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NATIONAL BUREAU OF STANDARDS REPORT

10 380

QUARTERLY PROGRESS REPORT OF RESEARCH ACTIVITY
TRUCK TIRE NOISE INVESTIGATION

May 1, 1970 – August 31, 1970

Office of Vehicle Systems Research

and

Sensory Environment Branch

Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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NATIONAL BUREAU OF STANDARDS REPORT

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CONTENTS

1. Program Objective

To identify and quantify the physical parameters which affect the noise generation characteristics of truck tires and to develop an information base that may lead to standardized tire-noise testing procedures and to highway noise reduction criteria, standards, and regulations.

2. Progress This Quarter

The major goal this quarter has been the establishment of a field test capability, both in manpower and instrumentation.

A suitable test site was selected, typical tread patterns representative of the tire population of today's trucks were identified and the instrumentation needs of the program defined.

Necessary instrumentation was purchased and mounted into the instrumentation van procured to house the equipment and transport it to and from the test site. Test vehicles were leased from the Ryder Truck Rental Company.

Field testing commenced in late July. Equipment checkout, establishment of the field test site, and feasibility testing to establish the measurement methodology were completed. In spite of tape recorder breakdowns and unfavorable weather conditions, the measurement array was finalized and measurement techniques were established.

A position-velocity sensing system was designed, fabricated, and tested. It is now operational and consists of start-stop circuitry which remotely controls the tape recorder plus five photosensors which monitor the time-position history of the truck during its pass through the test section. The sensors are activated by a light beam from a spotlight attached to the test vehicle.

In addition, a statistical test design was initiated and a state-of-the-art literature survey completed.

The data reduction and analysis scheme was determined and the necessary purchase of related equipment initiated. Initial data handling programs have been written to allow the analog data to be converted (using a real time spectrum analyzer and a Raytheon 704 computer) into a digital format acceptable to the NBS Univac 1108 computer. Late delivery and wiring problems with the interface unit between the real time analyzer and the Raytheon 704 computer have hampered data reduction; however, the debugging operation is nearly complete.

2.1 State-of-the-Art Survey

Trucks, of all vehicles on the road today, are the most notorious of the highway noise sources. At high speeds the exhaust and/or tire noise predominate. At low speeds and during acceleration, however, engine and transmission noise can be the loudest sounds. Even when stationary, a truck can be noisy. The noise at this time is usually generated by a refrigerator compressor or by a materials-handling compressor used to load and unload dry materials or fluids from or into tank trucks.

At speeds of 50 mph and greater -- which are becoming quite common on the nation's interstate highway system -- the noise from tires is the major contributor to the overall noise level provided the truck has a reasonably good exhaust muffler and is in a good state of repair. The importance of tire noise has grown over the years with the suppression of other sounds. The rapid expansion of a high-speed road system has also helped in bringing this factor to the fore.

The tire tread pattern is designed so as to provide a high degree of stability and road holding, particularly on wet roads, and this necessarily means that under certain conditions energy will be dissipated as noise. Figure 1 shows the frequency ranges of the most common noise sources in trucks. As can be seen, most of the tire noise is concentrated between 200 and 2000 Hz.

Much has been written on the subject of tread pattern noise which is the "hum" or "whine" that is generated by a tire running straight ahead on a relatively smooth surface. The generation mode is the impact of regularly placed features in the tread pattern with the highway surface.

Grooves on the tread of a tire are cut in two directions, i.e., circumferential and lateral with former called "rib pattern" and the latter "lug" or "cross-bar" pattern. It is well known that any regularity in the pattern causes a tire to generate sound waves with specific frequencies due to the fact that the air in the grooves is compressed and released as that part of the tread has contact with the road surface. Most of the available data in the public domain relates to the discussion of the generation modes and abatement procedures of tread pattern noise. The most advocated solution to this problem, which many manufacturers utilize, is the introduction of some degree of randomness in the tread element spacing. This spreads the sound energy over the entire spectrum and tends to lower or eliminate annoying tonal peaks.

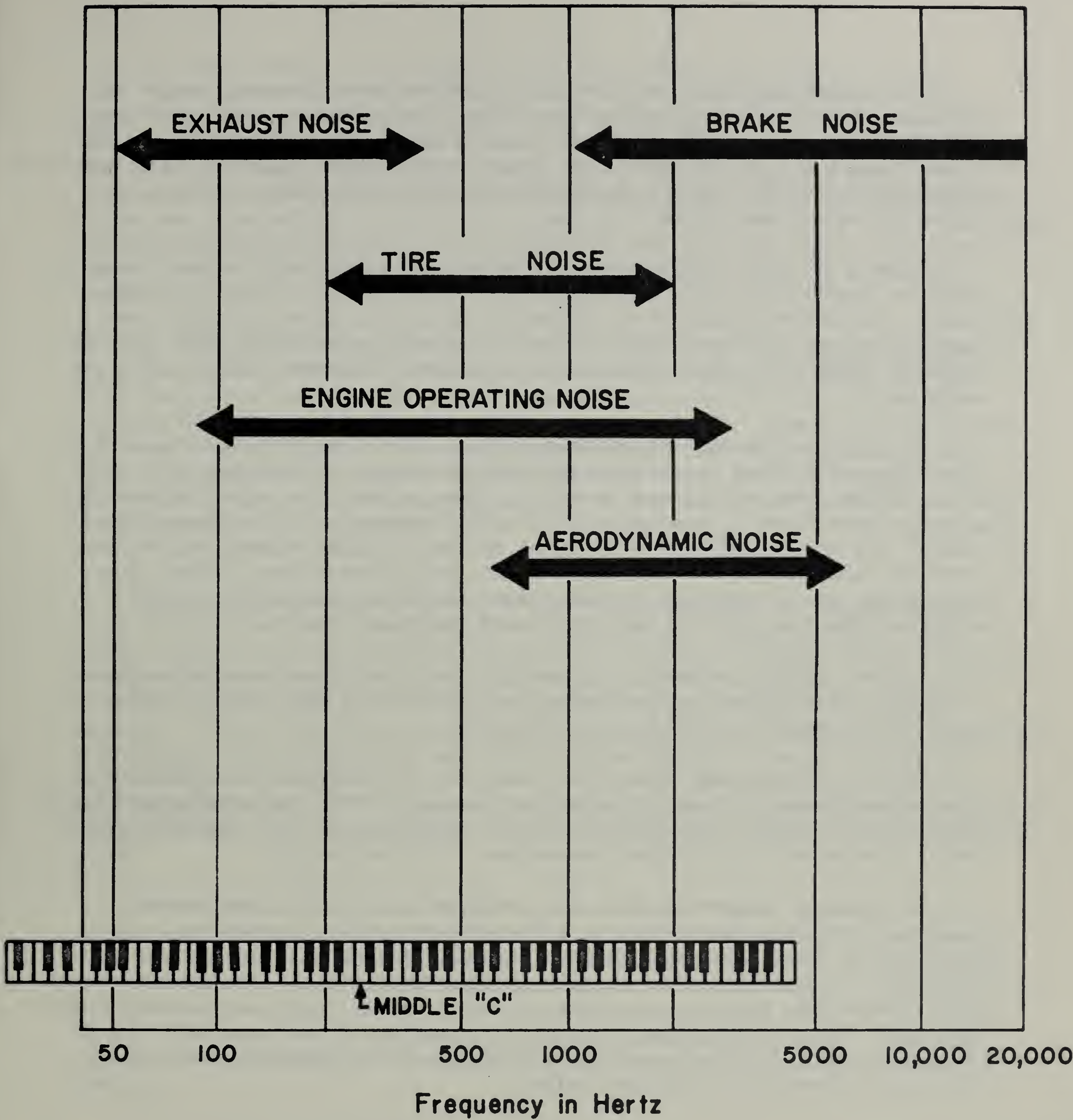

Figure 1. A diagram indicating the range of common truck noise sources in terms of frequency in cycles per second and musical pitch. The relative intensity of the noise sources is not implied by their relative location on the graph.

Some investigators feel that the tread-pavement interaction is the principal source of the highly-directional tire whine -- most prevalent at higher speeds -- which is heard after a truck has passed. The effect is well known but no research data are presently available on the directional characteristics (generation, propagation, and attenuation effects) of typically-used truck tires.

An automobile or truck when cornering may generate a "squeal" due to slip, or road/tread surface friction interaction. To prevent the independent vibration of the tread elements, irregular tread patterns and other fixes are utilized. Softer tread material also helps this problem since it tends to produce sounds having a lower frequency which are less annoying.

"Rumble" or "thump" is another typical tire sound which is caused by slight imperfections or discontinuities around the circumference of the tire. Aside from making more nearly perfect tires, the solution must lie in the elimination or reduction of the disturbance as it is transmitted through the suspension and structural system. Unlike squeal and whine, thump is transmitted through the chassis (structure-borne) rather than through the air. Thump is characterized by cyclic vibrations whose period equals that of the revolutions of the tire itself.

Another noise produced is caused by the flow of air over the tires. It is felt that this is only a minor contributor to the overall tire noise when compared with the other sources.

There are numerous parameters which are believed to contribute to tire noise levels. From the above discussion of the characteristic sounds emanated by a truck tire rolling along a highway, one can easily identify one of the major contributing parameters -- tread design.

It has been suggested that the tread pattern may be the primary factor in the production of tire noise and contributes greatly to the frequency of the noise emitted from tires. Cross-bar tires and certain retreads have been found to be much noisier than rib type tires. Although rib patterns are known to generate a comparatively lower noise level, many feel that they are interior in durability and driving characteristics to the lug pattern. These same people imply by their comments that noisy tires are necessary to provide safety.

The influence of the road surface has been questioned as to its importance in truck tire noise. It has been stated that since truck tires usually have a coarser tread than passenger car tires, it would be expected that truck tire noise would not be dependent on the nature of the road surface. Preliminary research, however, indicates that road roughness and tire noise are directly related. For instance, a half-worn cross bar tire appears quieter on a smooth surface than on a medium or rough surface while the opposite is true for certain retread tires. For these retreads the "cups" seal better on a smooth surface than on a rougher surface.

A third influencing factor is wear. Worn tires are usually noisier than new tires. This is especially true with cross-bar tires. It has been suggested that the curvature across the width of the tire may be the significant factor where wear is concerned. The reason the curvature is so important on the cross bar tires is that this determines how much load is carried on the outer sections of the tread where the major discontinuities in tread pattern exist. Since the tread pattern on a rib tire is essentially the same across the width of the tires, the curvature is not nearly as influential.

It has been observed that there are fluctuations in the noise level from truck tires with variations of the loading. Recent studies have shown as much as a 15 dB(A) difference in the noise produced by a "pocket" type retread between the no-load and fully loaded condition. Load compresses the tire and allows for a more perfect sealing of air in the pockets. Cross bar tires also exhibit a tendency for the noise to increase with load. Load appears to act in a similar manner to wear in that the increased load flattens the contour of the tire and places more loading on the outer edges of the tread. Rib tires are not significantly influenced by a variation in loading, the only effect being an increase of the contact area.

Speed also effects the level of tire noise. There appears to be a direct correlation between the speed of a vehicle and the noise emanating from the tires; however, there are considerable differences in the trends for individual tires. These five parameters -- tread design, road surface, wear, speed, and load -- appear to affect most greatly the overall noise level. However, other parameters also can have an influence. Secondary parameters with possible influence include inflation pressure and carcass design.

Increasing the inflation pressure increases the noise slightly, apparently as a result of an increase in vibrational frequencies.

As the number of plys in the tire increases, there is a slight decrease in the noise, i.e., a six ply tire will produce more noise than an eight ply tire. This is apparently due to lower hysteresis losses in the tire as a result of the lower rubber content, and consequently the high frequency road-induced vibrations are damped by them to a lesser extent.

Tread rubber composition and reinforcing fabric material appear to have little influence on noise level produced. A Bolt Beranek and Newman study of the effect of various tire constructions on the noise level revealed remarkable constancy of the noise spectrum with respect to changes in the fiber material of the tire-reinforcing fabric and tread rubber composition for a given set of operating conditions. Nylon appears to be slightly noisier than rayon, and the damping characteristics of the cord seem to play some part in the noise and vibration output of the tires.

At this point it must be stressed that the conclusions drawn above are based on the results of limited exploratory testing. There is a great probability that the parameters listed do not completely cover all factors contributing to tire noise. At this early stage of experimentation no definite assertions can be made.

The bibliography included at the end of this report includes numerous papers and articles which discuss the truck tire noise problem in extreme generalities. Although only a small amount of data are available in the public domain, tire noise is indeed a very real problem and much work is necessary before tire manufacturers and the buying public can be given the information necessary for the design and purchase of quieter tires, thus assuring a measure of environmental quality improvement.

Serendipity, Inc., in a quarterly report of a Study of the Magnitude of Transportation Noise Generation and Potential Abatement prepared for the Department of Transportation, state: "The entire area of tire noise and its potential abatement is clouded by the extreme lack of data which describe the generated noise."

Donald P. Loye, speaking of transportation noises in general during an address before the Second West Coast Noise Symposium in Los Angeles advocated, "Further work is desirable to determine the most satisfactory noise laws and enforcement procedures." He further stated that field measurements should also include at least octave-band frequency analysis in addition to a single number (usually dB(A)) criterion.

J. H. Venema of the Ford Motor Company reinforces this by the following words, "For the immediate task, we need to agree upon and define the objectives, and standardize test methods and acceptance criteria." He further states, "Because of the directivity of the sound pattern from a vehicle, the intensity of sound depends not only on the proximity but also on the position of the observer with respect to the vehicle. Maximum noise is not usually experienced when the vehicle is closest to the observer, but somewhat after it passes."

Derek Tetlow, of General Motors, concludes his report Truck Tire Noise - An Initial Survey of the Noise Variables with the recommendation that further work be conducted on truck tires and that this study should investigate the following two areas: (1) the effect at different distances from the source in addition to the usual fifty foot microphone (attenuation effect with distance of truck tire noise) and (2) more investigation into the process of tire noise generation.

Finally, Lewis C. Kibbee, director of the Engineering Department of the American Trucking Associations, Inc., recommends, "Tire manufacturers must devote a great deal more effort to the control of truck tire noise by designing quietness into truck tires in the same manner that has been done in passenger car tires."

A careful review of the presently available information and the above comments provide the basis for the following conclusions:

a. There is a definite lack of data in the public domain on the characteristics of noise generated by truck tires. A "catalog" or data inventory on the noises generated by typical rib, cross-bar, and retread tires utilized today by the trucking industry is a necessity. These data would provide law enforcement agencies and lawmakers with the information which they need to draft and enforce meaningful noise ordinances. In the past, due to the inexperience of the lawmakers in the control of noise, the laws were vague and indefinite. It is extremely difficult to issue citations on the terms "excessive", "unusual", or "unnecessary" noise. The present California law, which may prove to be a model one, is handicapped by the fact that no information is available to enable enforcement of a vehicle noise limitation when tires are the culprit. If tire whine is heard by the state trooper, no citation is given. A data base is needed to supply state and local officials with the information they need for the full enforcement of their laws.

b. Three types of analysis should be made at a minimum. Peak A-weighted sound levels must be measured so that correlation can be made with past as well as future studies -- especially since A-weighted sound level is emerging as the criterion most often utilized in objective and subjective studies. In addition, frequency analysis (octave, one-third octave, or finer) is necessary since it is only through this type of analysis that an understanding of the generation mechanisms by which tires produce their noise can be obtained. Finally, directionality information is needed so that sound propagation characteristics of truck tire noise can be identified. The prediction of noise levels in nearby communities depends heavily on the directional characteristics of the noises produced.

c. In addition to the data obtained to date, more research will be necessary to fully define the generation modes. Such items as carcass construction, tire deflection, and other influencing factors must be considered if the entire problem is to be understood and effective solutions implemented.

Once this information becomes available, it appears that a satisfactory model could be developed to enable prediction of noise generation characteristics from the tread design and other information concerning the tire's construction. The basis would then be established to enable the design of quieter tires -- the eventual goal.

2.2 Field Test Site

The research runway at the Wallops Island, Virginia, facility of the National Aeronautics and Space Administration was chosen as the test site for the road testing phase of the program. This location provides an adequate stretch of pavement (8750 feet), several different types of pavement surfaces, and a flat terrain providing an effective reflecting half-plane. An agreement was arranged with NASA for utilization of this facility for the data acquistion phase of the program.

On the 8750 foot length of research runway 4-22 (bearing 040° and 220°) two 1000 foot test sections have been established. One test area is designated as the concrete test section while the other is the asphalt test section.

Each test section is a lane 12 feet in width and 1000 feet in length. This lane is located 12 feet in from the west side of runway 4-22 to avoid the poorer surface existing near the edge of the runway.

Figure 2 shows an overall view of the research runway with the locations of both test sections noted.

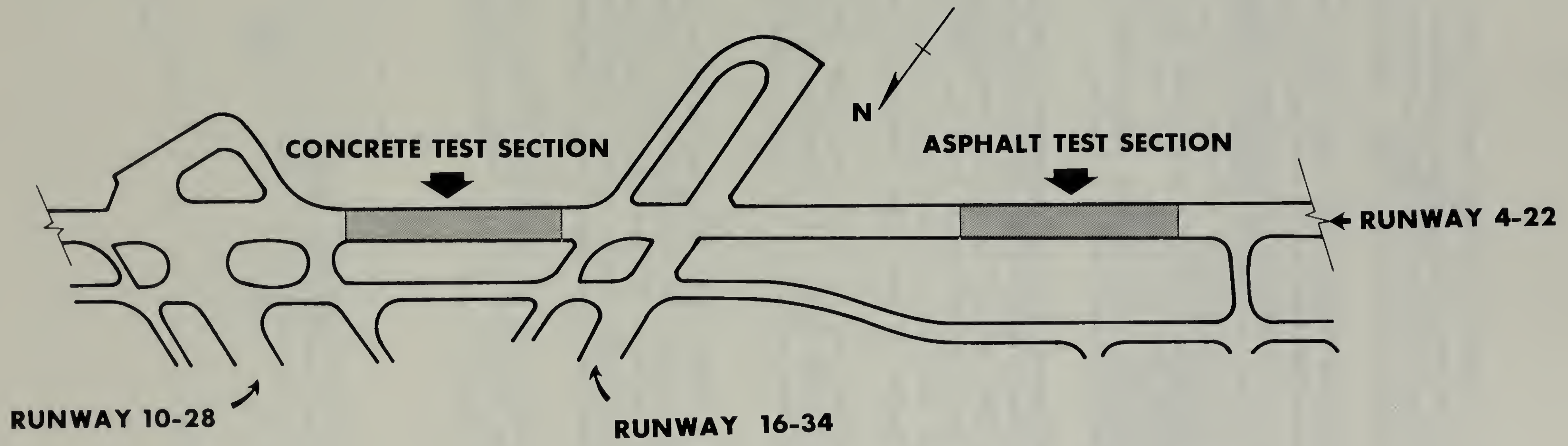

FIGURE 2 PLAN OF RESEARCH RUNWAY 4–22 WALLOPS STATION, VIRGINIA SHOWING THE LOCATIONS OF THE CONCRETE AND ASPHALT TEST SECTIONS

Appendix A contains a detailed discussion of the composition of each test section. These details were taken from a National Aeronautics and Space Administration, Wallops Station, Virginia, Specification numbered P-1643, entitled "Modification to Runway 4-22", and dated April 18, 1967.

The concrete test section begins 2650 feet from the northeast end of runway 4-22 and extends to 3650 feet. It consists of a substrate of reinforced, air-entrained Portland Cement concrete with two types of finishes. They are "C" finish or smooth concrete and "D" finish or textured concrete. The only difference between the two surface finishes is the method of final finishing. To the untrained eye, there appears to be no difference between the two sections. The "C" finish section of pavement was smoothed with a belt of canvas composition while the "D" finish section utilized a finishing belt of burlap.

Figure 3, a detailed layout of the concrete test section, shows three areas of grooved pavement sections. A grooved section extends 75 feet (50 foot wide section on the runway centerline) into the test area but does not interfere with the line-of-sight from the truck to the microphone array. The grooved smooth concrete section and the grooved textured concrete section, however, do lie between the truck and the microphone array.

The asphalt test section begins 5700 feet from the northeast end of runway 4-22 and extends to 6700 feet. It consists of a substrate of "B" surface course bituminous concrete. It is also referred to as "textured asphalt".

Reference to Figure 4 shows that the test section is a continuous surface of textured asphalt with the exception of a grooved textured asphalt section 150 feet long and 50 feet wide located along the centerline of the runway. Only a small corner of this grooved section is in the line of sight path from the test vehicle to the microphone array.

The effect of the grooves on reflection of sound has not been established at this time. More research is necessary to determine whether any significant diffraction effects occur.

