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A Model for the Subjective Effects of Listener Echo on Telephone Connections

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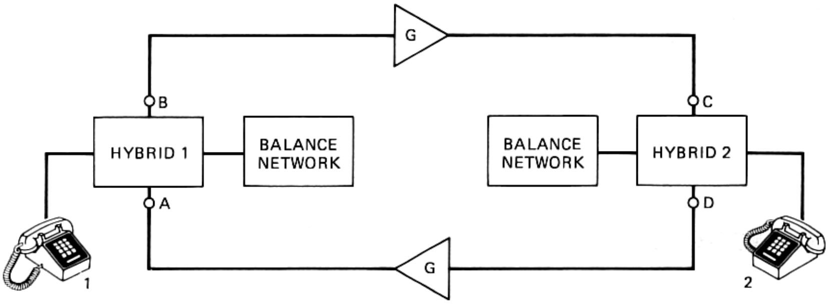
Any appreciable listener echo on telephone lines is perceived as undesirable, and considerable effort is expended to hold echo to acceptable levels. To provide a basis for appropriately controlling listener echo, a series of four subjective tests was conducted at Bell Laboratories to obtain subjective evaluations of the effects of listener echo on telephone transmission quality. The subjective tests included conditions in which the listener echo-path loss was flat or frequency-shaped by selective filtering. The test results showed that subjective opinions for conditions with the same singing margin (minimum value of echo-path loss) were highly dependent on the frequency shaping. A weighted echo-path loss (WEPL) is defined to provide a weighting on the frequency-shaped test conditions so that subjectively equivalent test conditions have approximately the same levels of WEPL. The results of these subjective tests are used to formulate a model of subjective opinion for use in network planning studies. The resulting listener echo opinion model is incorporated into an existing transmission rating model which encompasses loss, noise, and talker echo. Objectives are proposed for listener echo based on WEPL.

I. INTRODUCTION

The use of digital technology for both transmission and switching is increasing in the telephone network. Digital switching is inherently a 4-wire operation, and a class 5 digital switch will introduce a closed-loop 4-wire path in local line-to-line connections. A simplified diagram of a local connection which includes a 4-wire path is shown in Fig. 1. The hybrids perform the 2-wire to 4-wire and 4-wire to 2-wire conversions. For good network performance, the impedances of the terminations at opposite hybrid ports must be matched. In a class 5 office application, the critical match is between the hybrid balance network



LISTENER ECHO PATH LOSS = $L_{AB} + L_{CD} - 2G$

WHERE: L_{AB} = LOSS FROM POINTS A TO B THROUGH HYBRID 1
L_{CD} = LOSS FROM POINTS C TO D THROUGH HYBRID 2

SINGING MARGIN = MINIMUM VALUE OF LEPL OVER THE FREQUENCY BAND OF INTEREST

Fig. 1—Block diagram of a basic 4-wire system between 2-wire terminations.

and the impedance of the customer line. If these impedances do not match, energy will be transmitted across the hybrid from the 4-wire receive port to the 4-wire transmit port. If a mismatch occurs at both hybrid interfaces, energy will be transmitted across both hybrids and circulate in the closed loop formed by the 4-wire path. The circulating energy can lead to singing or near-singing distortion if the loss around the loop is not adequate. Singing is the oscillation which occurs when the closed loop has a unity voltage gain at a frequency at which the phase shift is a multiple of 360 degrees. Near-singing causes a hollow-sounding, or "rain-barrel," effect which occurs when there is only a small amount of loss around the closed loop. Near-singing conditions result in the effect commonly known as listener echo.

The net loss as a function of frequency around the closed loop 4-wire path is called the listener echo path loss. However, the traditional measure of the acceptability with respect to near-singing distortion of a 4-wire connection is the connection singing margin. As the name implies, singing margin is a measure of the connection's margin against singing. Since oscillations must be avoided at all frequencies, singing margin is typically defined as the minimum listener echo-path loss over the frequency band of interest.

Singing margin is clearly the appropriate measure when judging the stability performance of a connection. However, the listener echo-path loss is normally shaped with frequency, and the minimum value typically occurs at the edge of the voice frequency band. Therefore, singing margin is not the optimal measure for judging the subjective quality of a near-singing connection. To establish a better measure for the subjective effects of listener echo and to establish improved objectives for listener echo control, four subjective tests were conducted.

