NATIONAL BUREAU OF STANDARDS REPORT

10 292

AUTOMOBILE TIRE SOUNDS – ACOUSTICAL GRADING SYSTEM FEASIBILITY
1. ENDURANCE WHEEL STUDY

Prepared for

The Office of Noise Abatement
Department of Transportation
Washington, D. C. 20590

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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1. ENDURANCE WHEEL STUDY

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ABSTRACT

Introduction

At long last there is almost universal agreement concerning the presence of a "noise problem" in our modern society. This fact comes as no surprise to anyone familiar with acoustics or psychoacoustics but lately, government, industry and the general public have been sensitized to the pervasive presence of unwanted sounds. Among the leading contributors to this noisy environment is the automobile, which exerts a dominant influence in all communities, whether urban, suburban, or rural. The concern about road noise is manifested by the number of nations that are actively engaged in research programs designed first to document the nature and extent of the problem and then to develop methods of improving the situation. Among the countries currently engaged in "traffic noise" research are the U.S.S.R., France, Great Britain, Sweden and the United States.

Since the "automobile system" produces noise contributed by the engine, exhaust, body, tires, etc., it is difficult and possibly meaningless to attempt an identification of <u>the</u> major source of noise. Rather, it is obvious that several "subsystems" are major contributors to the overall noise level and by quieting one, another will attain a dominating influence. The ultimate solution to the problem will probably depend upon parallel efforts at quieting all major noise sources associated with vehicles until the levels produced are within acceptable limits. An extensive effort designed to lower exhaust sounds has already resulted in considerable improvement of mufflers, although the problem is still a major one for trucks. In contrast to the major undertakings directed at the exhaust system, tire sound has received comparatively little attention. A few tire manufacturers have initiated research to <u>change</u> the characteristics of the sound, thereby hoping to gain consumer acceptance of their products. However, these investigations are in their formative stages and at best will have little impact on tire tread design for several years. As a step toward controlling the sound output of automobile tires, the Office of Noise Abatement of the Department of Transportation wants to determine the feasibility of establishing an acoustical grading system for tire sound. That is, are subjective ratings of tire sounds consistent under a variety of experimental conditions and do they relate in some systematic manner with physical measurements of the sounds? The present study is the first of several designed to investigate this problem.

Hypothesis

Rankings of automobile tire sounds taped at an Endurance Wheel, based on physical and subjective measurement procedures under a series of "realistic" experimental conditions will be consistent with one another.

Historical Background

The information available concerning automobile tire sound is extremely limited, especially with respect to well controlled experimentation There are several factors that contribute to this situation. In the first instance, it is only in recent years that tire manufacturers seem to be reasonably satisfied that problems associated with safety, durability and riding characteristics of their products are under control and that more effort could be expended on "consumer acceptance" criteria such as sound output. Of the research that has been performed, many studies are not reported in detail in the open literature because the information obtained has been regarded as proprietary by the tire manufacturers. Another class of reports to be found consists of popularizations of research findings or opinions written in trade papers (e.g., Fleet Owner) and in popular magazines (e.g., Readers Digest). These articles are primarily directed toward the lay reader. Another difficulty with the available literature concerns the almost complete absence of findings related to automobile tire sound. Those investigations performed on tire sound are in most instances concerned with trucks rather than passenger tires. Finally, in the case of subjective assessment of tire sounds, it has not been possible to locate a single study that appears to be applicable to the present investigation. The documents reviewed below include studies, standards, regulations and articles directly applicable to the present investigation in terms of content, instrumentation or methodology. Reports concerned with traffic noise now constitute a major subject area but since they are only tangentially applicable to the present study, they have not been included in this survey.

Lippmann (1) indicates that the concern of automobile manufacturers has shifted from tire failure to comfort. In describing two types of noise emanating from tires, he identifies <u>thump</u> and <u>roughness</u>. Thump is defined as a cyclic train of vibrations and sound having the same period as the revolutions of a tire. Roughness has the same subjective characteristics as thump but the periodicity is not as evident to the observer. In both instances, the sound is ascribed to the spacing of the elements of the tire. Most researchers agree with Lippmann that tread pattern is a critical feature of tire design from the standpoint of sound output. Varterasian (2) describes a general approach for mathematically determining methods of varying the pitch of a tread thereby reducing discrete tones within the noise. His method is termed "Mechanical Frequency Modulation" and describes a method of obtaining the "optimum" tread pitch variations. In his formulation the number of tread elements and the maximum and minimum allowable pitch must be identified. The objective of the design is to achieve a "white noise". He notes that the pattern and other tire parameters determine the <u>amplitude</u> of the white noise.

Joy, et al (3) provide a description of the sounds produced by automobile tires and an explanation of them as follows:

1. Squeal : relaxation type oscillation of tread elements coupled to the casing which acts as a resonating chamber.
2. Squelch: squeal type noise due to the flattening of a curved tread on impact with the ground.
3. Rumble : vibration of the casing initiated by irregularities in the road surface.
4. Hum : intensity governed by:
    a. Number of edges in the tread pattern; angle these make with the axis of the tire and the width of the transverse grooves.
    b. The fundamental frequency which is inversely proportional to the length of each repeated pattern unit in the tire.
    c. The distribution of harmonics of the fundamental frequency which depends on the spacing of individual features with each repeated pattern unit.
    d. The "frequency modulation"--varying the length of the pattern units around the tire.

Davisson (4) stresses speed as a controlling factor determining the quality of tire sound. He notes that the sound produced is harmonically related to tire revolutions. Among the other important parameters identified were tread design, tire deflection and wear patterns. He also indicates that the frequency range of 200 to 3000 Hz were most critical in his studies of truck tire sound.

Weiner (5) tested tires of different construction on a variety of road surfaces. He indicates that the construction of the tire had very little impact on the type of sound produced for the particular sample of tires that were used. He further notes that changes in car speed resulted in only minor differences in the shape of the spectrum.

A number of standards are available which are helpful in specifying test procedures and methodologies employed in tire sound measurements. The SAE Standard J672a (Exterior Loudness, Evaluation of Heavy Trucks and Buses) (6) indicates procedures employed to determine the "loudness" of vehicles. The ISO Recommendation R362 (Measurement of Noise Emitted by Vehicles) (7) also provides a detailed measurement procedure.

A number of studies have been concerned with developing techniques appropriate for tire sound investigations. Bolt, Beranek and Newman (8) completed a study designed to test sounds produced by standard nylon and rayon tires. In this study they evolved a "tapping test" as an experimental tool. Their objective was to obtain physical and subjective measurements of tire sounds to determine parameters associated with "acceptable" sound. The test procedure was based on an impact sound produced by the tires which does not appear appropriate for the present investigation.

In "Reducing Road Noise" (9), the author indicates that a laboratory constructed with double walls was constructed to perform tire sound work. The stated objective was to develop a program of research which is designed to relate field and laboratory investigations. No research results of significance are reported. Andrews and Finch (10) indicate a set of procedures that they employed for measuring vehicle noise and determining the relationship between physical and subjective findings. The study provides some useful information concerning methodology but since it was primarily concerned with muffler noise, its applicability is somewhat limited.

Liska (11) indicates that in the early attempts to study tire generated noise and vibration, jury ride tests were conducted. These tests consisted of four or five people riding in a prescribed car over a prescribed route at a predetermined speed to rate different sets of tires. He notes that there were many difficulties associated with this procedure. Since individuals differed in their ratings, it was necessary to obtain majority opinions. Only full sets of tires could be used, and one bad tire of four would adversely affect the rating. It was difficult to accurately remember from one ride to another, especially when tests were made throughout the day. The data obtained were completely subjective and consequently did not lead to a constructive research program. He concluded that good objective test methods must be developed which would consist of studying the tire in isolation and correlating the results with the properties of the vehicle.

Robertson and Cox (12) also advocate an experimental methodology in their approach. They note that the two critical parameters in a general sense are tread surface and road surface, and that research should be initiated by eliminating one parameter. In their work they eliminated the road parameter first by using a smooth steel drum as the surface that the tire rode on. They performed their studies with a tire mounted on a truck which ran on a drum located under the ground surface in a pit. They accelerated to 50 mi/h, cut power and made recordings while the tire was "coasting". They used a series of test tires with a smooth tire which served as a control. Few detailed findings were included in the report.

The present study was planned essentially in response to the requirements noted in the two preceding papers. There is a recognized need to exercise experimental control over the collection of both subjective and objective data. There is also a requirement to enable subjective findings to be related to physical ones. This investigation was therefore designed to enable subjective and physical data collection under carefully controlled circumstances. The Endurance Wheel provided an excellent opportunity to obtain tire sounds under well controlled conditions and the taped sounds used for subjective judgements ensured that the experimental subjects would be responding to the same material in a laboratory environment. It is recognized that this study can at best only supply a partial answer to the feasibility of ranking tire sounds and that field studies will also be conducted. The next report will be concerned with this aspect of the problem.

General Approach

The specific objective of the present study was to determine the feasibility of using an Endurance Wheel to establish a grading system for automobile tires based on their acoustical and auditory properties. Since the tire sounds were to be used for both physical and subjective assessments, they were recorded based on an experimental plan consistent with two sets of requirements. The primary criteria for the physical measures was to maximize the SIGNAL (tire sound)/NOISE (endurance wheel sound) ratios and to obtain a broad spread of values for the sample as measured on the dBA scale. The subjective judgements necessitated a sample containing characteristics that "sounded like" the range of tires readily available to the consumer. That is, tires were included which during the pilot study (p. 51) were judged to have tonal and periodic components as well as those which were "quiet" and "noisy". The selection of parameters was based on a literature review, communications with researchers investigating characteristics of tires, and a limited set of empirical findings obtained during the pilot study. The variables judged to be of greatest interest were speed and loading conditions and they were therefore used as the basis for the experimental design. The speeds selected for the study were 30, 50 and 70 mi/h which roughly correspond to limits for city traffic, suburban roads, and expressways, respectively. In addition, the "regular" progression of speeds facilitates data analysis and comparisons. Two typical loading conditions and the associated pressures recommended by tire manufacturers, were the other independent variables employed in the investigation. Table 1 outlines the basic experimental conditions.

Table 1. Experimental conditions.

Tire types.	Speeds					
	A		B		C	
	Load-Pressures		Load-Pressures		Load-Pressures	
	1	2	1	2	1	2
I	IA$_1$	IA$_2$	IB$_1$	IB$_2$	IC$_1$	IC$_2$
II	IIA$_1$	IIA$_2$	IIB$_1$	IIB$_2$	IIC$_1$	IIC$_2$
III	IIIA$_1$	IIIA$_2$	IIIB$_1$	IIIB$_2$	IIIC$_1$	IIIC$_2$
IV	IVA$_1$	IVA$_2$	IVB$_1$	IVB$_2$	IVC$_1$	IVC$_2$
V	VA$_1$	VA$_2$	VB$_1$	VB$_2$	VC$_1$	VC$_2$

<u>Tires</u>

I. Firestone Champion 775.14
II. Michelin Champion 195R-14
III. General Standard Skid Tire - 750-14
IV. Goodrich Silvertown Trailmaker, F-78-14
V. Goodrich Silvertown HT 770 - 75-14

<u>Speeds</u>

A. 30 mi/h
B. 50 mi/h
C. 70 mi/h.

<u>Loading/Pressure Conditions</u>

1. Maximum load - 1500 lb, pressure - 32 lb/in^2
2. Medium load - 1150 lb, pressure - 24 lb/in^2

After the tire sounds were recorded at the Endurance Wheel under all experimental conditions, they were analyzed acoustically using standard procedures. Tape samples were obtained from these recordings and used to construct stimulus material to be used in the subjective assessments. Rank orderings of the five tires were then obtained using several alternative physical measurement procedures as well as a subjective evaluation. Correlations were then obtained between the rankings obtained using physical measures and those dependent on subjective responses.

Experimental Design

As noted earlier, the independent variables consisted of the particular tires, the load/pressure conditions and the wheel speeds employed. A listing of these variables and the specification of their characteristics or levels can be seen in Table 1. The overall plan was designed to facilitate objective and subjective comparisons among tire sounds within each condition and then to compare results across conditions to determine consistency of findings.

An inspection of the body of Table 1 indicates that for each of the three speeds employed, there were two loadings. These six conditions formed the framework for the experimental design. The basic experimental data consisted solely of tire sound comparisons <u>within</u> each of the six conditions, i.e., down the columns of the table. There was no rationale for making comparisons of sounds produced by one tire under a set of conditions with those of another tire collected under different circumstances.

The collection of subjective data was based upon a paired comparison technique commonly used in auditory assessments. This procedure requires the subject to make a relative judgement concerning two stimuli based on some criterion of interest. In the present study the task was to select the "more acceptable" of two recorded tire sounds. This judgement is a relatively simple one in contrast to listening to five sounds and then ordering the entire group in terms of acceptability. The latter task is especially difficult in the case of auditory material which is sequential by nature and therefore requires that the sounds be remembered. Using the paired comparisons approach, rankings can be obtained by first defining all possible pairs of interest. An exhaustive set of these pairings grouped by sound pairs, appears in the appendix (A, p. 47). The sound pairs were grouped on "lists" which served as the "stimulus material" for the subjective assessments. The lists were designed to include all possible pairings of the five tires for a fixed set of conditions (corresponding to the columns of Table 1). The ten combinations comprising the complete set of pairings defined the length of a test list. Lists 1-6 (A, p. 48) indicate the pairings used in the study and the content of the test lists. An inspection of the table indicates that the items within each pair were not ordered in a regular manner, instead the determination of whether a particular sound appeared first or second within the paired presentation was made on the basis of random selection. Six additional lists were constructed in order to counterbalance the order of presentation of the paired sounds. Lists 7-12 (A, p. 48) indicate the method employed in counterbalancing the first six lists. For example, if the first and second pairs of Lists 1 and 7 are compared, it can be noted that the sequence for List 1 is IA_1-IIA_1; IA_1-$IIIA_1$; while the corresponding order for List 7 is IIA_1-IA_1 and $IIIA_1$-IA_1. The actual lists used in the study appear in Appendix A, p. 49. It can be noted on these lists that the sequencing of item pairs within each list has also been randomized. As noted elsewhere, the order of list presentation differed from subject to subject in most instances although the lists were grouped by threes on tapes to facilitate the conduct of the experiment (A, p. 50).

The twelve lists were presented a total of six times to each of the fifteen subjects who completed the study. There were therefore 180 judgements for each experimental comparison.

Results and Analysis

Responses were tabulated for each subject on an individual basis and then punched on IBM cards to facilitate data processing. Table 4 indicates the summarized data concerning acceptability of tire sounds for all possible pairs, under each condition. The numbers in this table (as well as those in all succeeding tables presenting "acceptability" data) represent the total number of times that one tire sound was judged to be more acceptable than the tire sound with which it was compared. It is apparent from the TOTAL column, that pair preferences range from a minimum ratio difference of more than 2:1 in the case of pair I-V, to almost unanimity of agreement in several of the conditions. These results indicate a great degree of consistency especially when they are examined a little more closely. In the case of the aforementioned I-V pair, it can be noted that one particular reversal in preference, (from 24-156 to

131-49) resulting from a change in loading conditions, account for much of the "inconsistent" data.