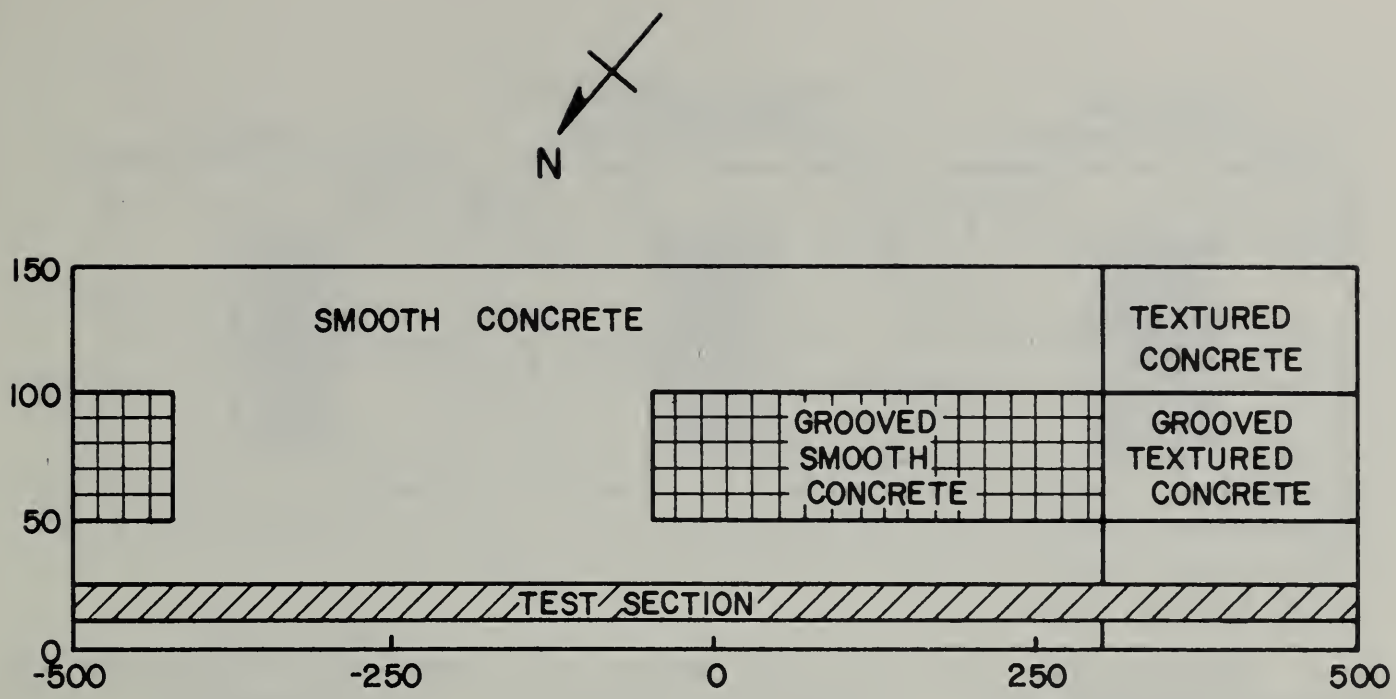

Figure 3. Plan of concrete test area on runway 4-22. Distances are in feet.

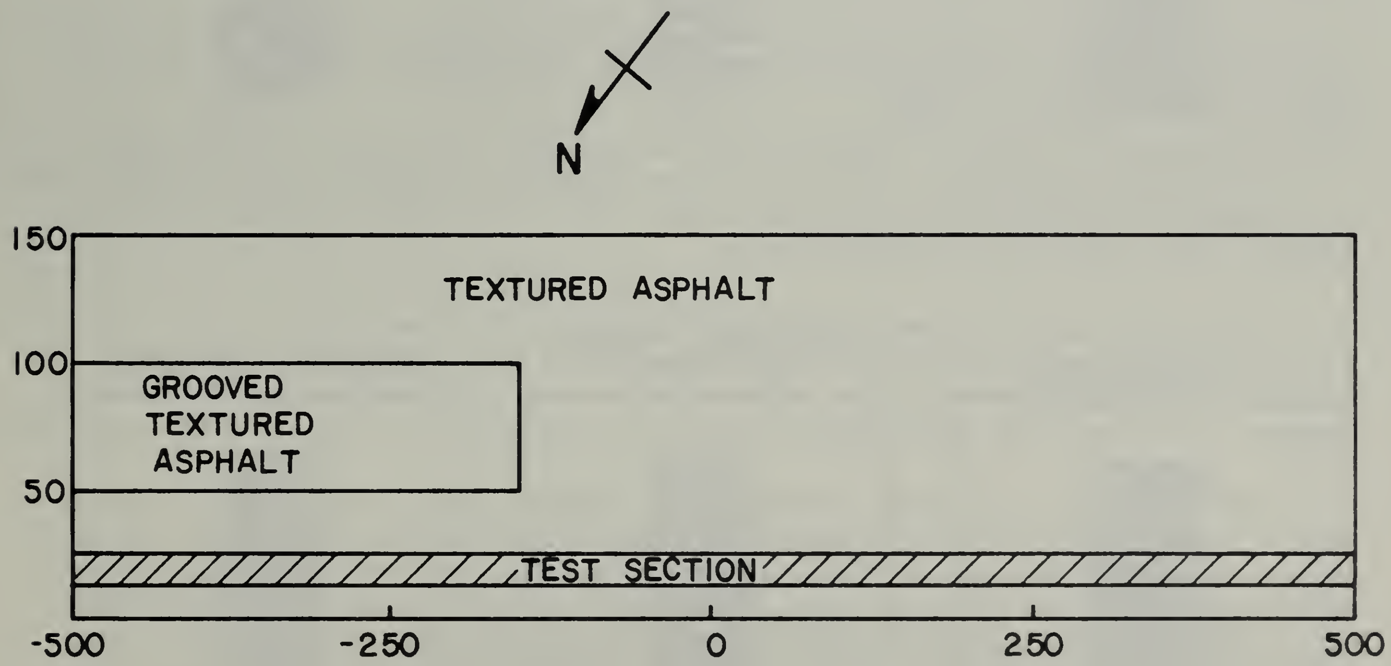

Figure 4. Plan of asphalt test area on runway 4-22. Distances are in feet.

2.3 Tire Tread Selection

The primary purpose of the tread design is to provide road holding and stability -- particularly on wet roads. Tread designs enhance the ability of the tire to transmit driving and braking torques.

Tread design is simply the division of a smooth tread into smaller elements. The elements are usually arranged in symmetric, repetitive patterns of ribs (circumferential) and lugs (lateral). The spaces between the raised tread elements are referred to as grooves or sipes. The tread elements are usually arranged within the pattern to give the tread design directional tractive characteristics as well as a specific ratio of net-to-gross contact area. This ratio decreases as traction is emphasized with rib designs usually in the 75 to 80 percent range and cross-bars the 70 to 75 percent range.

Tread patterns can be broadly characterized as either rib or cross bar. These patterns are typical both for original tires and for retreads.

Rib designs are the most common type and possess characteristics that provide overall service for all wheel positions. With the design elements oriented in the circumferential direction, these tires are noted for their lateral traction and uniform wear characteristics.

Lug or cross-bar tires, with the tread elements oriented in the lateral direction, are used primarily on the drive axles where fast wear occurs due to torque induced slip.

Retreads may possess tread patterns which are either rib or cross-bar in nature. In addition, retreads exist with a "pocket" design which is neither rib type nor cross-bar type.

For this study, three tires from each broad class have been selected for test purposes. Individual tires selected were carefully chosen to ensure a representative cross section of tires utilized by over-the-road trucks. Discussions with fleet operators allowed for proper tire selection.

Rib tires to be tested include the General HCR Neutral Rib, General Power Jet Nylon and the Firestone Transport 150 Premium Rib. The Uniroyal Fleet Traction, Firestone Transport 200 Premium, and the Goodyear Custom Cross Rib Hi-Miler are the representatives of the cross-bar population. The three retread types chosen for test purposes are the Rib-Saw Tooth, the Semi-Traction Bow Tie, and the Full Traction Hawkinson AR known as "Singing Sam".

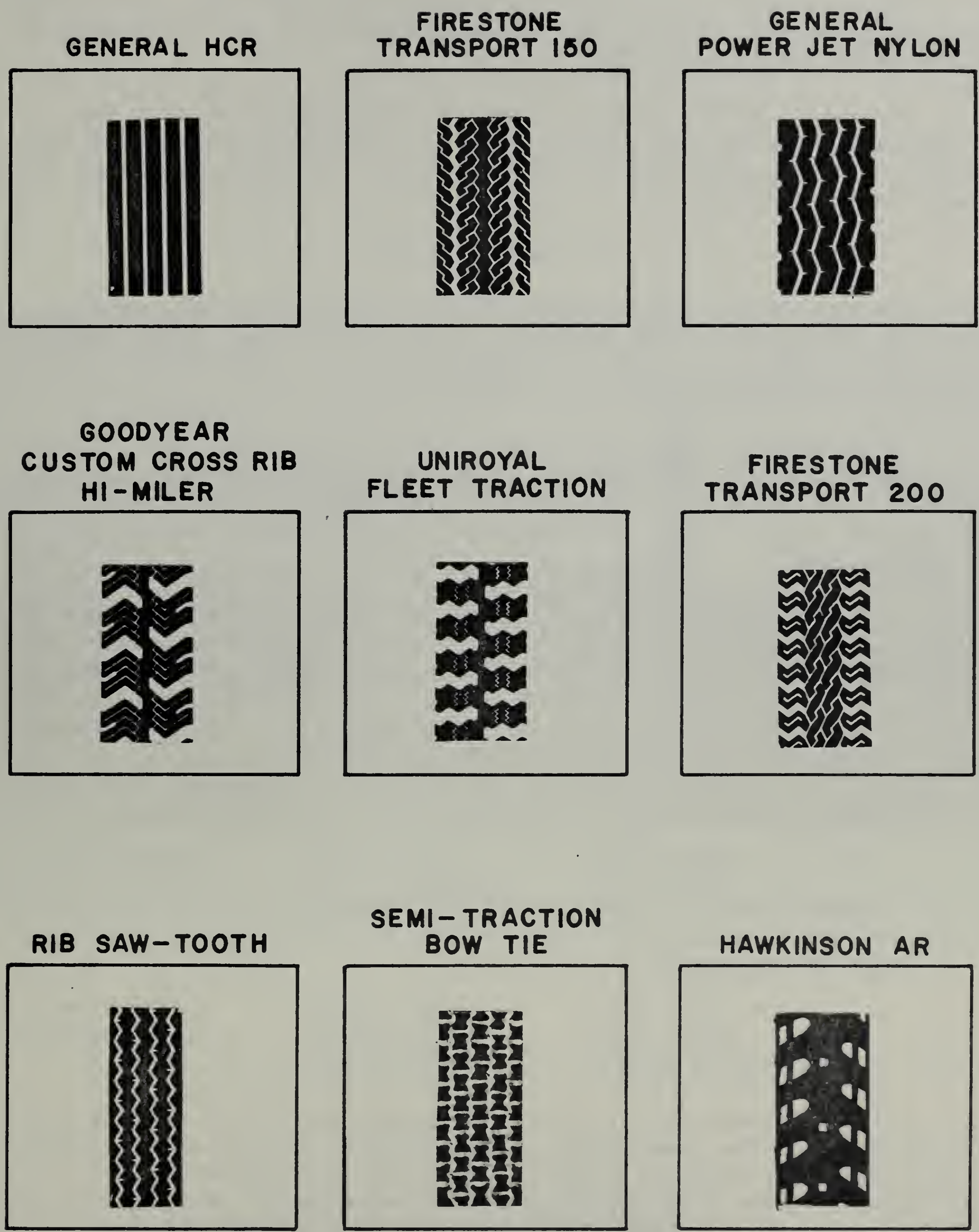

Figure 5. Test tire tread designs. These tread patterns are representative of typical truck tires in use today.

Figure 5 shows a footprint for each of the nine test tires. These are representative of the tread element patterns of the tires in a new state under static conditions.

The above listing of test tires includes one change from the originally-proposed test matrix. The B. F. Goodrich Company has discontinued its Traction Express tread pattern. The Uniroyal Fleet Traction has been substituted.

2.4 Test Vehicles

For the single vehicle (singel chassis with two axles) testing, two International Model #1890 chassis equipped with 20 foot stake bodies are being used. Figure 6 gives an overall view of the test vehicle utilized throughout the feasibility test program.

These vehicles are equipped with 9,000 pound front axles, V-345 gasoline engines, 13-inch clutch, 5-speed transmission, 2-speed 23,000 pound rear axle, heavy-duty springs, heavy-duty brakes, West Coast mirrors, and 10.00 x 20 tires. These vehicles have a gross weight capacity of 32,000 pounds.

One truck is operated in the unloaded condition, while the other carries 15,000 pounds of load. Figure 7 shows the loading arrangement. Thirty NBS-calibrated 500 pound weights are distributed to develop maximum loading on all tires. Both the loaded and unloaded test vehicles were weighed at a scale in the State of Virginia near the Wallops Station test site resulting in the following weight breakdown:

Truck #1 (Loaded)

Front Axle	7,920 pounds	(3,960 pounds/tire)
Rear Axle	17,720 pounds	(4,430 pounds/tire)
Gross Vehicle weight	25,640 pounds	

Truck #2 (unloaded)

Front Axle	4,680 pounds	(2,340 pounds/tire)
Rear Axle	6,120 pounds	(1,530 pounds/tire)
Gross Vehicle Weight	10,800 pounds	

All tire pressures were set at 70 pounds per square inch as specified by the Tire and Rim Association recommendations for the above loading range.

At this time no decision has been reached as to the specifications of the tractor-trailer for the combination vehicle testing phase of the program. It will be, however, a three-axle tractor, two-axle trailer with a total complement of 18 tires, and a gross weight capacity of approximately 70,000 pounds.

All test vehicles are being rented from Ryder Truck Rental, Inc., Baltimore, Maryland.

Figure 6. An International Model #1890 chassis equipped with a 20-foot stake body serves as the test vehicle. The vehicle possesses a gross weight capacity of 32,000 pounds.

Figure 7. A view of the test vehicle body showing the placement of the thirty 500 pound weights used to provide maximum tire loading.

2.5 Test Procedure

Prior to a discussion of the test procedure, a few words of description are necessary to establish the placement of all instrumentation within the test section. Figure 8 shows the placement of the microphones, photosensors, and the path of the test vehicle.

The microphones, six in all, are located along a line perpendicular to the path of travel of the test vehicle. The array itself is located midway in the test section. Photosensors, activated by a light beam produced by a spotlight mounted on the side of the truck, are located along the test lane parallel to the path of the vehicle. Although not shown in Figure 8, the mobile instrumentation van is located 500 feet back from the edge of the runway. Coaxial cables connect the microphones and photocells with the tape recording and monitoring equipment housed in the instrumentation van. The 500 feet distance is dictated because of an airfield ruling and also to avoid unwanted reflection effects.

For a nominal 40 mph run (the truck should be travelling at 40 mph as it passes the microphone array) the driver of the test vehicle accelerates the truck to slightly more than the desired speed to compensate for the deceleration characteristics of the particular vehicle. As the truck passes the initial photocell, the tape recorder in the instrumentation van is remotely commanded to turn on.

Since tire noise is being investigated, the testing is performed with the truck in a coasting mode and the engine shut off. The driver shuts down the engine prior to entering the test section. The initial photocell, which turns on the recorder, is located so that when the truck passes photocell No. 2 the tape recorder is up to speed (servo control system in phase lock) and data can be recorded. Data from each microphone are recorded on six channels of an F.M. tape recorder. The truck tire noise is recorded during the entire passby over the 1000 foot test section. The light beam striking the photocells causes voltage spikes which are recorded on the seventh channel (direct record) of the tape recorder. The photocells (photocells No. 2, 3, 4, 5, 6) are located 250 feet apart along the test section; the "blips" produced by the photocells serve as the time base for the experiment.

As the truck leaves the test section, a final photocell is triggered which remotely stops the tape recorder.

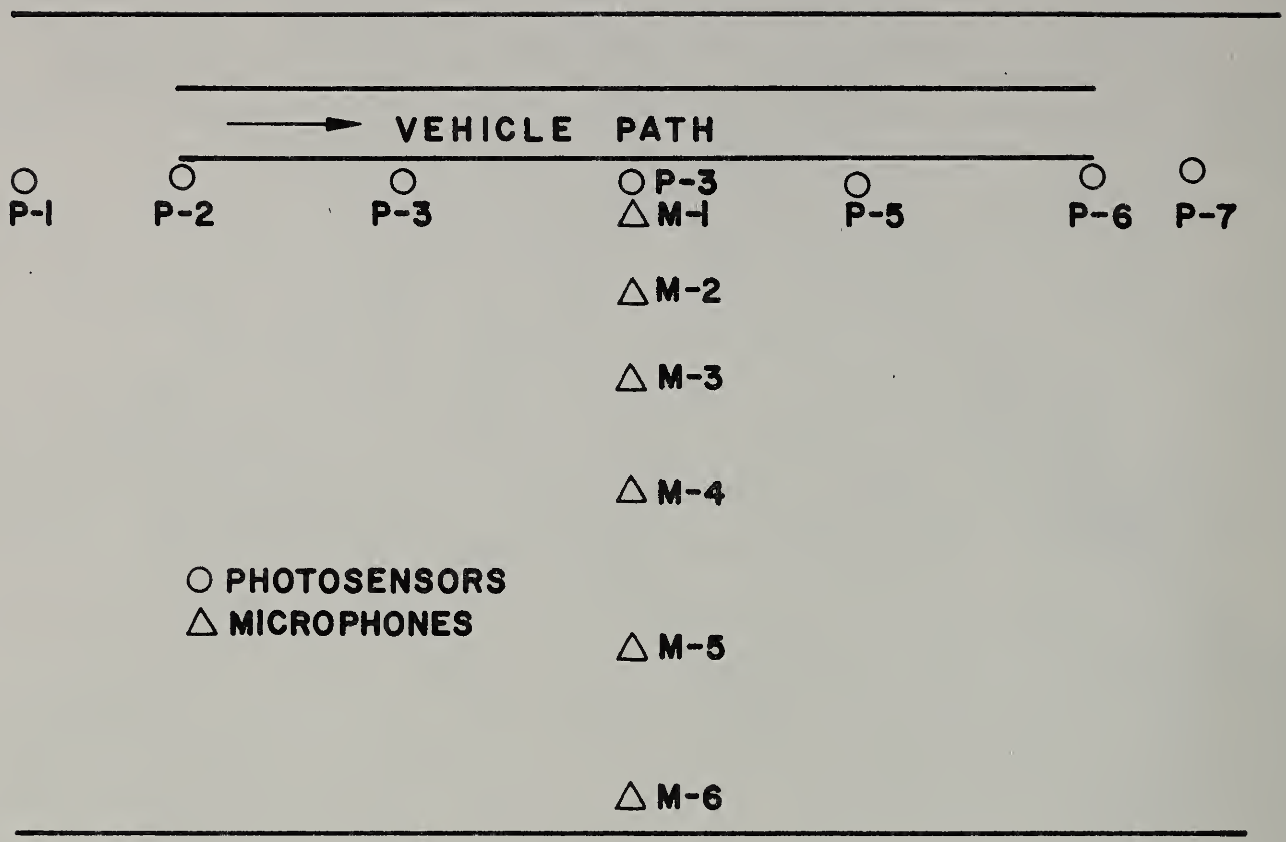

Figure 8. View of test section showing instrumentation placement plus vehicle path. (Not to scale)

a. Recording Instrumentation

Figure 9 identifies the components that constitute the data acquisition system. To describe the workings of the system, the following example is cited with the contribution of each component discussed.

Consider a truck passing an array of microphones (Figure 10). As the truck moves forward at a given velocity, it causes local fluctuations in the ambient pressure of the air surrounding the truck. These fluctuations, which the ear would perceive as sound, travel as waves and activate the microphone's diaphragm into vibration. These variations are transduced into an AC voltage which can be recorded for analysis at a later time. The microphone itself is a three-part subsystem comprised of a free-field microphone cartridge, protecting grid, and a microphone preamplifier. It is not practical to locate the tape recorder next to the microphone array since one wants to minimize undesired reflection effects. Therefore, long cables must carry the signal from the microphone to the recording facility. To maintain the voltage level of the signal some line amplification is mandatory. A unit at the array which supplys the polarization voltage to energize the microphones in addition provides the capability for 20 dB amplification. Once the signal reaches the tape recorder, there exists a need for signal conditioning prior to actual recording. The electronic voltmeters provide the capability for amplification/attenuation. The meter scale provides an indication as to whether or not a tape channel has become saturated (i.e., the signal has exceeded the dynamic range of the instrument) and thus the data are not acceptable. The signal is then recorded on one track of the F.M. tape recorder. The measurements are performed out-of-doors; therefore, windscreens are placed over the microphones to minimize the noise produced by the wind variation over the microphone.

Figure 11 gives an overall view of the equipment arrangement within the mobile instrumentation van. All instruments are mounted in such a manner as to be easily accessible to the operator.

Shown in Figure 12 is a view of the instrument racks which contain the F.M. tape recorder as well as some calibration and system checkout instrumentation.

