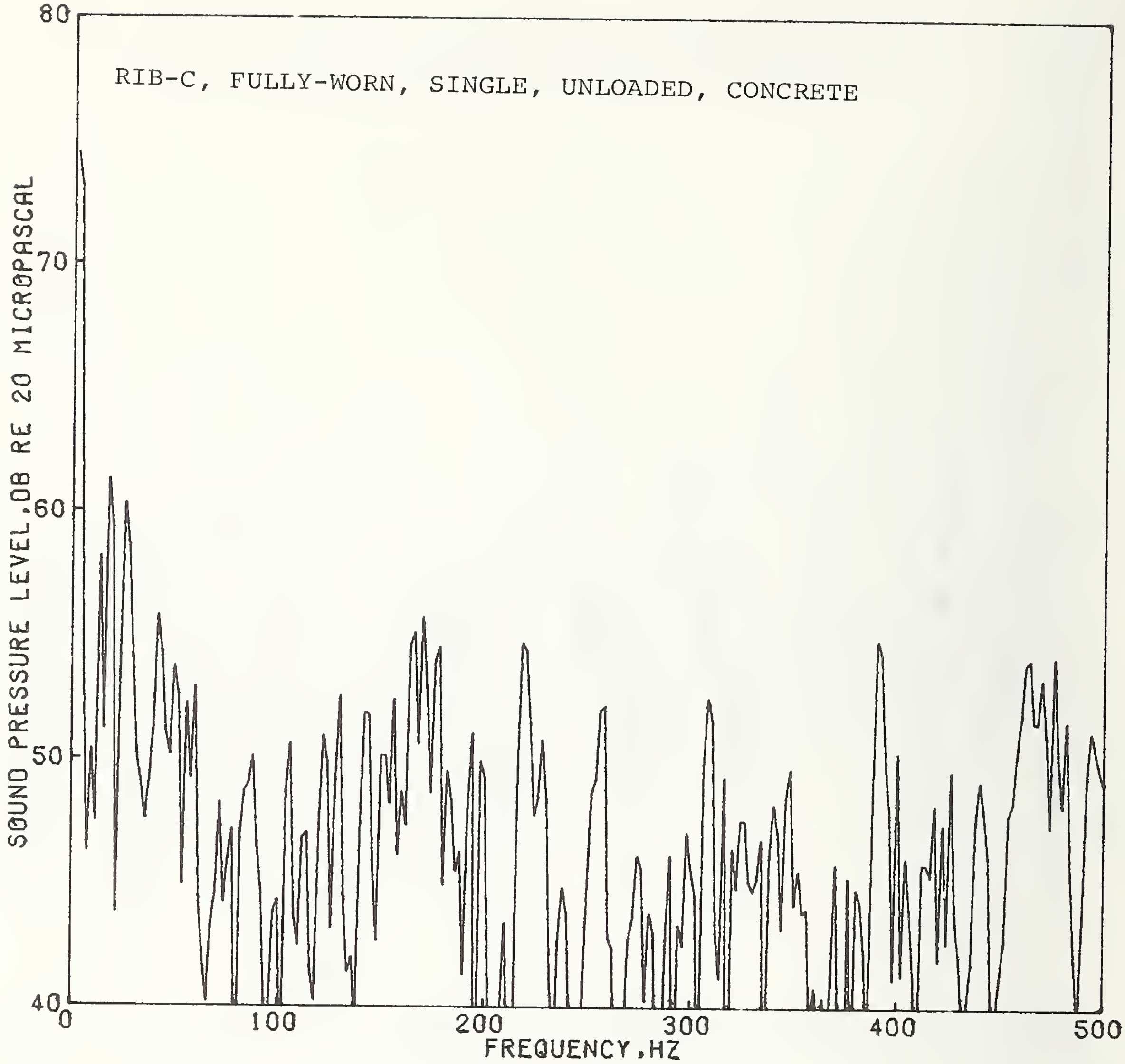


Figure C-17 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and fully-worn, single, rib-C tires on the drive axle. The 50 mph coastby was on a concrete surface.

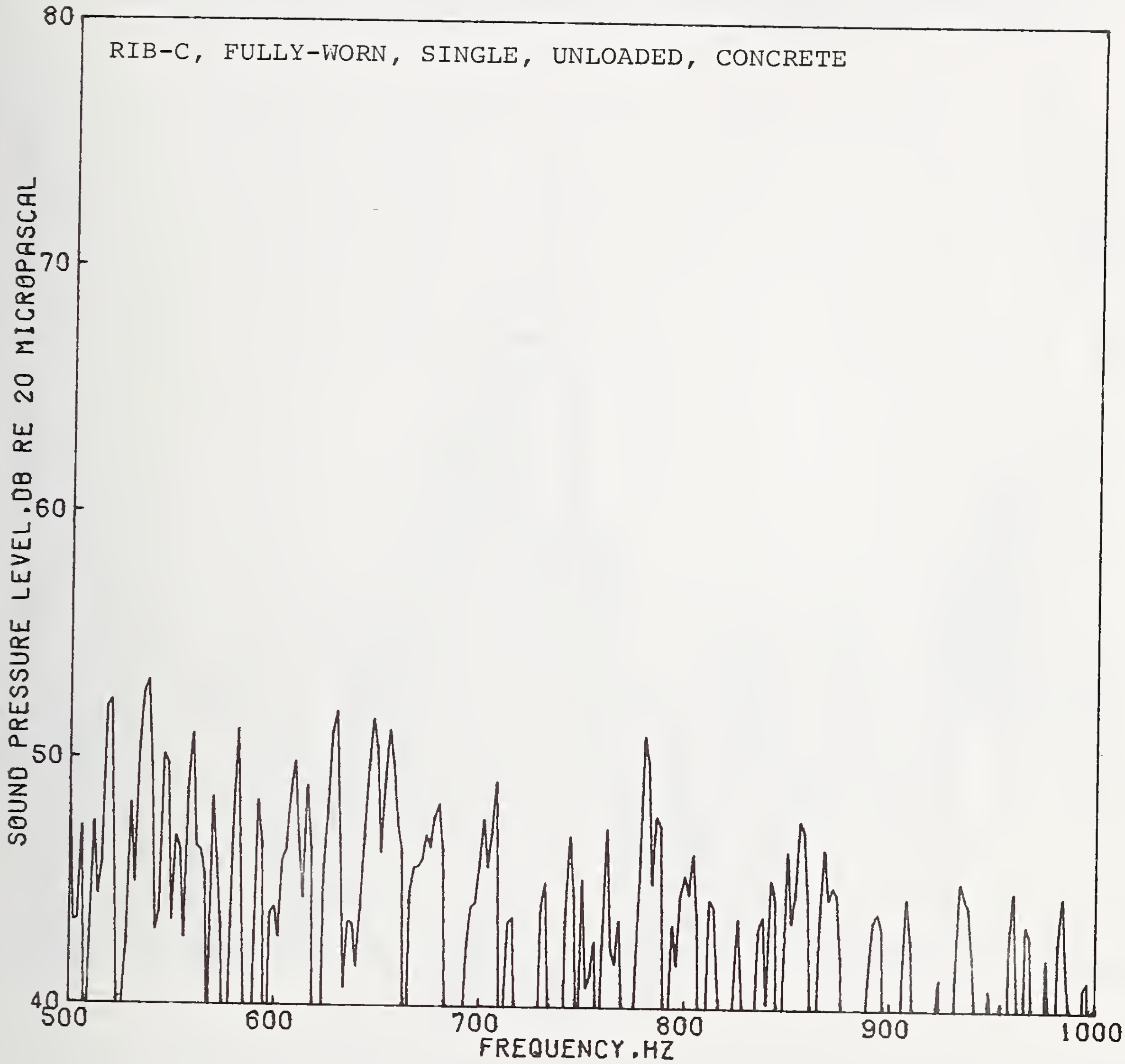


Figure C-18 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and fully-worn, single, rib-C tires on the drive axle. The 50 mph coastby was on a concrete surface.

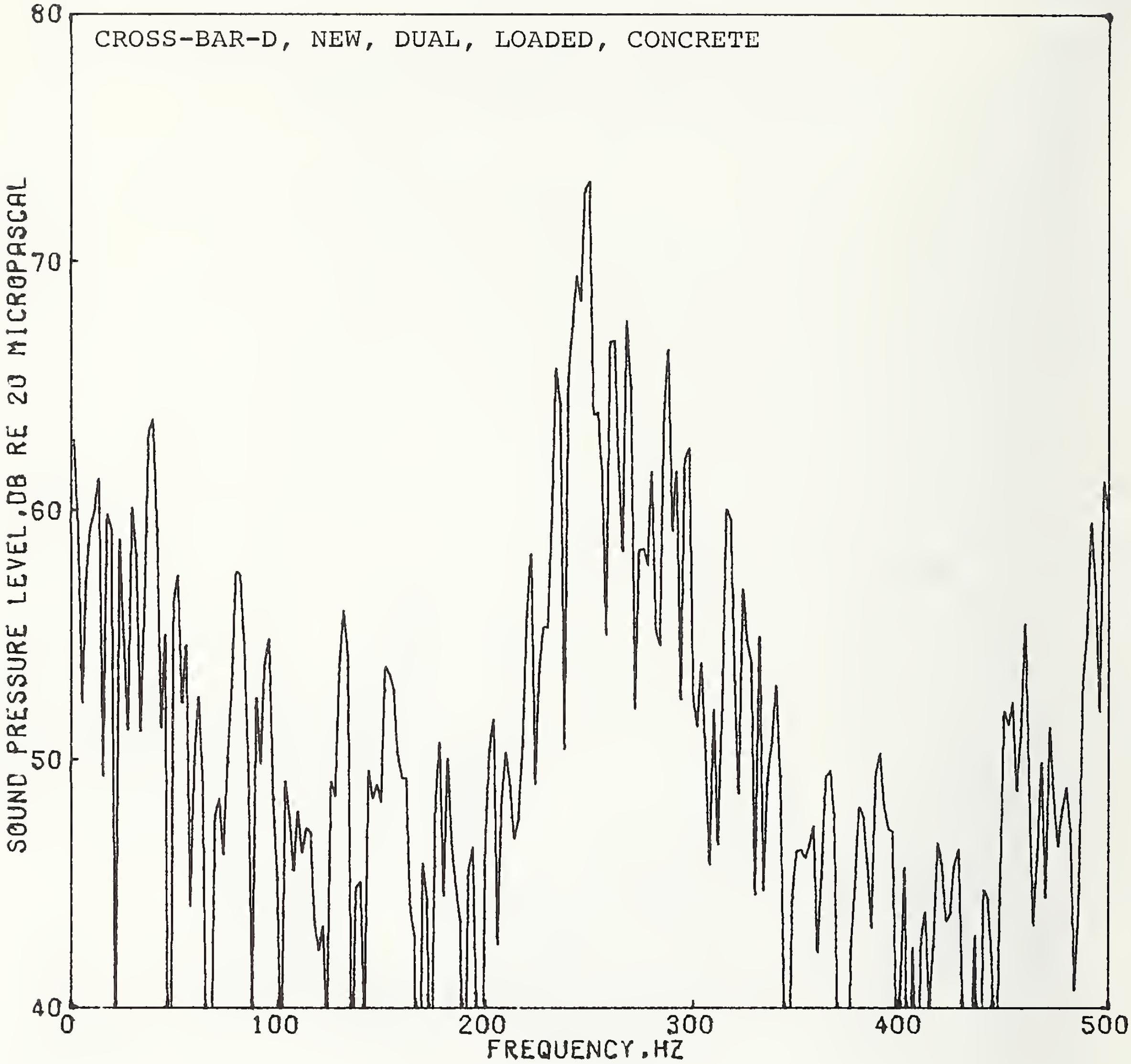


Figure C-19 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, cross-bar-D tires on the drive axle. The 50 mph coastby was on a concrete surface.

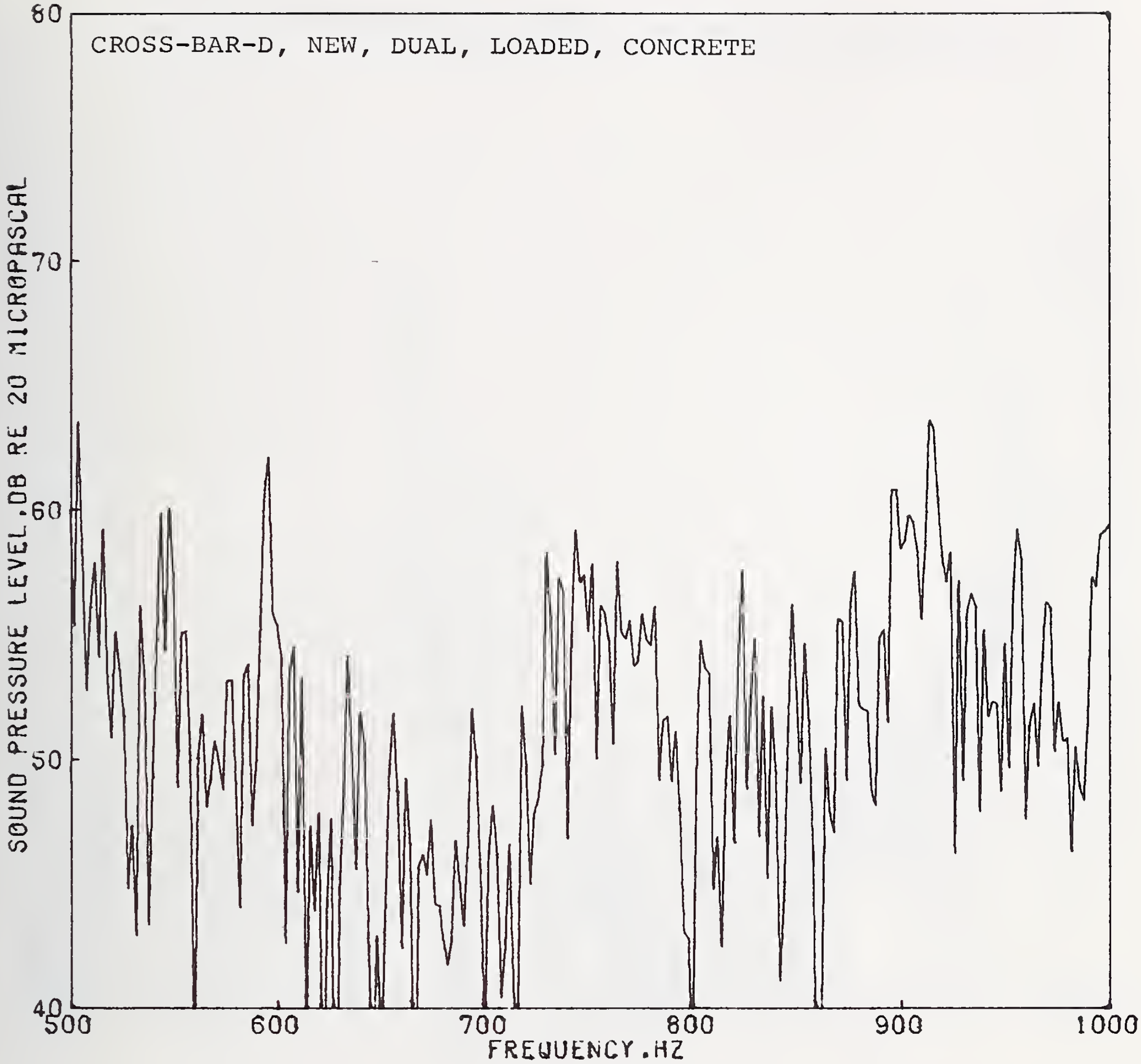


Figure C-20 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, cross-bar-D tires on the drive axle. The 50 mph coastby was on a concrete surface.