Figure 1 presents third octave band data for these two tires for the 30 MPH conditions. In the case of tire V, the change in loading conditions resulted in a rather constant change in 1/3 octave band levels throughout the frequency range. The data obtained from tire I present an altogether different picture and provide a possible explanation for the reversal in preferences associated with two loading/pressure conditions. It can be seen that in the 1500 lb condition, the third octave levels for tire I are considerably above those measured for tire V and therefore the preference for tire I is understandable in terms of overall sound pressure levels. However, under the 1500 lb loading condition the third octave levels for tire I fall off sharply in the high frequencies until they are below those of tire V. Since it is known that high frequency components are particularly unacceptable, the change in preferences is not surprising. It appears quite likely therefore that the reversal in preferences with different loading conditions may be attributed to an experimental artifact resulting from the particular values of loading selected and their effect at 30 mi/h on the tread pattern/surface interaction of the two tires being tested.

Table 3 presents an ordering of responses by tire acceptability from most to least reading from left to right. The only reversal (between tires 1 and 2) was not statistically significant.(13) The (√) indicates that there are no inconsistencies reading across the table. That is, in all instances when tire III ranks higher than tire V, and tire V is higher than for I, that tire III ranks higher than tire I.

Table 2. Summary.

Acceptability data for all comparisons.

Tire Pairs	1500 lb load 30 mi/h	1150 lb load 30 mi/h	1500 lb load 50 mi/h	1150 lb load 50 mi/h	1500 lb load 70 mi/h	1150 lb load 70 mi/h	Totals
1 2	114 66	155 25	128 52	86 94	144 36	140 40	767 313
1 3	18 162	8 172	12 168	0 180	4 176	7 173	49 1031
1 4	175 5	180 0	178 2	174 6	179 1	179 1	1065 15
1 5	24 156	131 49	53 127	19 161	46 134	85 95	358 722
2 3	40 140	4 176	11 169	4 176	4 176	1 179	64 1016
2 4	179 1	177 3	179 1	177 3	177 3	177 3	1066 14
2 5	28 152	14 166	33 147	34 146	21 159	23 157	153 927
3 4	179 1	179 1	179 1	180 0	179 1	180 0	1076 4
3 5	112 68	177 3	158 22	166 14	166 14	177 3	957 123
4 5	0 180	2 178	0 180	0 180	1 179	0 180	3 1077

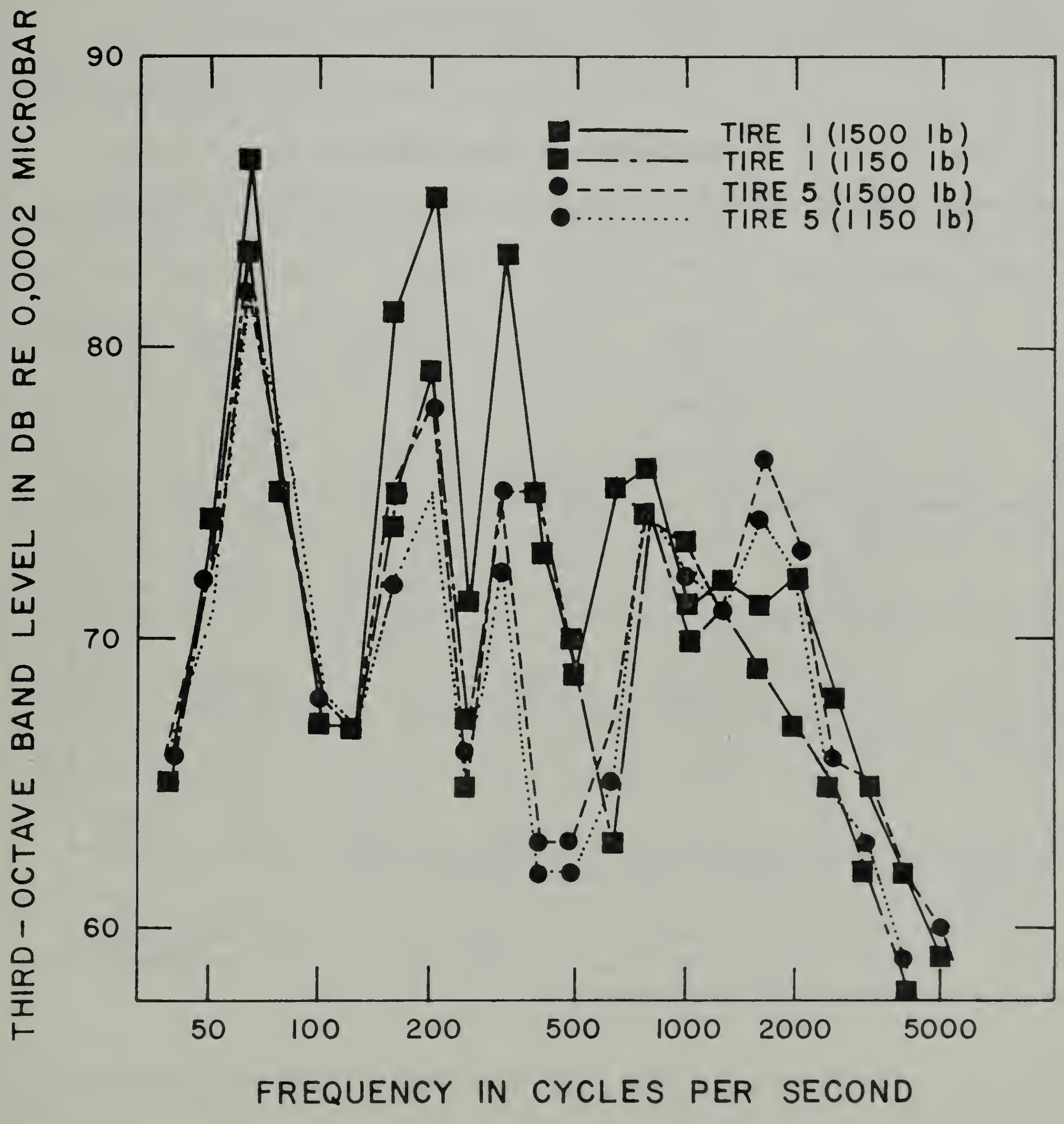

Figure 1, Acceptability reversal, 30 mi/hr.

Table 3. Order of preference - acceptability.

Total Responses (N = 1080)

Tire	3	5	1	2	4
3		957 (✓)	1031 (✓)	1016 (✓)	1076 (✓)
5	123 (x)		722 (✓)	927 (✓)	1077 (✓)
1	49 (x)	358 (x)		767 (✓)	1065 (✓)
2	64 (x)	153 (x)	313 (x)		1066 (✓)
4	4 (x)	3 (x)	15 (x)	14 (x)	

Read: Left to right (less acceptable - (✓))

(The table format is designed to facilitate paired comparisons, e.g., Tire 3 is rated more acceptable than tire 5, 957 times of a possible 1080 responses.)

Table 4 provides a summary of the data for each loading condition while combining speeds.

Table 5 provides another summary for the other major variable, speed, while loading conditions are combined.

It is evident that with respect to rank orders, the data for all experimental conditions are quite consistent.

The data were then examined to determine the extent to which the differences among preferences were similar for the five tires. Since the range of acceptability scores was so great (4 to 1076), the scores were scaled by means of an arbitrary scale.* (14)

Let a_{ij} = number of times tire i is preferred to tire j $(i \neq j)$

$n = a_{ij} + a_{ji}$ = number of comparisons.

Then for one experiment, or for a group of experiments combined, calculate the ith scale score by;

$$\nu_i = \frac{1}{5} [\sum_j \frac{a_{ij}}{n} - 2], \ i = 1, 2, 3, 4, 5$$

The factor 1/5 is quite arbitrary. With this definition, the scores computed from any combination of experiments lie between ± 0.4.

Tables 8 and 9 provide the data obtained using the scale scores, in summary form in the first instance and by individual subject in the latter case.

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*Discussion with NBS Statistician, Dr. Joan Rosenblatt.

Table 4. Combined results - acceptability data - speeds 30, 50, 70 mi/h

Tire Number	3	5	1	2	4	Loading Pressure
3		436	506	485	537	Max
		520	525	531	539	Med
5	104		417	458	539	Max
	19		305	469	538	Med
1	34	123		386	532	Max
	15	235		381	533	Med
2	55	82	154		535	Max
	9	71	159		531	Med
4	3	1	8	5		Max
	1	2	7	9		Med

Table 5. Combined results - acceptability data - loading conditions 1150 and 1500 lb.

Tire Numbers	3	5	1	2	4	Speed
3		289	334	316	358	30
		324	348	345	359	50
		343	349	355	359	70
5	71		205	318	358	30
	36		288	293	360	50
	16		229	316	359	70
1	26	155		269	355	30
	12	72		214	352	50
	11	131		284	358	70
2	44	42	91		356	30
	15	67	146		356	50
	5	44	76		354	70
4	2	2	5	4		30
	1	0	8	4		50
	1	1	2	6		70

Read - Left to right (less acceptable)

Table 6. Scale scores ν_i for differences among tire judgements (+.4 to -.4). (Combined data - by conditions)

	Tire 3	Tire 5	Tire 1	Tire 2	Tire 4
Conditions					
30/1500 lb	.259	.218	-.032	-.052	-.392
30/1150 lb	.382	.040	.127	-.156	-.393
50/1500 lb	.349	.129	.012	-.094	-.396
50/1150 lb	.380	.157	-.090	-.057	-.390
70/1500 lb	.374	.140	.014	-.136	-.393
70/1150 lb	.389	.082	.057	-.132	-.396
Combined Loads					
30	.321	.129	.047	-.104	-.393
50	.364	.143	-.039	-.076	-.393
70	.382	.111	.036	-.134	-.394
Combined Speeds					
1500 lb	.327	.162	-.002	-.094	-.394
1150 lb	.384	.093	.031	-.115	-.393
All Data Combined	.356	.128	.015	-.104	-.393

Table 7. Scale scores ν_i for differences among tire judgements (+.4 to -.4) (Individual Subjects - All Conditions)

Subject	Tire 3	Tire 5	Tire 1	Tire 2	Tire 4
1	.367	.161	-.014	-.117	-.397
2	.389	.114	.017	-.122	-.397
3	.375	.189	-.028	-.139	-.397
4	.350	.136	-.017	-.078	-.392
5	.372	.167	-.050	-.092	-.397
6	.386	.117	.022	-.125	-.400
7	.397	.097	.044	-.139	-.400
8	.256	.186	-.017	-.033	-.392
9	.308	.133	.053	-.100	-.394
10	.261	.192	-.017	-.042	-.394
11	.389	.114	.014	-.122	-.394
12	.375	.036	.036	-.078	-.369
13	.378	.117	.036	-.139	-.392
14	.331	.153	.019	-.114	-.389
15	.400	.003	.119	-.128	-.394

In the case where the actual separations among the responses of the subjects were equal, the score ν_i naturally would be .4, .2, 0, -.2, -.4 reading from left to right. Any reversals in magnitude from left to right indicate inconsistencies with the overall ordering of the tires. The data examined in this format again indicate the extent of agreement of subjects for all conditions and also point considerable separation among the preferences for tire sounds.

Table 8 indicates the dBA levels for all experimental conditions. It is notable that the ordering of tires with respect to dBA level is the converse of the order of acceptability. The third-octave data of all of the experimental tires appear in the appendix (B, p. 73-77).

Figure 2 (p. 26) presents scale scores and dBA levels for all experimental conditions. It is interesting to note that there are no line corssings in the figure and that the overall slopes of the lines were quite similar (realizing that there are only five points on each line). There is also consistency with respect to the parametric data in that changed speed and loading conditions resulted in a displacement of the curve in a very systematic fashion.

Table 8. Sound pressure levels, dBA - loadings high and low.

Tire No.	Load, 1500 lb Pressure, 32 lb/in^2			Load, 1150 lb Pressure, 24 lb/in^2		
	Speeds 70	50	30 mi/h	70	50	30 mi/h
4	101	96	91	99	93	90
2	94	90	84	93	89	83
1	91	87	84	90	87	81
5	90	87	82	89	85	81
3	81	80	80	80	79	76

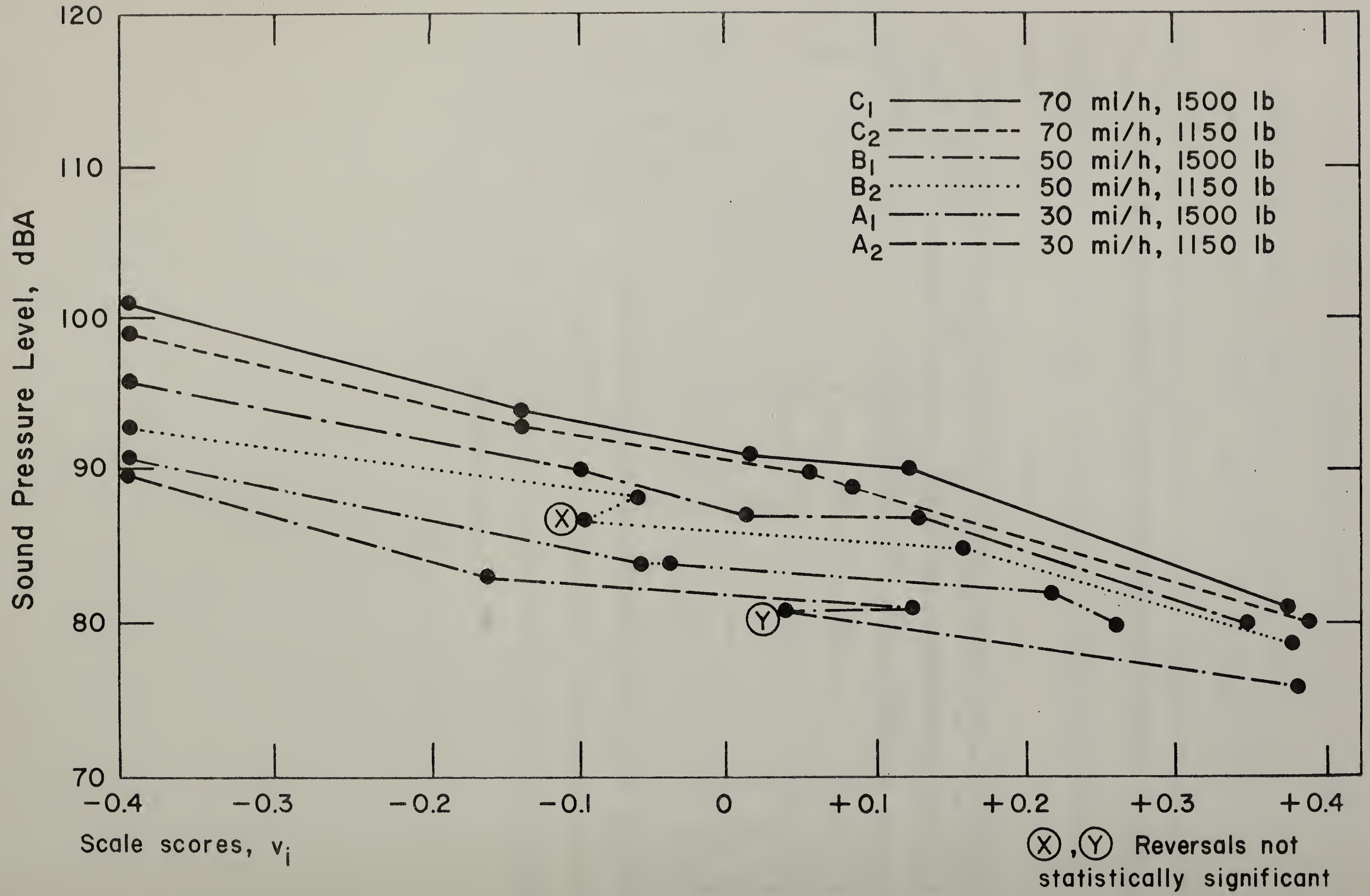


Figure 2. Agreement of dBA and subjective scores (scaled) using order 3, 5, 1, 2, 4.