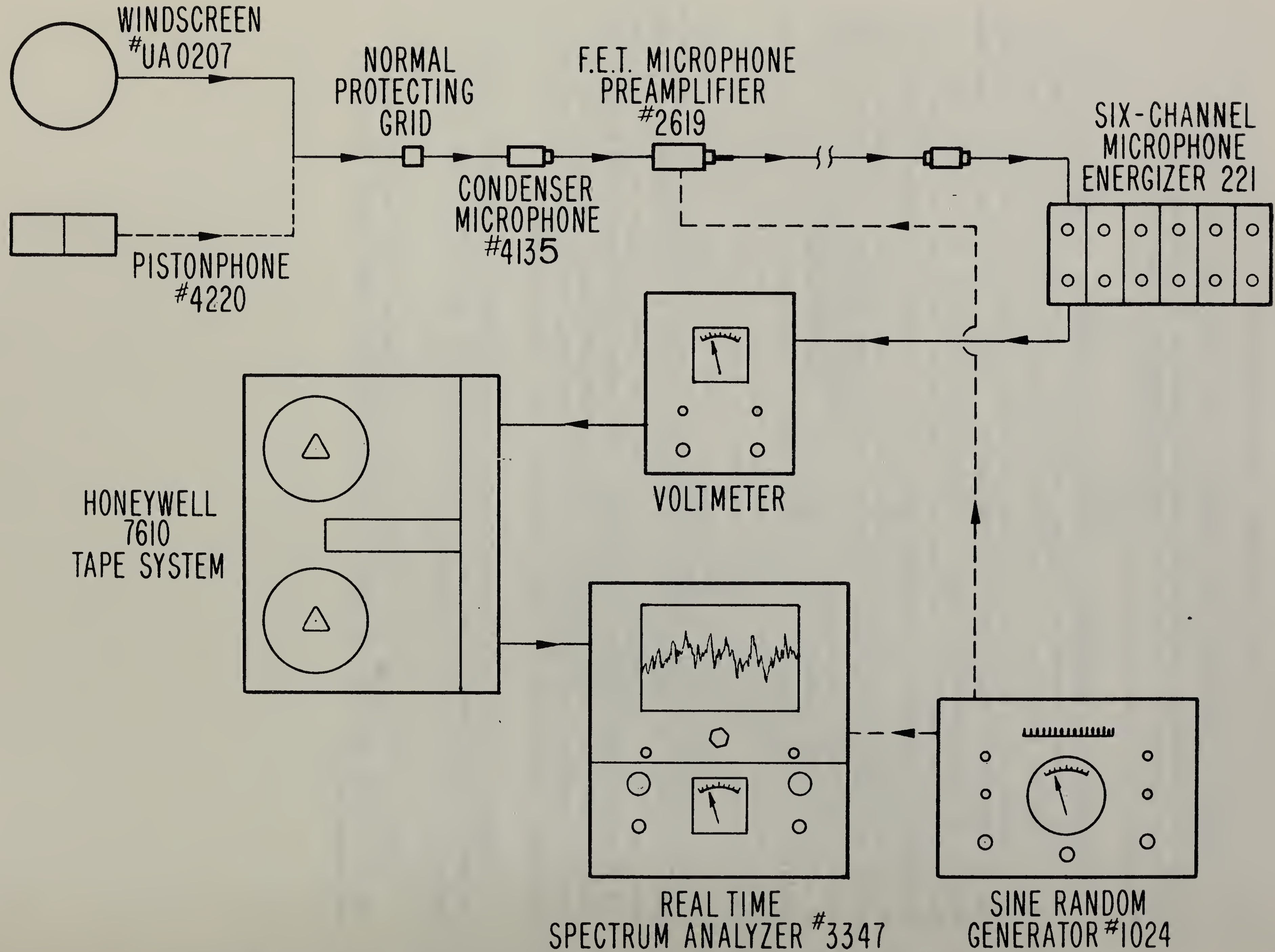

FIG.9 – DATA ACQUISITION & RECORDING SYSTEM

Figure 10. Overall view of the microphone array with the test vehicle approaching. Six tripod mounted microphones at a height of 48 inches above the road surface are located along a perpendicular line to the vehicle path and are spaced between 6 feet and 130 feet from the centerline of vehicle travel.

Figure 11. The interior of the mobile instrumentation van showing the instrument mounting arrangement. The operator is adjusting the gain of the signal conditioners to insure optimum signal-to-noise ratio.

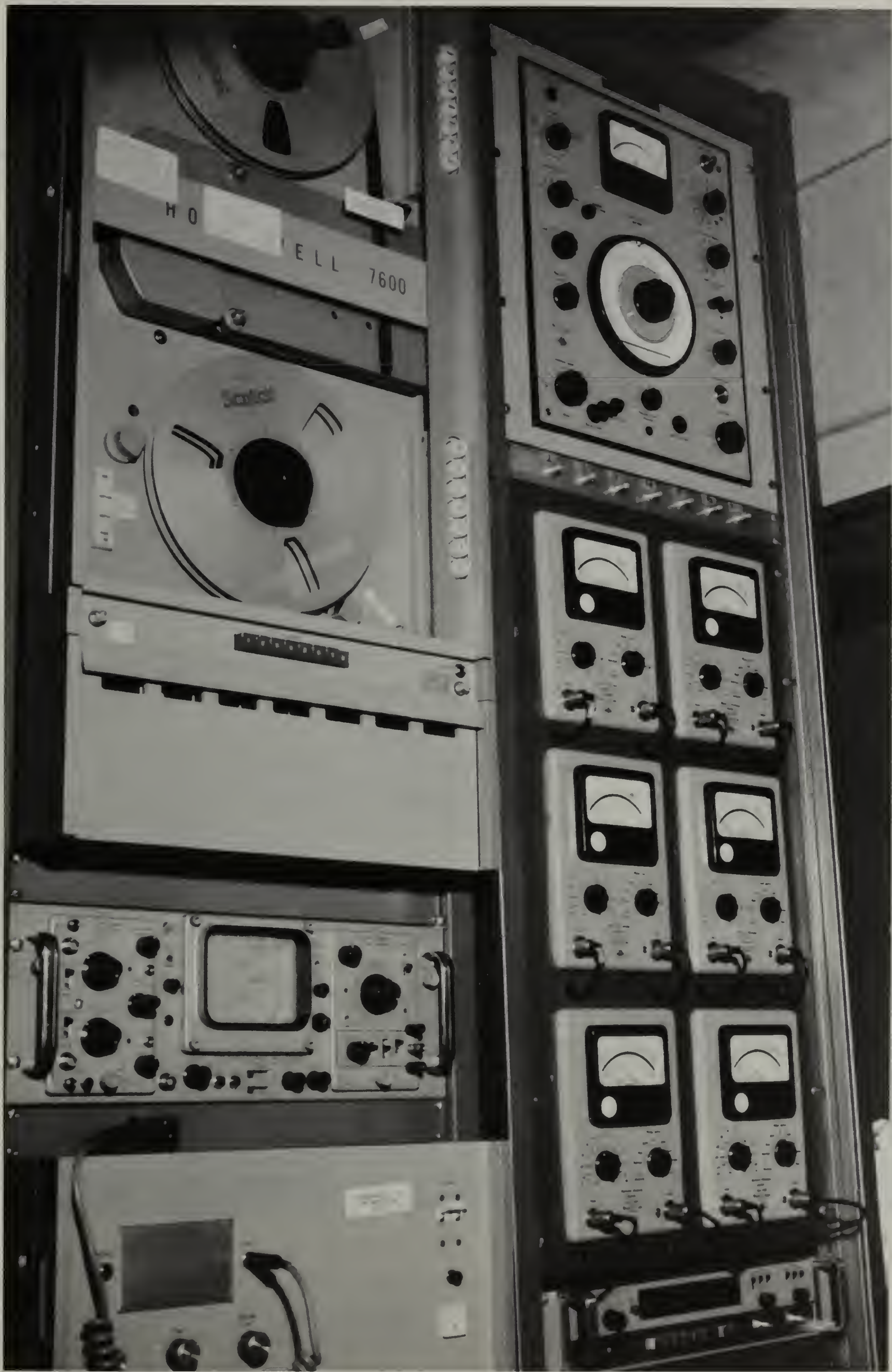

Figure 12. A detailed view of the recording and system checkout instrumentation. The left rack contains the seven channel F.M. tape recorder plus an oscilloscope. A signal generator, six signal conditioners, and a digital counter are housed in the remaining rack.

Calibration and system checkout are performed in two steps. The pistonphone produces a 124 dB sound pressure level (re 20 $\mu N/m^2$) at a frequency of 250 Hz. This single point calibration is used for microphone calibration in the field. Figure 13 shows a piston phone calibration being performed on one of the microphones. The system checkout involves running a frequency response of the system. To perform this checkout, the microphone cartridge is removed and replaced with an adapter which allows the sine-random signal generator to be coupled into the system. The sine-random generator is capable of producing wide band "pink noise" which is random noise weighted at -3 dB per octave. When a display unit, such as a real-time spectrum analyzer is coupled to the output terminals of the tape recorder, a flat frequency response can be observed. In general a lack of low frequency response is indicative of overloading of an amplifier and a lack of high frequency response is indicative of an amplifier failure. This operation also establishes the integrity of all connecting cables. During actual testing the real-time analyzer is used to provide some data with which to judge the progress of the testing prior to the later reduction and analysis of the data on the computer. The real time analyzer in its mounted configuration is shown in Figure 14.

The instrumentation van in its field configuration is shown in Figure 15.

Brief descriptions of the instruments are contained in Appendix A. Reference to the schematics provides an understanding of the contribution of each instrument to the overall system.

Once the data for a given period (probably a week) have been recorded, the analog tapes will be returned to NBS for reduction and analysis. Figure 16 defines the equipment which will be utilized for analysis purposes. Each tape is played back, a channel at a time, through the real-time analyzer. The interface-coupler, which is necessary to make the real-time analyzer and the Raytheon computer compatible, performs three basic functions in addition to serving as buffer storage for the data. It recognizes timing signals which have been laid down on one track of the tape, commands the real-time analyzer to begin its analysis, then, once all the data has been analyzed in one-third octave bands, it stores the data and dumps it onto digital magnetic tape in formated form which is acceptable to the Univac 1108 computer at NBS. All manipulations and calculations will be performed on the 1108 with graphical plots being generated by the Calcomp plotter system.

This instrumentation system provides for efficient data acquisition and data handling for the thousands of data points generated for each truck passby.

Figure 13. The pistonphone, which delivers a 124 dB sound pressure level at 250 Hz, is shown being coupled to the microphone for the one-point calibration.

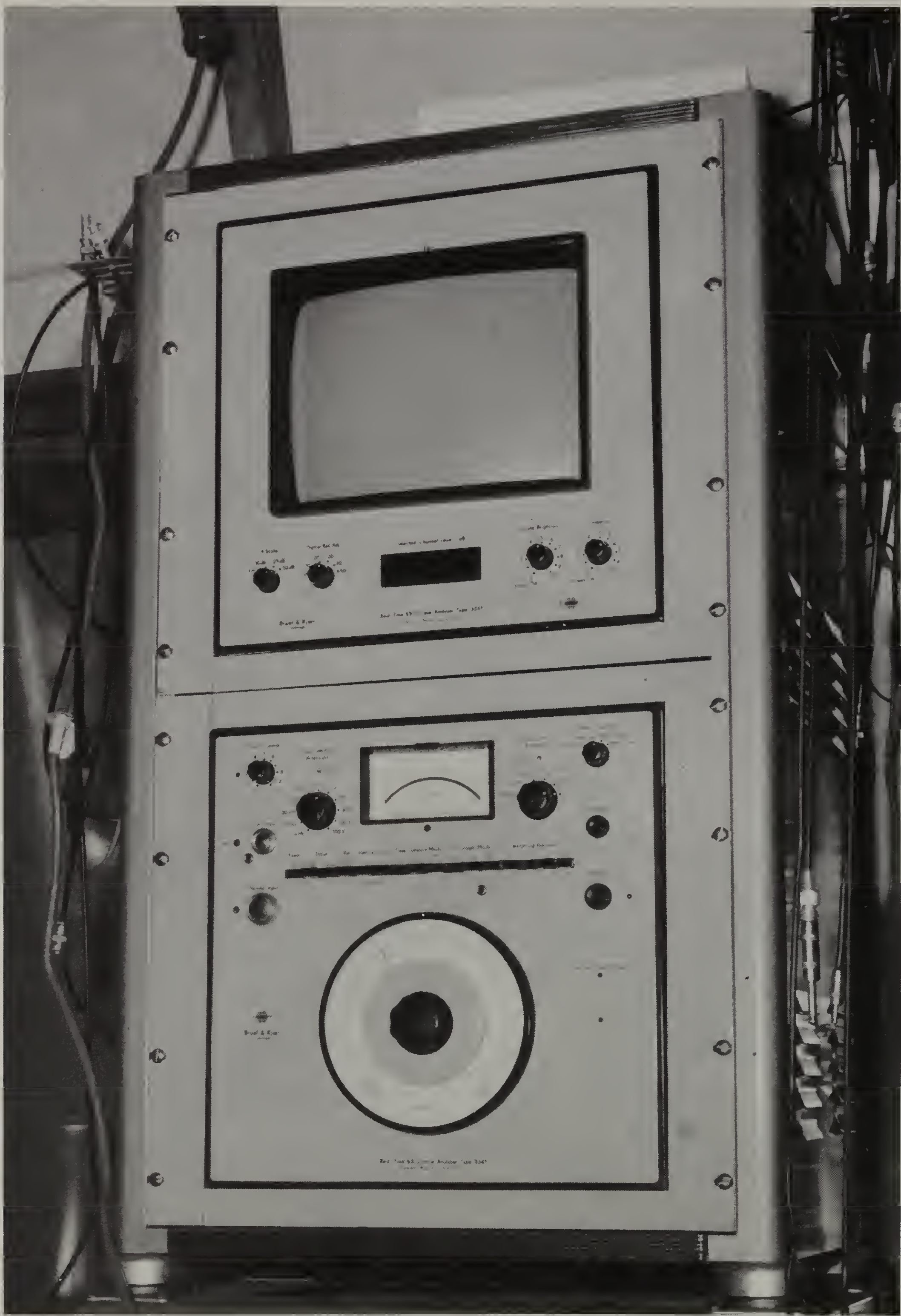

Figure 14. A view of the real time spectrum analyzer showing both the amplifier-filter section and the CRT display unit.

Figure 15. The mobile instrumentation van is shown in its field location. The wires strung on stakes in front of the truck are the signal wires between the microphone array and the recording facility within the van.

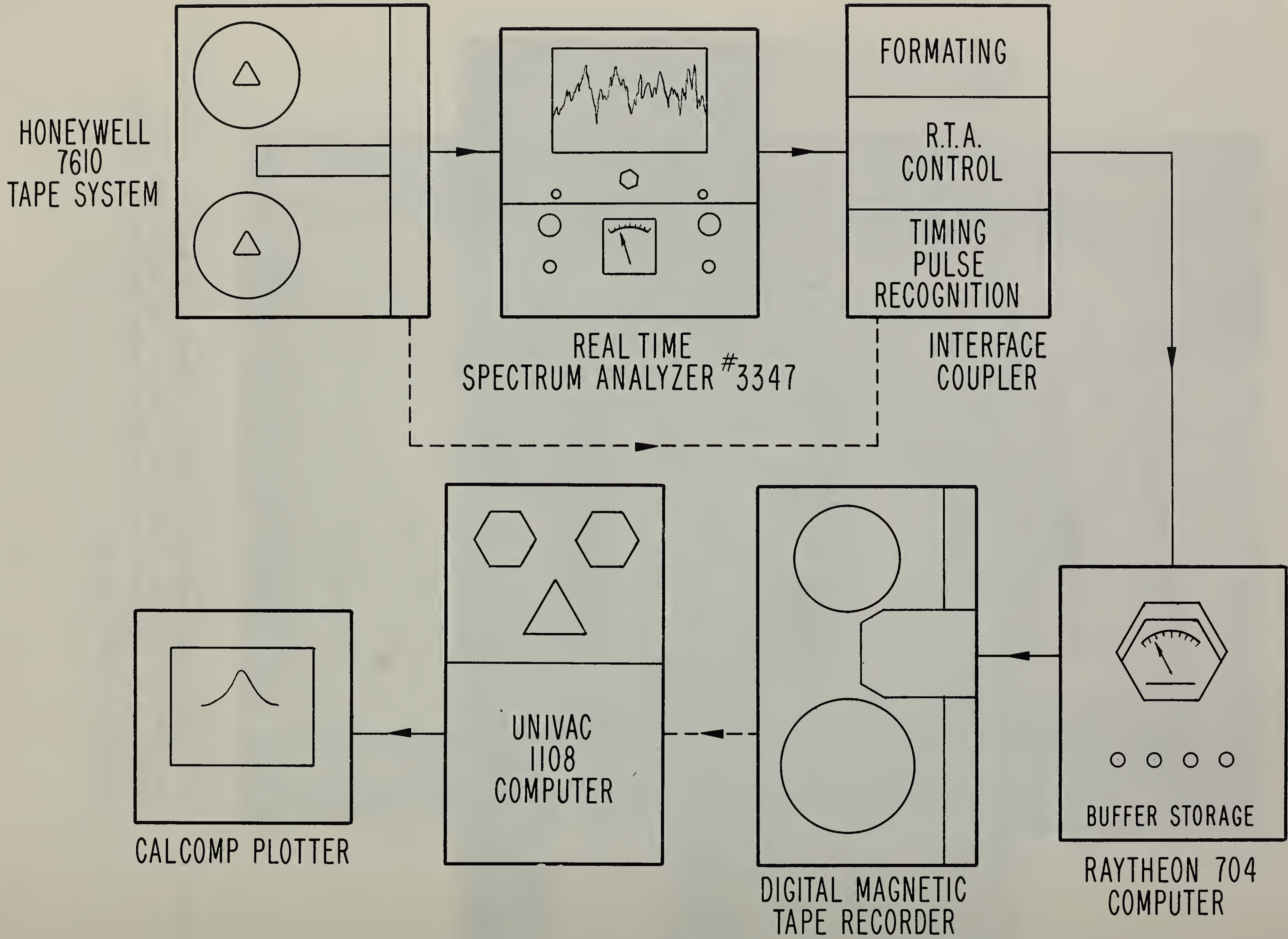

FIG. 16–DATA ACQUISITION & RECORDING SYSTEM

b. Position-Velocity Sensing System

The photosensor system for the determination of truck position with time during each run has been designed. A prototype model was initially built and tested. Following modifications to improve the response, sensitivity, and reliability of the system, final design was completed and fabrication begun. The final version, mounted on a tripod and battery operated, is shown in Figure 17. The photo detector is located directly behind the opening in the integrating sphere which is directly attached to a mini-box which houses the operational electronics.

In addition to position information, the system provides the data necessary for the calculation of instantaneous velocity. Since the photosensors are placed a known distance apart, once the time for travel between any two units has been recorded, velocity can be calculated.

The photosensor reacts to a traversing light beam by producing an appropriate signal which can be recorded on the direct record channel of the tape recorder. In addition, the first sensor which the truck passes is designed to interface with the Honeywell 7610 tape system so that the light beam hitting the first sensor will command the tape transport and record electronics to turn on. When the second sensor responds, the tape system will be up to speed and data can be taken. The final photosensor commands the tape system to stop.

Appendix C contains a detailed technical discussion of the photosensor, start-stop circuitry, and line amplifiers as well as schematics or block diagrams for each.

2.6 Feasibility Testing and Results

Once the test matrix had been finalized, there remained the necessity for the development of an optimum measurement methodology. The major objectives of the test program -- (1) peak A-weighted sound level for each microphone location, (2) 1/3-octave spectrum analysis of all data, (3) directionality information on truck tire noise, and (4) investigation of the noise generation characteristics of truck tires -- required a properly oriented microphone array to insure all necessary data would be obtained.

Rather than arbitrarily establish a test array and test conditions, a feasibility test program was devised to answer some of the questions which required answers prior to the finalization of the test design.

Figure 17. A closeup of the photosensor shows the $\pm$ 18 volt battery pack and the tripod-mounted photodetector. The minibox contains the electronics while the integrating sphere houses the photodetector.

What horizontal spacing of microphones should be utilized? At what height above the road surface should the microphones be placed? Is vertical directionality important? How repeatable are the data at each microphone location for a given set of test conditions? What effect does grass have on the attenuation of sound generated by truck tires? What signal amplification is necessary to assure optimum signal-to-noise ratio? Is there a noticeable difference in sound level with truck windows open or closed? What are the deceleration characteristics of the test vehicles? What is the possibility of running two surfaces on the same passby?

Once these questions had been answered, an optimum test program could confidently be established. Decisions were based on the evaluation of peak A-weighted sound level measurements taken during the feasibility test program. The loaded test truck fitted with representative "quiet" and "noisy" tires at low and maximum speed was tested. The "quiet" tire chosen was the General HCR while the Firestone T-200 cross-bar tire was the "noisy" choice. The path between the truck tire noise and the microphone array was concrete, asphalt, and a grassy field. Initially, electrical power was available only at the center of the runway; therefore, the maximum obtainable speed was 50 mph.

Basically five different microphone arrangements were tested with a minimum of two passbys at each of the two test speeds -- 30 and 50 mph. The microphone arrays were as follows:

1. Microphone Height - 60 in.
   Horizontal Spacing - 6 ft - 18 ft - 25 ft - 50 ft - 100 ft - 200 ft
2. Microphone Height - 50 in.
   Horizontal Spacing - 6 ft - 18 ft - 25 ft - 50 ft - 100 ft - 200 ft
3. Microphone Height - 38 in.
   Horizontal Spacing - 6 ft - 18 ft - 25 ft - 50 ft - 100 ft - 200 ft
4. Microphone Height - 6 in. - 18 in. - 25 in. - 50 in. - 96 in.
   Horizontal Spacing - 6 ft - 18 ft - 25 ft - 50 ft - 100 ft
5. Microphone Height - 50 in.
   Horizontal Spacing - 6 ft - 18 ft - 30 ft - 43 ft - 81 ft - 131 ft

These were the locations with the following exceptions. When the microphones were in the grass, only five microphones were utilized because the 200 foot location would have been hidden behind a small hill. During these tests the truck travelled on the concrete surface in the far lane on the east side of the runway. When the concrete test is referred to, microphones No. 1 through 5 were located on the concrete with microphone No. 6 located in the grass (runway width - 150 feet). The truck travelled in the far lane on the northwest side of the runway for both the concrete and asphalt testing. At the asphalt test section there existed a cross runway which provided more than the normal runway width of 150 feet and thus all microphones were located on the hard surface.

Truck passbys on both surfaces were recorded for later analysis. The analysis was performed by playing back the recorded passbys a channel at a time through a real time analyzer. At the beginning of each passby the "max. hold" button was depressed on the analyzer thus holding the maximum sound pressure level in each 1/3-octave band as well as peak readings for the various weightings (A, B, C, D, and linear). (It should be pointed out that the spectrum produced on the CRT display by max. hold selection represents the peak in each 1/3-octave band regardless of the time at which the peak occurred.) The peak A-weighted sound level was read from the digital display. The results of the feasibility testing are presented on semi-logarithmic plots of peak A-weighted sound level versus distance with distance plotted on the log scale. These are Figures 18 through 34.

Figure 18 shows that the difference in sound pressure level generated by truck tires with the test truck windows open and with its windows closed was not significant enough to warrant the discomfort of the driver of the test vehicle. The maximum difference at any microphone location was 2 dB(A) with the average difference being less than 1 dB(A).