The tests included simulations of connections with listener echo-path loss which was both uniform and shaped as a function of frequency. The shaped conditions included listener echo-path losses that had low-pass, high-pass, and band-elimination characteristics. The minimum values of listener echo-path loss ranged from 2 to 18 dB. Most conditions were tested at round-trip delays ranging from 0.75 ms to 5 ms. However, some uniform loss conditions were tested at delays as high as 60 ms. To permit comparisons of the test results with the results of previous tests, conditions which contained the undistorted source sentences and various levels of idle-circuit noise and Q (ratio of speech power to speech-correlated noise power) were included. All the tests were listening tests in which the subjects rated the transmission quality on the standard five-category comment scale: Excellent, Good, Fair, Poor, and Unsatisfactory. The tests were conducted with Western Electric 500-type telephone sets.[1]

The results of the tests were used to formulate a model of the subjective effects of listener echo. The resulting model was then combined with an existing transmission rating model for loudness loss and circuit noise.[2] Loudness loss values used in the loss-noise model describe the acoustic-to-acoustic transfer efficiency of overall telephone connections and are expressed in terms of the Electro-Acoustic Rating System (EARS) method.[3] All circuit noise values used in the loss-noise model are expressed in dBrnC at the input to a reference receiving system with a receiving loudness rating of 26 dB based on the EARS method. Although the loudness rating of the receiving system used in the listener echo tests was 21 dB, all noise values and speech levels in this paper have been referred to the input to a receiving system with a 26-dB rating to allow comparisons with the loss-noise model.

The following sections describe test design, generation of test conditions, raw test results, formulation of a listener echo model, and a combined loss-noise-listener echo model. A new measure for evaluating the subjective quality of listener echo, weighted echo-path loss (WEPL), is recommended. Objectives for listener echo control based on WEPL are proposed.

II. DISCUSSION OF LISTENER ECHO

Two significant factors that affect the subjective reactions to telephone connections having listener echo or near-singing distortion are the magnitude of the loss, as a function of frequency, and the round-trip delay of the 4-wire path. These factors can be illustrated by examining the closed loop, gain-frequency response of a 4-wire system.

A zero loss (open loop) 4-wire system is shown in Fig. 2 as a feedback control system. In this representation, $B(f)$ represents the voltage transfer response of the feedback path as a function of frequency and D represents the round-trip delay of the 4-wire system. The closed loop (analog 2-wire to 2-wire) gain can be expressed by

$$G(f) = \frac{1}{1 - B(f)e^{-j2\pi fD}}. \tag{1}$$

Plots of the closed loop, gain-frequency response for representative flat and shaped echo-path loss and different values of constant delay are shown in Fig. 3. The periodic ripples in these curves are due to the phase term, $2\pi fD$. The period of the ripples, in frequency, is the reciprocal of the round-trip system delay, $1/D$. Thus, as the round-trip delay is increased, the number of in-band ripples is also increased.

The magnitude of the ripples is determined by the magnitude of the transfer response of the listener echo path, $B(f)$. As the value of listener echo-path loss is increased, the magnitude of the ripples decreases. For a connection with a flat echo-path loss, the magnitude of the ripples in decibels varies between a maximum of $20 \log 1/(1 - B(f))$ and a minimum of $20 \log 1/(1 + B(f))$.

For telephone connections in which the listener echo-path loss varies with frequency (the normal case), the magnitude of the ripple at any particular frequency depends on the feedback path loss at that frequency. For typical connections, the minimum echo-path loss, and hence the maximum ripples, tends to occur at the edges of the voice frequency band. Whether the minimum listener echo-path loss occurs at the low or high frequency end depends on the type of customer loops making up the connection (loaded or nonloaded) and the hybrid balance termination.