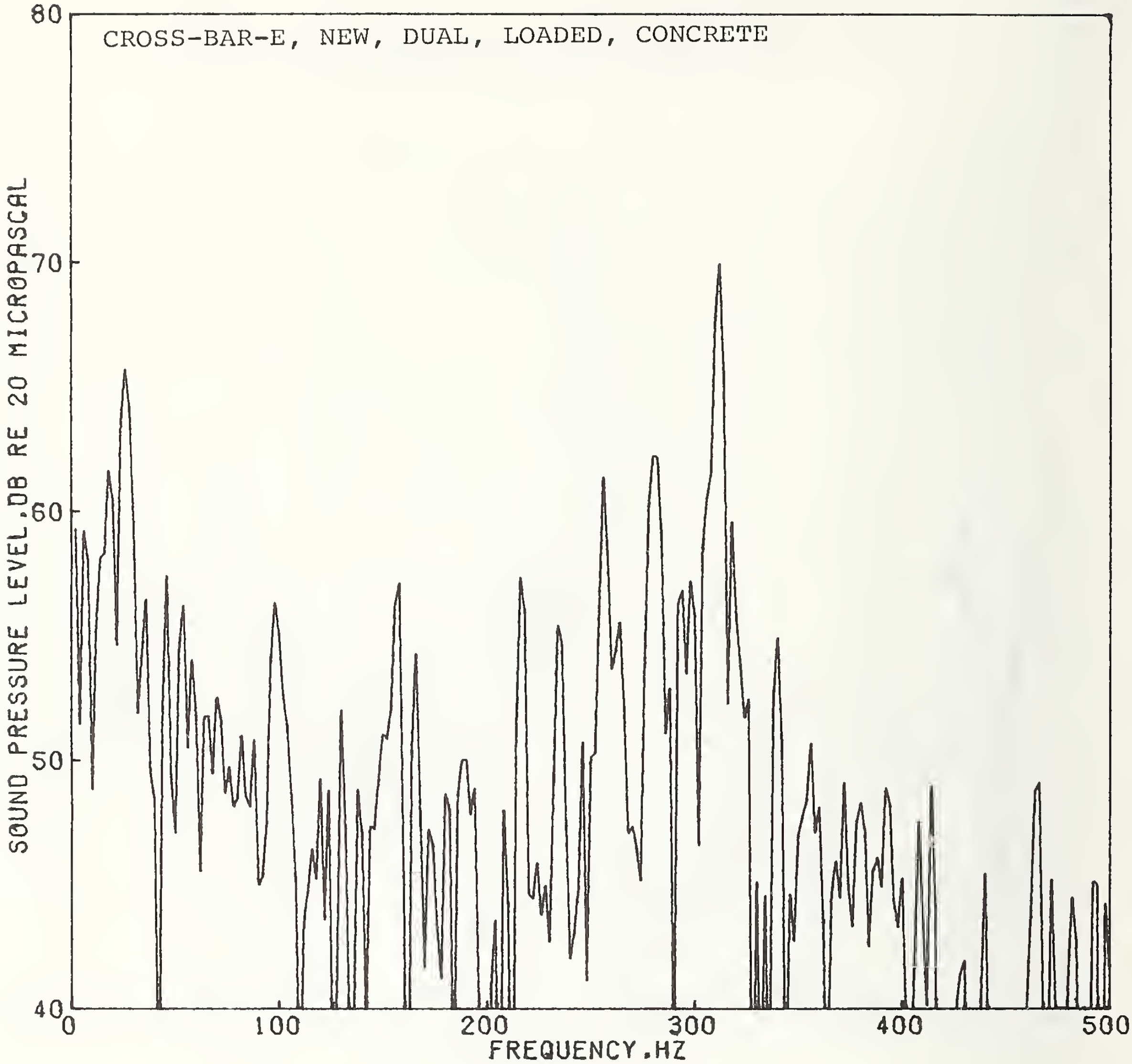


Figure C-21 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, cross-bar-E tires on the drive axle. The 50 mph coastby was on a concrete surface.

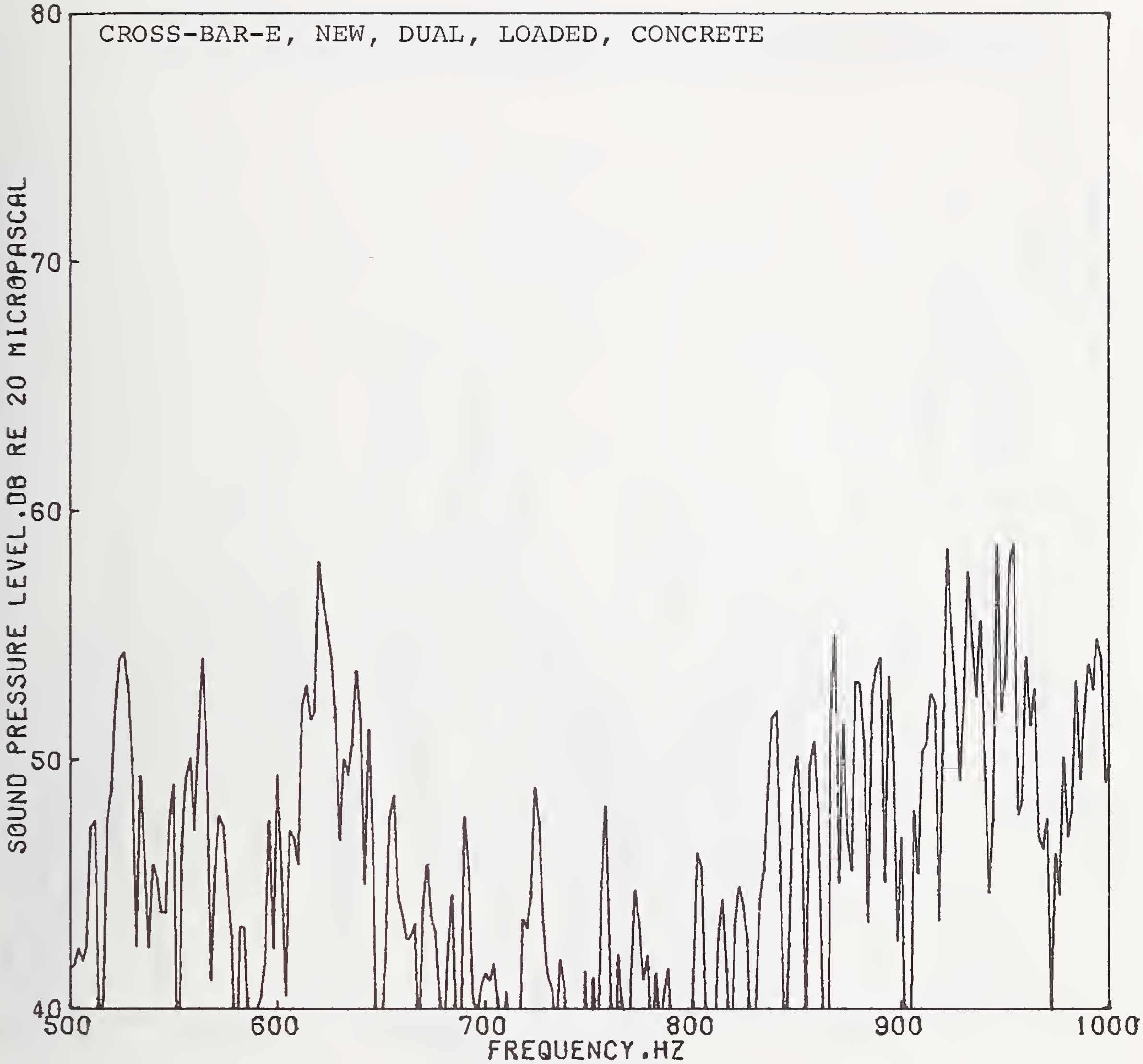


Figure C-22 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, cross-bar-E tires on the drive axle. The 50 mph coastby was on a concrete surface.

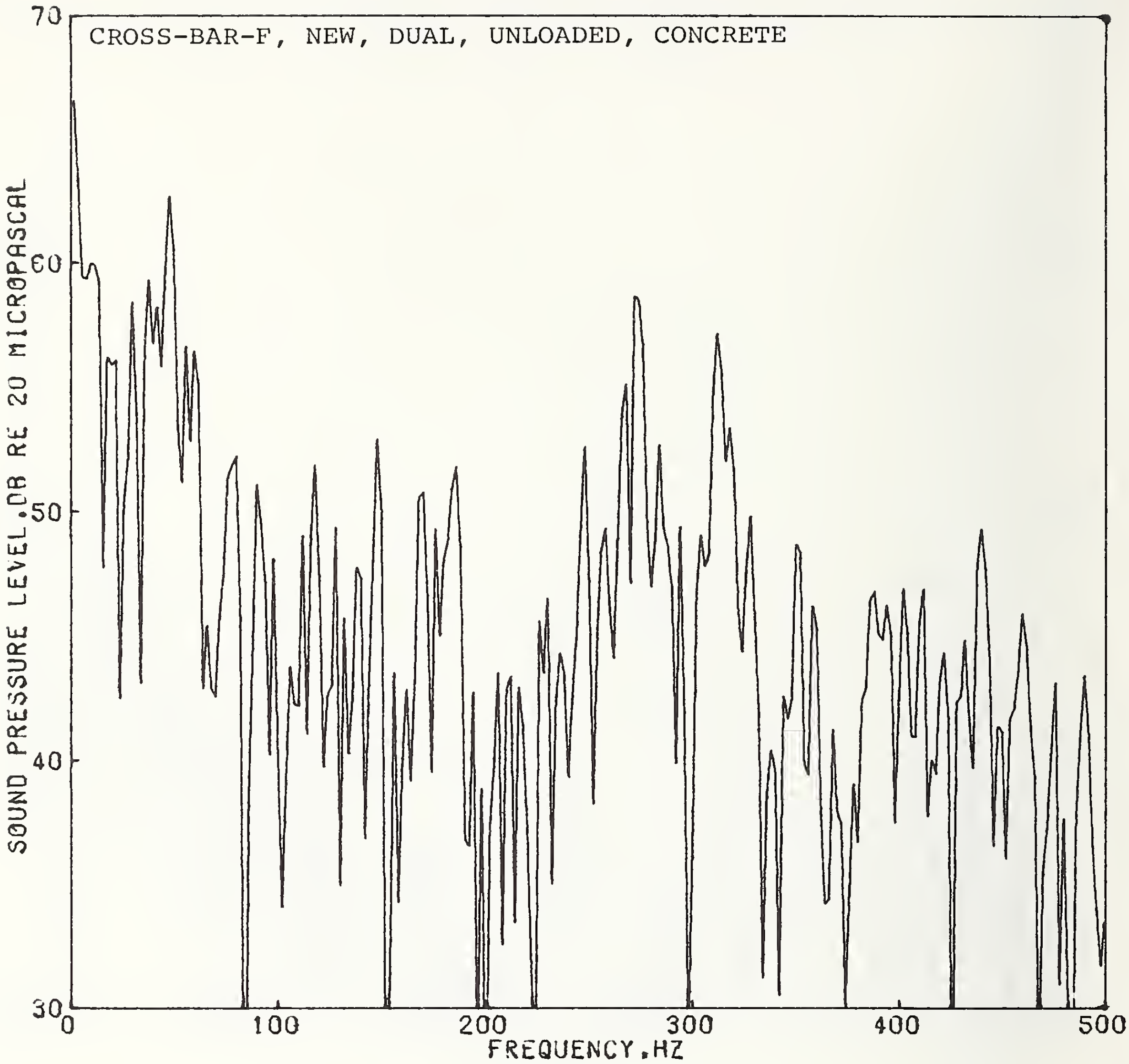


Figure C-23 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, cross-bar-F tires on the drive axle. The 50 mph coastby was on a concrete surface.

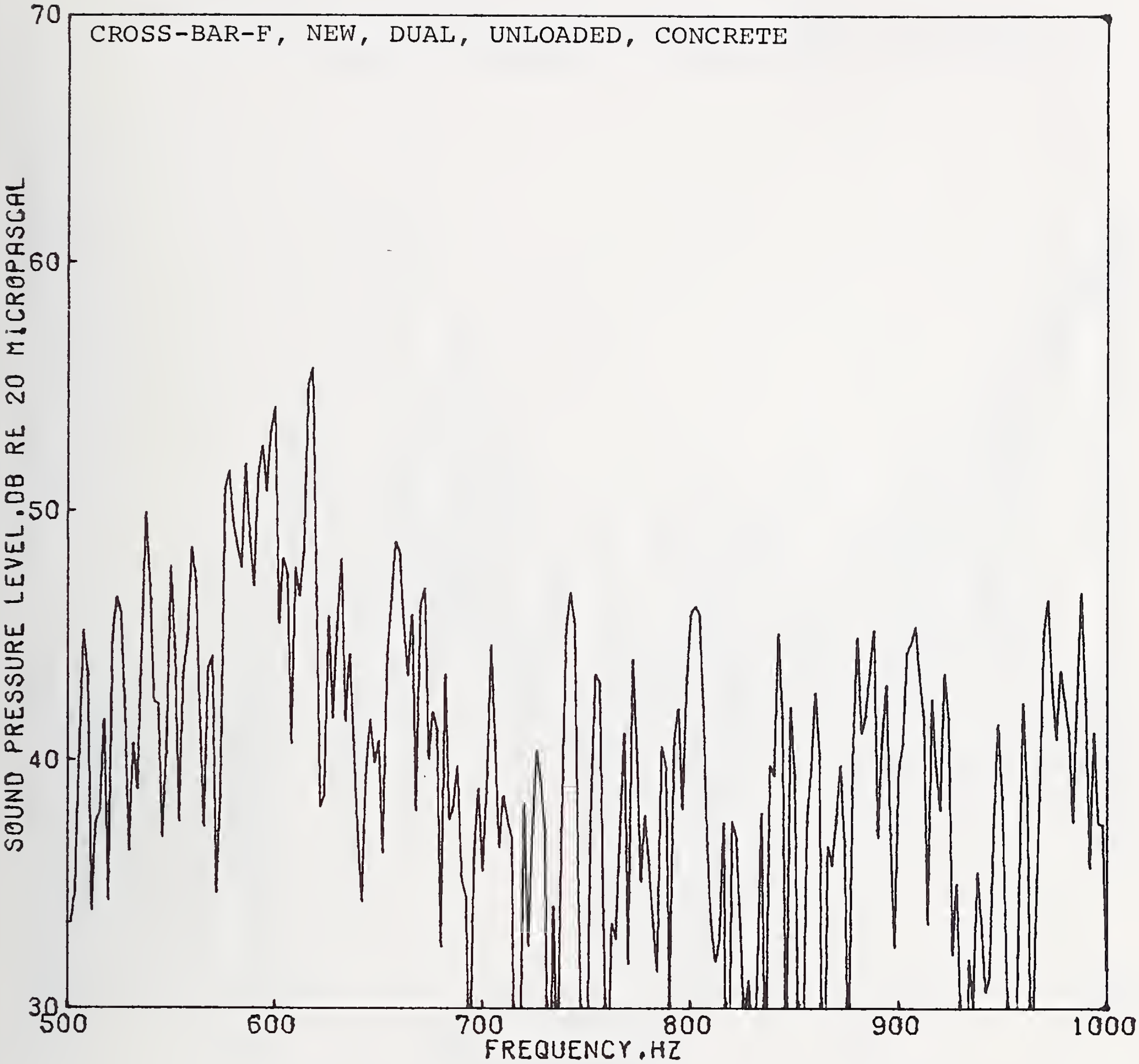


Figure C-24 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, cross-bar-F tires on the drive axle. The 50 mph coastby was on a concrete surface.