Tables 9 and 10 indicate the loudness and loudness level measures in sones and phons, respectively. These computations were based on the ISO method for calculating loudness level (15). An inspection of these data indicate that the results are in general agreement with those obtained using dBA readings. For particular experimental conditions it can be noted that in a few instances there are reversals and equal scores. It must be realized, however, that the expected errors of measurement are such that when any of the values are within one or two units of one another, that the scores cannot be said to be different from one another. In the present study, the dBA scale correlated as well with subjective judgements as did the phon or sone scales without the tedious computations required by these latter scales.

Table 9. Sone scale - all conditions. (diffuse field)

Tire No.	Load, 1500 lb Pressure 32 lb/in^2			Load, 1150 lb Pressure 24 lb/in^2		
	Speed 70	50	30	Speed 70	50	30
4	152	125	92	152	112	85
2	105	87	64	102	78	60
1	102	85	67	92	75	56
5	91	77	58	88	68	53
3	74	52	45	51	47	41

Table 10. **Phon scale - all conditions.** (diffuse field)

Tire No.	Load, 1500 lb Pressure, 32 lb/in^2			Load, 1150 lb Pressure, 24 lb/in^2		
	Speed			Speed		
	70	50	30	70	50	30
4	113	110	105	112	108	104
2	107	104	100	107	103	99
1	107	104	101	105	102	98
5	105	103	99	104	101	98
3	102	97	95	97	96	93

Exploration of Auditory Parameters.

One of the primary reasons for undertaking the tire sound research program was to further the basic understanding of the factors associated with "noise" and the reasons for its unacceptability. An identification of several of the many noise parameters is a necessary step toward its ultimate control. The present study provided an opportunity to work with the highly complex auditory stimuli of tire sounds which when compared with one another could provide some insight regarding which characteristics are associated with positive and negative judgements of acceptability. After the conclusion of the experiment, the subjects were interviewed on an individual basis to determine in some detail the criteria that were employed in making their judgements. The objective was to obtain a set of descriptive words or phrases which were used in defining preferences. In the follow-up experiment, a new group of subjects will participate in a similar procedure, with the sounds produced by tires on an automobile in a coastby situation as compared with those obtained at an Endurance Wheel as in the present study. Comparisons will then be made, to determine whether the descriptions of the properties of sounds made in the two studies are similar or different.

The "debriefing" was conducted in two phases. The first rather specific and the second, general. The practice list employed in the experiment was presented one pair at a time to the subjects who were asked to respond appropriately and to indicate in writing the reasons for their selection. The presentation rate was dependent on the needs of the individual subjects. After the list had been completed, the subjects were asked to indicate in general the criteria that they had employed during the study and whether they had been modified during the course of the experiment. To answer the last question first, the subjects indicated that the criteria employed were consistent throughout the study.

Table 11 summarizes the results of the general question regarding criteria. The words used to describe the parameters are not very surprising and conform very well to the findings in the available literature. Table 12 provides a compilation of descriptors used during the detailed paired comparison investigation and might be more fruitful in defining parameters than the other listing. A followup study is currently underway to determine whether the experimental subjects group these words and/or phrases in any systematic fashion. The objective is to construct a rating scale which ultimately might be used in subjective data collection procedures.

Table 11. Summary of subjective findings (criteria for judgements).

Description	Frequency of Response	Order of Response 1	2	3
Loudness	15	14		
Pitch				
High (Shrill)	12	1	9	2
Low (Hum)	5			4
Regularity				
Smooth	1		1	
Periodic	7		4	2
Complexity (Tonal Components)	4		1	2

Table 12. Descriptors (alphabetical order as used).

Annoying beat
Aperiodic
Apparent distance
Chatter
Compatibility of frequency
Complex
High frequency
Knocking
Loud
Low frequency
Machine-like
Modulated
Out of balance
Penetrating
Periodic
Piercing
Powerful
Pure sound
Pure tone components
Reverberant
Sharp
Shrill
Smooth
Steadiness
Vibrating

Discussion

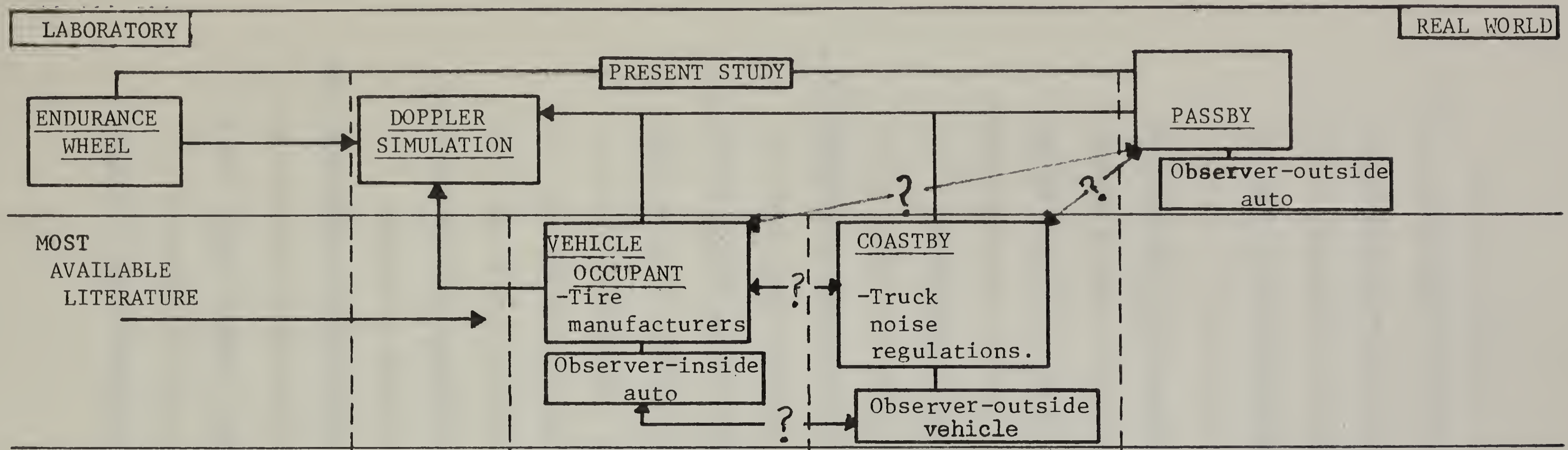
The data obtained in the present study support the feasibility of establishing an acoustical grading system for automobile tires. However, only one segment of a complex problem has been examined, namely the possibility of employing laboratory procedures to obtain acoustical measures of tire sound. It has been found that consistent objective and subjective ratings resulted from a limited sample of tires under a particular set of experimental conditions: the next phase of this investigation of tire sound will consist of field measurements of the same sample of tires mounted on a passenger vehicle. Recordings will be made at roadside at the same speeds and comparable loading conditions with the vehicle in a coastby condition. Physical and subjective analytical procedures identical to those used in the present study will then be performed and the results of the two studies will then be compared. Unfortunately, even if these findings are in complete agreement, there will continue to be many gaps in the "tire sound puzzle".

In reviewing the available literature it became evident that there was very little agreement among researchers regarding the nature of the problem. The reports produced by tire manufacturers were primarily concerned with reducing the "annoyance" of the sounds _within_ the vehicles. The jury tests consisting of subjects making ratings while riding in automobiles reflected this concern. Most of the reported investigations by the tire industry do not even have the stated objective of producing quiet tires, rather they are directed toward producing sounds equivalent to "white noise" which is thought to be more acceptable in terms of _quality_. In contrast to the emphasis on the passengers comfort placed on investigations by tire manufacturers, others concerned with tire sound are primarily interested in the reaction of the "roadside observer" in or out of doors. The specification of the location of the person relative to the sound source is not a trivial matter. Instead, it is a necessary step in carefully defining the nature and limits of the problem under investigation.

An acoustical grading system must rest ultimately on the auditory evaluation of the sound. A community observer, being remote from the vehicle receives a more integrated sound field than a passenger in the vehicle. The important question is whether observers in both locations are consistent in their evaluations of tire sound acceptability.

The studies that have been performed using either roadside or passenger observers have been severely deficient with respect to subjective measures. In addition, since these data were collected in field investigations there are serious questions regarding the adequacy of the physical measures taken as well. Climate, road surface, test vehicles and many other potential sources of uncontrolled variability which can result in experimental error are extremely difficult to quantify appropriately and relate to the variable of interest, tire sound. It is therefore suggested that an integrated approach using both laboratory and field techniques is needed to appropriately address the problem.

Figure 3 illustrates the "world" of tire sound research and summarizes the advantages and disadvantages associated with the different approaches. It should be noted that as the figure is read from left to right there is a transition from the laboratory to the "real world" environment. As noted earlier, researchers have traditionally employed measures taken in VEHICLE OCCUPANT and in COASTBY situations.



	ENDURANCE WHEEL		MOVING VEHICLE	COASTBY	PASSBY
ADVANTAGES	1. Maximum experimental control. 2. Well defined measurement procedures. 3. Specification of environmental characteristics. 4. Availability of standardized test apparatus-endurance wheel.		1. Consistent with available research data. 2. Considers sound from standpoint of vehicle occupants.	1. Lessens unwanted sounds produced by engine and muffler. 2. Consistent with existing data collection procedures.	1. Tires mounted on vehicle rather than artificial device. 2. Test environment typical of many real world situations. 3. Actual road surface provides tire contact area. 4. No "artificial" sounds introduced by wheel and enclosure. 5. Appears "realistic".
DISADVANTAGES	1. Doesn't resemble real world situation. 2. High sound level produced by endurance wheel. 3. Sound is continuous-unlike passby. 4. Smooth and rounded test surface may not be appropriate.		1. Instrumentation and measurement procedures difficult. 2. Difficulty in separating tire from other vehicle sounds.	1. Difficulty in maintaining desired speeds. 2. Less realistic situation.	1. Lack of control of general test environment-weather, geography. 2. Lack of precise control of experimental parameters; speed, tire, temperature. 3. Difficulty in accurately defining measurement procedures and test procedures. 4. Engine and body sounds mask tires.

← ? → Inability to relate research findings

Figure 3. Tire sound research "world".

It can be seen that these two conditions actually constitute only the middle range of research possibilities and have several inherent disadvantages associated with field studies without the advantage of being truly realistic. The major flaw in the body of available literature is that the research findings based on VEHICLE OCCUPANTS cannot be related to that obtained in a COASTBY condition because of the inconsistency of the relationship of the observer to the tire sound. One of the major differences between the sound heard within and outside a vehicle is the doppler shift apparent at roadside where the vehicle is moving and the observer is stationary. If it were possible to simulate the doppler effect and the rise-fall in sound pressure, then the tire sound rankings based on the acoustical environment within the vehicle could be compared with those based on roadside observations. With a passby sound simulation method available, it would be possible to develop a comprehensive research program to evaluate the feasibility of establishing a tire sound grading system. It could also serve to relate the findings of researchers using totally different experimental methodologies and criteria for assessment of tire sound. Referring again to the figure and the explanatory information, data collected at the ENDURANCE WHEEL (maximum experimental control) and in a PASSBY (maximum realism) can be compared with results obtained using traditional methodologies. If it is then determined that rankings are consistent among these experimental conditions, a great deal of progress will have been made toward establishing a tire sound grading system as well as demonstrating the validity of a laboratory approach in making measurements.

Conclusions

a. The subjective and physical data based on tire sounds recorded at the Endurance Wheel were remarkably consistent for all experimental conditions.

b. It is necessary to determine whether the results obtained in the study are validated in investigations based on field data obtained under "realistic" conditions.

c. The results of the study support the possibility of achieving an acoustical grading system for automobile tires.

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APPENDIX A

Subjective Data

Tables*

*The tables indicate the procedures employed to determine the exhaustive set of comparisons required (A_1), the method used in constructing and balancing the lists (A_2) and finally, the actual lists used in the study.

Subjects

The experimental subjects consisted of 15 males employed at the National Bureau of Standards who ranged in age from 23 to 48 years. They were screened by means of an auditory examination performed by the medical unit of the Bureau which indicated no serious hearing disorders. Three subjects selected to be in the study were not included in the sample. Two of them indicated that several sounds were "too loud" and declined to complete the study in the prescribed manner. The other subject misunderstood the instructions and the intent of the experiment and responded in an inappropriate manner.

Instructions

The primary purpose of the tests being conducted is to determine how people feel about the relative acceptability of one type or level of automobile tire sound when compared with another type or level of automobile tire noise.

You will hear a series of sounds from automobile tires. The sounds will occur in "pairs" and your task is to judge which sound in each pair is more acceptable to you if heard alongside a road or at home.

After you have heard each sound pair, please quickly decide which of the two you feel would be more acceptable to you. If the second sound of a pair is more acceptable, circle B for that pair. If the first sound of the pair is more acceptable, circle A.

Please concentrate on the judgement at hand and respond either A or B even though the two sounds may seem approximately equal in acceptability. If you can't detect any difference in acceptability between the two sounds, please make the best guess that you can.

There are no "right" or "wrong" answers. We are interested in how you judge the differences in acceptability among tire sounds and how your judgements compare with those of others.

An announcement will be made, identifying the list of sound pairs to be judged. Each list consists of ten paired sounds. After the presentation of each sound pair, the pair will be identified numerically as an aid in keeping track of your place in the list. Please record your judgement immediately after hearing the identifying number as there will not be much time between presentation of sound pairs.