The evaluation of the influence of microphone height as a variable was investigated with microphones at 60 inches, 50 inches, and 38 inches above the surface. Figures 19, 20, 21, (Firestone T-200 over concrete and grass) 29, 30, (Firestone T-200 over asphalt) 24, 25, 26, (HCR over concrete and grass) and 32 and 33 (HCR over asphalt) provide the data for evaluation of the height parameter. A review of the data shows that for the height range studied, the peak A-weighted sound level is little influenced by microphone height changes.

These plots also provide an insight into some of the other questions.

When any surface other than a hard reflecting surface exists between the produced sound and the microphone array, the peak A-weighted sound level is of less magnitude and in addition the slope falls off showing larger attenuation with distance. This is evident when a comparison is made between the concrete and grass test data for any test condition. It is further evidenced for the concrete surface by the drop in sound level at the 200 foot microphone which is in the grass. On the asphalt, where this microphone location is still on the hard surface, the data remain on the straight line.

These plots also show excellent repeatibility of the data at each microphone location for a given set of test conditions. This fact adds confidence to the decision (see below) to run a single pass at each of seven speeds rather than repeated runs at only a few speeds.

It is felt that truck tires produce a directional sound pattern. This is why the characteristic tire whine lingers on long after the truck has passed by. To investigate the importance of vertical directionality a microphone array was devised that would measure on a line drawn from the centerline of the truck lane through the 50 foot microphone at 50 inches above the roadway. This array provided information for heights ranging from 6 inches to 96 inches. The results show the existence of no difference between the data provided by this array and the arrays in which all of the microphones are at the same height above the ground.

Although microphone heights between ground level and eight feet had been investigated, there still existed a lack of knowledge of the effect for microphones extending higher than eight feet into the air. To answer this question a 50-foot pole test was devised. The pole was fabricated from 10 foot sections of electrical conduit. The 10 foot sections were connected using regular tee fittings. The microphones were placed 18 inches away from the pole on an "L" shaped piece of conduit extending from each tee. This placed microphones at 50, 40, 30, 20, and 10 feet above the surface. In addition, a microphone on a tripod at 50 inches height was placed at the base of the pole. The microphone array was located at the edge of the runway and was hoisted into place, held during the runs, then lowered with the assistance of a 65 foot cherry-picker. The test vehicle was the unloaded truck equipped with 50% worn Firestone T-200 tires. Due to the grooving in the center of the runway the truck ran past the array at a distance of 42 feet and 107 feet (first lane before and first lane after the grooves) as measured from the base of the array to the centerline of the truck lane.

Figures 35 and 36 present the results of the 50 foot pole test. The peak A-weighted sound levels measured during multiple runs at a given vehicle velocity were averaged* for each microphone location. Initially, these levels were plotted against the vertical height for each microphone. It was decided that the most practical way to discuss the data would be to look at the sound level (A-weighted) along a given angle. Thus the line-of-sight distance from the centerline of truck travel through a given angle was calculated and the bisection point on the pole array was noted. From these vertical heights (from ground level to angle intercept) the A-weighted sound levels were obtained by interpolation from the plot discussed above. The resulting A-weighted sound levels were then plotted against the line-of-sight distance (distance on a log scale). As can be seen from the graphs, there is little difference in the sound levels along the various angles.

The effect of various horizontal spacing was also studied (Figures 23, 28, 31 and 34). As expected, the far field data fell on a straight line and further established the fact that all of the microphones should be located on the hard surface.

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*The A-weighted sound levels were converted to power ratios, averaged, and then reconverted to A-weighted sound levels in decibels.

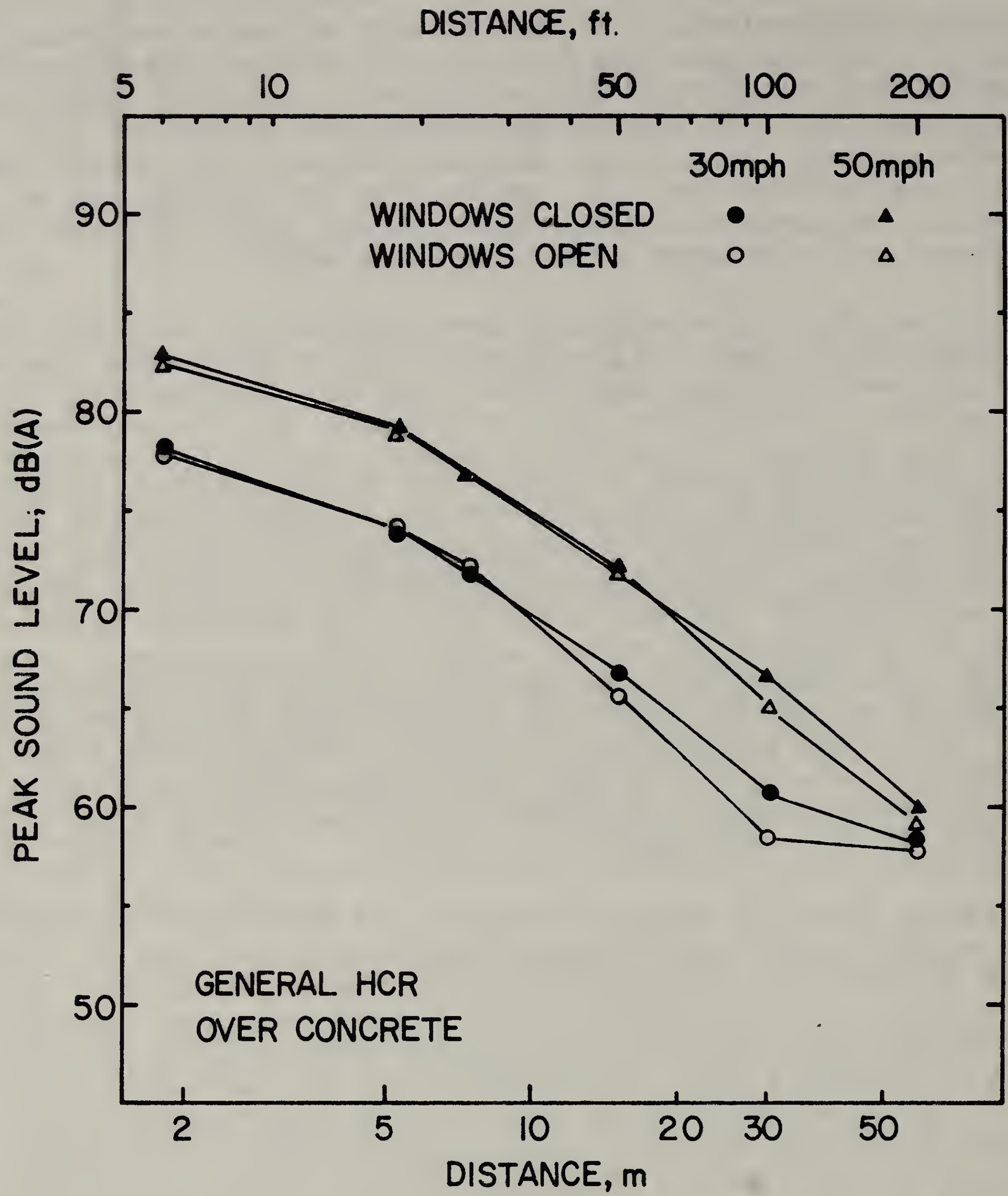

Figure 18. Effect of open and closed windows on the peak sound level. The microphone height was 50 inches. The test vehicle was the loaded truck with General HCR tires on a concrete surface.

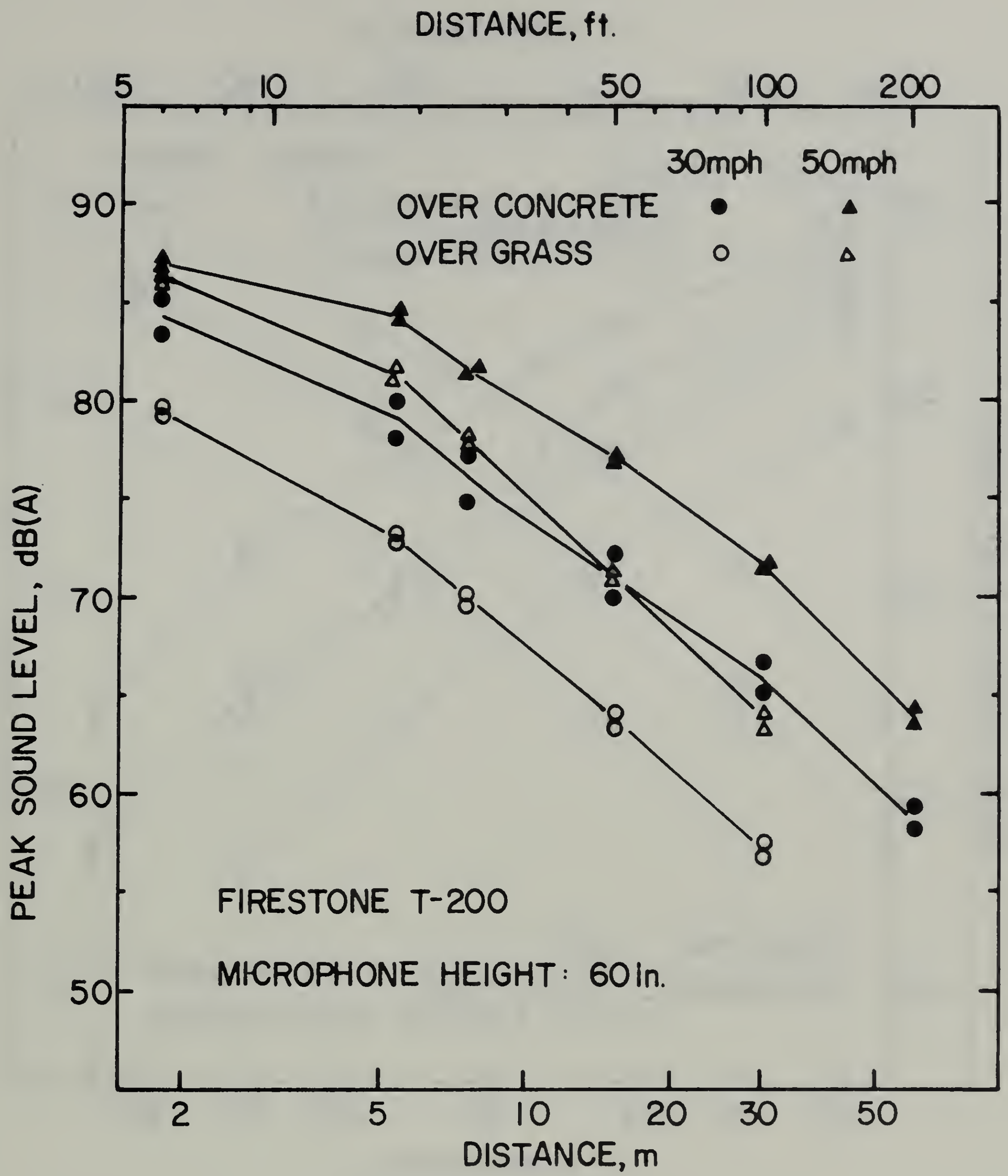

Figure 19. Peak sound levels generated by Firestone T-200 tires mounted on the loaded test vehicle as measured by an array of microphones located on a concrete surface and on grass. All microphones were at a height of 60 inches.

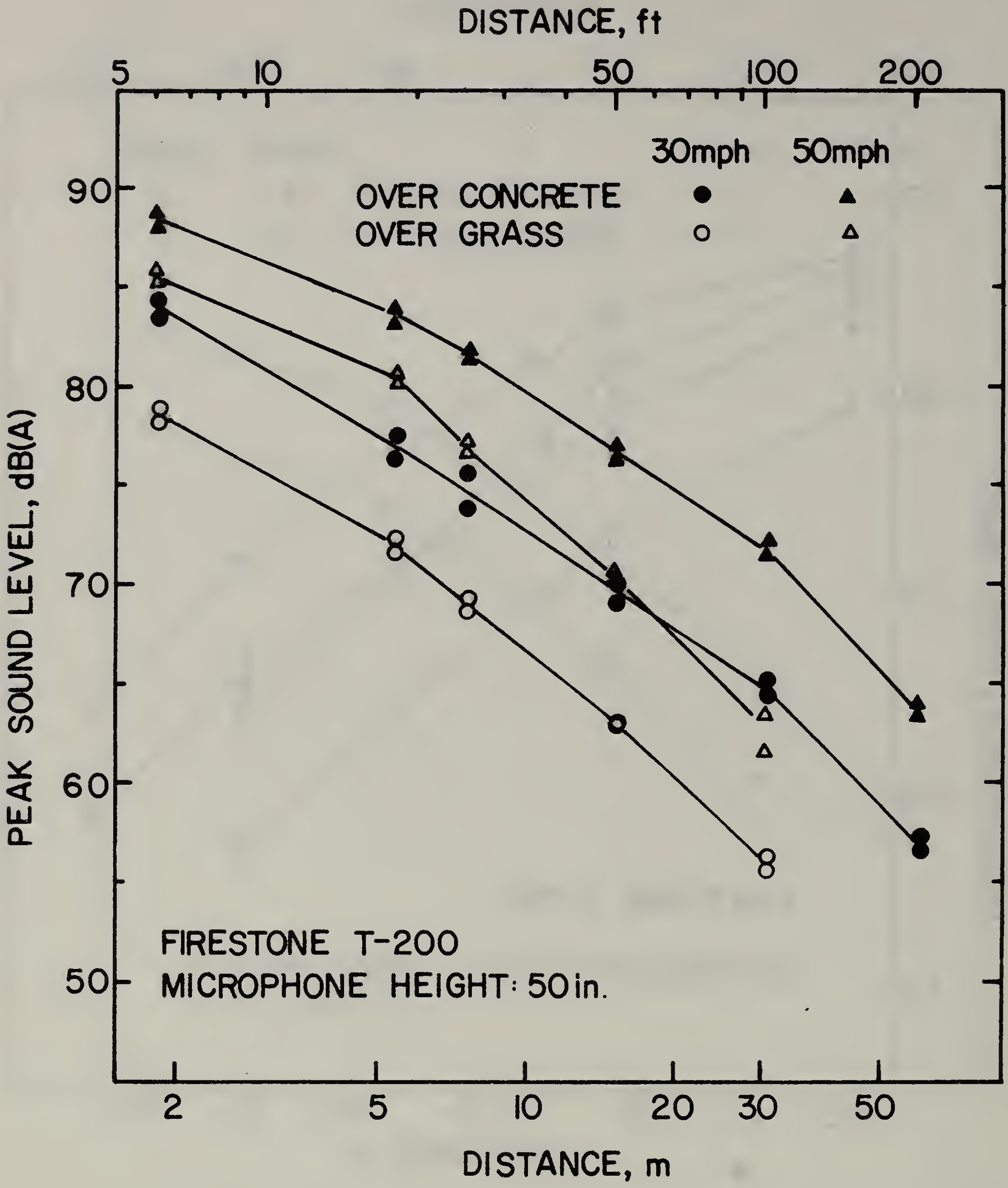

Figure 20. Peak sound levels generated by Firestone T-200 tires mounted on the loaded test vehicle as measured by an array of microphones located on a concrete surface and on grass. All microphones were at a height of 50 inches.

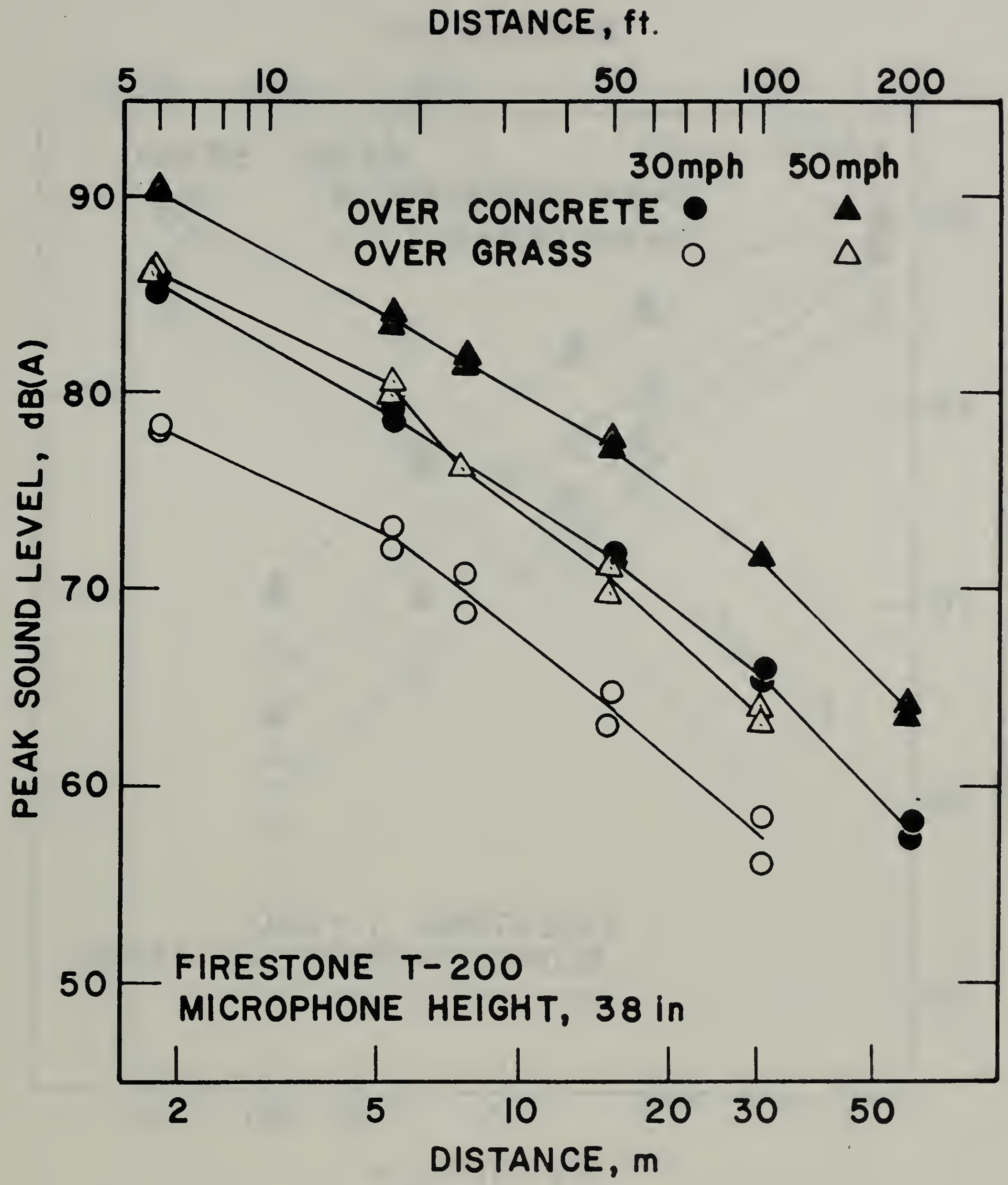

Figure 21. Peak sound levels generated by Firestone T-200 tires mounted on the loaded test vehicle as measured by an array of microphones located on a concrete surface and on grass. All microphones were at a height of 38 inches.

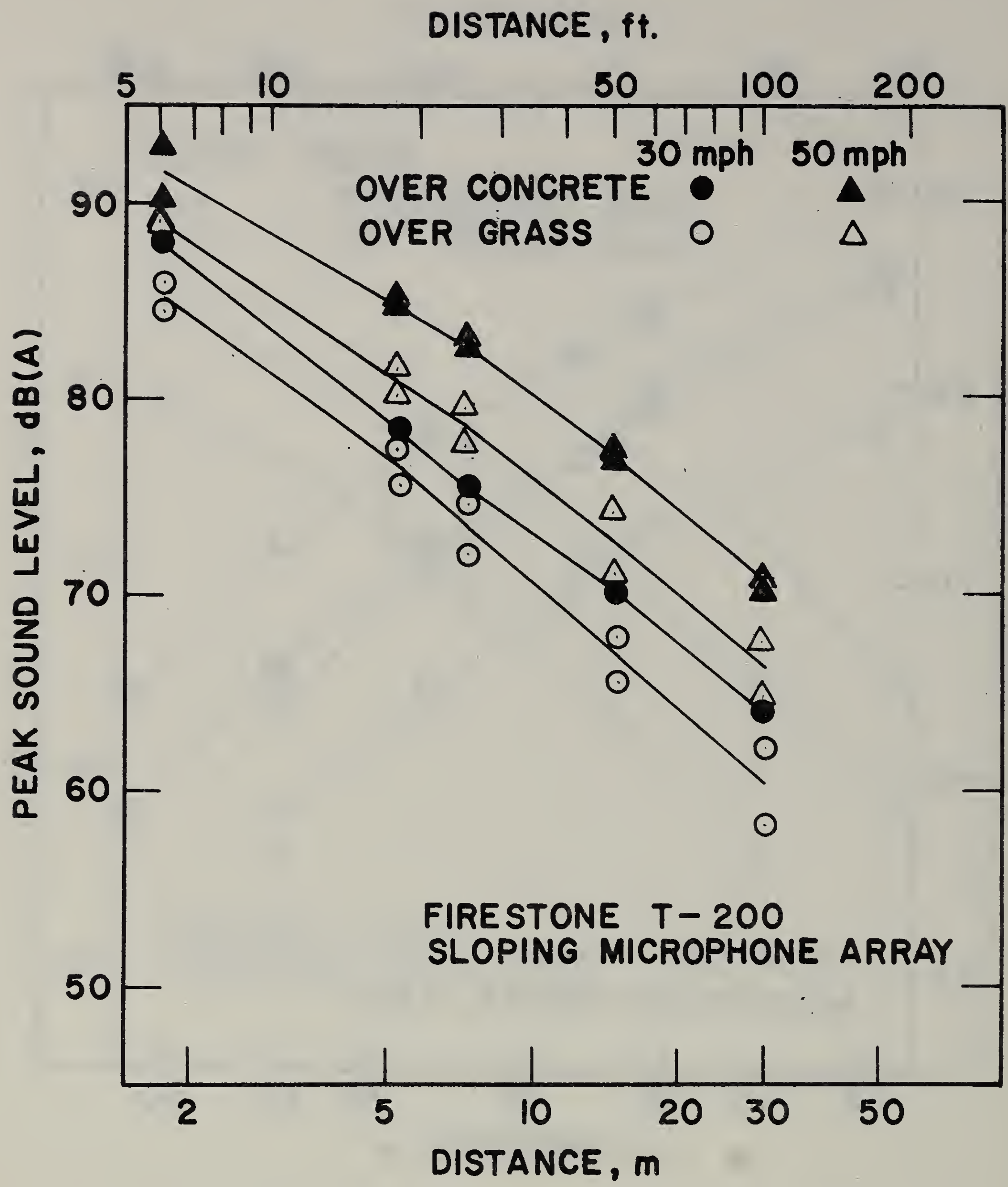

Figure 22. Peak sound levels generated by Firestone T-200 tires mounted on the loaded test vehicle as measured by an array of microphones located on a concrete surface and on grass. A sloping microphone array was utilized.