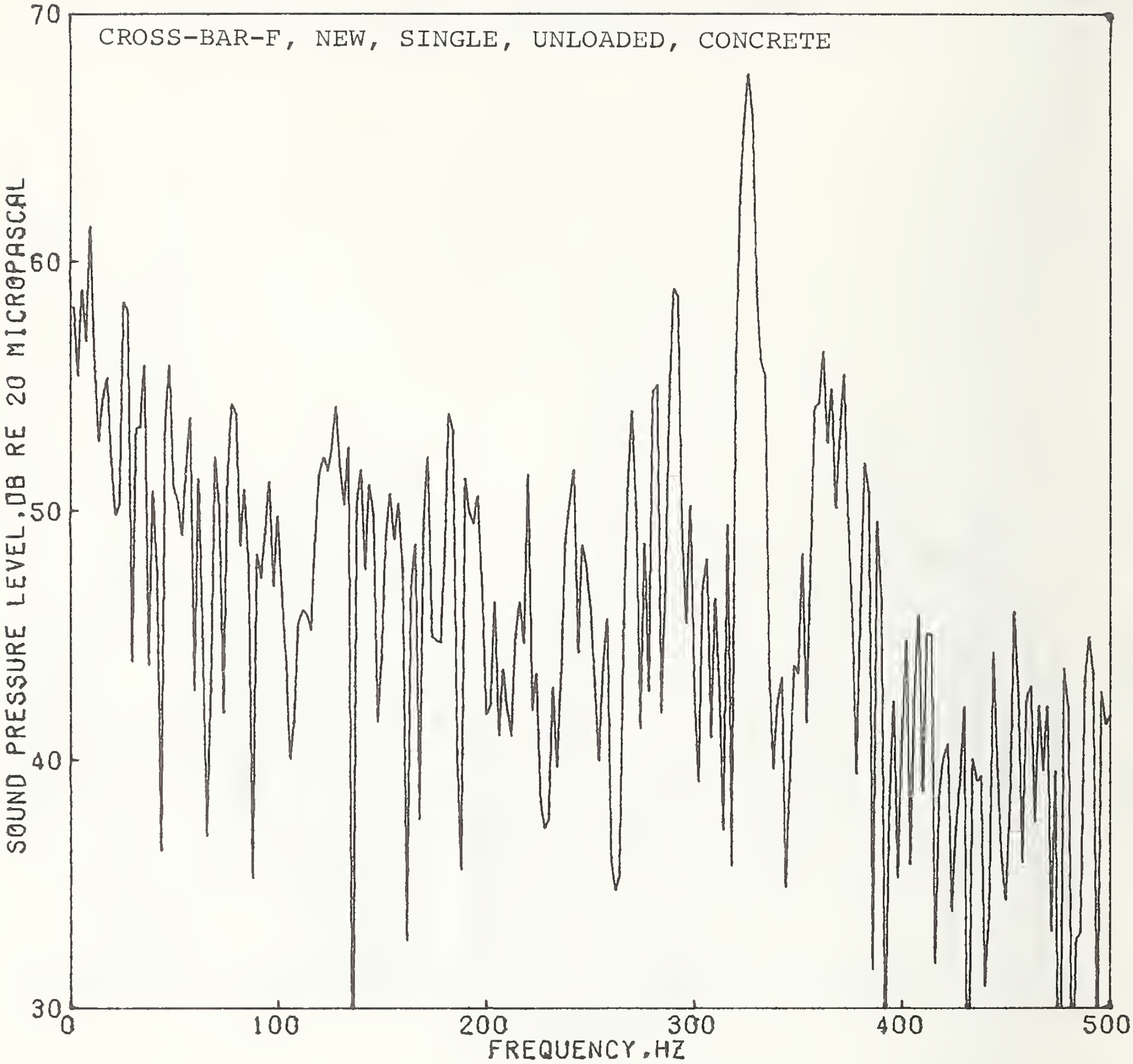


Figure C-25 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, cross-bar-F tires on the drive axle. The 50 mph coastby was on a concrete surface.

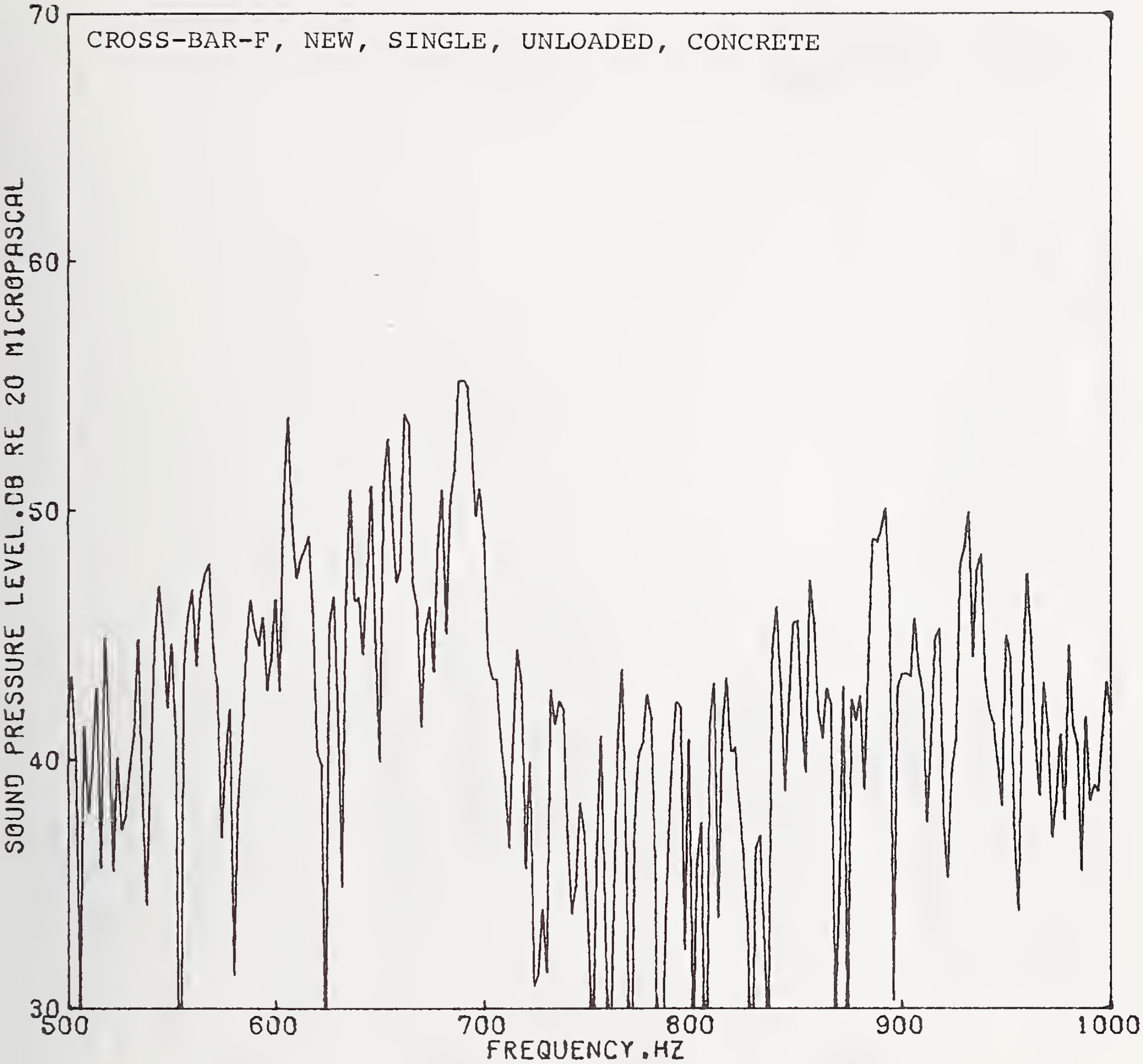


Figure C-26 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, cross-bar-F tires on the drive axle. The 50 mph coastby was on a concrete surface.

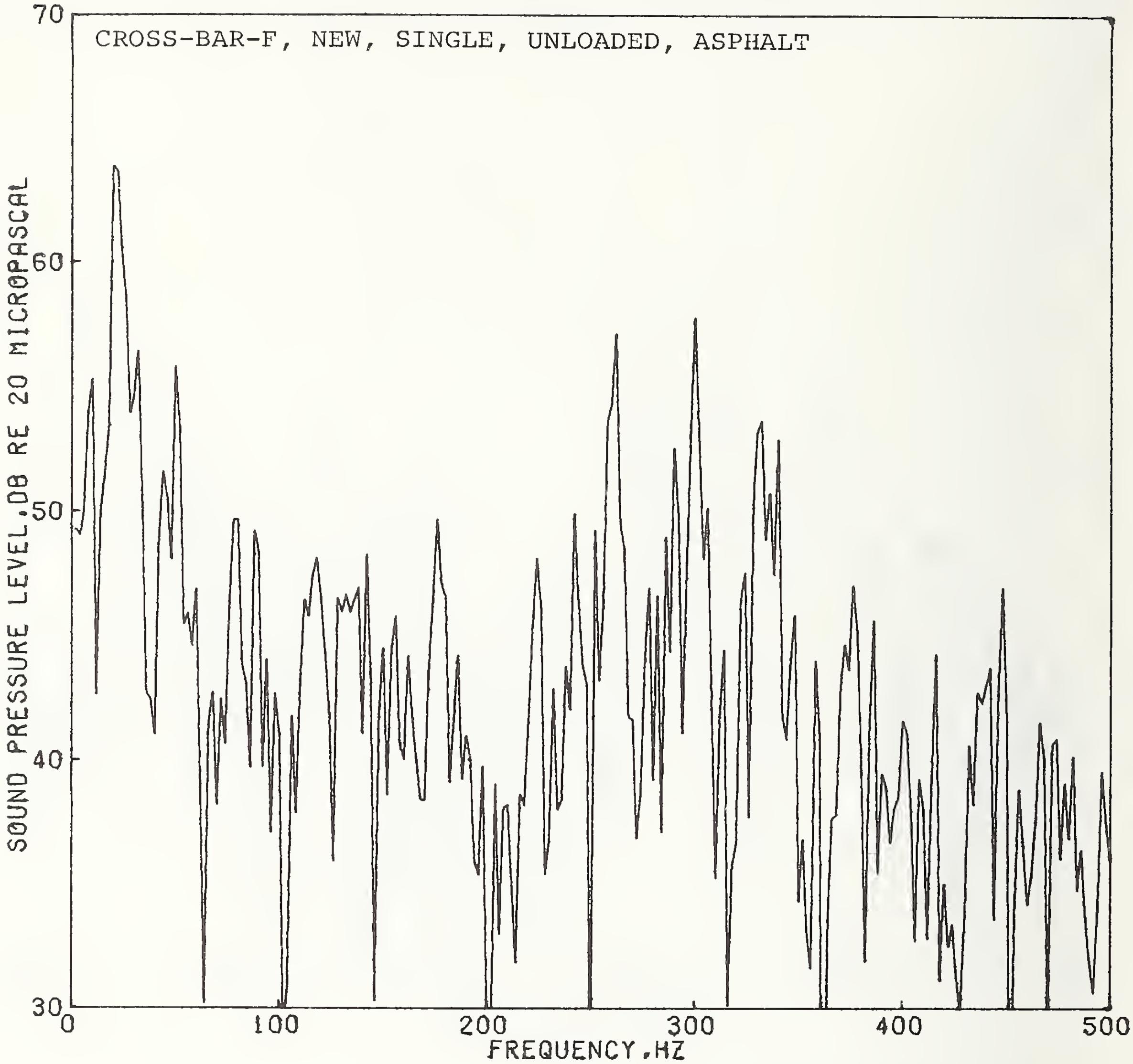


Figure C-27 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, cross-bar-F tires on the drive axle. The 50 mph coastby was on an asphalt surface.

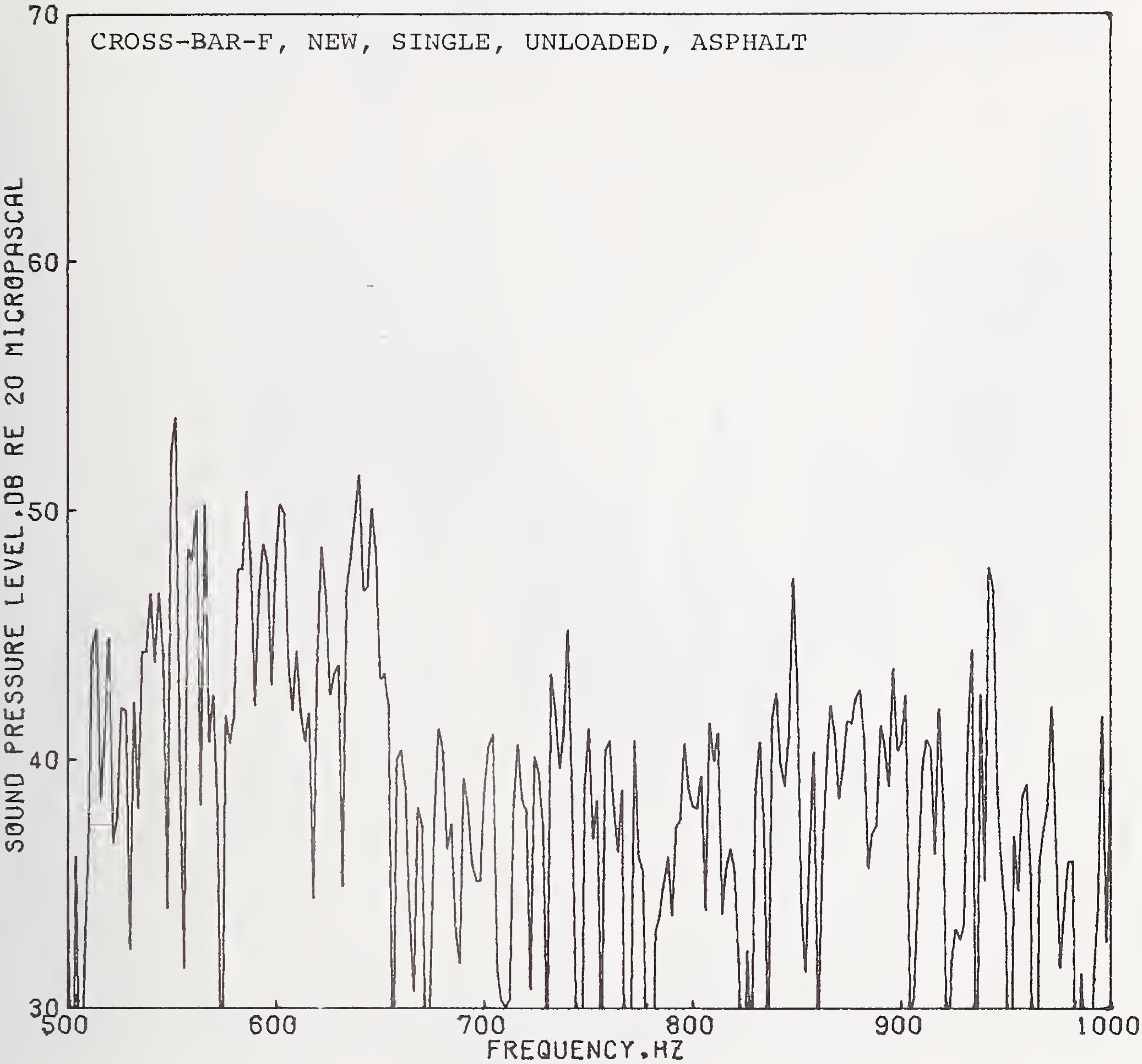


Figure C-28 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, cross-bar-F tires on the drive axle. The 50 mph coastby was on an asphalt surface.