Procedure

The auditory experiment was conducted in a laboratory module approximately 24 feet long and 11 feet wide. All of the required sound and electronic equipment were in the room as well as three chairs, a desk and a table. The experimenter was seated at the desk facing the table and had the tape recorder and its associated controls within easy reach. Two subjects were seated at adjacent sides of the table to minimize the possibility of reading answers from one anothers' score sheets. Junction boxes for the connections between the headsets used in the study, and the amplifier were attached to the table in order to avoid the presence of excess wires within the room. The experimenter presented tapes (three lists) in accordance with a predetermined schedule of presentation which was designed to be random except for two restrictions. There were no instances of successive presentations of the same tape. Also, two replications of all 12 lists were completed before the next randomized sequence was started. These procedures were employed to minimize the influence of responses on one list to those on later lists and to offset learning which might occur with an orderly repetition of material. As a further precaution, answer sheets were collected as soon as they were completed so they could not be referred to at a later time.

The experiment was divided into four sessions, each one lasting approximately one and one-half hours. During each session a total of six tapes (18 lists) were presented with a ten-minute break provided at the midpoint in the proceedings.

In the first session a standard set of instructions was read to the subjects indicating the nature of the study and specifying the task to be performed. They were instructed to respond by marking the answer sheet indicating which one of the pair of sounds that they were about to hear was more acceptable to them from the standpoint of a roadside observer or someone at home. The sheet consisted of pairs numbered from 1 to 10 with A and B designations for each pair (see Appendix for sample form). If the first member of the pair were judged more acceptable, then A would be circled. If the second pair member were selected, B was designated. The response was recorded when the pair designation was noted on the tape. This procedure served the functions of assisting the subject to keep his place in the list and to ensure that both sounds were heard for the same length of time. It was emphasized that there were no right or wrong answers and that if a clearcut judgement were not possible, that an arbitrary selection should be made.

A practice list consisting of ten sound pairs not used in the study was then introduced. This list was constructed by pairing sounds obtained during different experimental conditions. The practice list served to clarify the nature of the task for the subjects and in later sessions was used as a "warmup" prior to data collection. With the completion of the practice list, the subjects were permitted to ask questions concerning the nature of the task required of them. The experimental lists were then presented. As noted previously, each list consisted of 10 sound pairs, each pair member was five seconds in duration with a two second interval between sounds. At the conclusion of the pair, there was a five second interval during which time the response was made.

After the completion of the last session, the subjects were debriefed on an individual basis. The procedure consisted of the presentation of the practice list, one pair at a time. After each pair was heard, the subject was instructed to make a selection as to acceptability just as before, but was also encouraged to give reasons (if possible) for the selection. After all ten pairs were presented, two general questions were posed. The subject was asked to define the kinds of criteria that were used in making the previous selections and to indicate whether there were any changes in the criteria during the course of the experiment. The subjects made all of their comments in writing.

		Tire Pairs			
Loading/Pressure	Speeds	I-II	I-III	I-IV	I-V
1(Maximum)	A (30)	IA_1- IIA_1	IA_1-$IIIA_1$	IA_1- IVA_1	IA_1- VA_1
	B (50)	IB_1- IIB_1	IB_1-$IIIB_1$	IB_1- IVB_1	IB_1- VB_1
	C (70)	IC_1- IIC_1	IC_1-$IIIC_1$	IC_1- IVC_1	IC_1- VC_1
2 (Medium)	A (30)	IA_2- IIA_2	IA_2-$IIIA_2$	IA_2- IVA_2	IA_2- VA_2
	B (50)	IB_2- IIB_2	IB_2-$IIIB_2$	IB_2- IVB_2	IB_2- VB_2
	C (70)	IC_2- IIC_2	IC_2-$IIIC_2$	IC_2- IVC_2	IC_2- VC_2
		II-III	II-IV	II-V	
1	A	IIA_1-$IIIA_1$	IIA_1- IVA_1	IIA_1- VA_1	
	B	IIB_1-$IIIB_1$	IIB_1- IVB_1	IIB_1- VB_1	
	C	IIC_1-$IIIC_1$	IIC_1- IVC_1	IIC_1- VC_1	
2	A	IIA_2-$IIIA_2$	IIA_2- IVA_2	IIA_2- VA_2	
	B	IIB_2-$IIIB_2$	IIB_2- IVB_2	IIB_2- VB_2	
	C	IIC_2-$IIIC_2$	IIC_2- IVC_2	IIC_2- VC_2	
		III-IV	III-V		
1	A	$IIIA_1$- IVA_1	$IIIA_1$- VA_1		
	B	$IIIB_1$- IVB_1	$IIIB_1$- VB_1		
	C	$IIIC_1$- IVC_1	$IIIC_1$- VC_1		
2	A	$IIIA_2$- IVA_2	$IIIA_2$- VA_2		
	B	$IIIB_2$- IVB_2	$IIIB_2$- VB_2		
	C	$IIIC_2$- IVC_2	$IIIC_2$- VC_2		
		IV-V			
1	A	IVA_1- VA_1			
	B	IVB_1- VB_1			
	C	IVC_1- VC_1			
2	A	IVA_2- VA_2			
	B	IVB_2- VB_2			
	C	IVC_2- VC_2			

Table A_2. Comparisons made within lists.

Lists	1	2	3	4	5	6
Tire Pairs	A_1	A_2	B_1	B_2	C_1	C_2
I-II (II -I)	$IA_1- IIA_1$	$IIA_2- IA_2$	$IIB_1- IB_1$	$IB_2- IIB_2$	$IIC_1- IC_1$	$IC_2- IIC_2$
I-III(III-I)	IA_1-IIIA_1	$IIIA_2- IA_2$	IB_1-IIIB_1	$IIIB_2- IB_2$	IC_1-IIIC_1	$IIIC_2- IC_2$
I-IV	$IVA_1- IA_1$	$IVA_2- IA_2$	$IB_1- IVB_1$	$IVB_2- IB_2$	$IC_1- IVC_1$	$IVC_2- IC_2$
I-V	$VA_1- IA_1$	$VA_2- IA_2$	$IB_1- VB_1$	$IB_2- VB_2$	$VC_1- IC_1$	$IC_2- VC_2$
II-III	IIA_1-IIIA_1	IIA_2-IIIA_2	IIB_1-IIIB_1	IIB_2-IIIB_2	$IIIC_1- IIC_1$	IIC_2-IIIC_2
II-IV	$IIA_1- IVA_1$	$IIA_2- IVA_2$	$IIB_1- IVB_1$	$IVB_2- IIB_2$	$IVC_1- IIC_1$	$IVC_2- IIC_2$
II-V	$VA_1- IIA_1$	$IIA_2- VA_2$	$VB_1- IIB_1$	$IIB_2- VB_2$	$IIC_1- VC_1$	$IIC_2- VC_2$
III-IV	IVA_1-IIIA_1	IVA_2-IIIA_2	$IIIB_1- IVB_1$	IVB_2-IIIB_2	$IIIC_1- IVC_1$	$IIIC_2- IVC_2$
III-V	$IIIA_1- VA_1$	$IIIA_2- VA_2$	VB_1-IIIB_1	$IIIB_2- VB_2$	$IIIC_1- VC_1$	$IIIC_2- VC_2$
IV-V	$VA_1- IVA_1$	$VA_2- IVA_2$	$VB_1- IVB_1$	$VB_2- IVB_2$	$VC_1- IVC_1$	$VC_2- IVC_2$
Lists	7	8	9	10	11	12
Tire Pairs	A_1	A_2	B_1	B_2	C_1	C_2
I-II (II -I)	$IIA_1- IA_1$	$IA_2- IIA_2$	$IB_1- IIB_1$	$IIB_2- IB_2$	$IC_1- IIC_1$	$IIC_2- IC_2$
I-III(III-I)	$IIIA_1- IA_1$	IA_2-IIIA_2	$IIIB_1- IB_1$	IB_2-IIIB_2	$IIIC_1- IC_1$	IC_2-IIIC_2
I-IV	$IA_1- IVA_1$	$IA_2- IVA_2$	$IVB_1- IB_1$	$IB_2- IVB_2$	$IVC_1- IC_1$	$IC_2- IVC_2$
I-V	$IA_1- VA_1$	$IA_2- VA_2$	$VB_1- IB_1$	$VB_2- IB_2$	$IC_1- VC_1$	$VC_2- IC_2$
II-III	$IIIA_1- IIA_1$	$IIIA_2- IIA_2$	$IIIB_1- IIB_1$	$IIIB_2- IIB_2$	IIC_1-IIIC_1	IIC_2-IIIC_2
II-IV	$IVA_1- IIA_1$	$IVA_2- IIA_2$	$IVB_1- IIB_1$	$IIB_2- IVB_2$	$IIC_1- IVC_1$	$IIC_2- IVC_2$
II-V	$IIA_1- VA_1$	$VA_2- IIA_2$	$IIB_1- VB_1$	$VB_2- IIB_2$	$VC_1- IIC_1$	$VC_2- IIC_2$
III-IV	$IIIA_1- IVA_1$	$IIIA_2- IVA_2$	IVB_1-IIIB_1	$IIIB_2- IVB_2$	IVC_1-IIIC_1	IVC_2-IIIC_2
III-V	VA_1-IIIA_1	VA_2-IIIA_2	$IIIB_1- VB_1$	VB_2-IIIB_2	VC_1-IIIC_1	VC_2-IIIC_2
IV-V	$IVA_1- VA_1$	$IVA_2- VA_2$	$IVB_1- VB_1$	$IVB_2- VB_2$	$IVC_1- VC_1$	$IVC_2- VC_2$

Table A_3. Lists used in the experiment.

Pairs	A_1	A_2	B_1	B_2	C_1	C_2
1.	IIA_1-IVA_1	$IIIA_2$-IA_2	VB_1-IVB_1	$IIIB_2$-IB_2	VC_1-$IIIC_1$	IC_2-IIC_2
2.	III-IV	V-II	V-I	V-III	IV-I	V-II
3.	V-III	II-III	III-V	IV-V	I-V	III-II
4.	IV-I	I-V	II-I	I-V	I-III	V-III
5.	I-II	I-IV	I-III	II-I	II-III	IV-I
6.	V-II	IV-III	II-IV	IV-II	IV-II	III-IV
7.	V-IV	II-IV	I-IV	IV-I	II-V	I-III
8.	II-III	I-II	V-II	II-V	I-II	II-IV
9.	I-V	V-III	III-IV	III-IV	V-IV	I-V
10.	III-I	V-IV	III-II	II-III	IV-III	V-IV

Pairs	A_1	A_2	B_1	B_2	C_1	C_2
1.	IIA_1-VA_1	$IIIA_2$-VA_2	IVB_1-IB_1	IIB_2-IVB_2	IIC_1-IC_1	IIC_2-IC_2
2.	I-III	II-V	IV-V	III-II	V-I	IV-V
3.	IV-V	II-I	IV-III	I-III	II-IV	IV-III
4.	V-I	III-IV	I-II	IV-III	III-IV	I-IV
5.	I-IV	V-I	V-III	I-IV	III-I	IV-II
6.	IV-III	III-II	III-I	III-V	IV-V	V-I
7.	III-II	I-III	II-V	I-II	III-II	II-V
8.	II-I	II-IV	II-III	V-IV	III-V	II-III
9.	III-V	IV-I	IV-II	V-I	I-IV	III-I
10.	IV-II	IV-V	I-V	V-II	V-II	III-V

Table A_4. Sequence of list presentation (first of three lists).

Subject Number	Session 1						Session 2						Session 3						Session 4					
1, 2	10	7	10	7	4	1	4	1	4	1	10	1	7	4	7	10	7	4	1	10	1	7	4	10
3	7	4	7	10	4	1	10	1	4	1	10	7	1	7	4	10	1	10	4	7	1	4	10	7
4, 5	10	1	10	1	7	4	7	4	1	4	7	10	4	7	10	1	7	10	7	4	10	1	4	1
6	10	7	10	1	4	1	4	7	4	10	1	10	1	7	4	7	4	1	10	4	7	10	7	1
7, 8	1	4	1	10	7	10	7	4	7	1	4	10	10	7	1	4	1	7	4	7	10	1	10	4
9	10	4	7	10	4	1	7	1	7	10	1	4	10	1	7	4	7	4	1	4	10	1	10	7
10	4	7	4	10	1	10	10	7	10	1	4	1	7	1	4	7	10	4	1	7	4	10	7	1
11	7	4	7	10	4	1	10	1	10	4	1	10	1	10	7	1	4	7	4	7	10	4	1	7
12	10	7	10	1	4	1	1	7	4	7	4	1	1	10	7	7	7	10	10	4	7	1	10	4
13	7	4	1	10	7	4	4	1	10	7	10	1	10	1	4	4	1	10	4	7	1	10	4	7
14	1	7	4	10	7	1	10	4	7	1	7	4	10	7	4	1	10	4	10	1	4	7	1	10
15	1	4	10	1	10	7	7	4	1	10	4	7	4	7	1	10	4	7	1	10	1	4	7	10

APPENDIX B

Tire Selection Study

Tire Selection (Pilot Study)

In choosing the particular automobile tires to be used in the experiment, the goal was to obtain a representative sample from those in general use. Because of the large number of manufacturers and the many sizes and types made by each, it was totally impractical to make an empirical determination of the tires to be used in the study. Instead, an initial selection of seven tires was made by a member of the staff of the Office of Vehicle Systems who by virtue of his extensive experience with tire testing research can be termed "tire expert". The criteria he imposed for selection were: (1) ready availability, (2) a "broad range" of acoustic characteristics, (3) a variety of structural characteristics (4) consistent dimensions. In all cases the properties were not unique to the tire selected but rather were "typical" of other tires on the market. The tires, which all have a fourteen inch rim diameter were:

1.	4 ply bias	7:35-14	Goodyear
2.	4 ply snow tire	7:35-14	Goodrich
3.	2/2 ply belted	7:75-14	General
4.	4 ply radial	195-14	Michelin X
5.	Experimental skid test tire	7:50-14	General
6.	4 ply bias	7:50-14	Firestone
7.	4 ply bias	7:50-14	Goodrich

The tires were tested on the Endurance Wheel at the Office of Vehicle Systems under uniform loading (1160 lb) and inflation pressure (24 lb/in^2) conditions as specified by the tire expert. Since the measures were to serve only a screening function designed to reduce the tire sample, all four tire positions on the wheel were employed in the expectation that any error introduced would not be significant. This procedure made the task of mounting the tires much easier for the Office of Vehicle Systems staff and considerably reduced the time required to make the needed measurements. In all cases, the microphone was positioned approximately 40" from the top surface of the tire being measured, facing the sidewall. A microphone extension cable was used to permit measurements to be made in an adjoining room on the sound level meter and the octave band analyzer.

The tires were run at 30, 50 and 70 mi/h speeds, in that order. Two sets of octave band readings were made at each of the speeds as well as A and C scale measurements. Simultaneous with the objective measurements, a subjective assessment was conducted. Tonal and periodic components apparent in the tire sounds were noted in a general way. Since the instrumentation available gave no readings that could be associated with these characteristics, it was necessary to make qualitative statements describing the sounds.