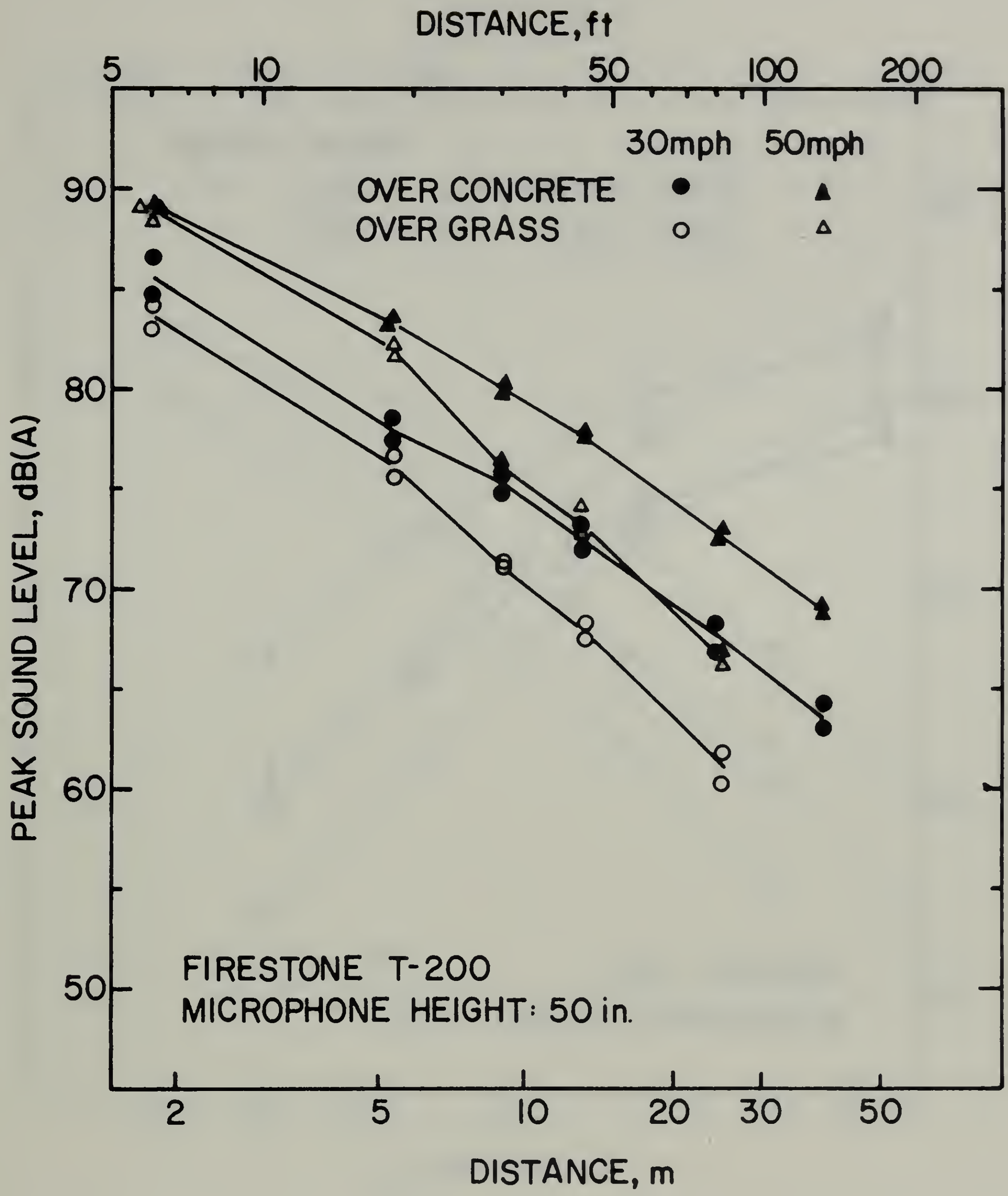

Figure 23. Peak sound levels generated by Firestone T-200 tires mounted on the loaded test vehicle as measured by an array of microphones located on a concrete surface and on grass. All microphones were at a height of 50 inches with various horizontal spacing.

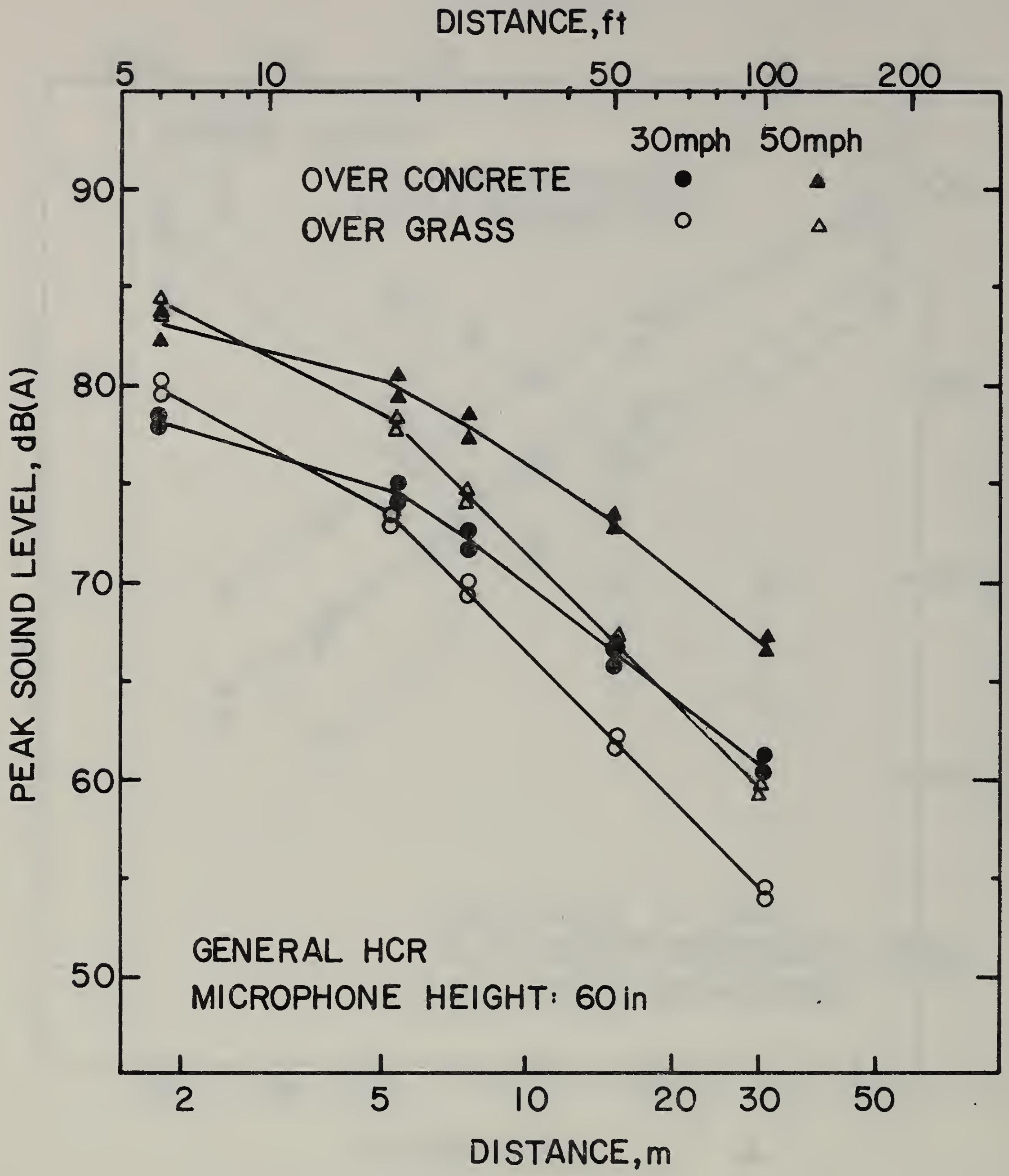

Figure 24. Peak sound levels generated by General HCR tires mounted on the loaded test vehicle as measured by an array of microphones located on a concrete surface and on grass. All microphones were at a height of 60 inches.

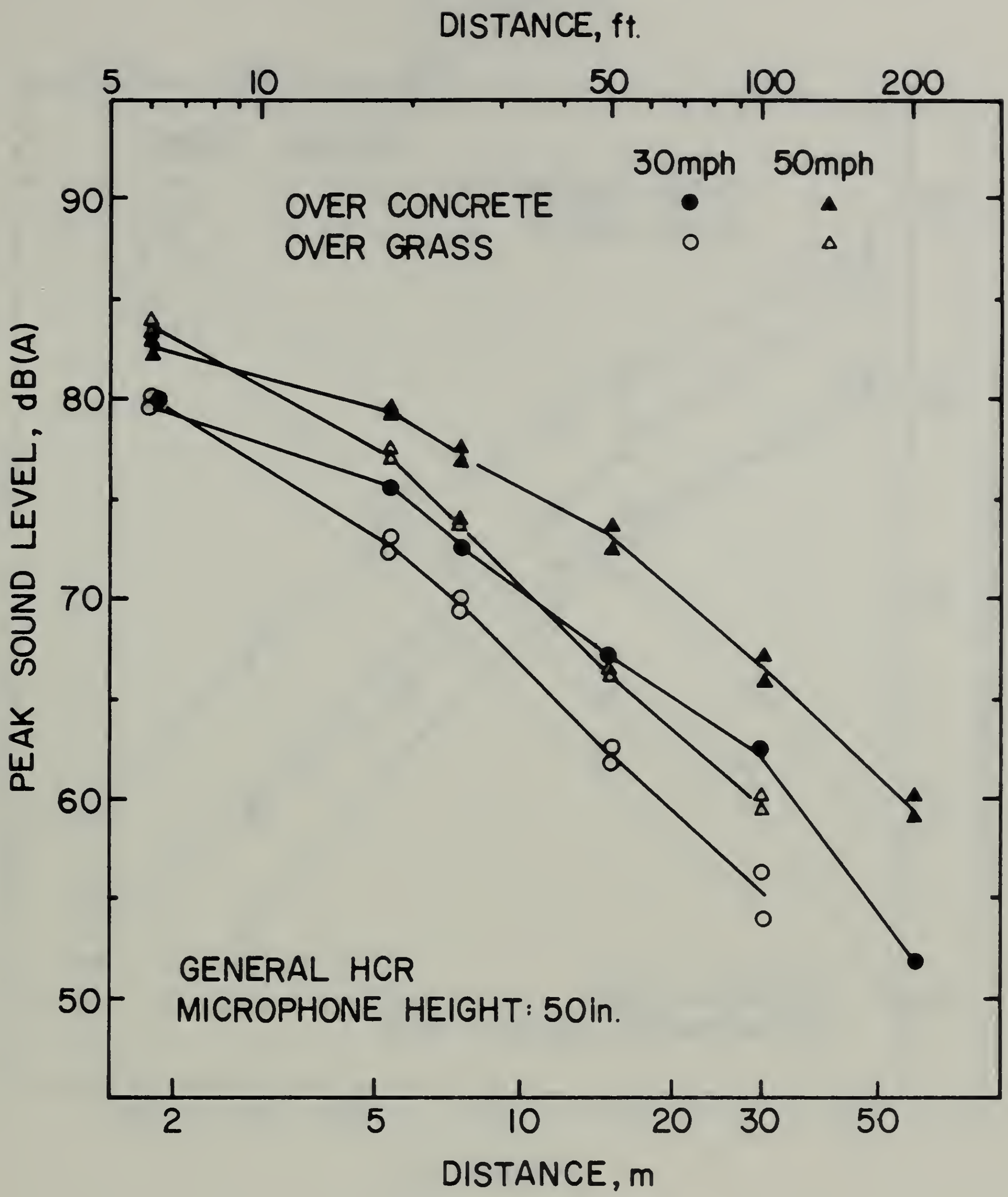

Figure 25. Peak sound levels generated by General HCR tires mounted on the loaded test vehicle as measured by an array of microphones located on a concrete surface and on grass. All microphones were at a height of 50 inches.

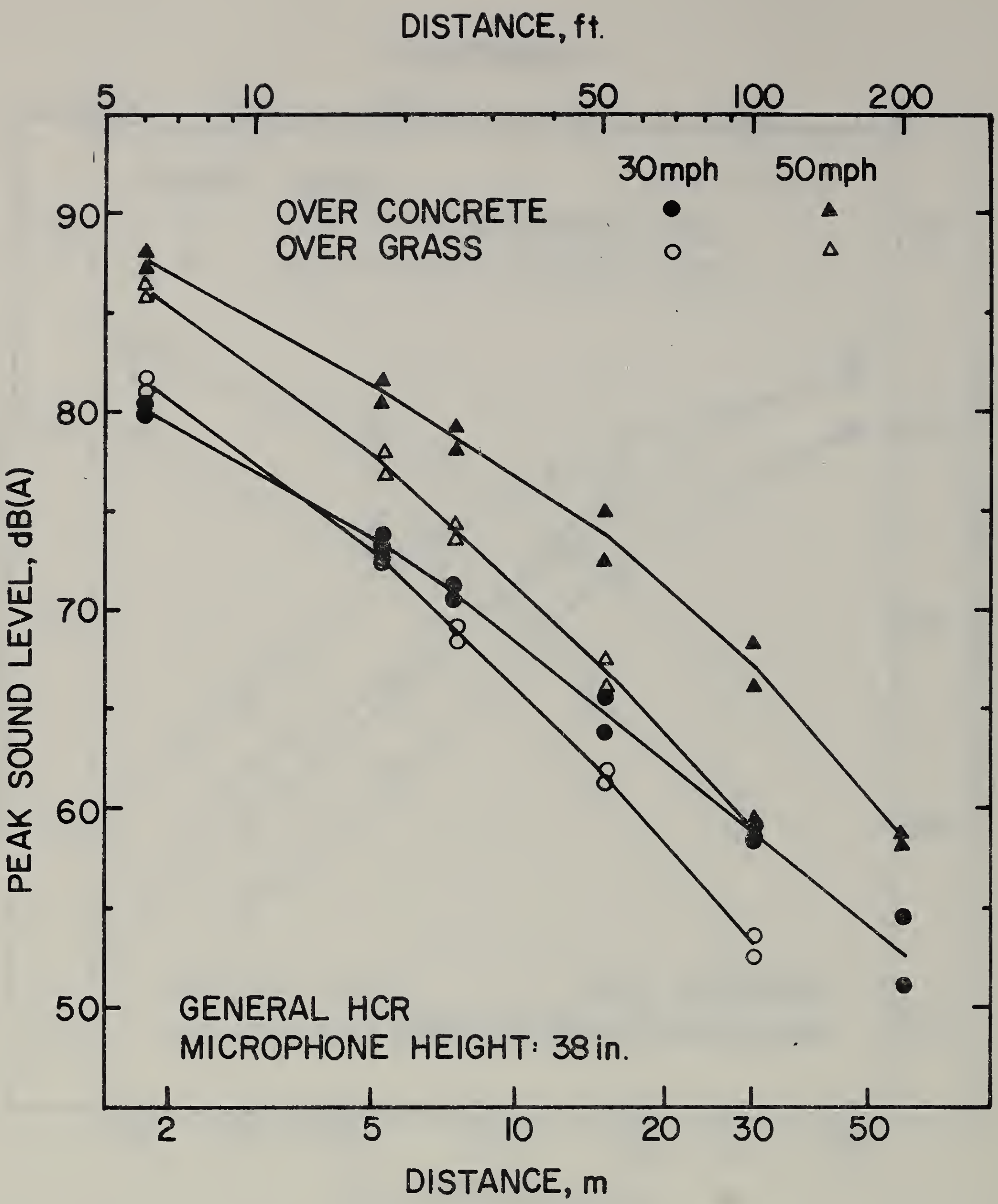

Figure 26. Peak sound levels generated by General HCR tires mounted on the loaded test vehicle as measured by an array of microphones located on a concrete surface and on grass. All microphones were at a height of 38 inches.

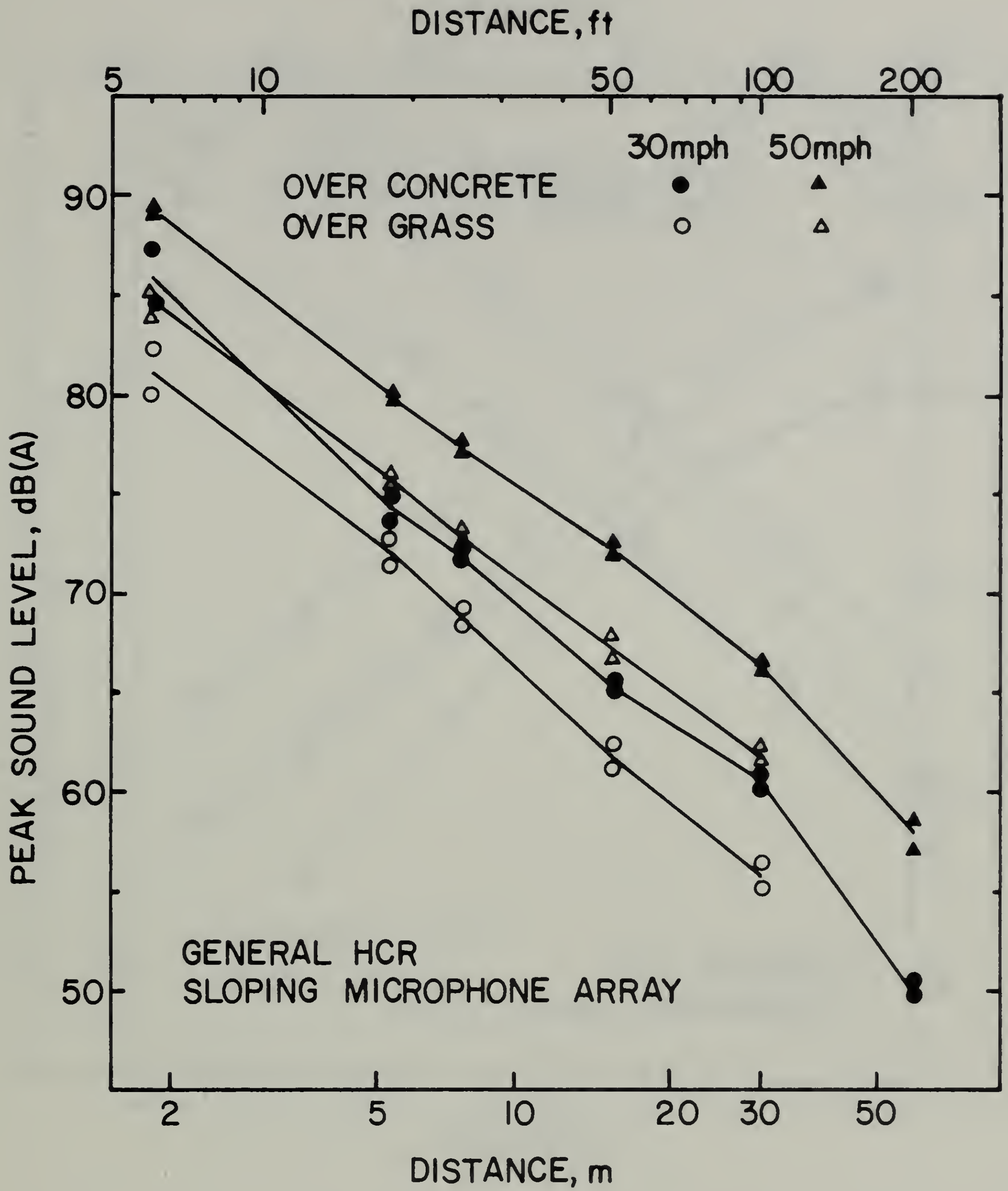

Figure 27. Peak sound levels generated by General HCR tires mounted on the loaded test vehicle as measured by an array of microphones located on a concrete surface and on grass. A sloping microphone array was utilized.