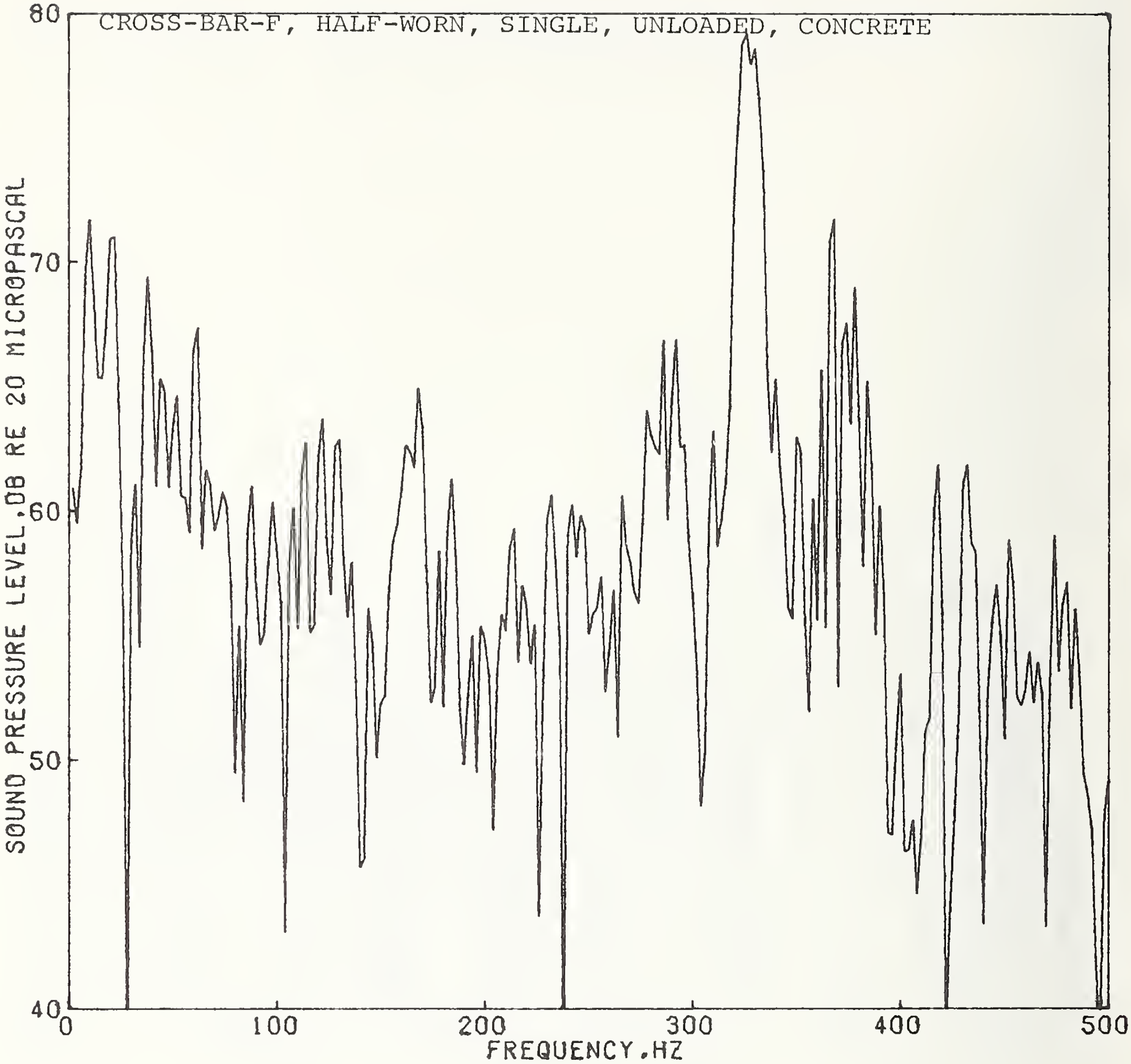


Figure C-29 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and half-worn, single, cross-bar-F tires on the drive axle. The 50 mph coastby was on a concrete surface.

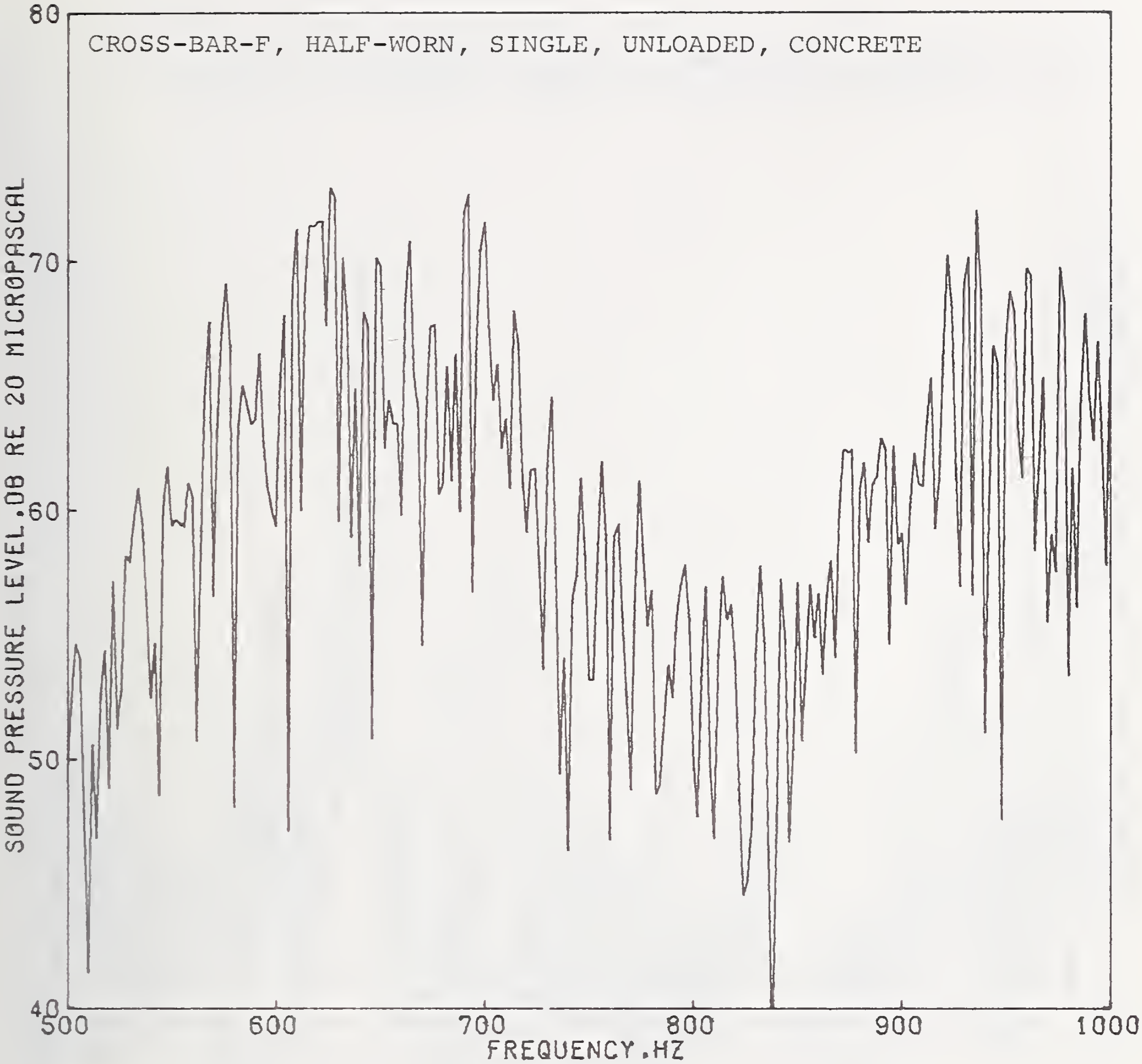


Figure C-30 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and half-worn, single, cross-bar-F tires on the drive axle. The 50 mph coastby was on a concrete surface.

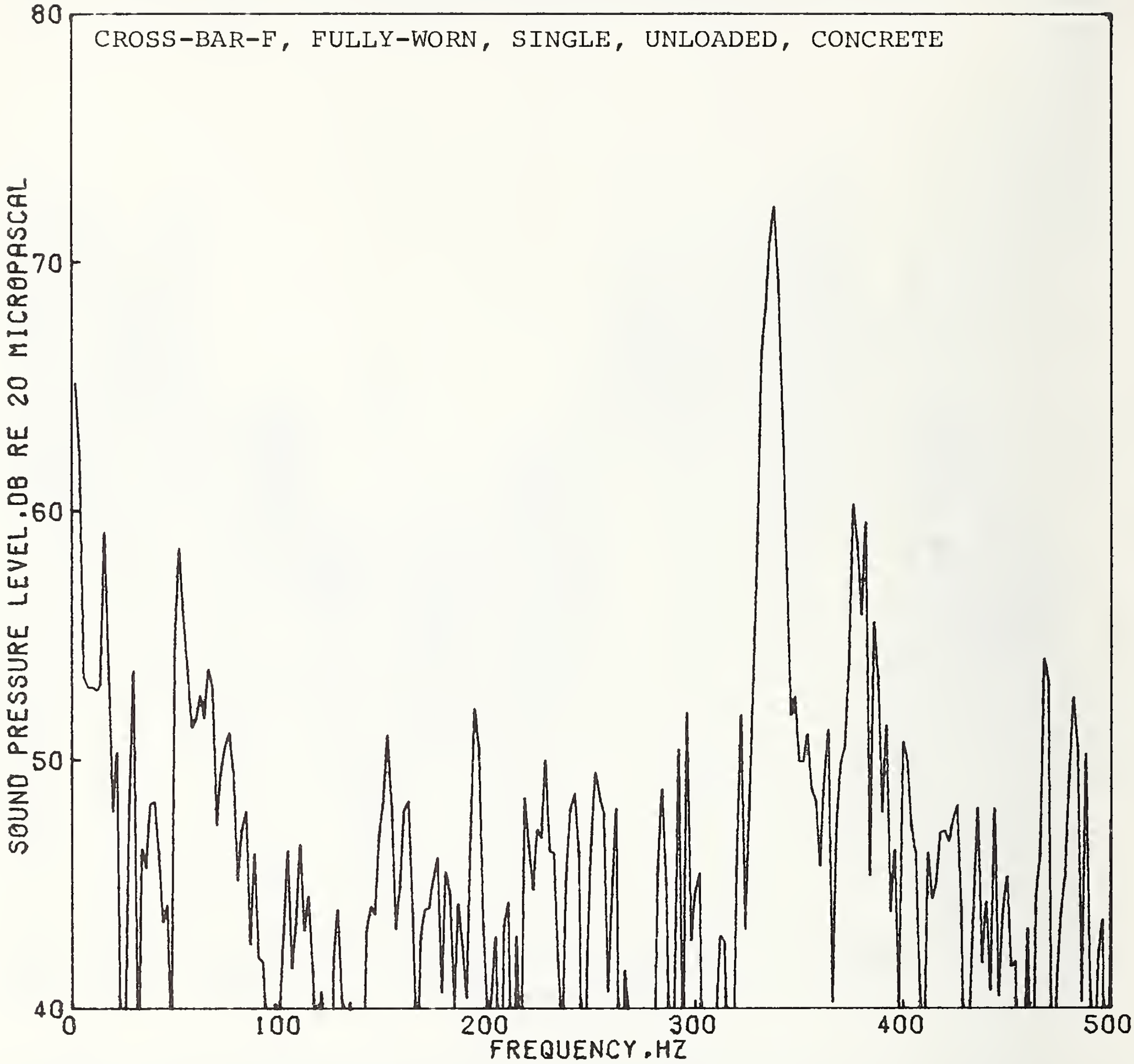


Figure C-31 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and fully-worn, single, cross-bar-F tires on the drive axle. The 50 mph coastby was on a concrete surface.

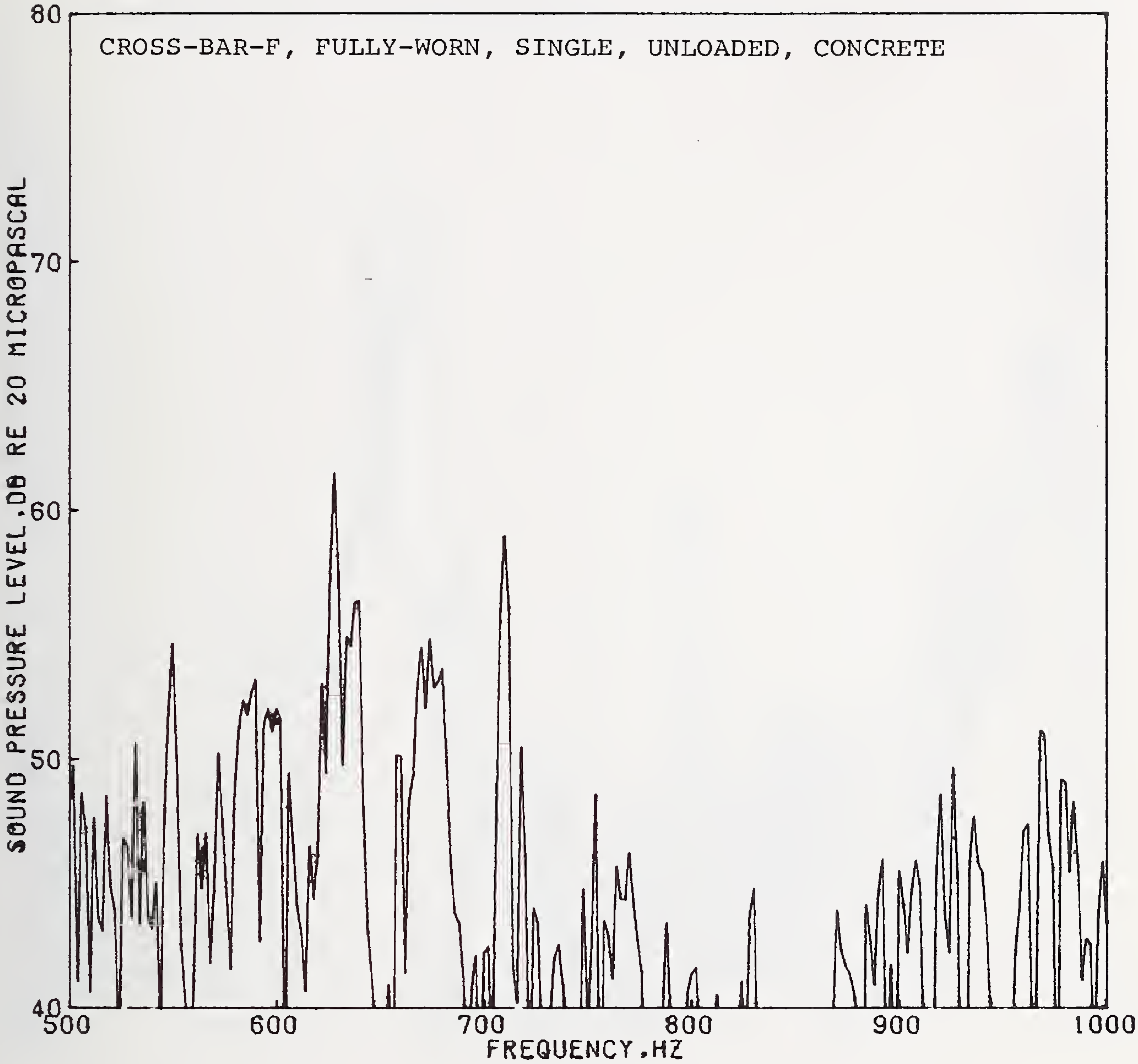


Figure C-32 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and fully-worn, single, cross-bar-F tires on the drive axle. The 50 mph coastby was on a concrete surface.