The objective and subjective data describing the seven tires were then examined (Tables 20 thru 23) and a final sample selection was made. The choice of the tires to be used in the study were dictated by the following criteria:

1. The desirability of obtaining as great a range in dBA readings as possible.
2. Including sounds that were not uniform throughout the spectrum, i.e., containing pure tone components.
3. Including sounds with periodic components typified by some belted and radial tires.
4. Minimizing the total number of tires examined while still having a large enough sample to permit the construction of a rank order scale for each experimental condition.

On the basis of these criteria, tires 1 (4 ply bias 7:35-14, Goodyear) and 3 (2/2 ply belted 7:75-14, General) were eliminated from the study. These two tires had characteristics and acoustic profiles very similar to two tires included in the study and were therefore considered unnecessary.

Table B_1. Sound pressure levels, dBA and dBC - 7 tires

	A Scale			C Scale		
	Speeds			Speeds		
Tires	30	50	70	30	50	70
1	79	86	90	83	86	89
2	89	94	99	90	96	99
3	79	83	90	84	86	90
4	84	92	95	85	92	96
5	83	82	83	82	83	84
6	81	86	93	85	88	93
7	82	85	90	83	86	90

Table B_2. Sound pressure levels (dB) - 7 tires (30 mi/h and ambient).

Tire	1	2	3	4	5	6	7	Ambient
A Scale	79	89	79	84	83	81	82	67
C Scale	83	90	84	85	82	85	83	70
OCTAVE BAND (Center Frequency)								
31.5	70	71	72	70	70	71	70	68
63	76	80	78	75	75	80	73	63
125	74	74	76	80	74	74	78	55
250	73	83	72	73	72	73	74	60
500	78	87	75	78	74	79	76	60
1000	79	82	77	80	74	78	78	62
2000	71	76	70	77	69	72	73	62
4000	70	71	65	75	63	66	70	53
8000	71	61	58	71	55	60	68	44
16000	62	48	50	57	48	48	61	34

Table B$_3$. Sound pressure levels (dB) - 7 tires (50 mi/h).

Tire	1	2	3	4	5	6	7
A Scale	86	94	83	92	82	86	85
C Scale	86	96	86	92	83	88	86
OCTAVE BAND (Center Frequencies)							
31.5	71	72	72	72	71	71	72
63	75	80	79	75	75	80	74
125	76	79	77	81	76	75	77
250	74	84	75	79	73	78	75
500	80	96	78	79	76	85	78
1000	80	87	80	87	77	84	80
2000	79	83	77	87	74	79	82
4000	76	80	70	82	66	72	76
8000	78	70	63	76	61	67	74
16000	68	57	54	62	56	55	65

Table B_4. Sound pressure levels (dB) - 7 tires (70 mi/h).

Tire	1	2	3	4	5	6	7
A Scale	90	99	90	95	83	93	90
C Scale	89	99	90	96	84	93	90
OCTAVE BAND (Center Frequencies)							
31.5	72	73	72	72	72	70	73
63	75	80	80	75	77	80	75
125	76	82	82	83	78	80	80
250	77	82	81	89	76	80	78
500	82	96	82	88	77	86	80
1000	83	93	83	89	78	90	81
2000	84	90	83	90	74	86	85
4000	80	85	76	88	67	78	81
8000	84	78	68	82	62	75	84
16000	73	65	57	68	58	60	72

APPENDIX C

Physical Data

Figures

Tables

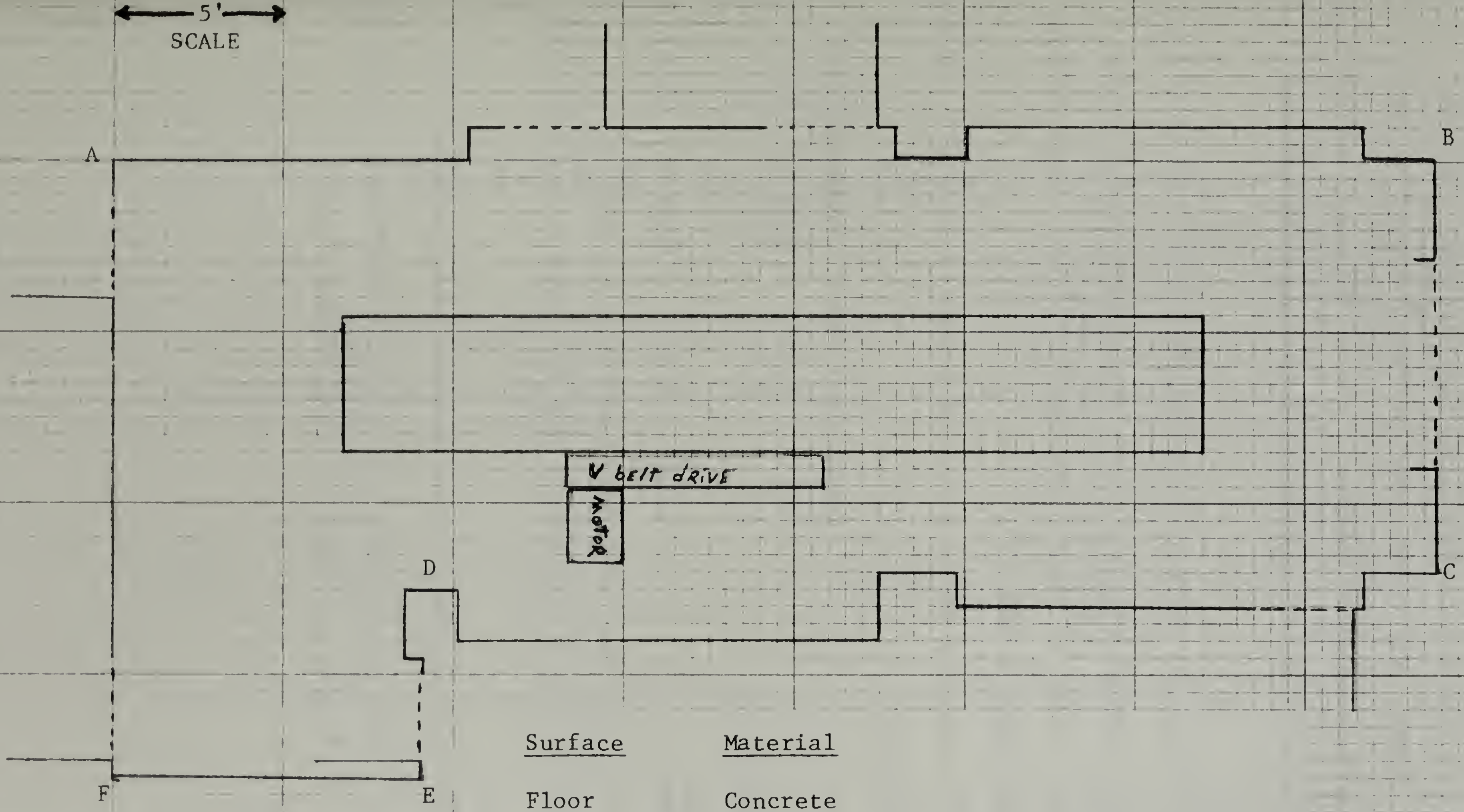
Endurance Wheel Room

The Endurance Wheel provided reasonably good laboratory conditions for the collection of continuous sounds of rolling tires (figure C_1). The main disadvantage was the rather high background sound level of the Endurance Wheel's D.C. drive motor and the blower used to cool the motor. The four tire positions available around the wheel were mechanically equivalent since tires at any of the four positions could be loaded using a system of levers and weights. Acoustically, however, position 2 (figure C_3) proved to meet the three criteria necessary for the tire sound recording (p. 67).

The 17.6 ft circumference steel Endurance Wheel was driven by a variable speed D.C. motor using a V-belt drive. The D.C. motor was cooled with a centrifugal air blower. The Endurance Wheel's surface velocity was monitored and controlled to ±1 mi/h in the control room adjacent to the Endurance Wheel room. The Endurance Wheel room was maintained at 100 °F throughout the recording sessions.

The tires were properly inflated after stabilizing at the 100° room temperature (24 lb/in^2 for a 1150 lb load, 32 lb/in^2 for a 1500 lb load) to give a consistent baseline for the experiment.

The five tires were indelibly marked with a paint crayon with the designations A1, A2, A3, A4, A5. An identical set labeled B1, B2, B3, B4, B5 were held in reserve for the highway studies where each pair would be mounted in turn on the rear wheels of a vehicle.



Surface		Material
Floor		Concrete
Ceiling		Plaster
Wall:	AB	Plaster
	BC	Plaster
	CD	Stud Frame; Wood Panels & Glass Windows
	EF	Plaster Board
	FA	Stud Frame; Plaster Board

Figure C_1. Endurance wheel room plan.

To obtain a general idea of the sound diffusion in the Endurance Wheel room, an approximate determination of the sound decay was undertaken. Decay rates were regular which indicated that the sound diffusion was satisfactory.

The average absorption coefficients calculated were consistent for the room surfaces, although slightly higher than published figures for the materials. The volume of the room was about 9100 ft^3; total surface area measured approximately 3100 ft^2.

The acoustical characteristics of the room were as follows: (within the order of 20% error)

	Octave band center frequency (Hz)			
	500	1000	2000	4000
Reverberation time, s	1.9	1.6	1.3	1.2
Average absorption coefficient, sabins	0.08	0.09	0.11	0.12

The plan of the room and its surface materials are shown in figure C_1. Figures C_5 and C_6 depict the equipment used to determine the reverberation time.

A third-octave band analysis of the Endurance Wheel machinery is given in table C_1. This third-octave band analysis (along with Tables C_2 through C_6, pp. 73-77) were performed with the equipment shown in figure C_7, p. 80.

Table C_1. Machine sound (no tire) - 1/3 octave band analysis (dB).

Center Frequency	(Blower - On)	Speeds - MPH		
		30	50	70
25	55	57	60	55
31.5	53	58	59	60
40	65	67	68	68
50	70	73	73	73
63	81	83	83	82
80	74	78	77	78
100	67	70	71	70
125	66	68	67	68
160	73	74	75	74
200	76	78	78	78
250	64	67	67	69
315	72	75	75	75
400	58	62	64	64
500	55	62	64	65
630	55	64	66	70
800	54	68	70	70
1000	57	63	68	69
1250	57	61	63	64
1600	58	61	62	63
2000	54	58	61	62
2500	52	56	58	60
3150	49	55	56	57
4000	46	51	52	52
5000	--	48	49	48
A Scale	71	75	77	78
C Scale	84	86	86	86

Recording Instrumentation

The Mobile Acoustical Laboratory of the Building Research Division (figure C_2) was parked inside the Vehicle Systems Research Building 15 ft from the Endurance Wheel room. Power cords and shielded signal lines were passed under a door into the room.

The Mobile Laboratory was connected to the local 120 V AC power line. The voltage was stabilized on a Sorensen regulator[†] and used on all instrumentation except the battery-powered B & K 2204 sound level meter.

The 4131 B & K condensor microphone was placed about 3 ft from the test tire mounted in position 2 in such a manner to avoid standing waves. The tire sound signal was amplified by a 2619 B & K preamplifier and further amplified by a 222-2 B & K conditioner. The signal was applied to the channel 1 input of the 1525 General Radio tape recorder and to the input of the 2204 B & K sound level meter. (figure C_8, p.81)

The level of the recorded signal could be adjusted by either the 10 dB step attenuator on the 1525 recorder or by the 10 dB step gain control on the 222-2 conditioner. (The exact settings are given in the procedural outline.) A simultaneous verbal description of the experimental conditions were recorded on track 2 via a second 4131 microphone, 2619 preamplifier, and a 222-2 conditioner by the experimenter in the Mobile Laboratory.

[†] Certain commercial equipment, instruments, or materials are identified in this paper 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 material or equipment identified is necessarily the best available for the purpose.

Figure C_2. Mobile acoustical laboratory.

Faithful reproduction of the tire sound signal was maintained by simultaneously monitoring its dB(C) level on the 2305 B & K graphic level recorder.

Microphone Placement

The criteria for the position of the microphone relative to the tire were:

(a) maximum signal to noise ratio; tire + machinery sound to machinery sound.

(b) minimum change in machinery sound with changing speed.

(c) freedom from standing waves.

The first criterion (a) was met by testing the space around the wheel for minimum sound position with the 2203 sound level meter while the machinery was running without an engaged test tire. Batts of acoustically absorbent material placed around the drive mechanism and motor reduced the machinery noise several dB.

The second criterion (b) was established without engaging a tire and running the wheel at various speeds to find a position with the least variations in sound level. Although positions close to the wheel assisted the first criterion, dynamic sounds from the wheel motor and surface air motion failed to meet the second criterion.

The third criterion was met by moving the microphone back and forth from an engaged tire, noting any sharp variations in sound pressure. Positions less than 2.5 ft from a reflecting surface were avoided.

A final position is recorded in figures C_3 and C_4, which seemed to meet the requirements for A and C weighted sound level measurements.