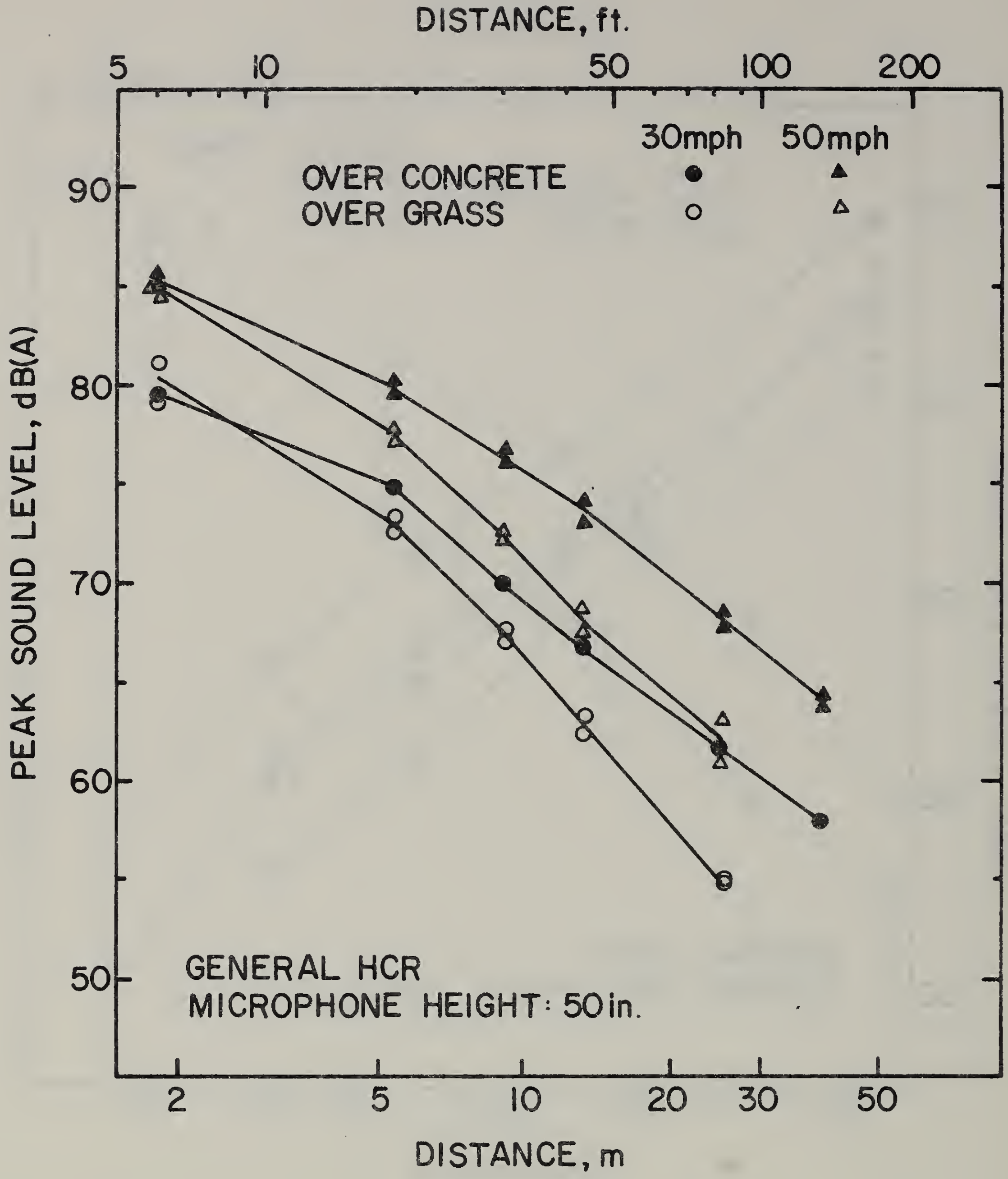

Figure 28. Peak sound levels generated by General HCR tires mounted on the loaded test vehicle as measured by an array of microphones located on a concrete surface and on grass. All microphones were at a height of 50 inches with various horizontal spacing.

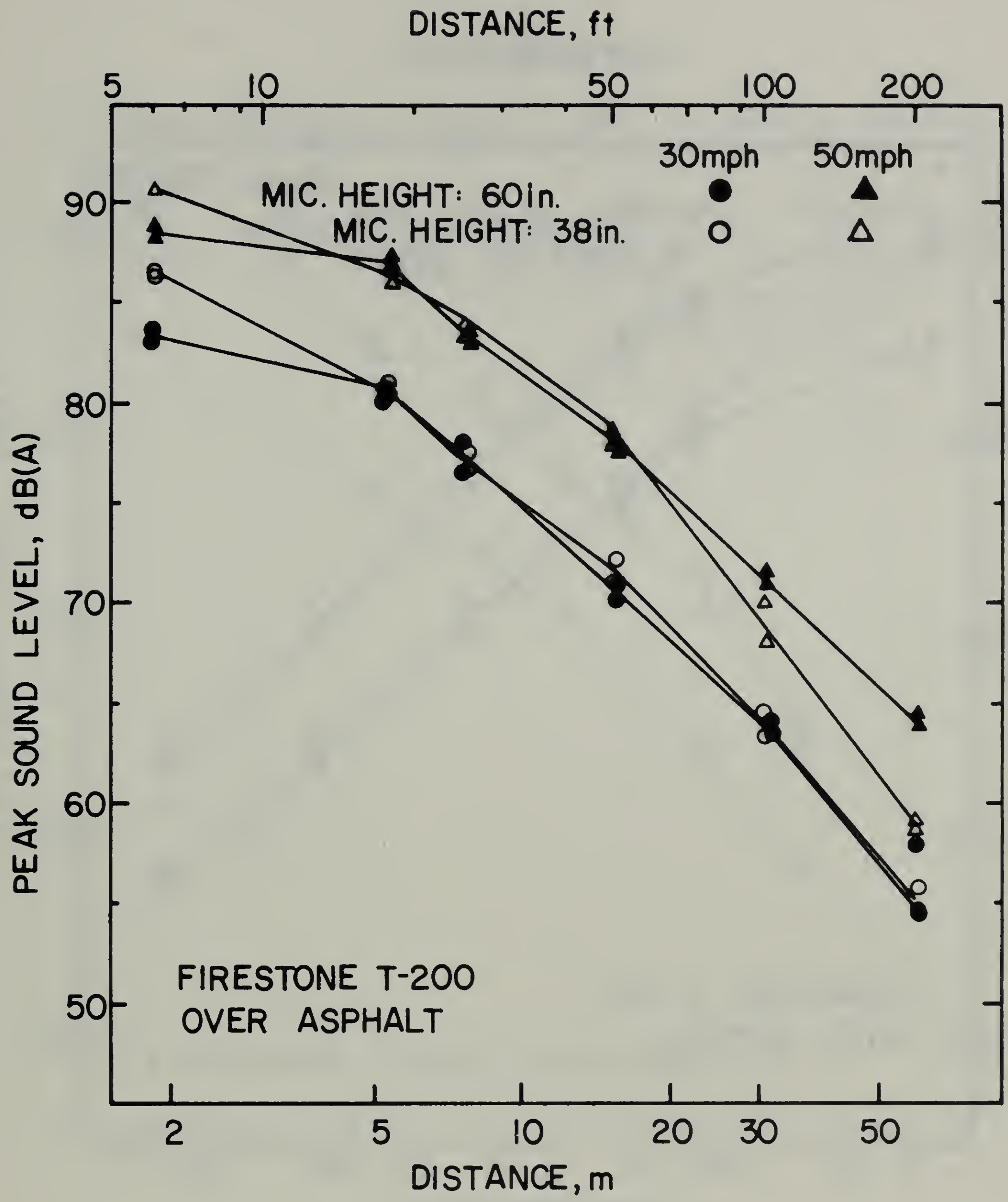

Figure 29. Peak sound levels generated by Firestone T-200 tires mounted on the loaded test vehicle as measured by an array of microphones located on an asphalt surface. Results of both the 60-inch and 38-inch microphone height condition are shown.

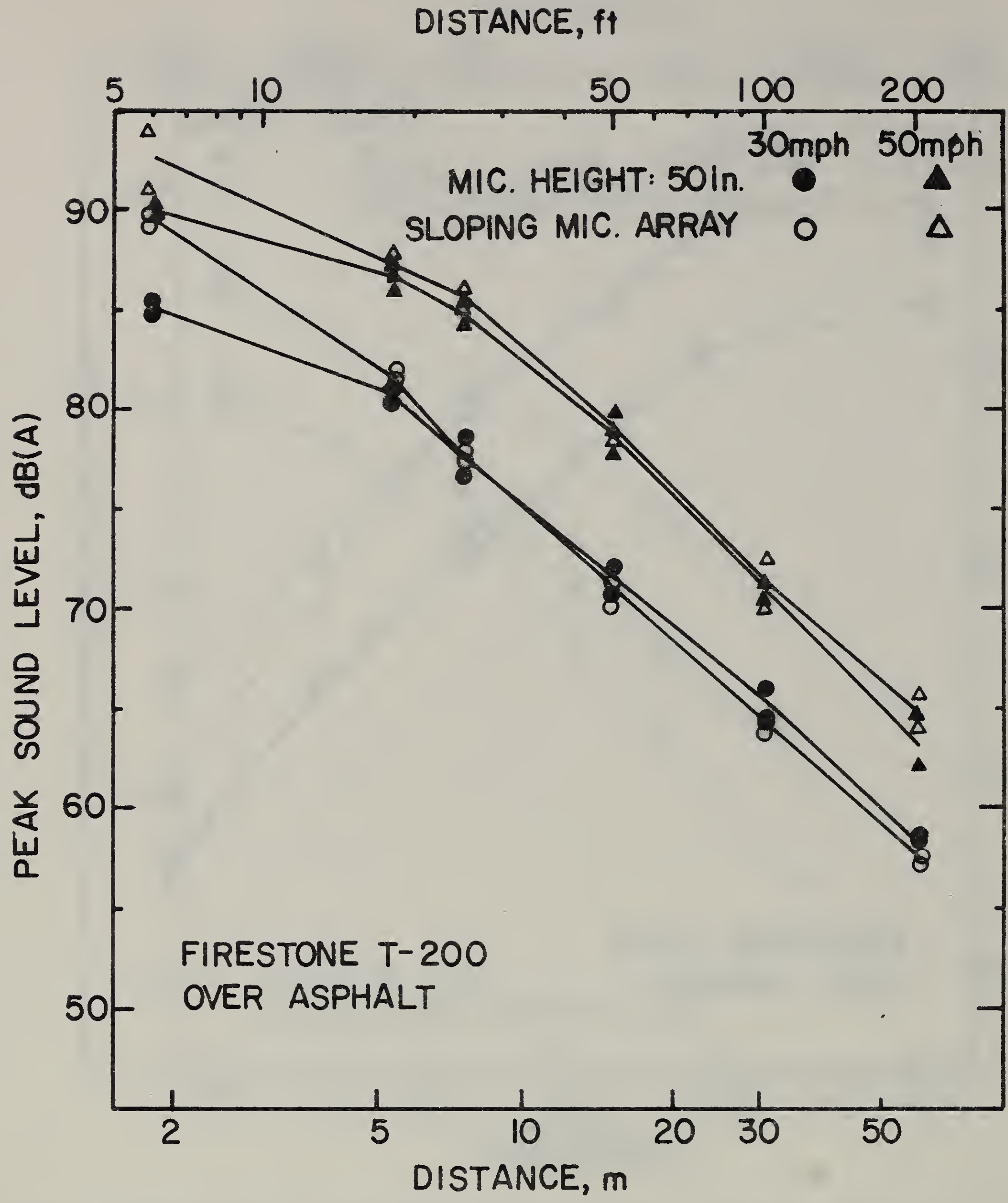

Figure 30. Peak sound levels generated by Firestone T-200 tires mounted on the loaded test vehicle as measured by an array of microphones located on an asphalt surface. Results of the 50-inch microphone height condition and the sloping microphone array are shown.

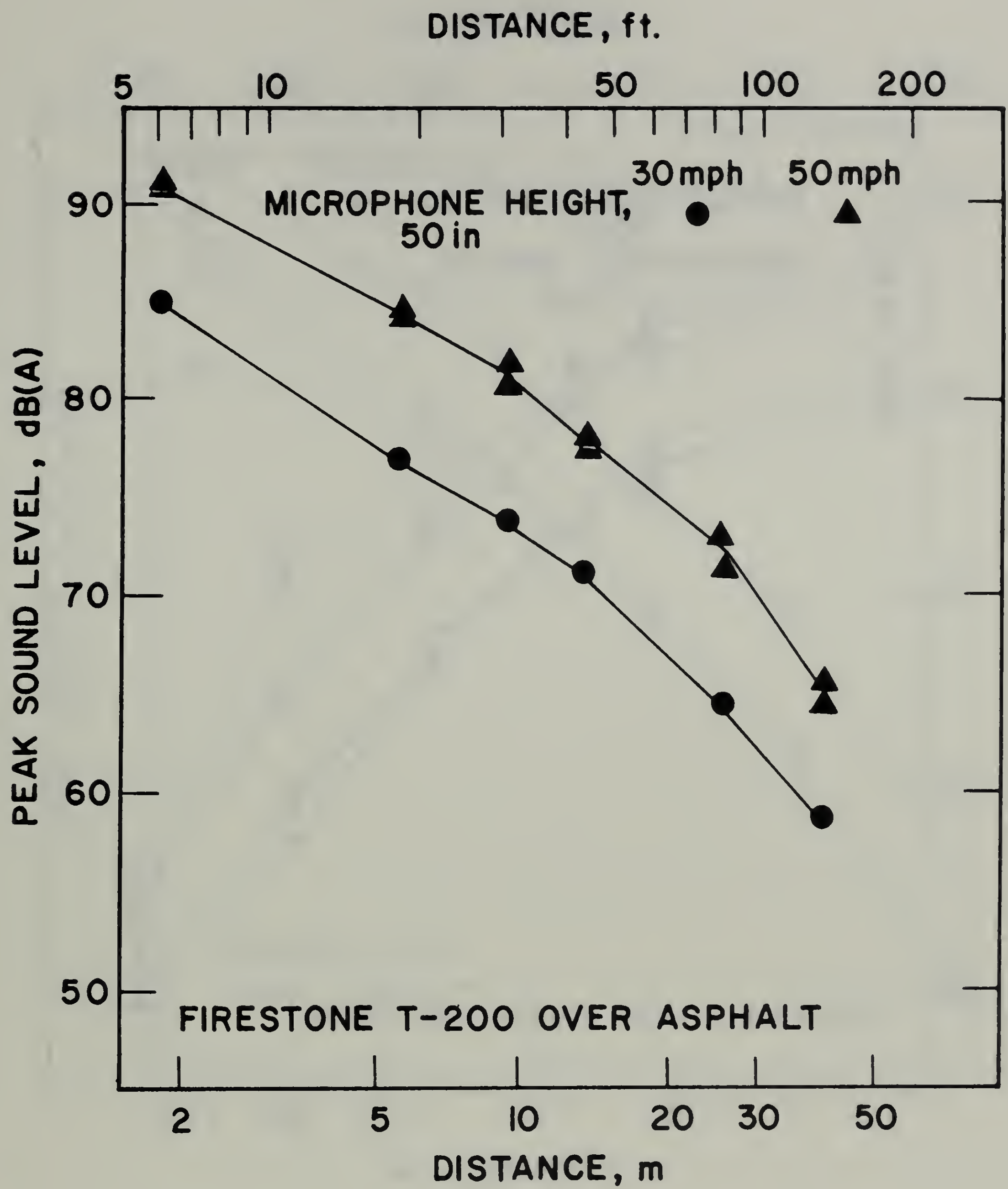

Figure 31. Peak sound levels generated by Firestone T-200 tires mounted on the loaded test vehicle as measured by an array of microphones located on an asphalt surface. All microphones were at a height of 50 inches with various horizontal spacing.

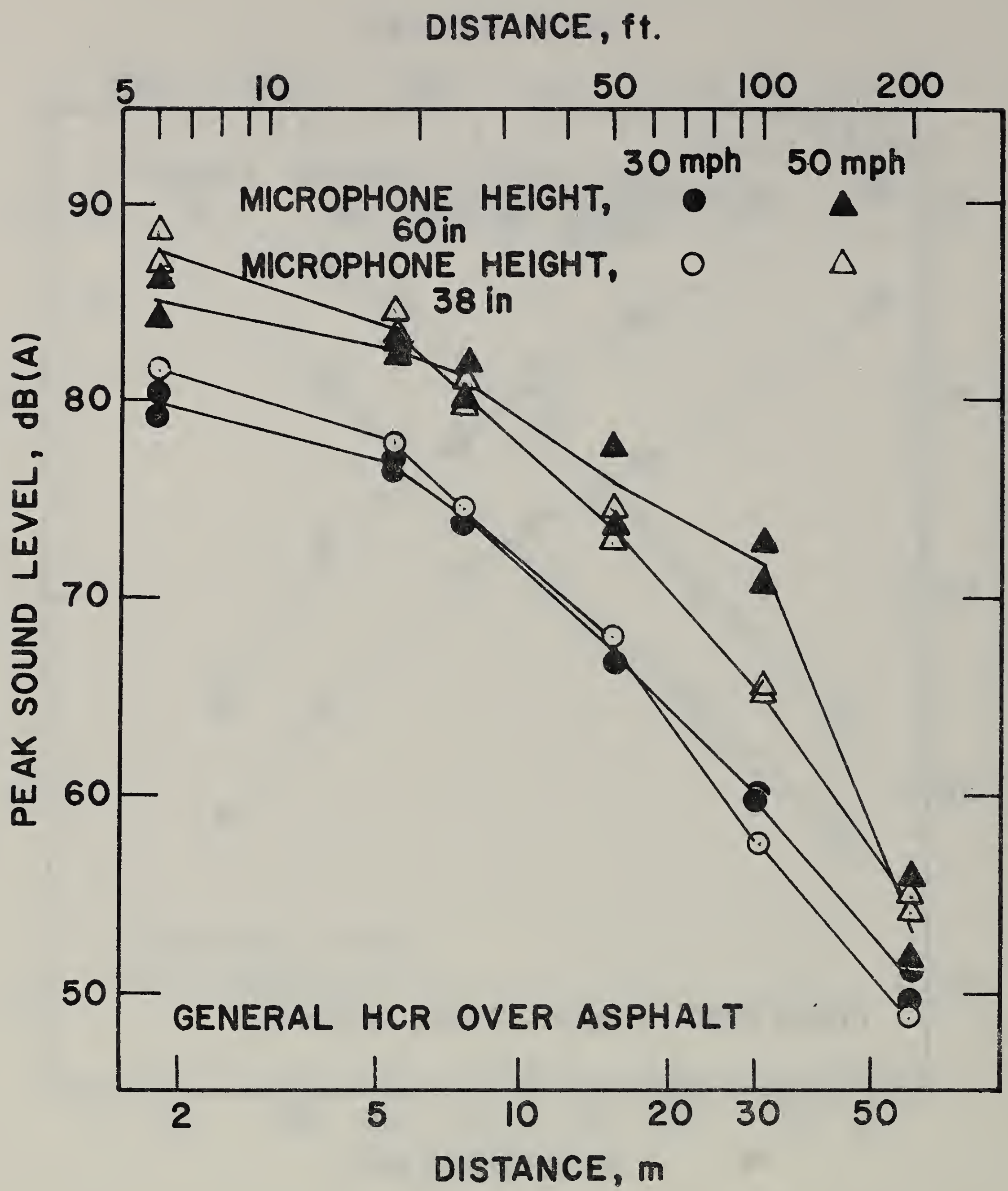

Figure 32. Peak sound levels generated by General HCR tires mounted on the loaded test vehicle as measured by an array of microphones located on an asphalt surface. Results of both the 60 inch and 38 inch microphone height condition are shown.

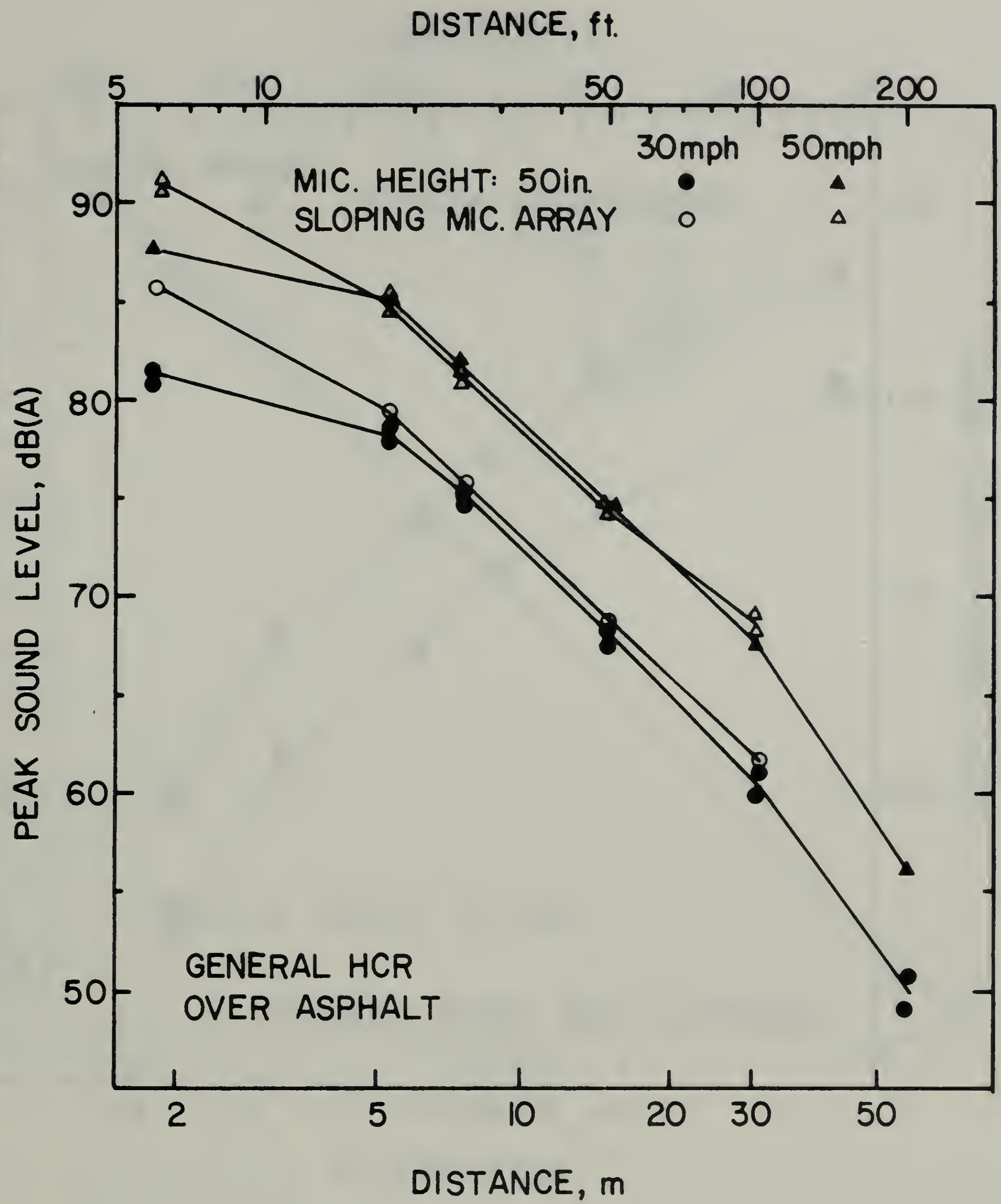

Figure 33. Peak sound levels generated by General HCR tires mounted on the loaded test vehicle as measured by an array of microphones located on an asphalt surface. Results of the 50 inch microphone height condition and the sloping microphone array are shown.