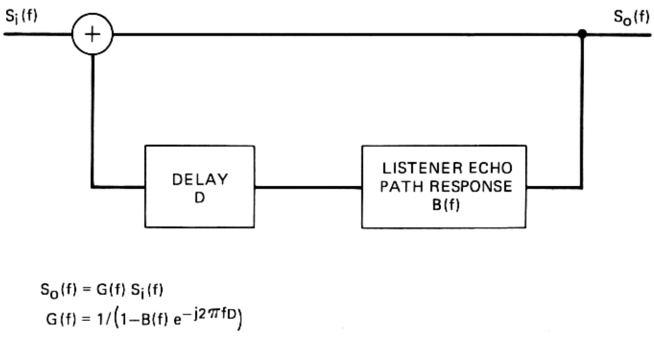


Fig. 2—Gain-frequency response for a zero loss, 4-wire system between 2-wire terminations.

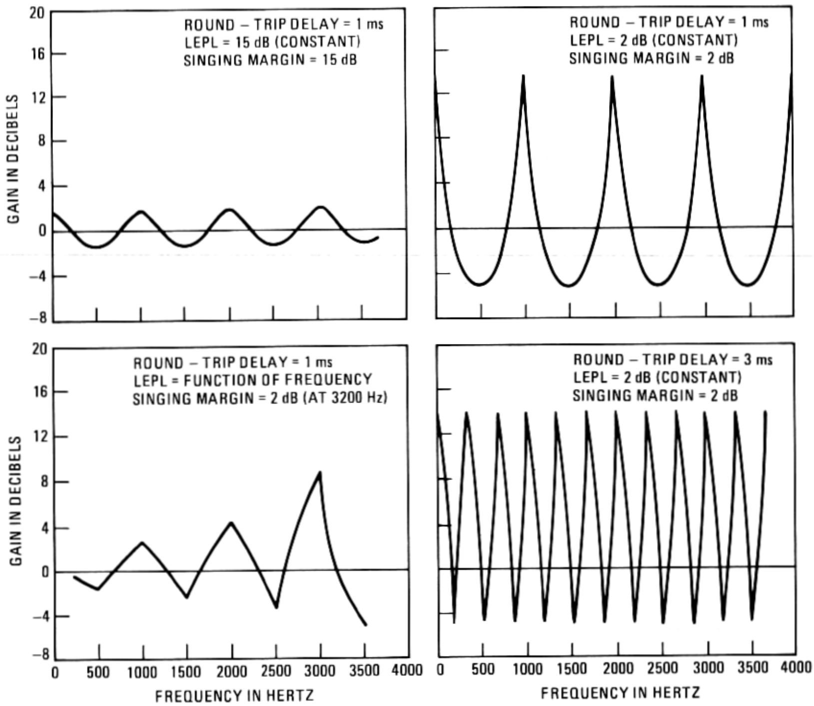


Fig. 3—Gain-frequency responses between points 1 and 2 of Fig. 1.

III. THE SUBJECTIVE TESTS

Four tests were conducted at Bell Laboratories to determine the subjective effects of listener echo on received speech quality. The test subjects listened to prerecorded speech and voted on the perceived transmission quality. Information concerning the test facilities, subjects, test administration, test circuitry, speech source, and test conditions are provided in this section.

3.1 Description of tests and facilities

The subjective tests were conducted in an acoustically treated test room which contained 11 test cubicles. Thus, up to 11 subjects could be tested simultaneously. Each cubicle contained a test handset, with the transmitter replaced by a resistor and a keyboard consisting of five keys labeled "Excellent," "Good," "Fair," "Poor," and "Unsatisfactory" for registering the rating for each test condition.

The ratings were recorded using a minicomputer system. A terminal permitted monitoring of the ratings during the tests and provided a printout of ratings by test position. All ratings were also recorded on magnetic tape for subsequent analysis.

3.2 Test playback system

The subjective test system is shown in Fig. 4. A dual-track tape recorder (Ampex 440G) equipped with a Dolby noise reduction unit was used to drive a standard 500-type telephone set through 6 kft of 26-gauge, nonloaded cable and a 400-ohm, 48-V dc feeding bridge (central office battery supply circuit). The receiving system had a receiving loudness rating of 21 dB. The carbon transmitter was replaced by a 90-ohm resistor to eliminate room noise pickup. The master telephone set receiver was replaced by a 120-ohm resistor, and a transformer-amplifier bridge on this resistor drove the 11 telephone set receivers in the 11 test cubicles.