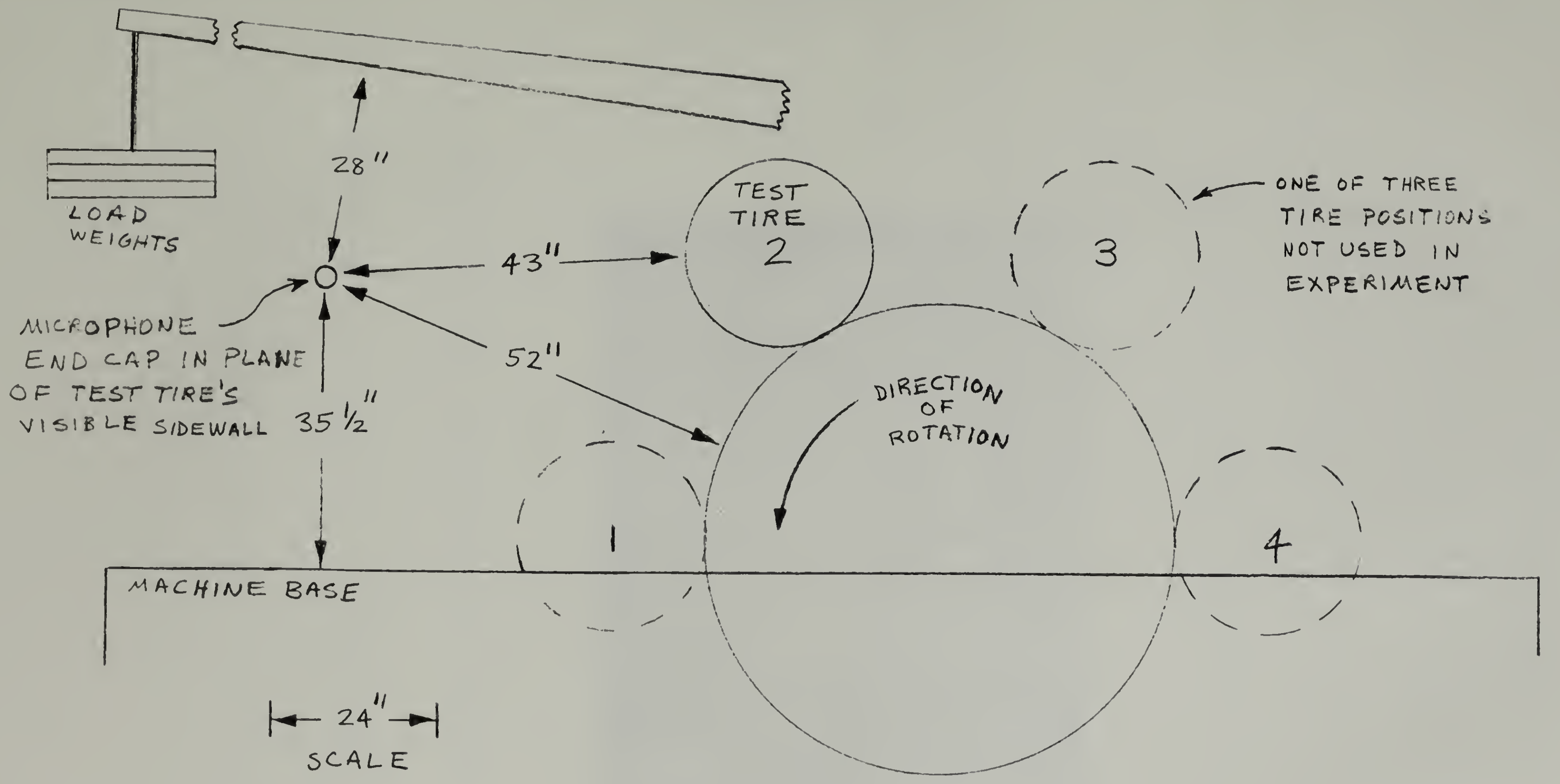


Figure C_3. Microphone position diagram.

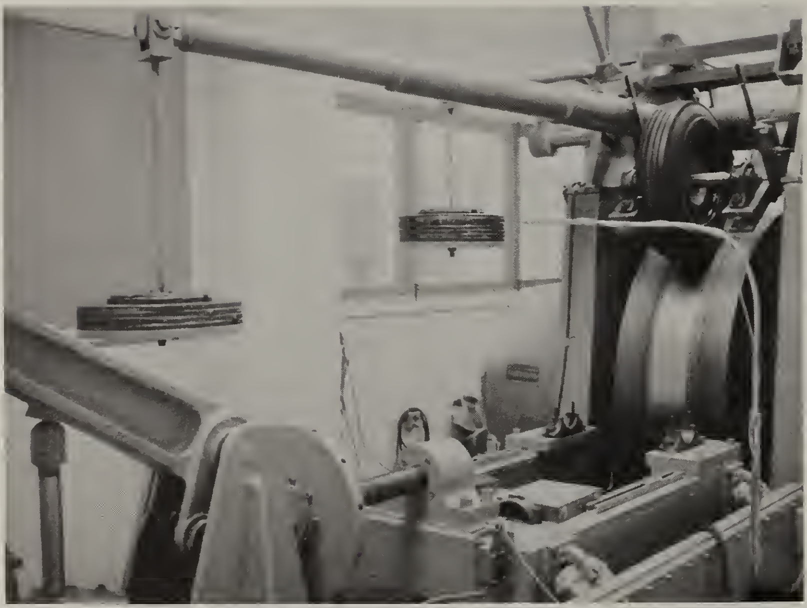


Figure C_4. Photograph of microphone position at endurance wheel.

Recording Procedure

A total of ten tapes were recorded. Each tape contained the three speeds (30, 50, 70 mi/h) of one tire for a given pressure and loading condition. There were, however, several necessary steps taken before each recording session began. After the five tires had stabilized at the 100 °F room temperature, they were pressurized to 32 lb/in^2. The recording microphone position was checked. A 124 dB pistonphone calibration signal was then recorded for 30 s on the beginning of a tape with the tape recorder attenuator set at 130 dB. (The actual recorded level was 94 dB for 30 and 50 mi/h tire sounds because 30 dB extra attenuation was used during the recording of the pistonphone signal.) The tape recorder attenuator was reset to 100 dB in readiness for a run at 30 mi/h.

The selected tire was run for 5 minutes at 30 mi/h at 1500 lb load on the Endurance Wheel to allow the tire to stabilize its temperature. A 5 min. tape recording was made on track one.

During the 5 min. run the experimenter in the Mobile Laboratory recorded on track two a verbal description of the number, load, speed, and attenuator settings. While the 5 min. recording session progressed, the 2305 level recorder produced a graphic record of the dB (C) level at the recording microphone position. If there were fluctuations greater than ± 1 dB during the recording session, the tape was rewound and a new 5 min. session at the same speed begun. If fluctuations were ± 1 dB or less the 5 min. warm-up at 50 mi/h was begun.

The procedure for the 70 mi/h recording session was identical to the 30 and 50 mi/h runs except that the input attenuator on the tape recorder was set at 110 dB. A 30 second pistonphone recording was made at the end of the 70 mi/h recording.

After each of the five tires had been run at 1500 lb load and 32 lb/in^2 pressure, it was left in the Endurance Wheel room to stabilize to the 100 °F level present in the room. The tire pressure was lowered to 24 lb/in^2. The tires were then run in the same sequence as before with a 1150 lb load.

Preparation of Stimulus Material

List Construction.

The "raw data" for the lists consisted of tire sounds recorded at the Endurance Wheel during the thirty experimental conditions (5 tires x 2 loadings/pressures x 3 speeds). The lists were constructed by splicing together samples of tire sounds, prerecorded list and pair identifications and "blank" tape lengths. Each list was prepared in the following manner. An introductory identification of the list lasting 10 s was followed by 5 s of tire sound, next, a blank interval of 2 s duration, then a 5 s sample of another tire sound and finally a 5 s period containing the pair identification number to indicate when to respond and the appropriate place on the answer sheet. The sequence of sound-pause-sound-interval was repeated ten times during each list. The lists were therefore three minutes in duration (17 s x 10 + 10 s introduction). The sequencing of the particular list was determined on the basis of Table A_3, p. 49.

A practice list was constructed using the same format as that employed in the test lists, but the pairs consisted of sounds produced under different experimental conditions.

Generation of Stimulus Tapes.

The generation of stimulus tapes for use on the Ampex AG500 tape recorder required the splicing of tire sound segments from the 5 min. recordings and the copying the spliced lists along with calibration tones on the Ampex machine.

These spliced master lists were copied on the Ampex AG500 to obtain splice-free stimulus tapes using the equipment in Figure C_9, p. 82. The 20 s pistonphone calibration signal from a tire sound tape made at the Endurance Wheel room was played back on the 1525 General Radio recorder and recorded on the Ampex AG500, establishing a 104 dB reference tone. A 400 Hz earphone reference tone was then recorded on the Ampex for 30 s at 104 dB using the 1022 B & K Beat Frequency Oscillator. The spliced practice list was then played back on the 1525 General Radio and recorded on the Ampex. In the same manner three spliced lists were recorded on the Ampex to complete one stimulus tape consisting of a 250 Hz pistonphone tone, a 400 Hz earphone level tone, a practice list, and three stimulus lists. Lists with 70 mi/h sounds were recorded at a 10 dB higher level than 30 and 50 mi/h sounds to negate the original 10 dB difference between the recording attenuator settings.

Stimulus Presentation System

The tire sound pair tapes were played back on the system depicted in Figure C_{10}, p. 83 which presented the sounds to two subjects at the same dB level present at the microphone position in the Endurance Wheel room.

Four reels of tape, each containing a calibration tone, practice list and three test lists, were used to present the material. This procedure was employed to facilitate a randomized presentation of lists thereby offsetting any learning attributable to a fixed sequence of presentation (serial learning). Grouping the lists by threes was a compromise solution necessitated by the time required to present a fully randomized sequence of lists to each subject. Table A_4, p. 50 indicates the presentation sequence by subject, used in the study. It can be noted that although the study was planned to permit the running of two subjects simultaneously, in most instances the subjects had different sequences of presentation, indicating that they were run separately.

The detailed circuit diagram of Figure C_{11}, p. 84 shows the relationship between the monitoring volt ohm meter and the dB level at the subjects' and monitor's earphones. The resistors and headphones formed an 80:1 voltage dividing network. One volt rms at 400 Hz will produce a level of 127 dB (ref. .0002 μbar) in a Koss 727 headphone. The 400 Hz calibration signal on the tire sound pair tapes was reproduced at the required 104 dB level when the voltage across the headphones was 0.0705 VAC rms. This lead to a calibration reading of 5.6 VAC rms on the Triplet volt ohm meter and was checked at the beginning of each session.

Table C$_2$. Tire I - 1/3 Octave band Analysis, (dB).

Center Frequency (Hz)	Load-1500 lb, Pressure 32 lb/in^2(1)			Load-1150 lb, Pressure 24 lb/in^2(2)		
	Speeds - MPH			Speeds - MPH		
	30 (A)	50 (B)	70 (C)	30 (A)	50 (B)	70 (C)
25	55	54	65	54	56	53
31.5	54	56	62	56	56	57
40	66	68	67	65	66	66
50	74	75	73	72	72	70
63	86	86	85	83	82	81
80	75	76	76	75	75	76
100	67	69	68	68	68	72
125	67	68	71	67	67	78
160	81	82	77	74	73	77
200	85	85	85	78	76	77
250	71	72	73	67	68	73
315	83	84	83	75	73	80
400	73	75	79	75	71	79
500	69	77	77	70	73	77
630	75	76	80	73	80	76
800	76	75	84	74	79	82
1000	71	75	78	70	74	78
1250	72	81	81	71	83	81
1600	71	80	83	69	78	83
2000	72	76	80	67	74	81
2500	68	75	79	65	72	78
3150	65	72	76	62	70	76
4000	62	69	74	58	69	73
5000	58	68	72	54	65	71
6300	54	62	70	49	61	69
8000	47	56	67	--	57	67
10000	--	49	66	--	48	61
A Scale	84	87	91	81	87	90
C Scale	90	91	93	87	89	91

Table C_3. Tire II - 1/3 Octave band analysis, **(dB)**.

Center Frequency (Hz)	Load-1500 lb, Pressure 32 lb/in^2(1)			Load-1150 lb, Pressure 24 lb/in^2(2		
	Speeds - MPH			Speeds - MPH		
	30 (A)	50 (B)	70 (C)	30 (A)	50 (B)	70 (C)
25	56	56	--	54	54	55
31.5	56	58	58	56	56	59
40	66	67	66	66	66	66
50	72	72	70	71	71	69
63	83	83	81	82	82	83
80	76	77	76	75	75	76
100	67	69	68	67	69	69
125	67	80	72	66	77	71
160	78	78	76	78	77	77
200	78	78	82	77	77	84
250	67	75	71	66	75	71
315	75	75	75	73	74	75
400	66	69	72	66	66	78
500	71	77	73	74	74	76
630	69	77	81	69	75	87
800	74	80	82	74	79	87
1000	75	76	82	77	77	83
1250	80	80	88	77	76	83
1600	73	82	82	72	79	81
2000	73	84	88	71	84	84
2500	68	80	84	68	76	83
3150	65	73	77	63	71	77
4000	60	69	74	59	68	75
5000	56	66	72	55	65	72
6300	55	63	70	53	62	68
8000	50	59	63	48	58	63
10000	--	50	56	--	48	56
A Scale	84	90	94	83	89	93
C Scale	88	91	94	87	90	93

Table C_4. Tire III - 1/3 Octave band analysis, (dB).

Center Frequency (Hz)	Load-1500 lb, Pressure 32 lb/in^2(1)			Load-1150 lb, Pressure 24 lb/in^2(2)		
	Speeds - MPH			Speeds - MPH		
	30 (A)	50 (B)	70 (C)	30 (A)	50 (B)	70 (C)
25	--	--	--	56	56	55
31.5	--	--	55	56	55	57
40	65	64	65	65	65	66
50	74	73	73	72	72	72
63	85	84	84	83	82	82
80	74	74	74	75	75	75
100	66	66	65	67	68	78
125	65	68	65	66	69	69
160	82	81	81	74	74	74
200	85	84	84	77	78	63
250	70	69	71	66	68	65
315	83	82	82	74	74	70
400	71	70	70	61	63	73
500	63	63	65	62	64	69
630	66	67	69	63	67	66
800	67	70	70	68	71	70
1000	64	66	67	65	68	69
1250	62	65	65	63	67	66
1600	60	68	68	63	69	70
2000	56	66	68	61	68	69
2500	54	60	65	57	62	65
3150	--	57	61	55	59	62
4000	--	53	57	52	55	59
5000	--	--	54	47	52	55
6300	--	--	--	--	47	51
8000	--	--	--	--	--	47
10000	--	--	--	--	--	45
A Scale	80	80	81	76	79	80
C Scale	90	89	90	85	86	86

Table C_5. Tire IV - 1/3 Octave band analysis, (dB).

Center requency (Hz)	Load-1500 lb, Pressure 32 lb/in^2(1)			Load-1150 lb, Pressure 24 lb/in^2(2)		
	Speeds - MPH			Speeds - MPH		
	30 (A)	50 (B)	70 (C)	30 (A)	50 (B)	70 (C)
25	57	60	--	55	61	72
31.5	56	60	--	55	63	73
40	65	65	69	65	68	74
50	70	70	73	70	71	75
63	81	82	79	82	82	83
80	74	75	69	75	76	77
100	68	66	65	68	69	73
125	65	66	67	66	72	74
160	75	74	73	73	75	75
200	78	77	75	76	76	76
250	74	67	68	69	70	73
315	75	80	78	74	80	76
400	76	93	85	76	87	84
500	90	86	96	89	81	93
630	82	86	91	78	79	86
800	75	88	81	78	85	83
1000	83	87	95	82	83	93
1250	83	89	91	81	87	93
1600	77	85	89	76	85	90
2000	78	83	89	75	82	87
2500	76	83	87	74	82	88
3150	73	82	85	72	82	86
4000	70	77	82	69	77	84
5000	68	75	80	66	76	82
6300	63	69	75	59	71	78
8000	55	61	67	50	62	69
0000	46	--	59	--	54	63
Scale	91	96	100	90	93	99
Scale	93	97	101	92	94	99

Table C_6. Tire V - 1/3 Octave band analysis, (dB).