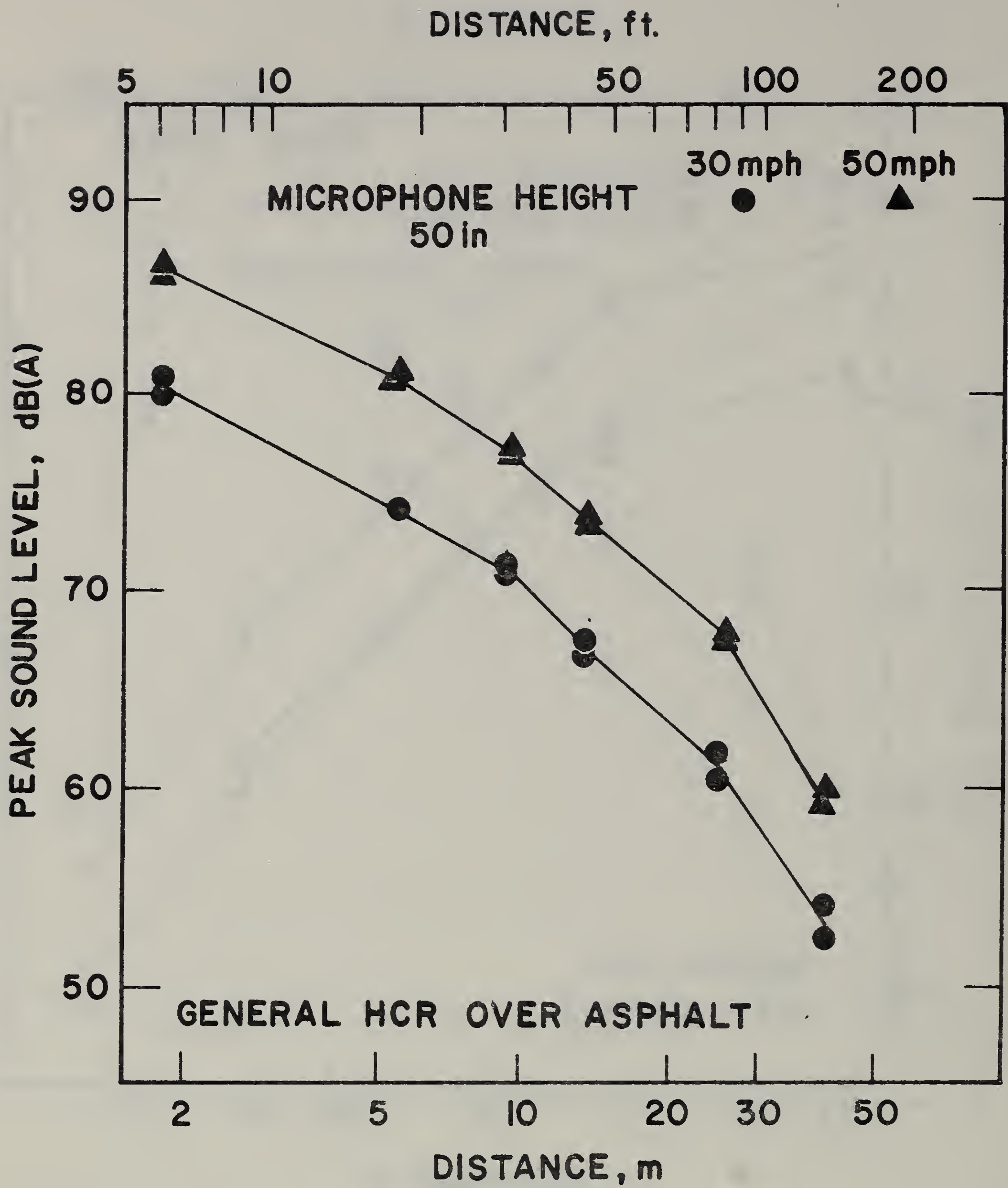

Figure 34. Peak sound levels generated by General HCR tires mounted on the loaded test vehicle as measured by an array of microphones located on an asphalt surface. All microphones were at a height of 50 inches with various horizontal spacing.

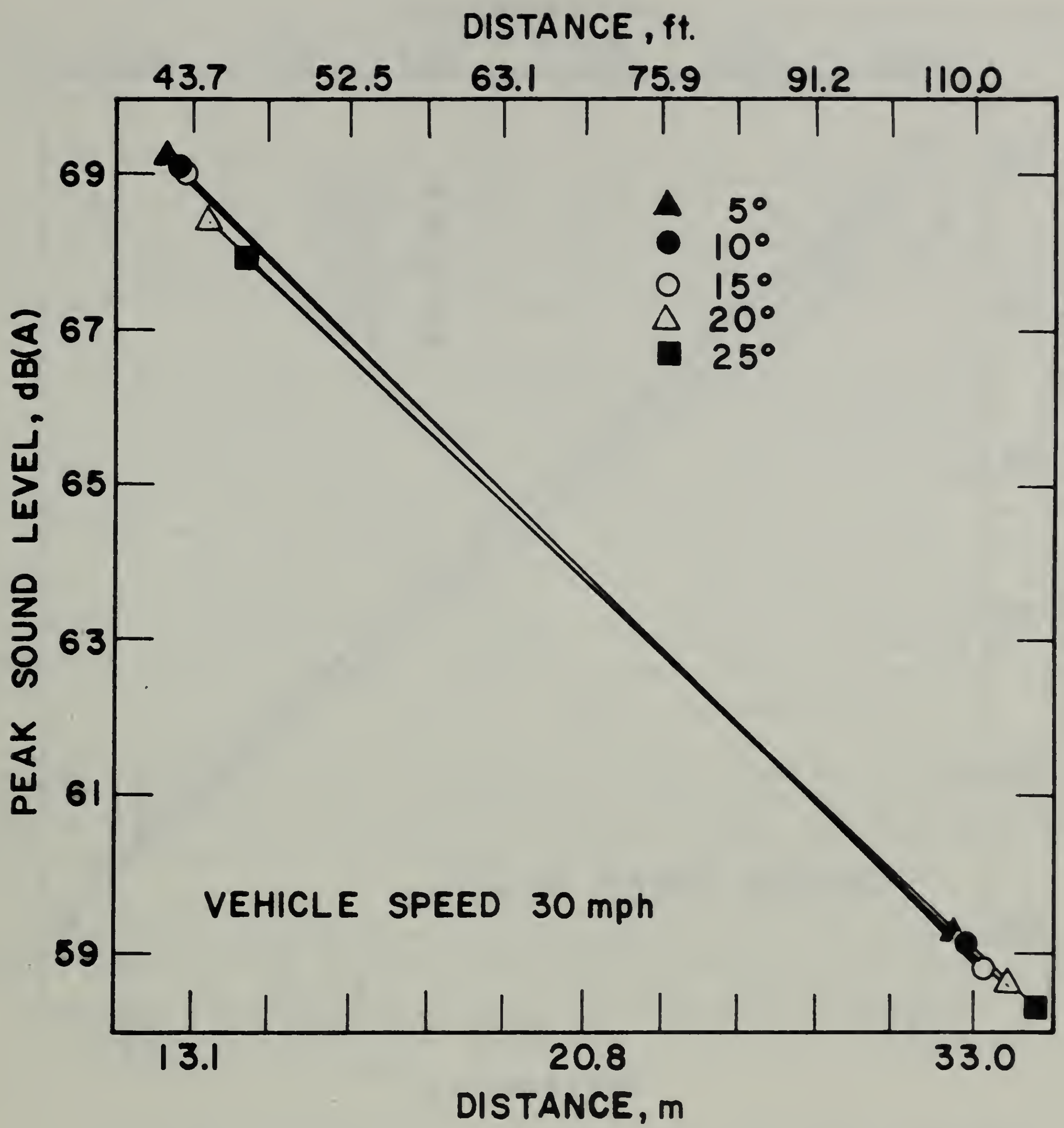

Figure 35. Peak A-weighted sound level versus the line-of-sight distance from the centerline of vehicle path to the pole on which the microphones were attached along various angles. The test vehicle was the unloaded truck with 50% worn Firestone T-200 cross-bar tires. Vehicle speed was 30 mph.

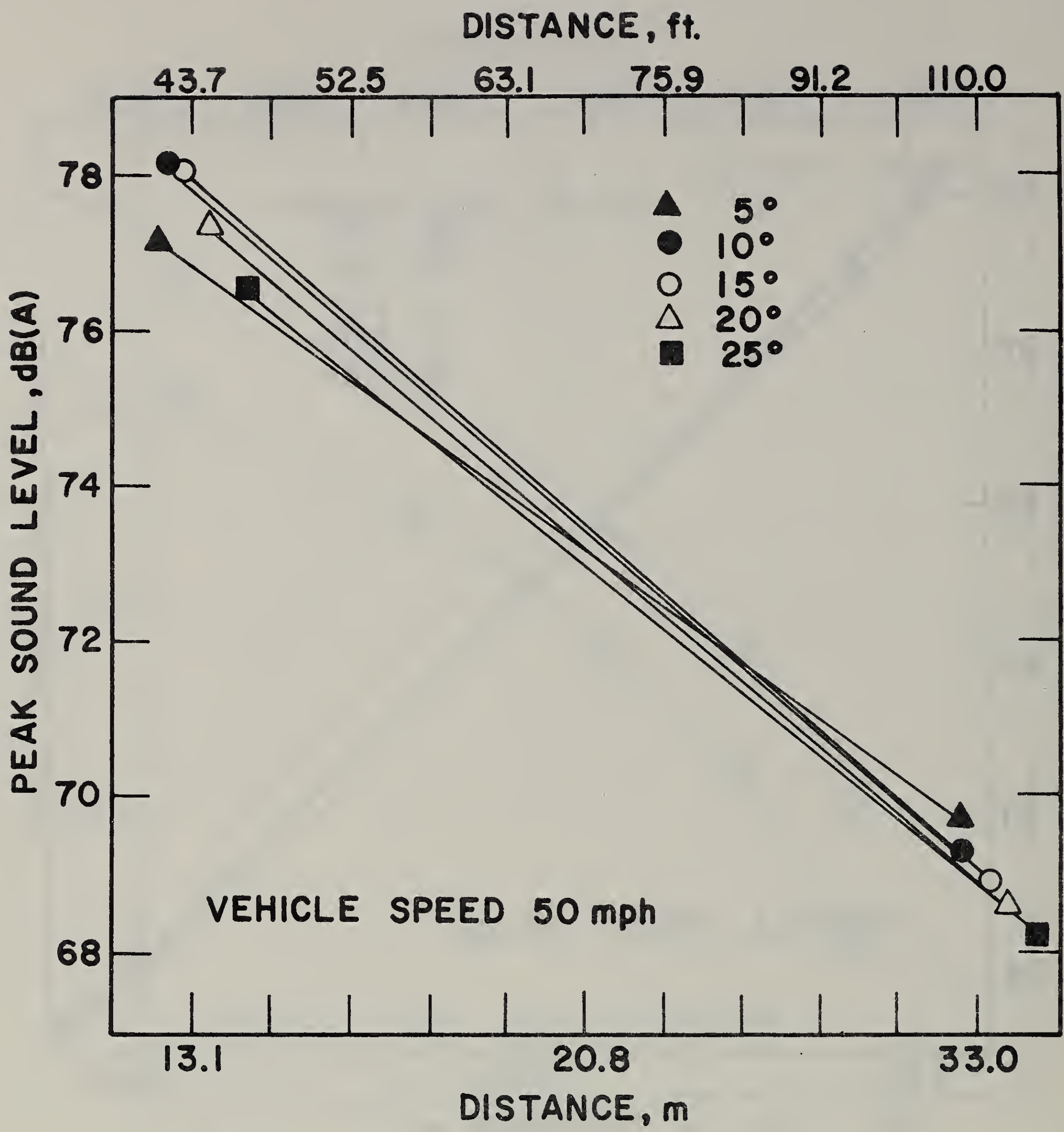

Figure 36. Peak A-weighted sound level versus the line-of-sight distance from the centerline of vehicle path to the pole on which the microphones were attached along various angles. The test vehicle was the unloaded truck with 50% worn Firestone T-200 cross-bar tires. Vehicle speed was 50 mph.

In addition to providing data necessary for the establishment of the test plan, the feasibility testing also afforded an opportunity for a thorough checkout of all instrumentation and evaluation of test vehicle characteristics.

It was found that the loaded truck could only attain a maximum speed of 60 mph in the allowable runway length and its characteristic deceleration is a loss of 1 mph every 200 ft. This figure is little influenced by vehicle speed. The unloaded truck drops in speed at a much faster rate when coasting and its top speed is also 60 mph.

Because of the truck's acceleration capability, or rather the lack of it, the higher speeds cannot be attained until near the end of the runway. To run two surfaces at the same time, which would be possible at lower speeds, the test section would be adjacent to the center of the runway while the higher speed test sections would be located near the end of the runway. This would mean that instead of two different test surfaces there would actually be four since different surfaces exist near the ends than are present at the center of the runway. In addition the necessary cable, photocells and operational circuitry, additional microphones and a switching capability, when evaluated from a time and monetary viewpoint, made the two-surface testing on a single run impractical.

An evaluation of the frequency spectra resulting from feasibility testing has allowed for the operation of the tape recorder in a mode whereby a tape speed of 30 in./s provides a bandwidth from 0 to 10,000 Hz. This range covers the frequencies generated by truck tires.

A careful evaluation of the feasibility test data has led to the establishment of the following microphone array for the test program.

1. All microphones will be located on the hard surface, be it concrete or asphalt.

2. All microphones will be placed upon tripods at a height of 48 inches above the surface of the roadway. This height corresponds to the height recommended by the S.A.E., I.S.O., and the California state law governing motor vehicle noise.

3. All microphones will be located along a line perpendicular to the path of the vehicle and spaced at distances of 6, 12, 25, 50, 80 and 130 feet as measured from the centerline of the lane in which the truck runs. The rationale of these horizontal locations is as follows: The six foot location is as near as the microphone can be placed to the passing truck. The 130 foot location represents the limit of the hard surface before the grass begins. The 25 and 50 foot locations both represent the location specified by existing state laws on motor vehicle noise. (Connecticut specifies the 25-foot microphone location while California prefers the 50-foot location.) In addition much of the research work that has been performed and is in the public domain has utilized a microphone placed 50 feet from the centerline of the highway lane in which the test vehicle operated. The remaining two locations at 80 feet and 12 feet were selected to fill in the gaps in the array thus ensuring adequate coverage between 6 ft and 130 ft.

All test data will be taken utilizing this microphone array to obtain the data necessary to achieve the goals of the program.

3. Scheduled Work for Next Period

The work next period will be concentrated in two distinct areas -- field testing and data handling and analysis.

3.1 Data Acquisition

The completion of the feasibility test program has resulted in (1) the complete checkout of the instrumentation system, (2) the establishment of the field test site, and (3) the arrangement of the measuring instrumentation and the finalization of the measurement methodology. Full scale testing in accordance with the test matrix will now commence.

The initial shipment of test tires included the following: Firestone T-150 (new), Goodyear Custom Cross Rib Hi-Miler (new and 50% worn), Firestone T-200 (new), Rib-Saw Tooth Retread (new), and the Bow Tie Retread (new). In addition, General HCR tires were purchased to serve as the baseline for the field testing.

The second shipment is expected to include the Hawkinson Retread (new and 50% worn), Firestone T-150 (50% worn), Firestone T-200 (50% worn), and the Goodyear Custom Cross Rib Hi-Miler (worn to legal limit).

In addition to acquiring the data for the inventory on truck tire noise, work is continuing on the development of a satisfactory method for making 360° tire footprints with the tires actually mounted on the truck in their test configuration. Various inks and papers are presently being tested to determine the optimum combination to insure clear, sharp, accurate reproductions of the tire contact area under a loaded condition.

3.2 Data Handling and Analysis

The interface between the real time analyzer and the Raytheon computer was delivered later than expected (mid-August) and the debugging operation is underway. Once the coupler is working properly, data taken up to that time will be reduced with initial emphasis on the calculation of the peak A-weighted sound levels at each microphone as well as the point in time when the peak reading occurred. In addition, further work is underway on the developmentof the more sophisticated computer programs necessary for the analysis of directionality data and the generation of graphic displays of the final data.

Two problems became apparent when the initial triggering of the computer with the timing signals was attempted. The interrupt channel was triggering on the noise on the direct record channel even though the level of the timing pulses was well above the noise. In addition, the timing pulse itself was not a "clean" signal but was ringing. An electronics circuit is presently being designed which will filter out the noise on the direct record channel and will modify the incoming timing pulse and output a sharp, clean signal for computer acceptance.

4. Appendix A

Instrument Descriptions

Unless otherwise stated, all instruments are Brüel and Kjaer (B & K).

Type UA 0207 Windscreen: When a microphone is exposed to wind, the turbulence created around the microphone and wind velocity variations will cause a noise to be generated due to a variation of air pressure on the diaphragm. To reduce this extraneous wind noise, a spherical windscreen constructed of specially prepared porous polyurethane sponge will be utilized.

The use of any windscreen requires that corrections be made to the sound pressure level measured to account for the presence of the windscreen. Free-field corrections for the windscreen will be made.

Type 4220 Pistonphone: This instrument is a small, battery-operated precision sound source which provides quick and accurate direct calibration of sound measuring equipment. When fitted to a B & K microphone, the pistonphone produces a sound pressure level of 124 $\pm$ 0.2 dB, re 20 $\mu N/m^2$, at a frequency of 250 Hz $\pm$ 1% (controlled by means of a transistor circuit). Maximum stability and very low distortion (less than 3% at 250 Hz) result from the piston arrangement consisting of two pistons moving in opposite phase. The calibration of the pistonphone is performed at normal atmospheric pressure. Ambient pressure corrections are necessary for pressures other than 776 mm Hg. This calibration is not influenced by relative humidities up to 100% or temperatures within the range of 0 - 60 °C (32 - 140 °F).

Microphone: When one speaks of a microphone, a three part system is implied: (1) a protecting grid; (2) a condensor microphone cartridge; and (3) a microphone preamplifier or cathode follower. For this testing the following components will be utilized:

Type 4135 one-inch condensor microphone

The one-inch free-field condensor microphone is of the omnidirective type possessing relatively high sensitivity and covering a range of applicability from 20 Hz to 18 kHz (frequency) and 15 dB to 146 dB (pressure). The most outstanding feature of these microphones is long-term stability under a variety of environmental conditions and insensitivity to temperature variations. Condensor microphones, in addition, were chosen because of their higher dynamic range, ease in calibration, and uniform frequency response. The cartridge which houses the microphone diaphragm is protected by the grid on one side and on the other is screwed onto the preamplifier.

Type 2619 half-inch FET preamplifier

This preamplifier features a very high input impedance field-effect transistor input, which presents virtually no load to the microphone cartridge. To mate the 2619 with the 4135 a suitable adapter must be utilized (Model DB-0375).

Built into the preamplifier itself is a 6.3V heating coil to prevent condensation when operation must be carried out in cold or humid environments.

The above described microphone subassembly provides reliable operation over a wide range of temperature, humidity, and vibration and allows precision sound pressure measurements to be made over a wide frequency and dynamic range.

Type 221 microphone energizer: This unit houses a six channel microphone power supply with individual line driving amplifiers. In conjunction with the type 2409 signal conditioners, the microphone energizer provides the necessary gain and impedance match to supply the multi-channel tape recording system.

Type 2409 electronic voltmeter: These vacuum tube voltmeters cover the frequency range from 2 Hz to 200 kHz and provide signal conditioning (signal amplification or attenuation) prior to F.M. tape recording. The instrument consists of a calibrated attenuator, a stabilized amplifier with cathode-follower stages in the input and output circuits and a moving coil meter equipped with special rectifier circuits for the measurement of true RMS, average, or peak values with either small or high meter damping characteristics. The screened output terminal enables the instrument to operate as a calibrated amplifier featuring a low output impedance and an amplification of 60 dB max., variable in 10 dB steps. A built-in reference voltage makes it possible to check the sensitivity of the instrument by simply turning a knob. A screwdriver operated potentiometer is available to correct any possible deviations.

Frequency response:	Linear to within $\pm$ 0.2 dB from 2 Hz to 200 kHz.
Meter accuracy :	Better than 1% of full scale at 1000 Hz.
Distortion :	Less than 0.2% with an output voltage of 10 volts.
Stability :	For a 10% variation in the line voltage the meter deflection will change less than 2%.

Model 7610 medium band magnetic tape system (Honeywell): A seven-channel instrumentation tape recorder with a bandwidth range from 0 - 80 kHz was selected for this program because of its low and uniform frequency response. The model purchased can be expanded to a full fourteen channels with the addition of the record/reproduce electronics for the additional channels and a modification of the heads and hub to accommodate the one-inch tape (7 channel recording utilizes 1/2 inch tape).