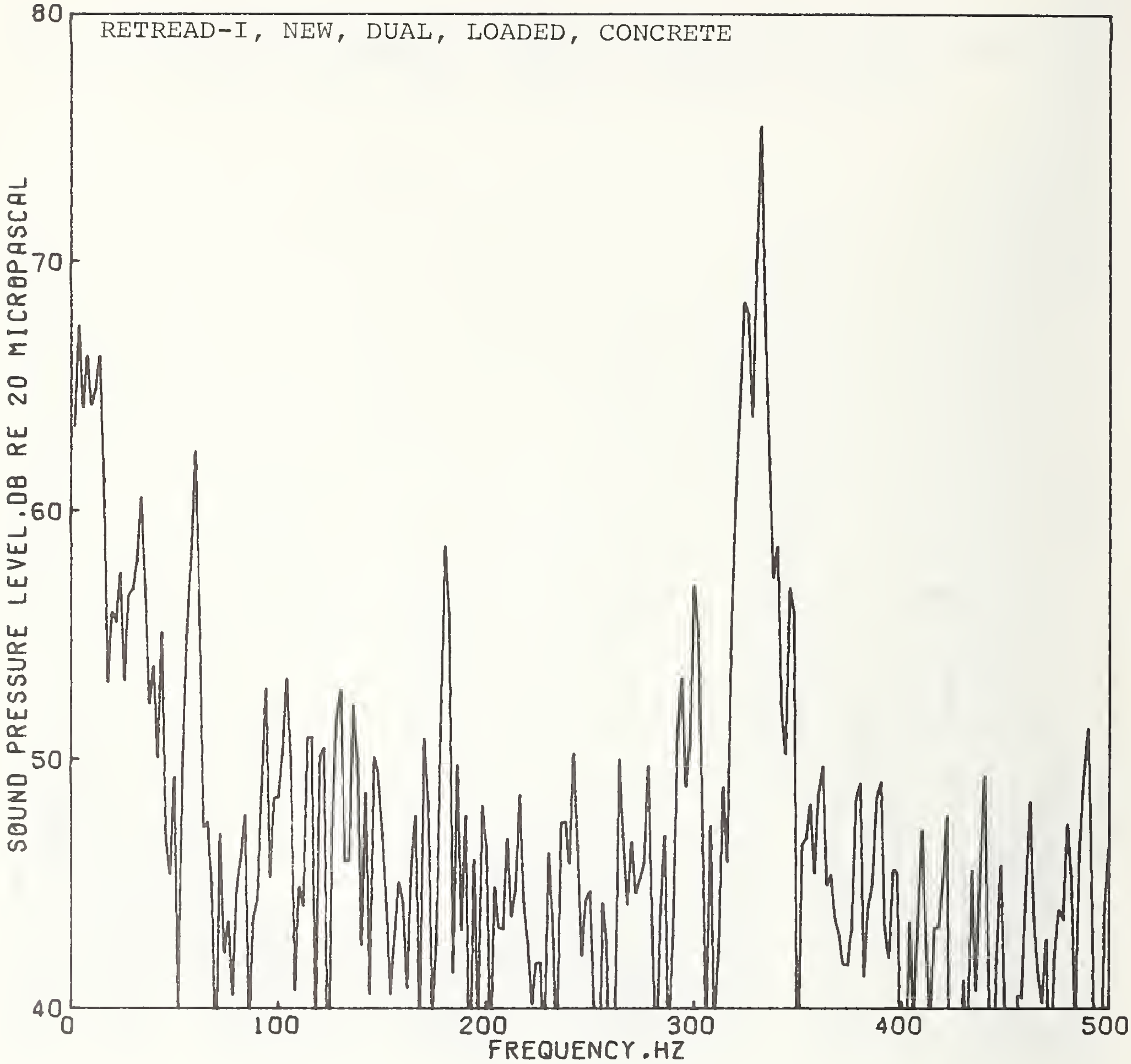


Figure C-33 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, retread-I tires on the drive axle. The 50 mph coastby was on a concrete surface.

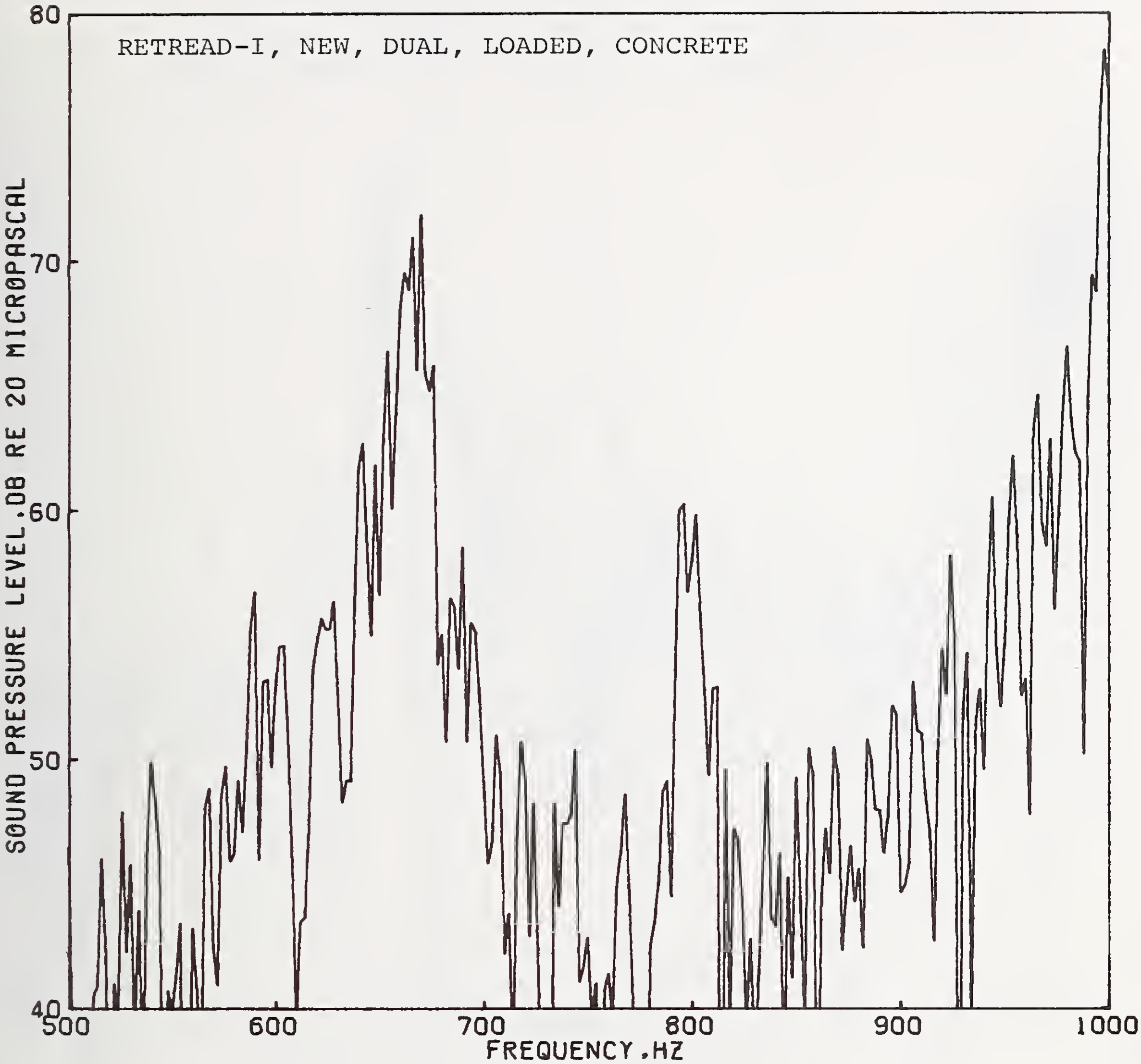


Figure C-34 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The loaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, retread-I tires on the drive axle. The 50 mph coastby was on a concrete surface.

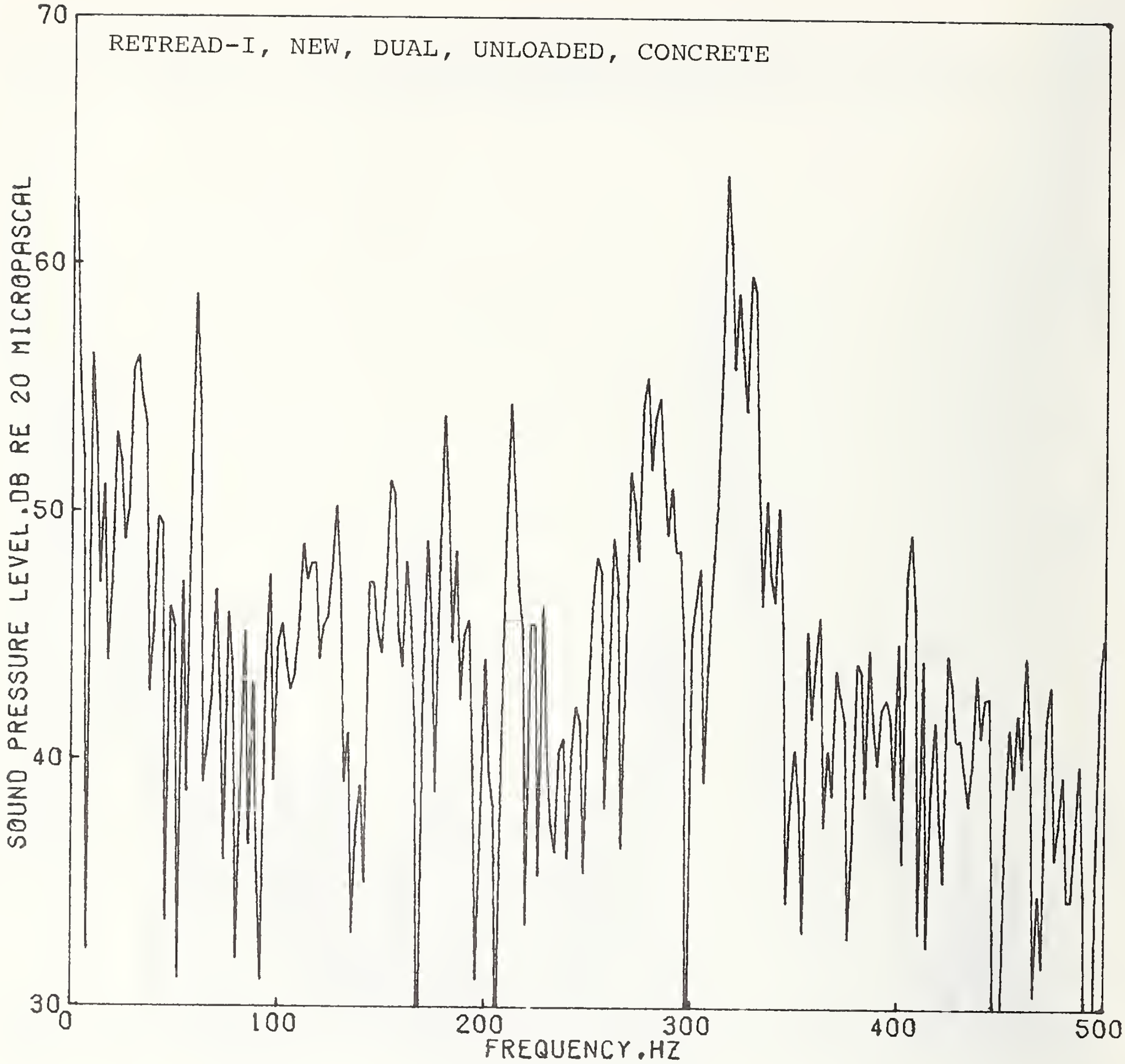


Figure C-35 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, retread-I tires on the drive axle. The 50 mph coastby was on a concrete surface.