Center equency (Hz)	Load-1500 lb, Pressure 32 lb/in^2(1)			Load-1150 lb, Pressure 24 lb/in^2(2)		
	Speeds - MPH			Speeds - MPH		
	30 (A)	50 (B)	70 (C)	30 (A)	50 (B)	70 (C)
25	54	55	--	56	55	54
31.5	56	55	--	55	55	56
40	66	67	66	66	65	66
50	72	72	70	71	70	70
63	82	83	83	82	81	80
80	76	77	75	76	75	75
100	68	71	70	68	69	75
125	67	68	78	67	67	85
160	75	76	77	72	72	75
200	78	79	80	75	75	77
250	66	68	73	65	65	73
315	75	76	76	72	72	74
400	63	65	68	62	63	67
500	63	66	71	62	66	73
630	67	72	71	65	67	73
800	74	75	78	74	73	79
1000	73	76	74	72	75	74
1250	71	79	80	71	77	78
1600	76	82	84	74	79	82
2000	73	77	82	72	76	80
2500	66	75	80	65	74	79
3150	65	74	79	63	74	78
4000	62	71	77	59	69	76
5000	60	68	74	57	67	73
6300	55	64	69	52	61	68
8000	49	58	62	45	55	62
0000	--	51	56	--	47	56
Scale	82	87	90	81	85	89
Scale	86	89	91	85	87	91

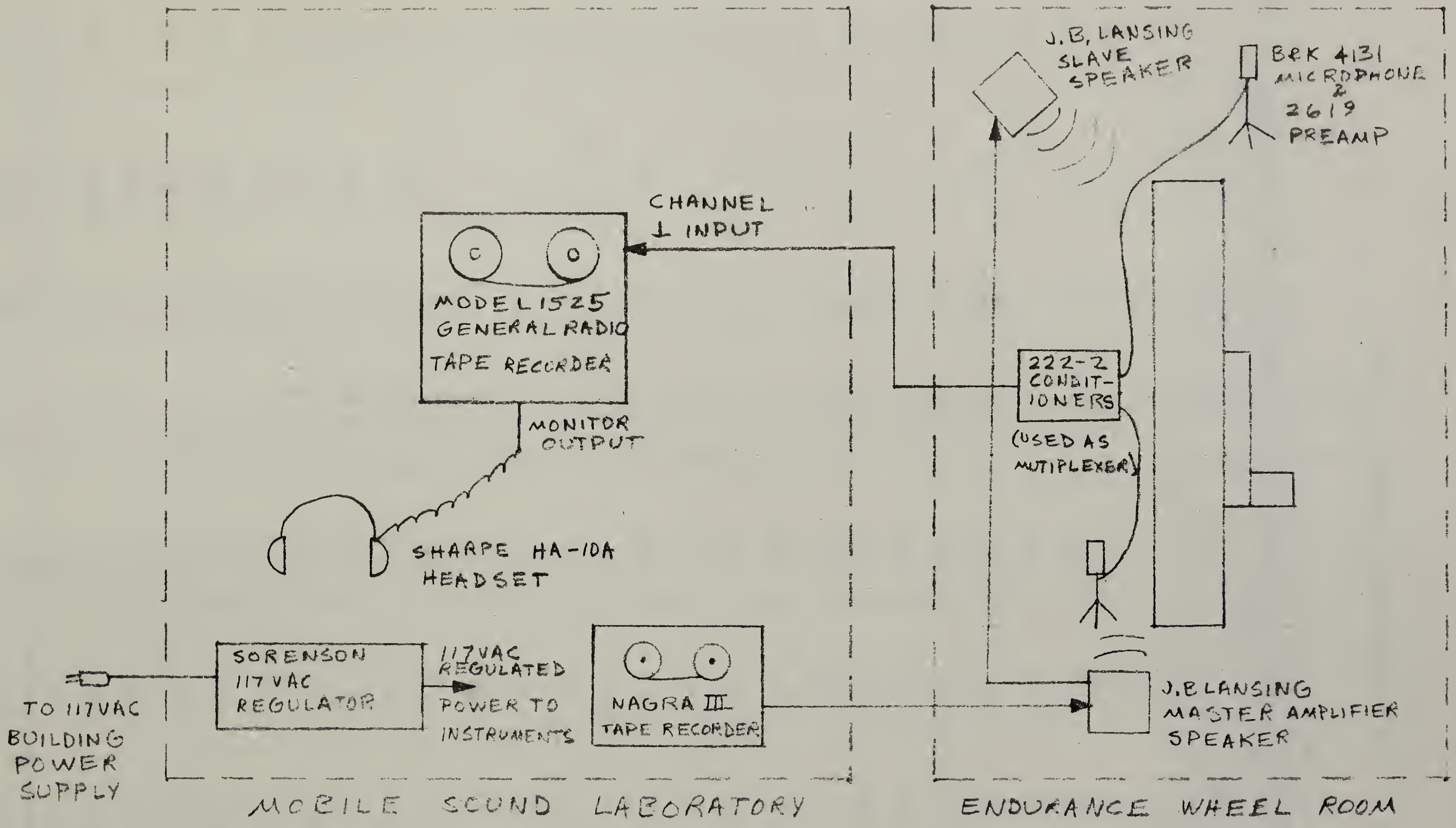


Figure C_5. System for recording reverberant time of Endurance Wheel room.

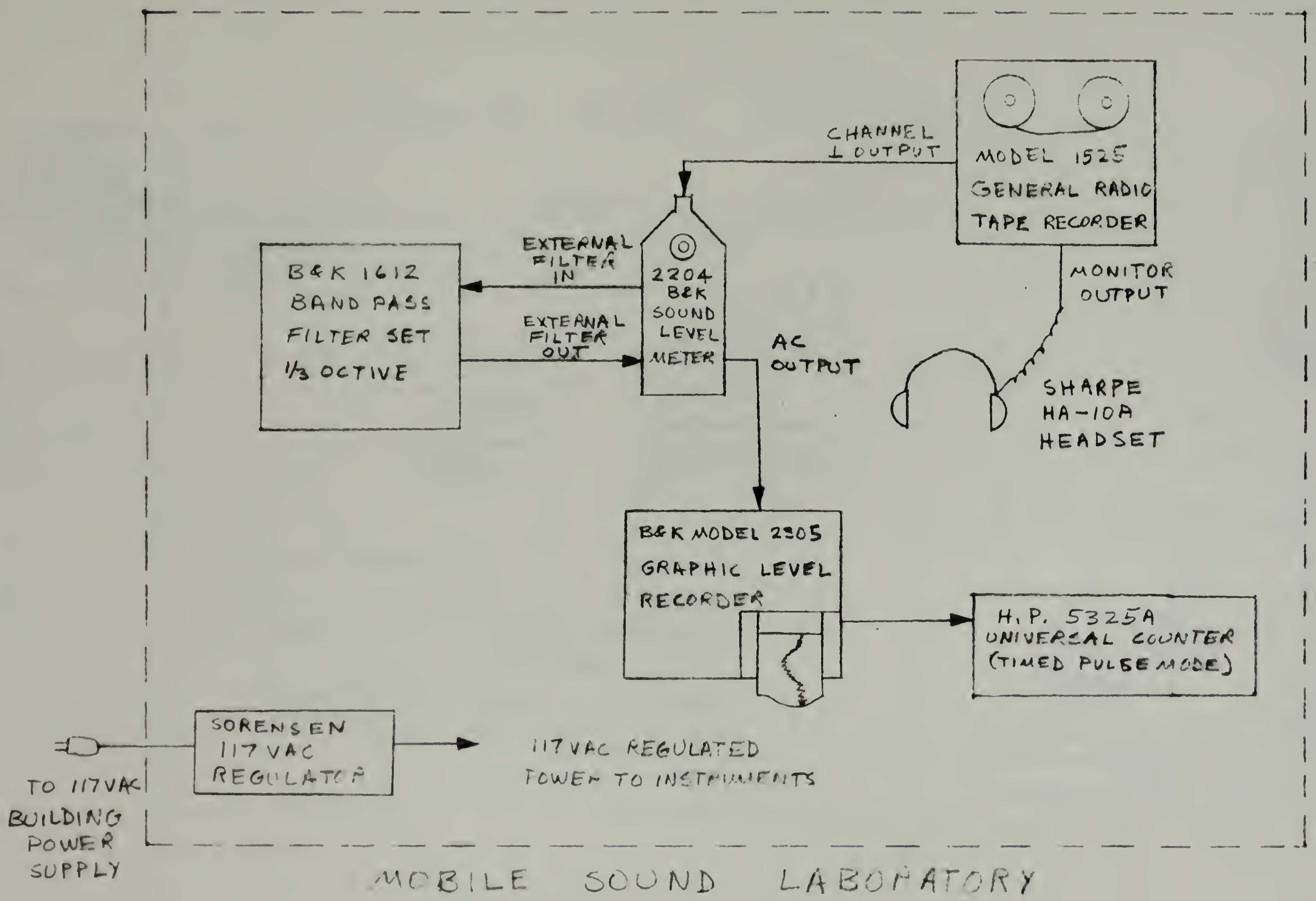


Figure C_6. System for measuring reverberant time of Endurance Wheel room.

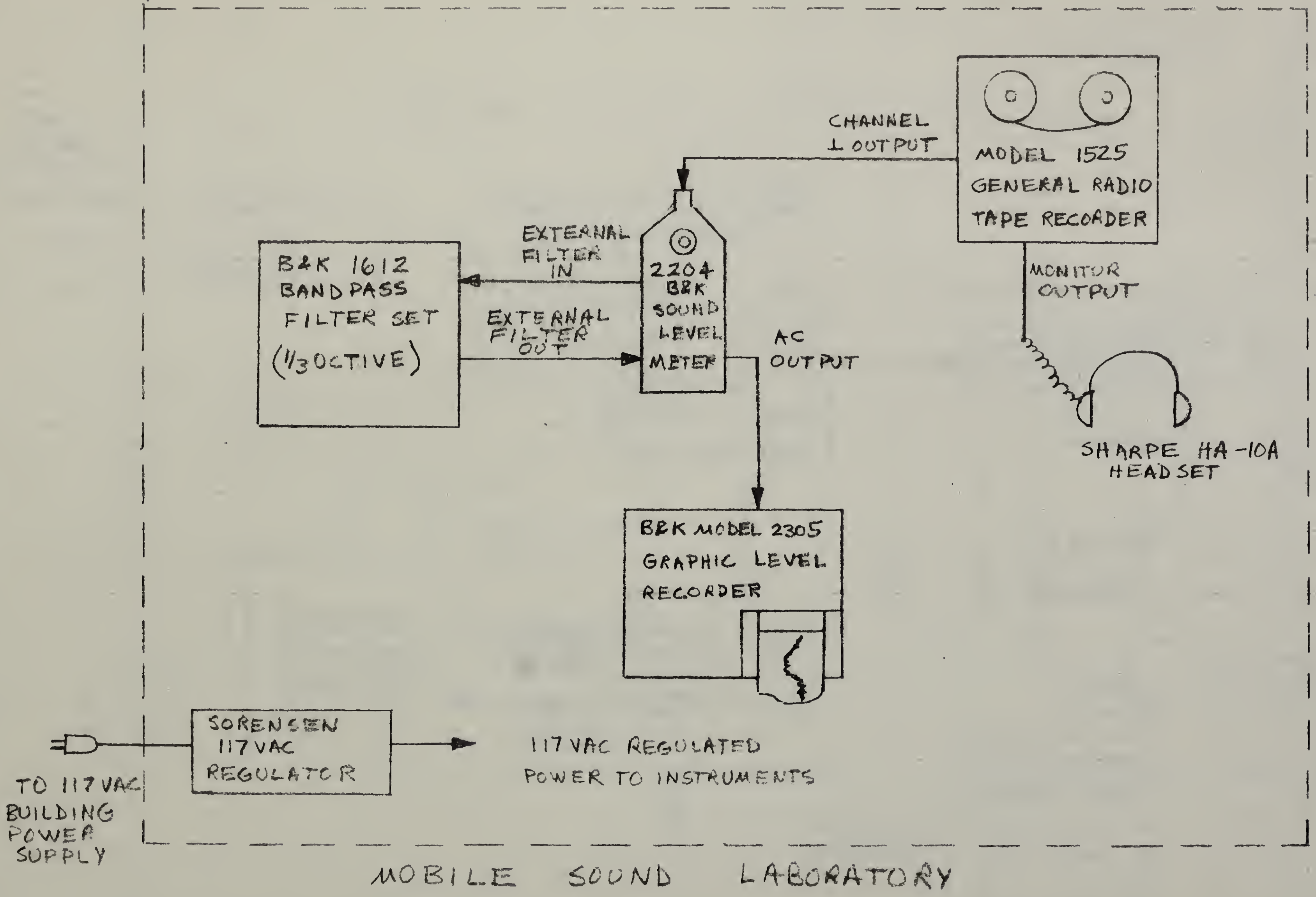


Figure C_7. System for 1/3 octave band analysis.

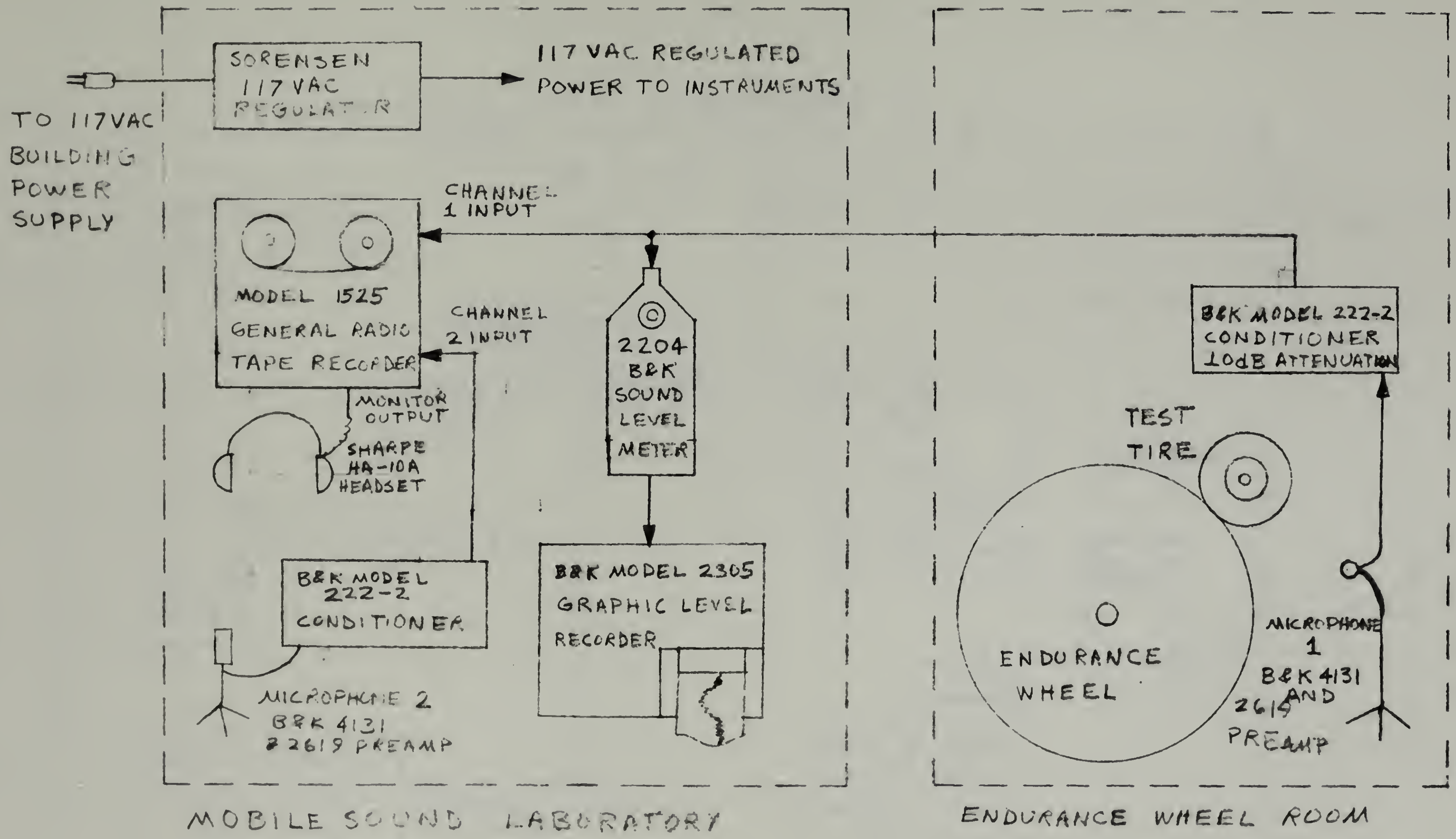


Figure C_8. Physical data collection system.