The wide bandwidth range results from a feature which allows the selectability of three different modes of operation:

(1) Standard : 0 - 20 kHz at 120 ips
(2) Extended : 0 - 40 kHz at 120 ips
(3) Double Extended: 0 - 80 kHz at 120 ips

The present unit has six channels of F.M. record electronics and one channel of direct record electronics. One channel of F.M. and one channel of direct reproduce electronics are in the system. In addition, a voice record/reproduce amplifier unit is included. The voice is recorded on the edge track of the tape.

Additional features include a phase lock servo control system, a tape footage counter, a shuttle, electrically selectable tape speeds (seven in all) ranging from 1-7/8 ips to 120 ips, and pushbutton selectability of the reproduce channel.

Type 3347 real time analyzer: The real time analyzer is composed of two basic units: (1) type 2130 frequency analyzer and (2) type 4710 control and display unit.

The 2130 contains a measuring amplifier, filter channels with 1/3-octave bandwidth, a linear channel, weighting channels, true RMS detectors, and the synchronization system for scanning the channels.

The analyzer contains 38 parallel channels. 33 of these channels contain 1/3-octave filters with center frequencies from 12.5 Hz to 20 kHz. The remaining five channels are reserved for the four weighting network filters -- A, B, C, and D -- and one linear response channel.

The 4710 contains the circuitry for the 12-inch cathode ray tube (CRT), the Nixie displays, digital readout, and the logic control. The logic control section controls the analog/digital conversion and the communication sequence for external systems, as well as the internal synchronization in the 3347 during display or read-out modes.

The level in each channel can be read in dB directly on the screen, while a Nixie display shows the output level of any selected channel. This channel is indicated on the CRT as a brighter trace. The complete channel display is renewed every 20 msec.

Outputs are provided for both analog instruments (X-Y or level recorders) as well as digital (on-line computer or tape puncher). The digital output is in binary coded decimal (BCD) code.

Time constants may be selected from 20 msec to 20 sec so that confidence limits can be maintained throughout the frequency range.

Type 1024 sine-random generator: This audio frequency generator is a multipurpose signal source. It covers a frequency range extending from 20 to 200 KHz and consists of a wide band noise generator, a beat frequency oscillator, several filters, amplifiers and an automatic output regulator. It is capable of producing three types of output signals: (1) sine waves, (2) narrow bands of random noise, and (3) wide band random noise. Since this unit will be utilized for calibration purposes (frequency response testing), wide band random noise or "pink noise" will be generated. Pink noise is noise whose spectrum level decreases with increasing frequency to yield constant energy per octave of bandwidth. When in the wide band random noise mode, the frequency range is 20 Hz to 20 kHz with the frequencv spectrum flat to within ± 1 dB.

Model 704 Raytheon Computer System: The Raytheon 704 computer system is a general purpose digital system that provides a 16-bit central processor unit with 900 nanosecond cycle time for on-line, real time applications.

The hardware configuration includes an 8K (expandable to 32K) memory system, direct input/output bus, automatic priority interrupt, direct and indexed addressing, and byte and word addressing and instructions. Standard peripherals such as high speed paper tape, ASR-33 teletype, card equipment, and a magnetic tape unit are also included.

The software is tailored to the complete range of hardware configurations. The 704 program library includes over 300 programs and subroutines, containing more than 200,000 instructions. Important software characteristics include conversational FORTRAN, real-time FORTRAN IV, true isolation hardware diagnostics, batch processing and extensive utility programs.

5. Appendix B

Test Sections Substrate Details

Substrate details discussed in Appendix B are not the exact details of the test pavements; however, they represent the specifications followed in the construction of the pavements. Since surface details are most important when considering the effect of the pavement on noise generation characteristics of truck tires, special note should be taken to the discussion of surface finishing techniques.

1. Asphalt Test Section (Bituminous binder and surface course).

A. <u>Description</u>

This test section consists of a "B" surface course of bituminous concrete otherwise known as "textured asphalt".

This section consists of binder and surface courses composed of mineral aggregate and bituminous material.

B. <u>Materials</u>

The aggregate consists of crushed stone, crushed gravel, screenings, gravel, sand-gravel, sand and other natural granular material having essentially the same qualities and meeting all the requirements when combined within the limits for gradation.

For the surface course, one hundred percent by weight of the mineral aggregate including filler was produced by the crushing of stone and gravel. When produced from gravel, only those particles having one or more fractured faces were considered as crushed.

The aggregate is tough, durable and sound and consists of angular fragments reasonably uniform in density and quality and contains no more than eight percent of either thin, elongated and soft pieces, or dirt or other objectionable matter. The coarse aggreagte was tested in accordance with the Los Angeles Abrasion Test. After five hundred revolutions the percent of wear was less than forty-five according to the A.A.S.H.O. Method T-96.* The coarse aggregate showed no evidence of disintegration, nor a total loss greater than twelve percent when subjected to five cycles of the sodium sulphate accelerated soundness test using A.A.S.H.O. Method T-104.

The portion of the materials retained on a No. 4 sieve was known as coarse aggregate; that portion passing as No. 4 sieve was known as fine aggregate, and the material passing the No. 200 sieve was known as filler. The composite material met the gradation requirements discussed later which were determined by A.A.S.H.O. Methods T-11 and T-27.

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*Details of these test methods are contained in the references cited at the end of Appendix B.

That portion of the fine aggregate, including any blended filler passing a No. 40 sieve had a plasticity index of not more than six, as determined by A.A.S.H.O. T-89.

The composite aggregate was free from vegetable matter, lumps or balls of clay, adherent films of clay, or other material that would prevent thorough coating with bituminous material. The bituminized aggregate had a swell of less than one and one-half percent as determined by A.A.S.H.O. Method T-101.

Prior to find acceptance of the aggregate, the inherent characteristics of the aggregate relative to stripping were determined by the contractor. This was done by preparing a test sample of the paving mixture in conformity with the following specifications. After the mixture was made, it was spread out in a loose thin layer and allowed to air season for twenty-four hours before testing. A suitable size sample (approximately one-half of the contents of container) was tested by placing it in a glass jar fitted with a tight screw cap. The sample was completely covered with distilled water at a temperature between 80°F and 100°F. The jar must be thoroughly cleaned and free from any traces of soap or other saponaceous material. The jar and contents were allowed to stand for a period of twenty-four hours. Then the sample was vigorously shaken for a period of fifteen minutes. The sample was then examined for stripping. If stripping or sloughing off of the bitominous coasting occured, it would be necessary to treat said aggregate by a method which has proven successful in changing the material from a hydrophilie to a hydrophobic state or the aggregate was rejected.

If filler in addition to that naturally present in the aggregate was necessary; it consisted of stone dust, Portland Cement or other standard approved types. The filler met the requirements of A.A.S.H.O. Specification M-17.

The bituminous material was mixed with the mineral aggregate conformed to the requirements of A.A.S.H.O. Specification M-20, penetration grade 85-100. In addition, the material showed a negative spot when determined by A.A.S.H.O. Method T-102, using standard naphtha.

C. Composition of Mixture

The mineral aggregates for the binder and surface course was of such size that the percentage composition by weight, as determined by laboratory sieves, conformed to the following gradations. The percent by weight for the bituminous material was within the limits given below.

Square Sieve Sizes	Binder Course	"B" Surface Course
1 inch	100	-
3/4 inch	82-100	100
1/2 inch	70-90	82-100
3/8 inch	60-82	68-90
No. 4	42-70	50-79
No. 10	30-60	36-67
No. 20	-	-
No. 40	15-40	17-44
No. 80	8-26	9-29
No. 200	3-8	3-8
Percent Bituminous Material	4.0-6.0%	5.0-7.5%

The gradations above represent the limits which determined the stability of the aggregate. The final gradations were uniformly graded from coarse to fine, and did not vary from the low limit on one sieve to the high limit on the adjacent sieve or vice versa.

A Sample of the coarse and fine aggregates was washed to determine the percentage of the total material passing the No. 200 mesh sieve. Of the amount passing the No. 200 mesh sieve, at least one-half passed by dry sieving.

D. Determination of percentage of Bituminous Material and Stability

The percentage of bituminous material, by weight, to be added to the approved aggregate was fixed on the basis of several laboratory tests which allowed for plotting a Marshall Stability curve and to determine the maximum stability attainable and the corresponding density. In no event was the Marshall Stability less than 1800.

E. Weather Conditions

Binder and surface course were constructed only when the surface on which they were placed was dry, when the atmospheric and underlying course temperatures were above 40°F, and when the weather was not foggy or rainy.

2. Concrete Test Section (Reinforced Portland Cement Concrete Pavement)

A. Description

This test section consists of a wearing surface of reinforced air-entrained Portland Cement concrete pavement with two types of finishes on a suitably prepared subbase.

B. Materials

The cement used in this work was a standard brand of Portland cement with air-entraining properties. The air-entrained cement conformed to A.S.T.M. designation C-175.

In no case was the use of pit run or naturally mixed course aggregates permitted. Naturally mixed aggregates were in every case screened and washed and all fine and coarse aggregates were stored separately and kept clean. In no case were aggregates containing lumps of frozen or partially cemented material used.

The coarse aggregate conformed to the requirements of A.A.S.H.O. Specification M-80. Also, at least sixty percent of the gravel aggregate had at least one fractured face. The coarse aggregate had no more than one percent of material removable by the decantation test, using A.A.S.H.O. Method T-11 nor more than one percent of shale, nor more than one percent of clay lumps. Chart did not exceed one percent. The total of shale, coal, clay lumps, chart, soft fragments, and other deleterious materials did not exceed five percent. The coarse aggregate did not show evidence of disintegration nor show a total loss greater than twelve percent when subjected to five cycles of the Sodium Sulfate Soundness test using A.A.S.H.O. T-104.

The coarse aggregate conformed to the following gradations:

Sieve Size	Percent Passing by Weight	
Square Mesh	Gradation A	Gradation B
2 inch	100	-
1 1/2 inch	90-100	-
1 inch	20-55	100
3/4 inch	0-15	90-100
3/8 inch	0-15	20-55
No. 4	-	0-10
No. 8	-	0-5

The coarse aggregate were batched in two separate sizes which could be varied within a range from forty to sixty percent by weight to secure the most desirable and uniform gradation of the combined mix.

The fine aggregates conformed to the requirements of A.A.S.H.O. Specification M-6.

When subjected to five cycles of the sodium sulfate soundness test using A.A.S.H.O. Method T-104, the fine aggregate had a total loss less than ten percent by weight. It also contained less than three percent of meterial removable by a decantation test, using A.A.S.H.O. Method T-11. Percentages of shale, clay lumps, etc. permissible were the same as for the coarse aggregate.

The fine aggregate was well graded from fine to coarse and met the following gradation requirements, using A.A.S.H.O. Method T-27.

Sieve Designation (Square Mesh)	Percentage Passing by Weight
3/8 inch	100
No. 4	95-100
No. 16	45- 80
No. 30	25- 55
No. 50	10- 30
No. 100	2- 10

The water used in the concrete and for curing was clean, clear, and free of injurious amounts of sewage, oil, acid, strong alkalies, or vegetable matter, and, also, free of clay and loam.

C. Composition of Mixture

The weights o fine and coarse aggregate and the quantity of water per bag of cement were determined from the weights given in the following table:

Type of Aggregate	Minimum Cement Content Per Cubic Yard of Concrete	Maximum Net Water Content, Gallons Per Bag	Weights in pounds of dry Aggregate per bag of cement			
			Fine Aggregate	Coarse Aggregate	Total	Slump Range, Inches
Gravel	5.8 bags	5 1/2	169	394	563	1-1/2
Crushed Stone	5.8 bags	5 3/4	195	366	561	1-1/2

Yield tests in accordance with ASTM Specification C-138 were made to determine the cement content per cubic yard of concrete. If at any time, the content was found to be less than that specified, the batch weights were reduced until the requirements were met.

Air-entrained Portland cement concrete causes a bulking of the mortar of the concrete due to the amount of entrained air. To keep the cement factor specified at the correct amount, the weight of the fine aggregate was reduced as required. The air content of the fresh concrete was determined by ASTM Designation C-231.

The proportions in the above table produced a concrete of satisfactory plasticity and workability which attained, after fourteen days, a minimum compressive strength of 3000 pounds per square inch and a modulus of rupture of 700 pounds per square inch after twenty-one days. The specimens were cured and tested in accordance with A.A.S.H.O. Methods T-22, T-23, and T-97.

D. Placing and Finishing

The concrete was deposited and apread so that any segregation would be corrected and a uniform layer of concrete whose thickness was approximately one inch greater than that required for the finished pavement.

After the first operation of the finishing machine, additional concrete was added to all low places and the concrete recreeded.

After the final pass of the finishing machine, the placing of all joints longitudinal and transverse, and the concrete had started to dry, the surface of the pavement was finished with a longitudinal float.

After the concrete was brought to the required grade, contour, and smoothness, it was finished by means of a finishing belt. The belt was eight to twelve inches in width and at least two feet longer than the width of the pavement section to be finished. On the "C" (smooth) finish section of pavement a belt of canvas composition was used. On the "D" (regular) finish section of pavement the finishing belt was of burlap composition. The three-ply burlap belt was worked with a combined longitudinal and transverse motion, until all surface irregularities were eliminated.

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6. Appendix C

Photosensor System for Position-Velocity Determination and Tape Recorder Actuation

The system for position and velocity determination consists of three units; a photosensor, start stop circuitry for the tape recorder, and a digital line driver.

The block diagram of the photosensor is shown in Figure 1. The photosensor contains a photo detector, two clipping amplifiers and a monostable multivibrator. Whenever a light source is moved across the photo detector surface, a change in the output voltage of the detector is obtained. The output voltage is capacitance coupled to an operational amplifier with a gain of 100. The capacitance coupling is necessary to avoid amplification of ambient light effects. To avoid over-driving of the amplifier, and subsequent saturation, and for signal shaping purposes, two Zener diodes are used in the feedback loop of the first amplifier. The output of the first amplifier is coupled to the second amplifier by a diode such that only negative pulses are amplified. The second amplifier has a gain of ten and uses a Zener diode in the feedback loop for the previous mentioned reasons. The second amplifier is connected to a Schmitt trigger and monostable multivibrator. The multivibrator has the advantage over other circuitry that the period of the time pulse can be accurately determined by external passive components. A pulse period of 28 milli-seconds was chosen on the basis of analysis time; however, any pulse period between 40 ns and 40 seconds can be obtained by changing the timing resistors and capacitors of the multivibrator. The entire photosensor system is powered by batteries using matched Zener diodes for voltage regulation.

The Honeywell 7610 magnetic tape system requires actuation of first the Record mode and then the Forward Drive mode. The time required between modes is a minimum of 50 milliseconds. This functional switching may take place external to the recorder. The timing system consists of digital networks; the block diagram of the system and timing are shown in Figure 2. When a pulse is applied to the monostable multivibrator from a photosensor, monostable one and monostable two are turned "on". The output of monostable one (Q) is connected to a grounded emitter circuit which in turn activates a Record mode relay. The duration of the "on" state is approximately 200 milliseconds. The Q output of the first multivibrator is connected to an AND gate of a third multivibrator. When the second multivibrator is triggered a pulse of 100 milliseconds is generated. The output Q of the second multivibrator is connected to a NOR gate of the third multivibrator. The output of the NOR gate is connected to the AND gate previsouly described. Thus, the third multivibrator has an output only when the first multivibrator is "on" and the second multivibrator is "off". A delay of 100 milliseconds between Record and Foward Drive functions is achieved. The output of the third multivibrator is also connected to a grounded emitter circuit which in turn activates the Forward Drive mode relay. The action of the start circuitry may be overridden at any time by use of the normal tape recorder function switches. The stop circuitry consists of a multivibrator and grounded emitter circuit for actuating a Stop relay.

The digital line driver is useful for long cables as might be encountered in the start stop circuitry previously described. The line driver consists of a multivibrator and a grounded emitter for impedance matching. The output of the circuit is 6 volts. This circuit will easily drive 1 mile of RG58C/U cable.

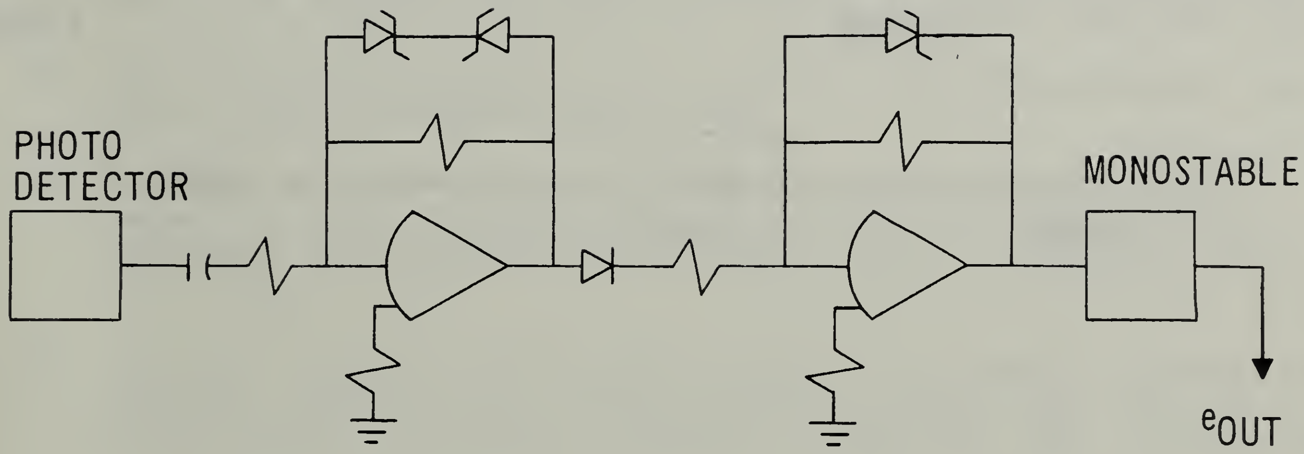

Figure C1. Block Diagram of Photodetector.

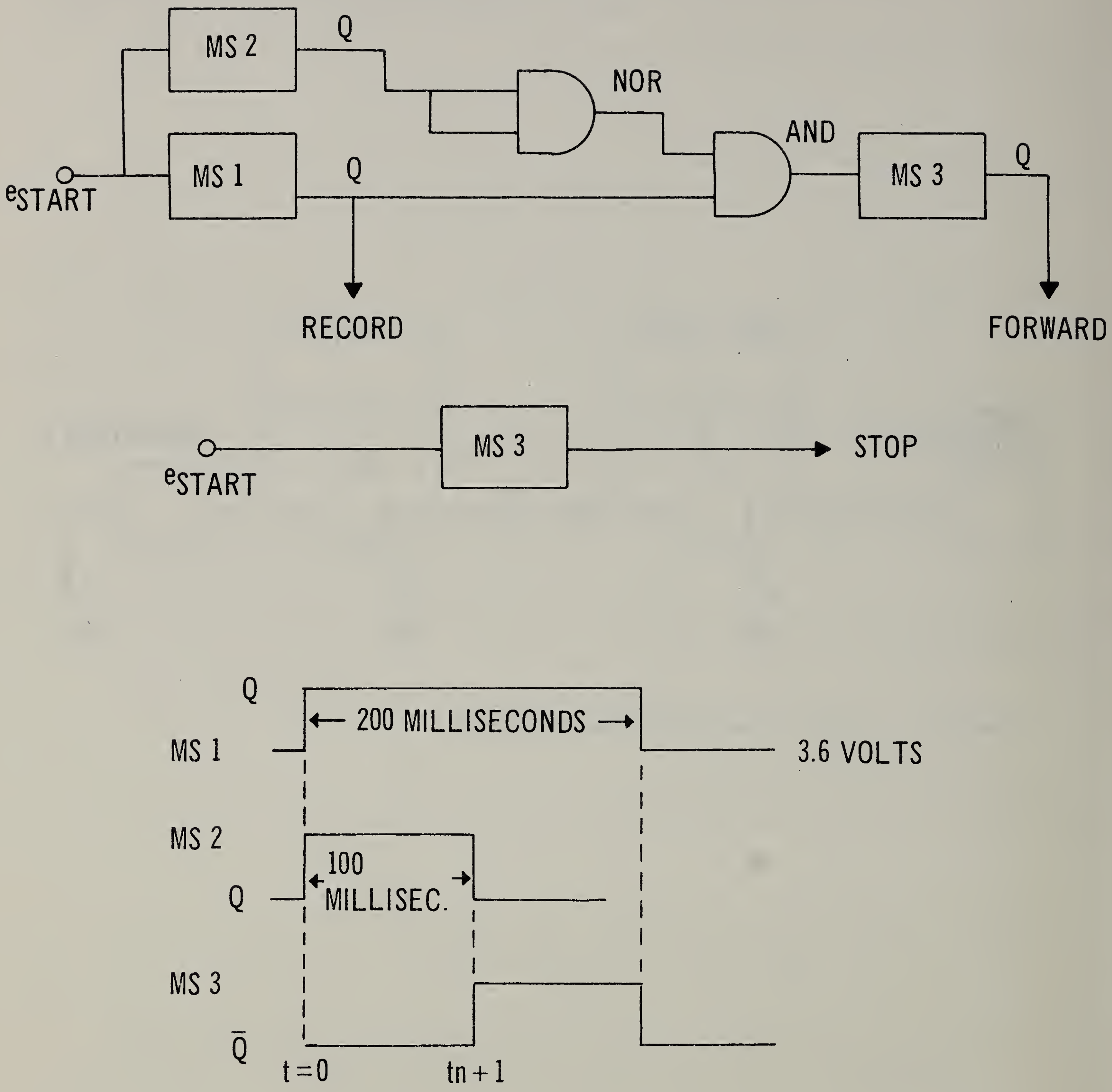

Figure C2. Block Diagram and Timing of Start-stop Circuitry.

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