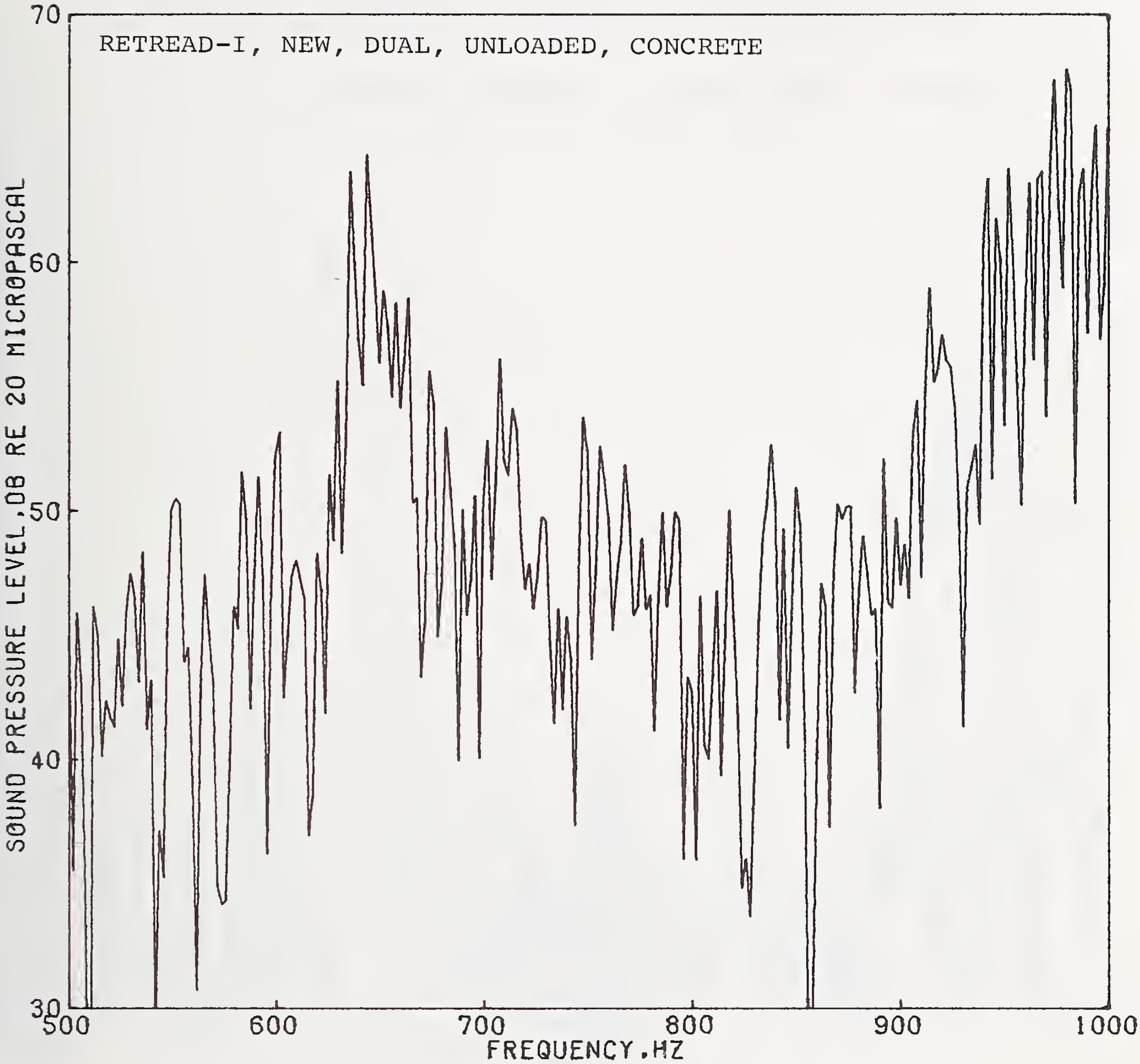


Figure C-36 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, dual, retread-I tires on the drive axle. The 50 mph coastby was on a concrete surface.

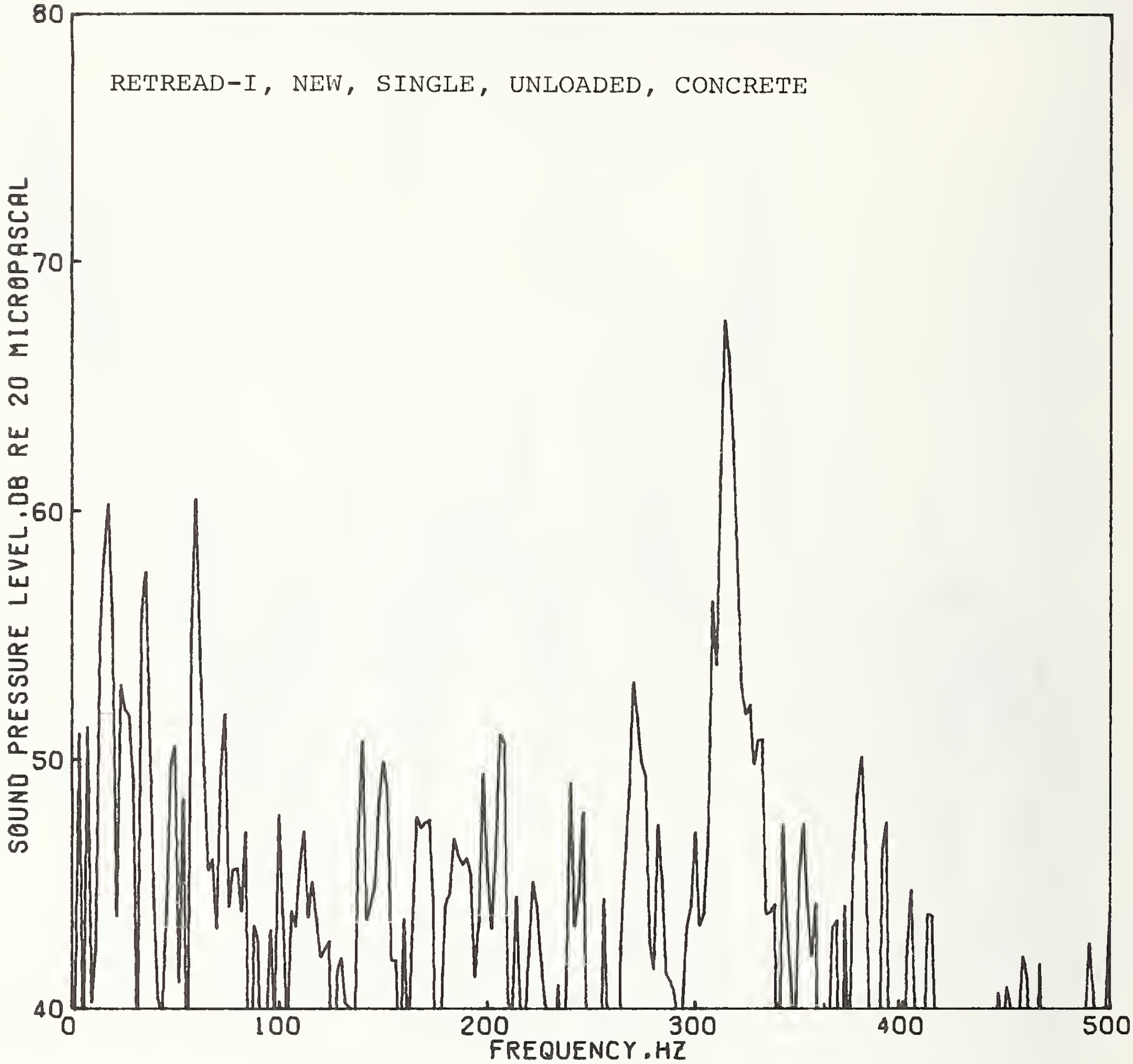


Figure C-37 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, retread-I tires on the drive axle. The 50 mph coastby was on a concrete surface.

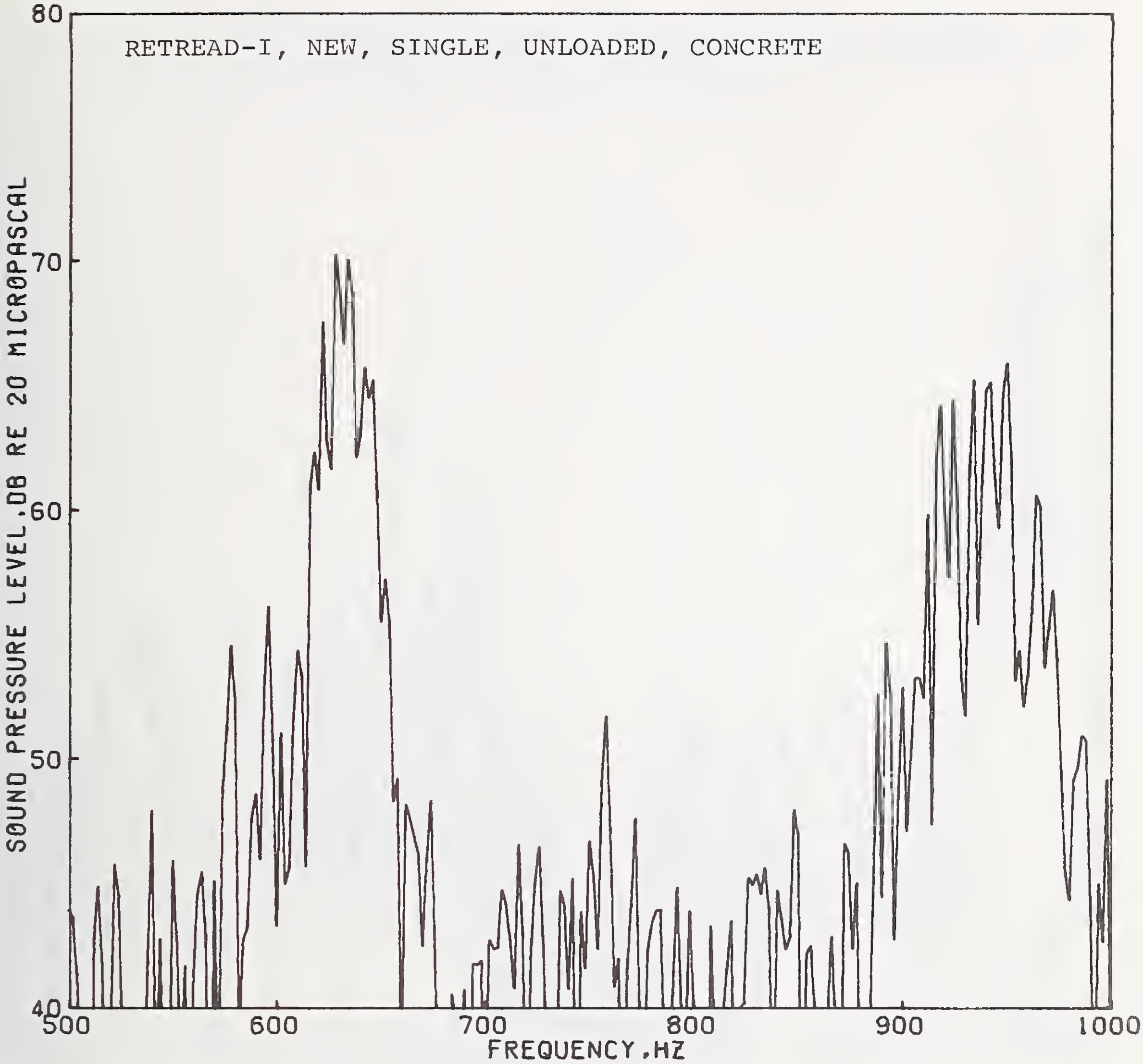


Figure C-38 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, retread-I tires on the drive axle. The 50 mph coastby was on a concrete surface.

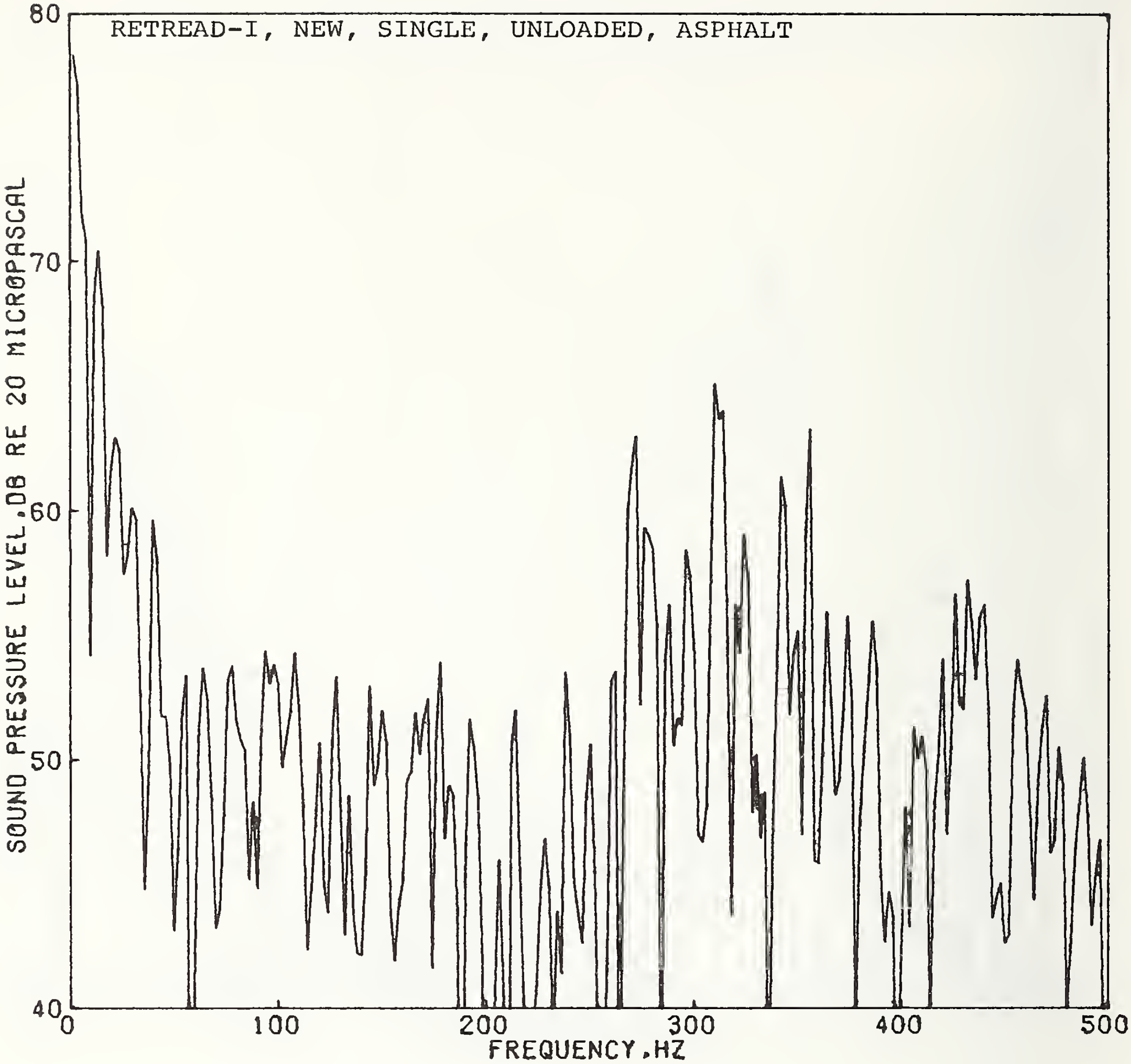


Figure C-39 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, retread-I tires on the drive axle. The 50 mph coastby was on an asphalt surface.