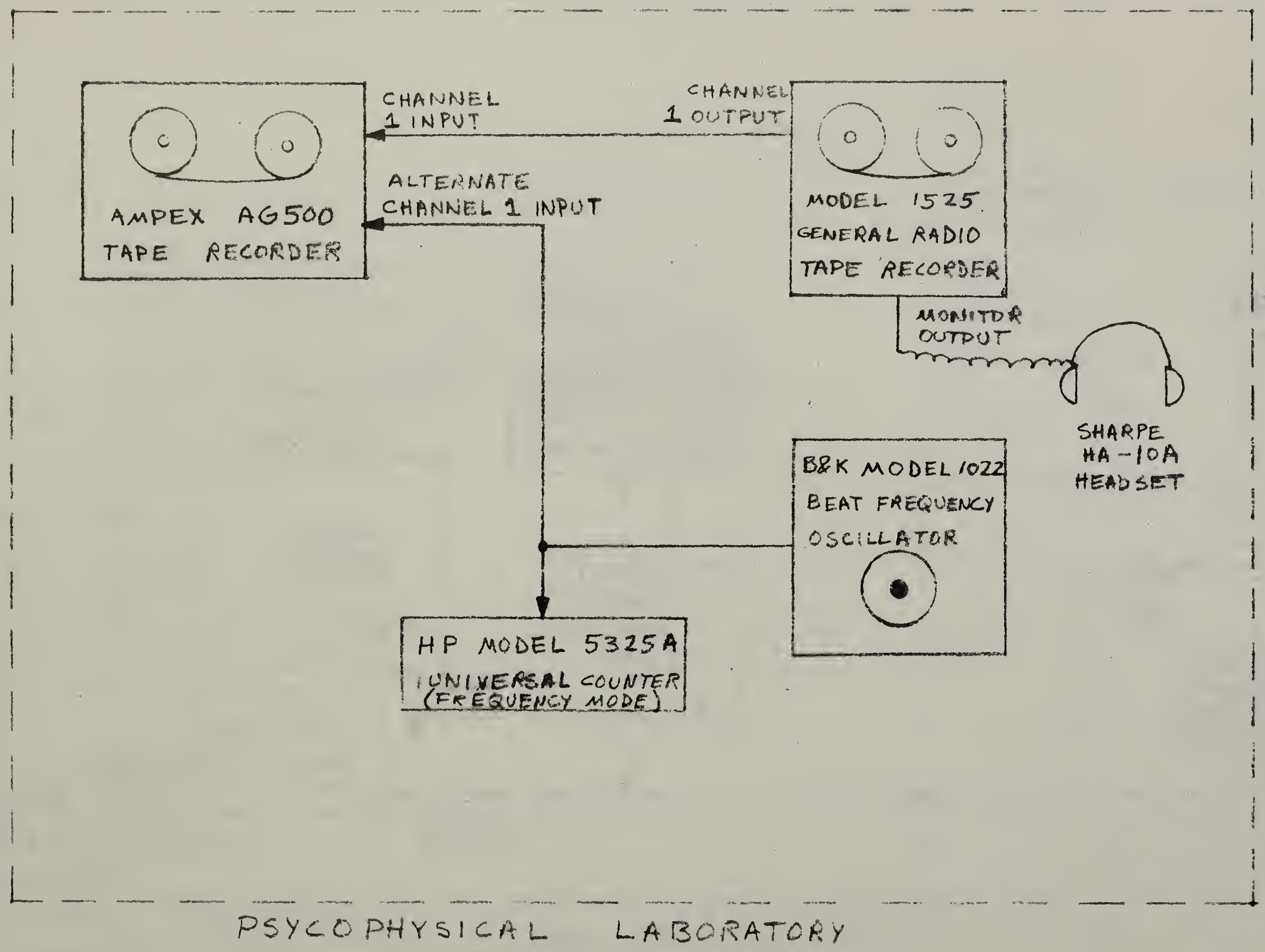


Figure C_9. System for generating stimulus tape recordings from spliced master tapes.

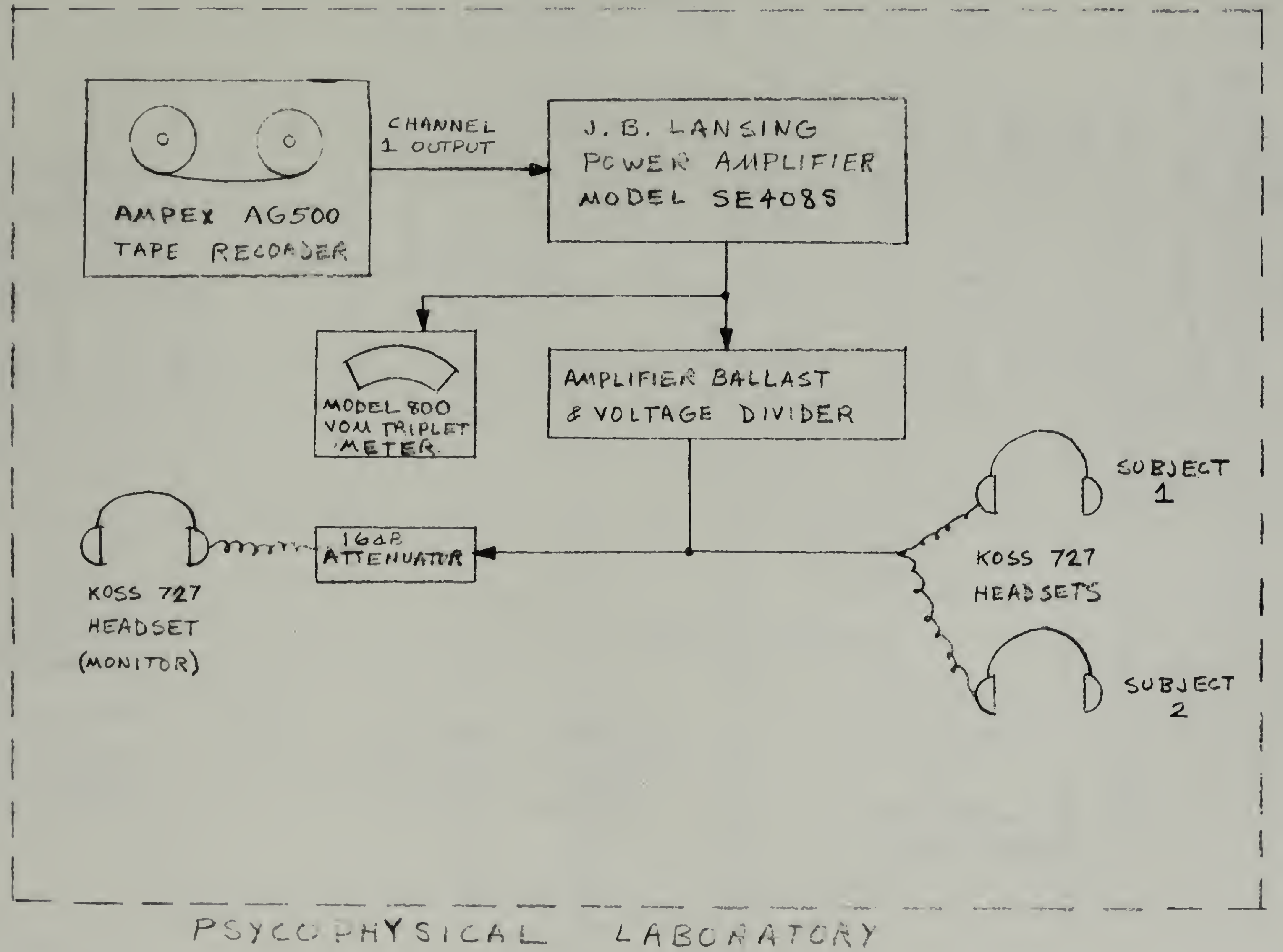


Figure C_{10}. Stimulus presentation system.

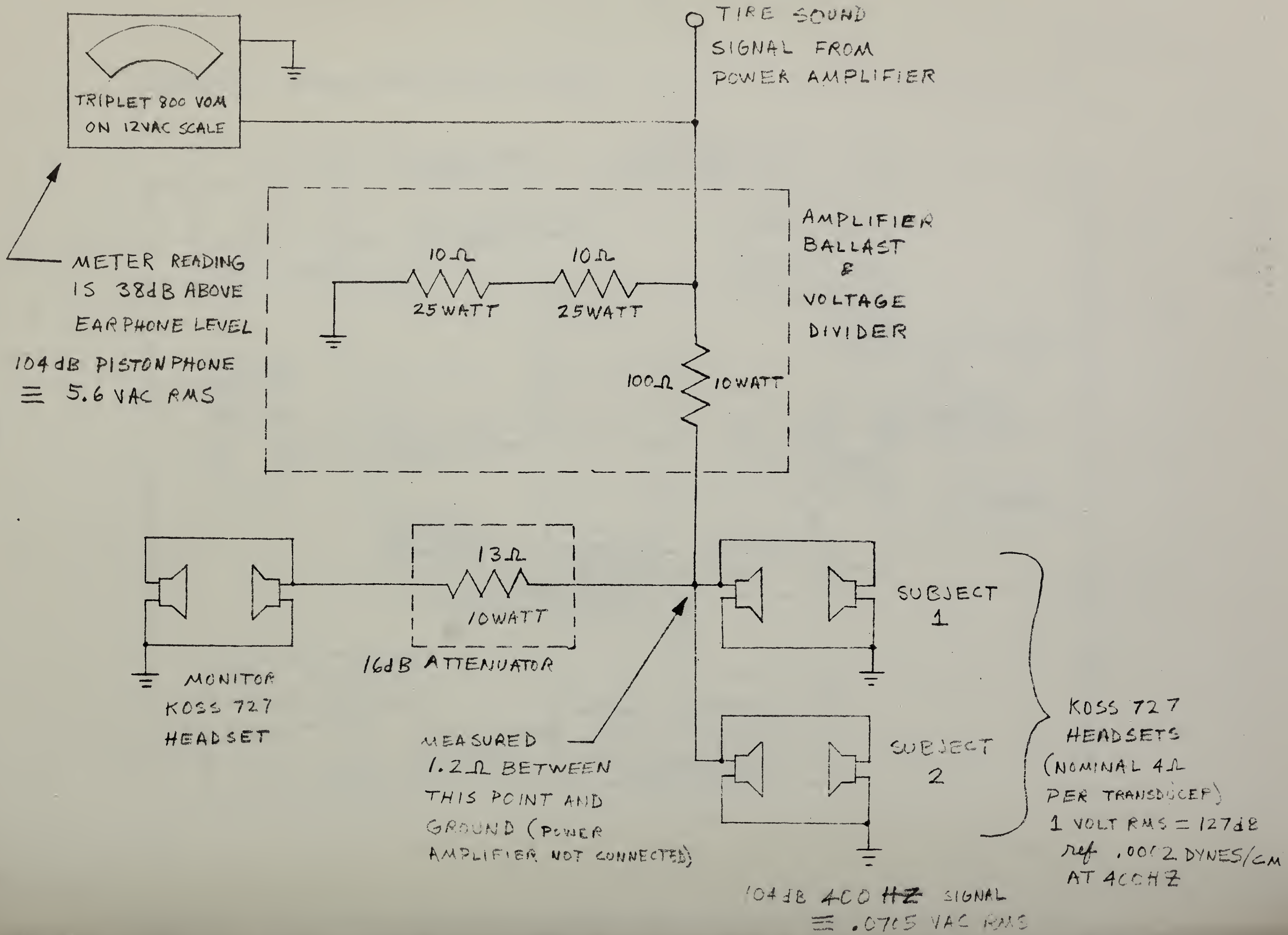
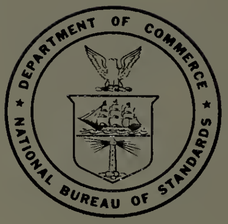


Figure C_{11}. Detail of stimulus presentation circuit.

Equipment List

1. Model 1525 General Radio Instrumentation Magnetic Tape Recorder.
2. Model 2305 B & K Graphic Level Recorder
3. Model 2204 B & K Precision Sound Level Meter
4. Two Model 4131 B & K (Condensor) Microphones/Stands
5. Two Model 222-2 B & K Conditioners (Microphone Amplifiers)
6. Sorensen Model ACR 3000 AC Regulator
7. Model 1612 B & K Band Pass Filter Set
8. Model 1022 B & K Beat Frequency Oscillator
9. Model 5325A H. P. Universal Counter
10. Model AG500 Ampex Tape Recorder
11. Three Koss 727 Headsets (8Ω)
12. Amplifier Ballast & Voltage Divider
13. J. B. Lansing Amplifier Model SE408S and Two J. B. Lansing Speaker Systems
14. Nagra III Tape Recorder
15. Tape Recording Containing 15 s on, 10 s off of pink noise
16. Monitor Headset Attenuator
17. 203-1/4-1800 Scotch Magnetic Tape
18. S-3 Editall Splicer
19. Editab Splices
20. Reeves Soundcraft Leader Tape
21. Power Extension Cords and Shielded Cable
22. Two B & K 2619 Microphone Preamplifiers
23. B & K Pistonphone Type 4220
24. Model 800 Triplet VOM
25. Sharpe HA-10A Headset (100Ω)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