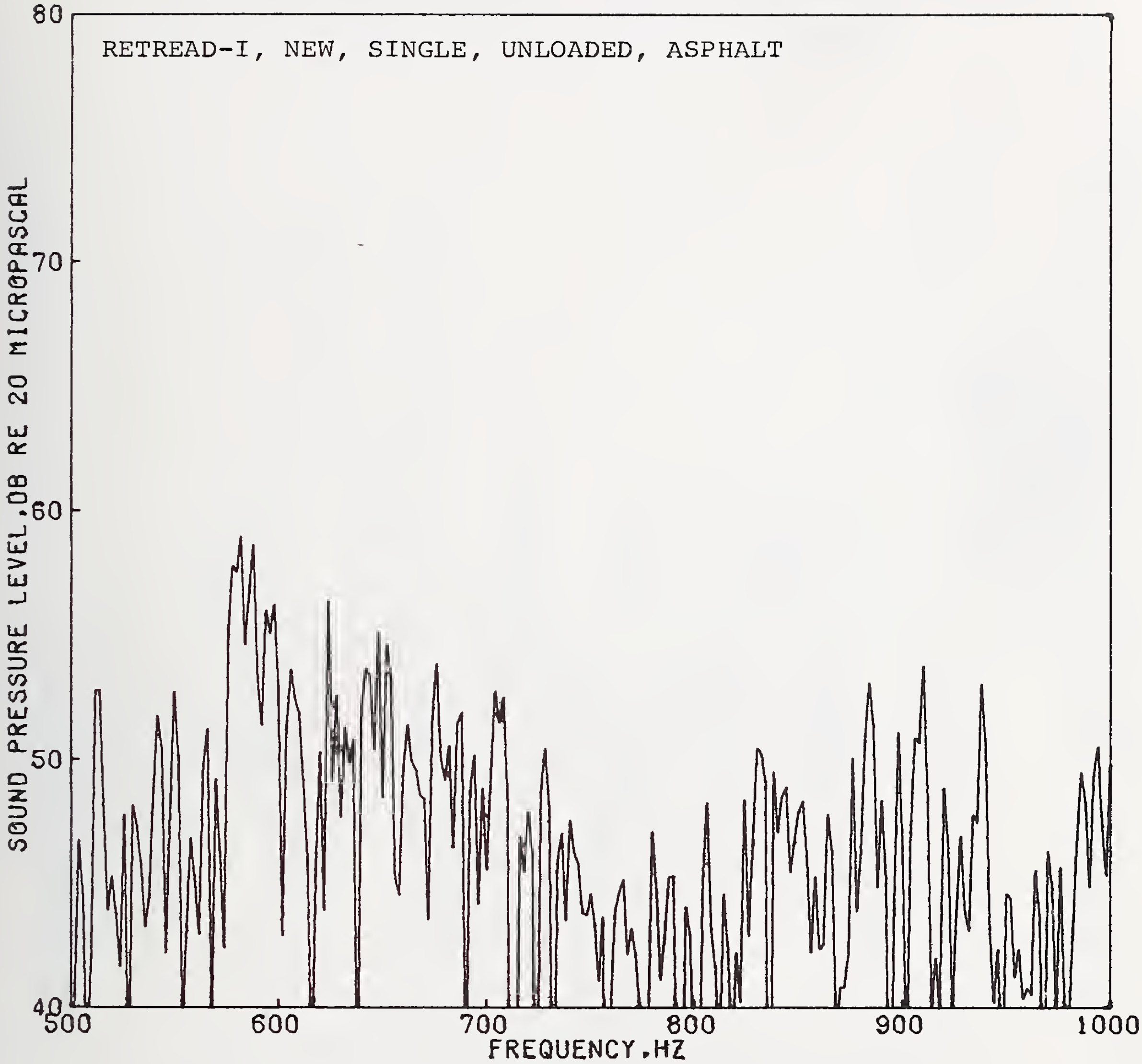


Figure C-40 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and new, single, retread-I tires on the drive axle. The 50 mph coastby was on an asphalt surface.

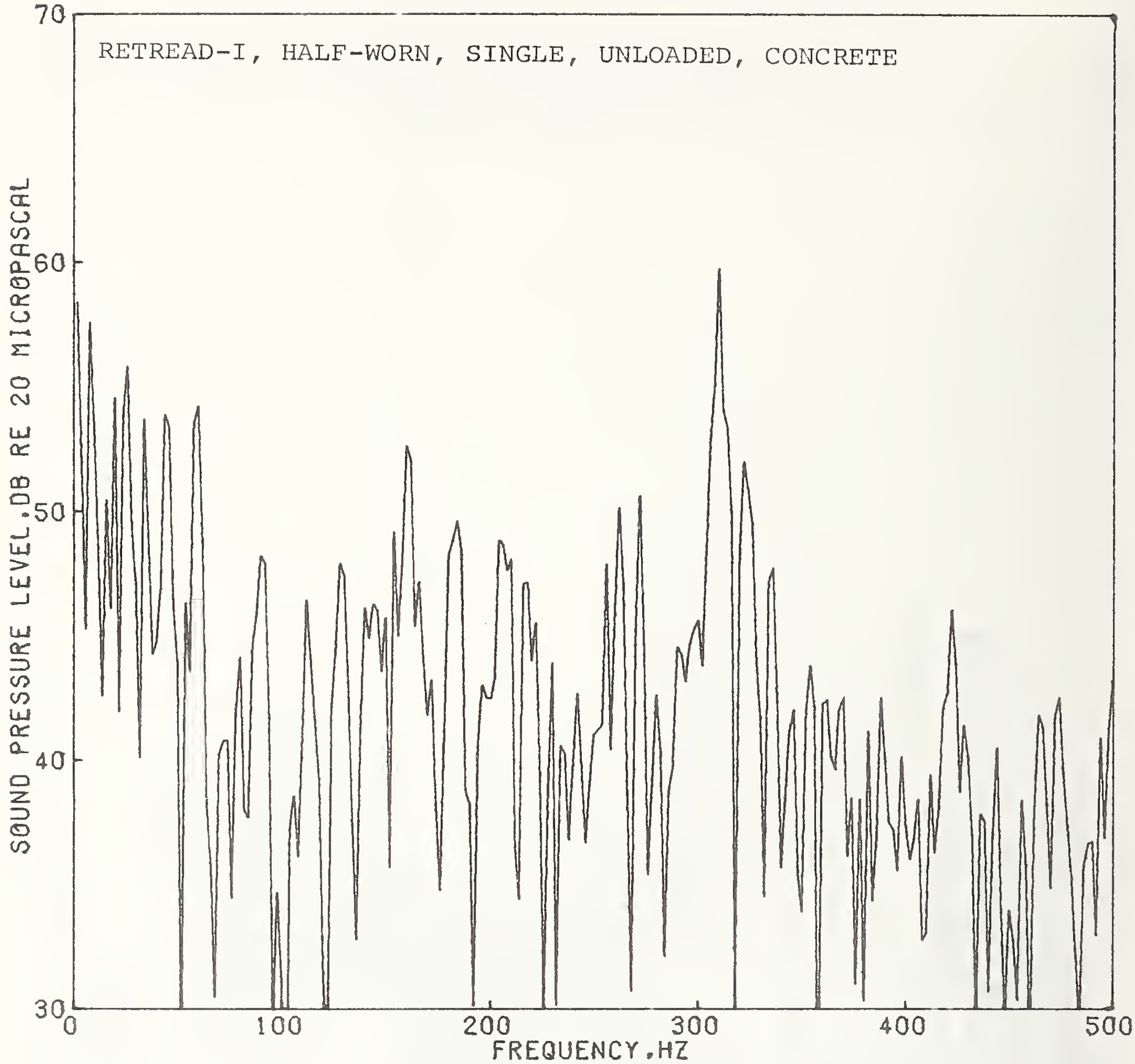


Figure C-41 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and half-worn, single retread-I tires on the drive axle. The 50 mph coastby was on a concrete surface.

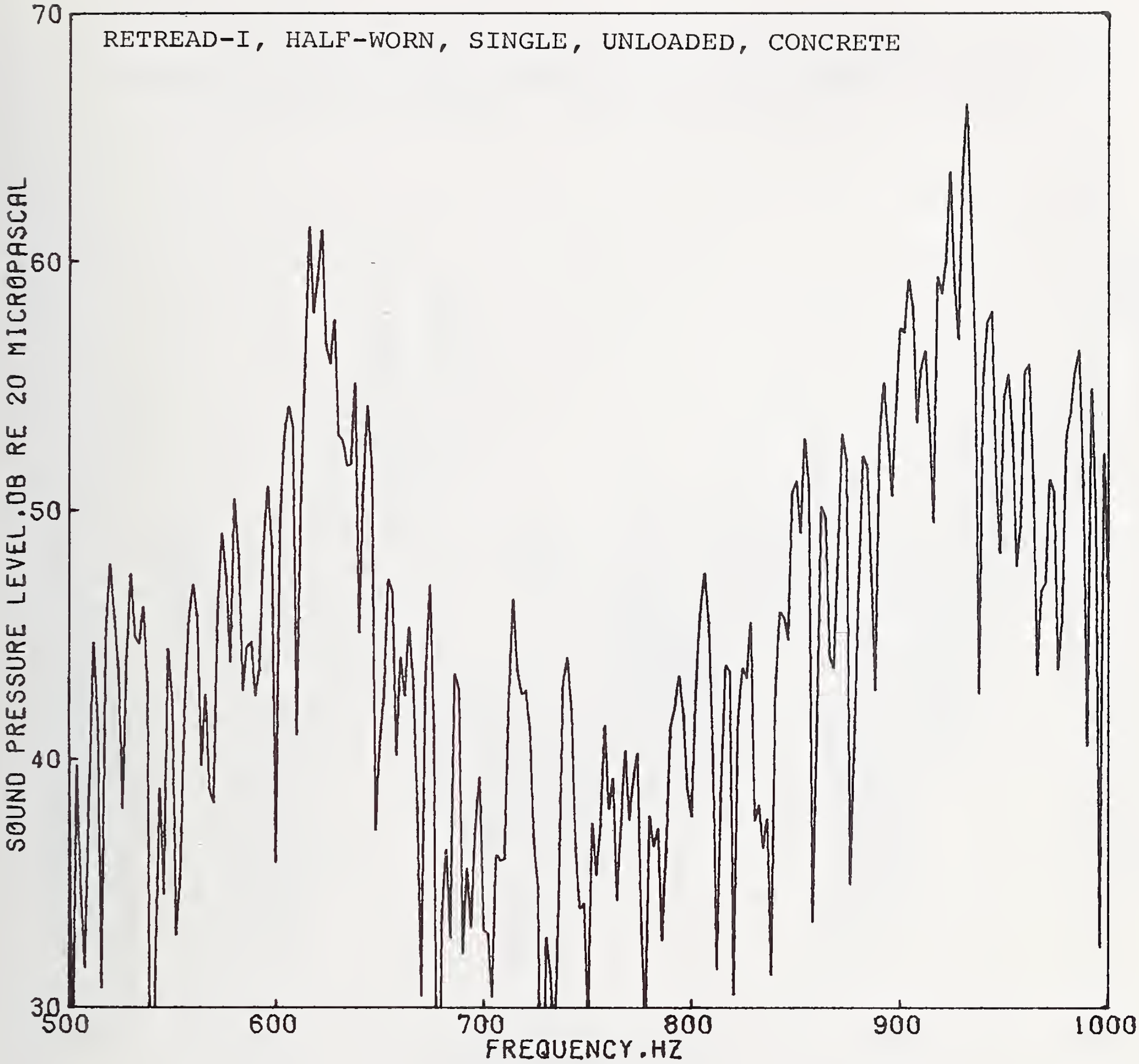


Figure C-42 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and half-worn, single, retread-I tires on the drive axle. The 50 mph coastby was on a concrete surface.

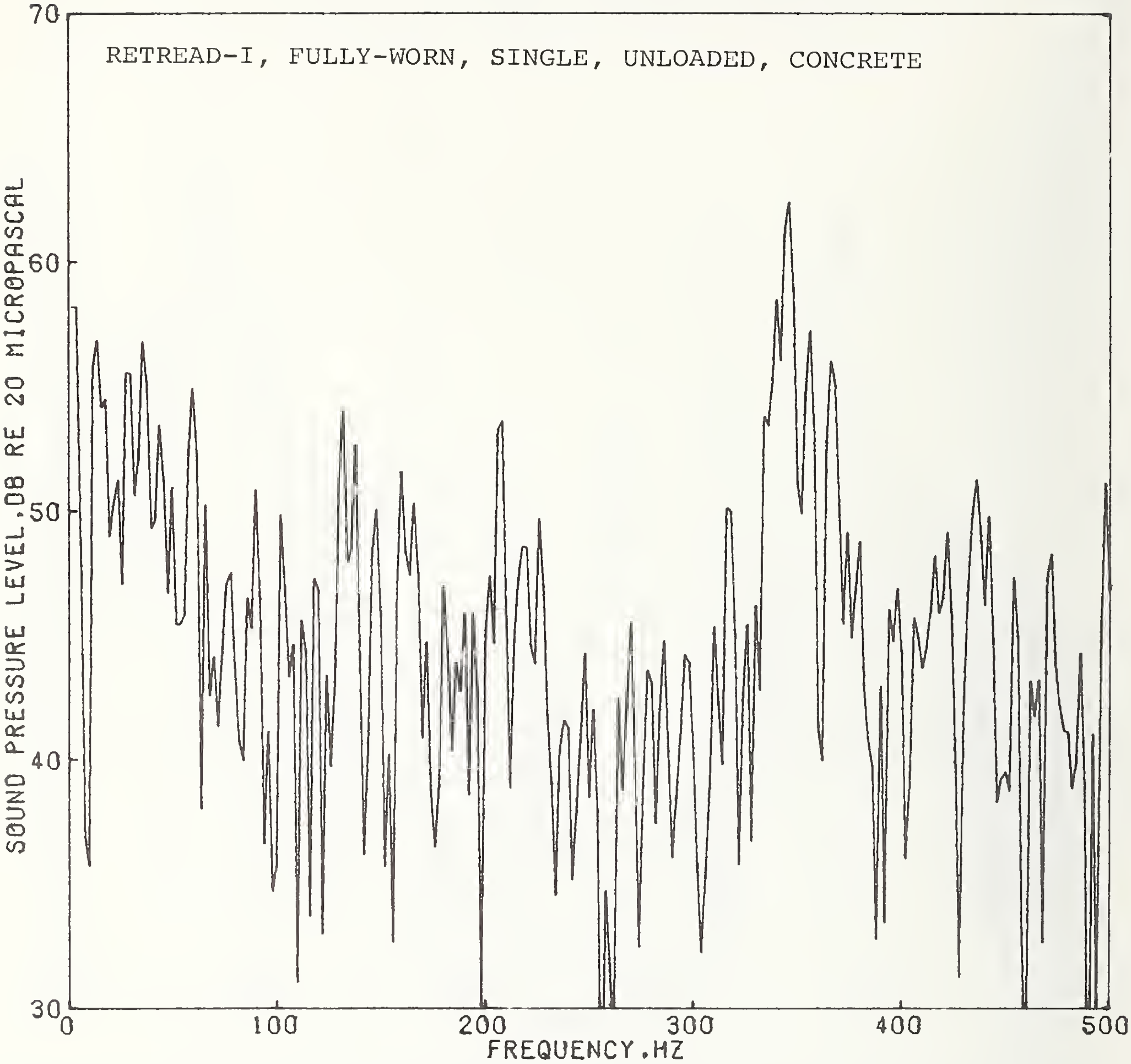


Figure C-43 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 0-500 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and fully-worn, single, retread-I tires on the drive axle. The 50 mph coastby was on a concrete surface.

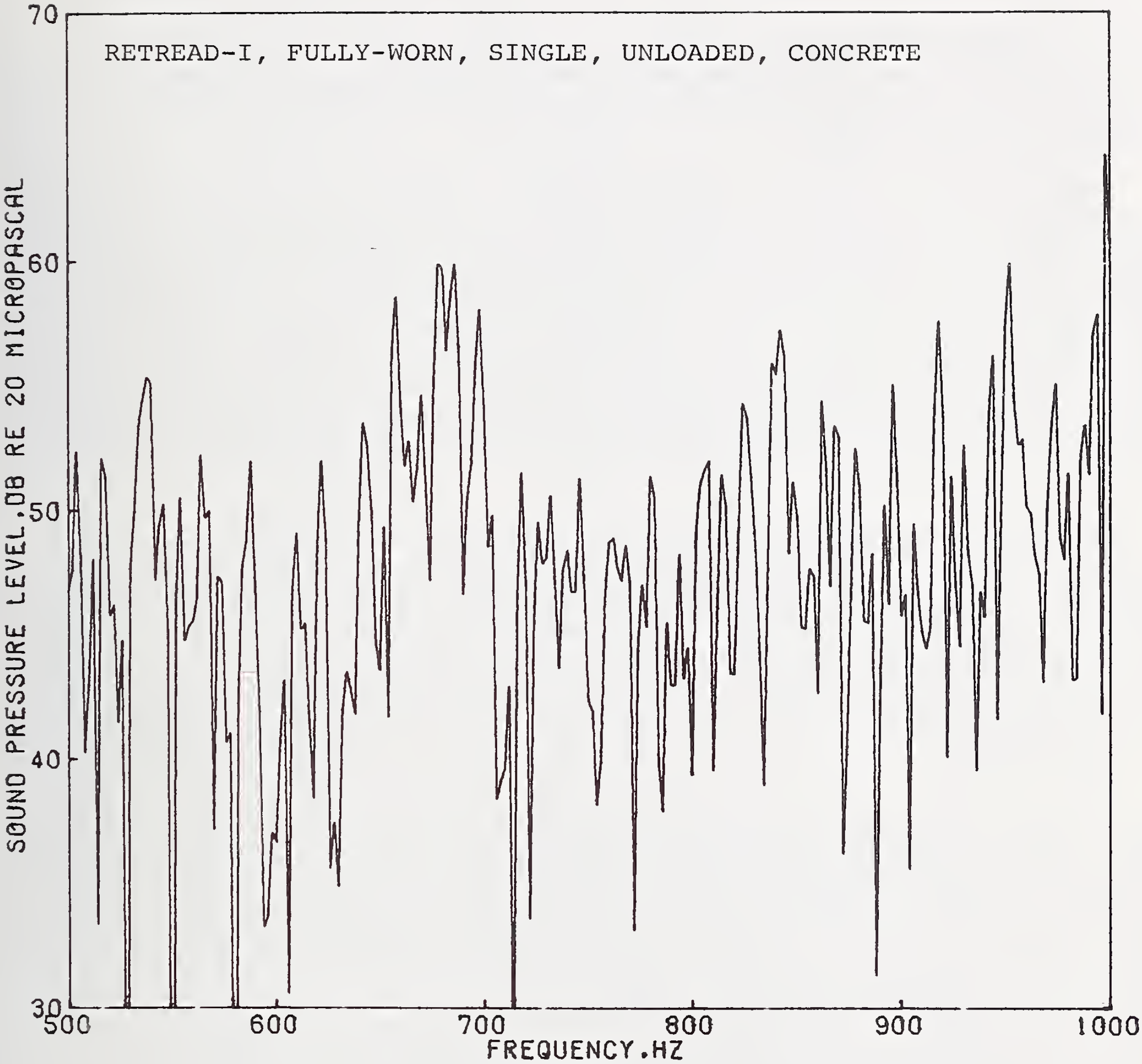


Figure C-44 Narrow band (2 Hz bandwidth) sound pressure levels versus frequency for the range 500-1000 Hz as measured at the 50 foot microphone location at the time corresponding to the occurrence of the maximum A-weighted sound level. The unloaded single-chassis vehicle was equipped with neutral rib (rib-A) tires on the steering axle and fully-worn, single retread-I tires on the drive axle. The 50 mph coastby was on a concrete surface.

## 7. Appendix D. Synopsis of DOT Reports OST-ONA-71-9 [1] and OST/TST-72-1 [2]

The first two reports, published as a result of Department of Transportation sponsored truck tire noise research conducted by the National Bureau of Standards, contain details of the test design, test procedures and inventory of maximum A-weighted sound levels generated by truck tires. Both single-chassis vehicles and tractor-trailers were utilized as test vehicles while the effect of tread design, tread wear, loading, speed, pavement surface and tire location on the noise generated by truck tires was investigated. The following is a brief synopsis of the program design and the data contained in the first two reports.

A review of the data from past studies indicated that although numerous parameters contribute to tire noise levels the following parameters are believed to be the most influential: tread design, degree of wear, type of pavement surface, vehicle speed, loading and tire location. These were the study parameters for this investigation. Secondary parameters such as carcass design, rubber composition, inflation pressure and other design features also influence tire noise; however, the limited available data indicated that their contribution would be significantly less than that of the principal parameters cited above. Test matrices for both single-chassis and tractor-trailer test vehicles were developed based on the principal parameters.

This study attempted to select a relatively small sample from the hundreds of tread patterns that exist for truck tires. Discussions with fleet operators provided an opportunity to gain and apply their knowledge, acquired through years of experience, toward the proper selection of representative tire types. Utilizing their expertise in the field, a total of nine tread designs was chosen (figure D-1). In our estimation these exact tread designs represent 70-80% of the total truck tire population in use on the road today.

In accordance with standard operating procedure, the tires utilized during this test program were not balanced. The tires were inflated to the pressures recommended by the Tire and Rim Associations for the particular load range. Tires were not considered acceptable test specimens until they had undergone a break-in period of 100-200 miles under actual driving conditions. The break-in procedure ensured the removal of all mold marks and manufacturing irregularities. Immediately prior to actual test of a given set of tires, a warm-up procedure was followed. It required the driver to operate the test vehicle until he no longer could sense any "thumping" or "heavy vibration" which could be expected when the tires were cold (a phenomena referred to as flatspotting).

Prior to finalization of the overall test design, a feasibility test program was conducted to develop an accurate and appropriate measurement methodology. Various microphone array configurations (microphones placed along a line perpendicular to the path of the test vehicle) were utilized to evaluate the following parameters: microphone height and vertical directionality, hard versus soft reflecting surface and the attenuation effect of rubber mud flaps on the propagation of the noise generated by truck tires. The evaluation of the feasibility test data led to the establishment of the following test design and measurement methodology which was utilized throughout the parametric study.

Two test sections, each 1000 feet in length, were established on the research runway at the Wallops Island, Virginia facility of the National Aeronautics and Space Administration. The test section surfaces were smooth concrete and textured asphalt. The microphone array, located midway in the test section, consisted of six microphones placed along a line perpendicular to the path of the test vehicle. The microphones were mounted on tripods at a height of 48 inches above the hard reflecting surface of the runway. They were spaced at distances of 6, 12, 25, 50, 80, and 130 feet as measured from the centerline of the lane in which the truck travelled (see figure D-2). The photosensor system for the determination of truck speed and position with time was located along the test lane parallel to the path of the vehicle. Microphones and photosensors were connected by coaxial cables to the recording and monitoring equipment which was housed in an instrumentation van located 500 feet from the edge of the runway. The van was so located to avoid unwanted reflection effects.

For a given test run, the driver of the test vehicle accelerated the truck to slightly more than the desired speed to compensate for the deceleration characteristics of the particular test vehicle. The characteristic deceleration for the loaded single chassis test vehicle was a loss of 1 mph every 200 feet. Since tire noise was being investigated, the driver shut down the engine before entering the test section and coasted through the test area. As the truck passed the initial photocell, which was interfaced with the analog tape system, the tape transport and record electronics were remotely activated. This initial photocell was located so that when the truck passed the second photocell the tape recorder was up to speed and data could be recorded. Data from each microphone were recorded on one of six channels of an F.M. tape recorder during the entire passby over the 1000 foot test section. A light source on the truck activated the photocells, generating voltage spikes which were recorded on the seventh channel (direct record) of the tape recorder. Photocells number 2, 3, 4, 5, and 6 were located 250 feet apart along the test section; the signal produced by these photocells provided information on truck position with time which was used for the calculation of vehicle speed. As the truck left the test section, a final photocell was triggered which remotely stopped the tape recorder. Each analog tape recorded in the field was returned to the National Bureau of Standards for reduction and analysis.

The detailed maximum A-weighted sound level data for all the runs were plotted versus vehicle speed and microphone distance. The data were also presented in tabular form. Also included were tire footprints of one of the actual test tires utilized, showing the characteristic tread element pattern in its given state of wear and the associated tread depth and rubber hardness. For ease of comparison and establishment of general trends, summary plots of the data were developed showing the effect of the various parameters on tire noise levels.

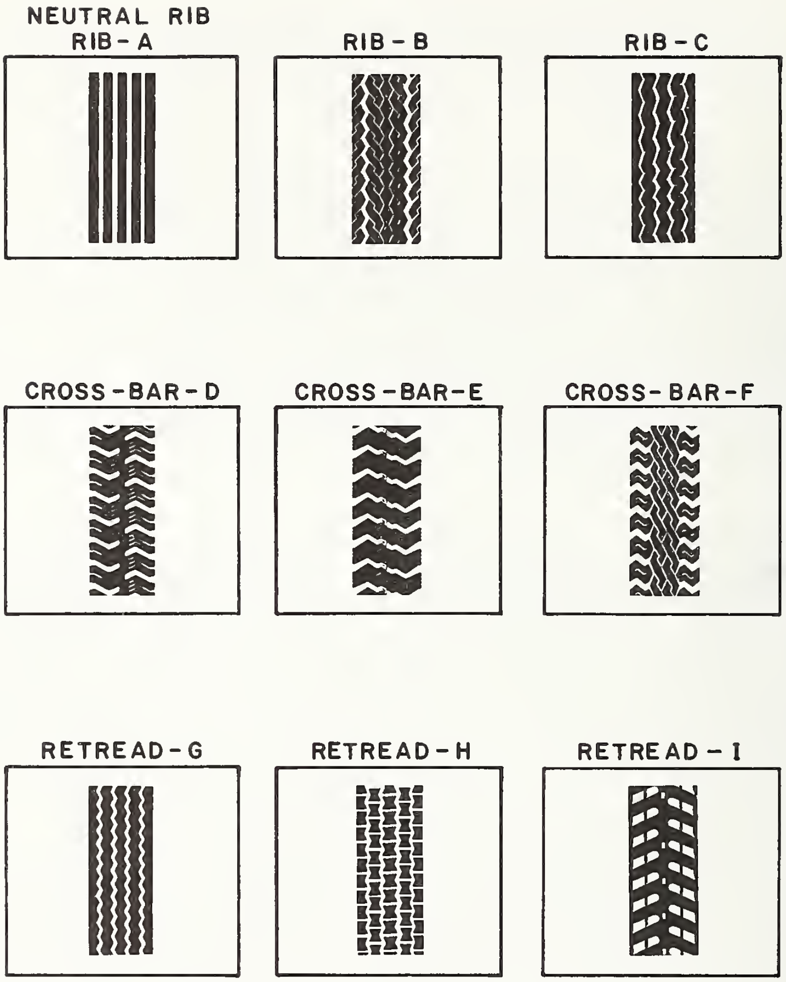


Figure D-1 Test tire tread designs. These exact tread patterns represent 70-80% of the total truck tire population in use on the road today. Scale-1:16.

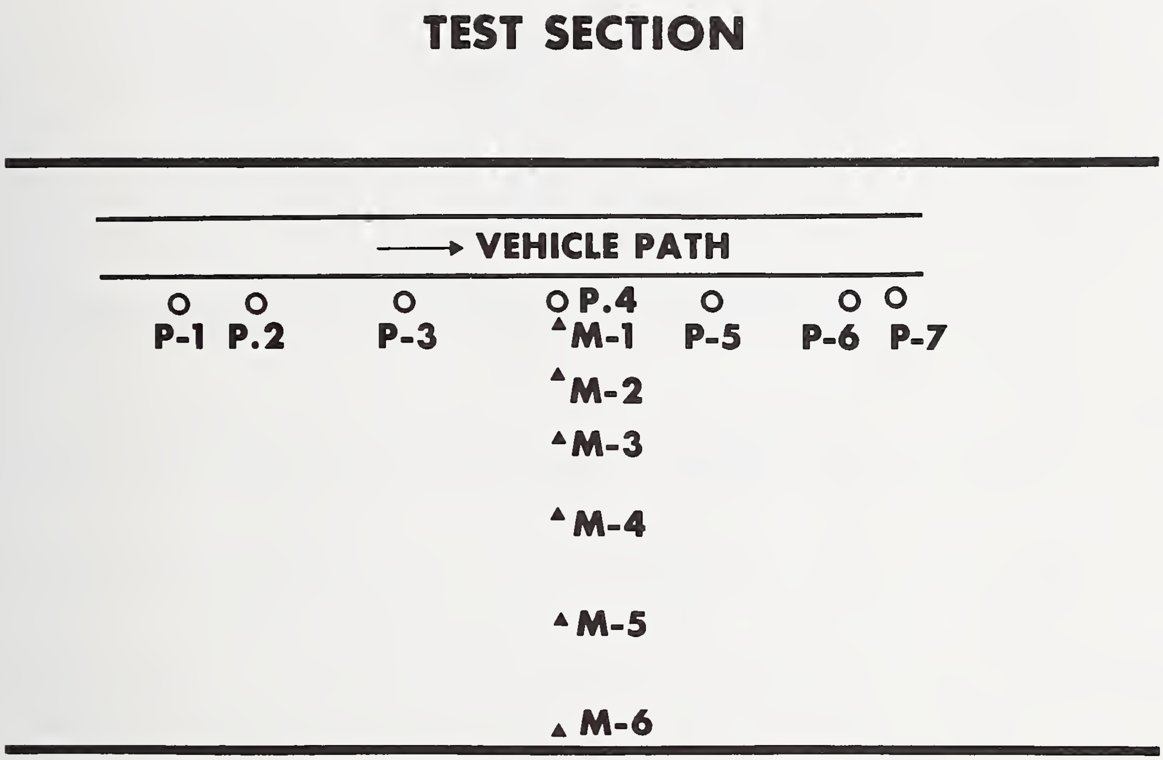


Figure D-2 View of test section showing instrumentation placement plus vehicle path. (not to scale)

## 8. References


[1] Anon., Truck noise-I, peak A-weighted sound levels due to truck tires, U. S. Department of Transportation Report OST-ONA-71-9 (National Bureau of Standards, Washington, D. C., 1970). Available from the National Technical Information Service, Springfield, Virginia, Accession No. PB 204188.

[2] Leasure, Jr., W. A., Corley, D. M., Flynn, D. R., and Forrer, J. S., Addendum truck noise-I, peak A-weighted sound levels due to truck tires, U. S. Department of Transportation Report OST/TST-72-1 (National Bureau of Standards, Washington, D. C., 1972). Available from the U. S. Department of Transportation, Washington, D. C.

[3] Archibald, F. R., An elementary analysis of a vehicle tire tread noise source, Journal of Sound and Vibration 34 (2), 285-286 (1974).

[4] Siddon, T. E., Noise generation mechanisms for car tires, presented at the 84th meeting of the Acoustical Society of America, Miami, Florida (1972).

[5] Hayden, R. E., Roadside noise from the interaction of a rolling tire with the road surface, Proceedings of the Purdue Noise Control Conference, Purdue University, West Lafayette, Indiana (1971).

[6] Reiter, W. F., Jr. and Eberhardt, A. C., Truck tire vibration noise, Society of Automotive Engineers, Inc., Paper 740609 (Society of Automotive Engineers, Inc., New York, New York, 1974).

[7] Truck tire noise, Society of Automotive Engineers, Inc. Report SP-373 (Society of Automotive Engineers, Inc., New York, New York, 1972).