The measured responses of the playback system are given in Ref. 4. The listening amplifier was adjusted such that a speech level of −29 VU (volume units) at the line terminals of the telephone set (point V_2 in Fig. 4) produced an acoustic pressure of −12 dBPa* (82 dB relative to 20 μPa) at each of the 11 receivers. The value of −12 dBPa approximates the preferred speech pressure level.

3.3 Subject selection and test administration

All test subjects were selected from a test pool of employees in various job classifications and age groups at Bell Laboratories in Holmdel, N.J. Each test was independently administered using different subject groups.

For each test session, a maximum of 11 subjects was seated in the test cubicles and supplied with the test instructions. Four practice test conditions were given before the start of the test. The subjects were told to vote on the four practice conditions as if they were part of the actual test. The actual test conditions were presented in random order to the subjects.

3.4 Speech source and control conditions

The source tape was made by recording male speech (one talker) consisting of three test sentences from the output of a 500-type telephone set carbon transmitter through a Western Electric 111C repeater coil and a simulated 6-kft loop using a Dolby noise reduction unit. The speech was then processed through the simulated connections to derive the other test conditions.

Idle-circuit noise conditions were included in all the tests. These conditions were generated by adding white noise bandlimited from 200 Hz to 3.4 kHz to the speech such that, when referred to the input of a receiving system with a receiving loudness rating of 26 dB, the noise

* dBPa = decibels relative to 1 Pascal, which corresponds to 1 Newton per square meter.

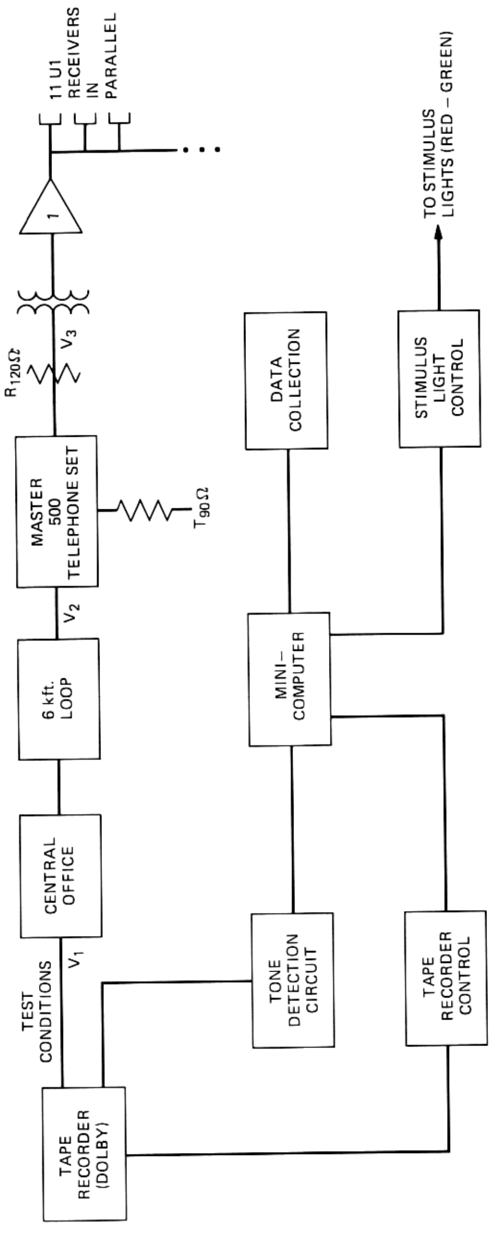


Fig. 4—Multiple listening playback system.

was at a level of 15, 25, 35, or 45 dBrnC as specified in the test conditions. Note that the noise tested was at 10, 20, 30, and 40 dBrnC as measured at the input to the test system which had a receiving loudness rating of 21 dB.

Speech-correlated noise conditions were included in each of the first three tests. These conditions were produced by using a device called the Modulated Noise Reference Unit (MNRU).[5] This device added to the speech signal a noise signal with an amplitude directly proportional to the instantaneous amplitude of the speech. These conditions are designated $Q = 5$, $Q = 10$, etc., where Q denotes the ratio, in decibels, of the speech power to the speech-correlated noise power.

The idle-circuit noise and Q conditions were included in the tests to serve as control conditions and to provide a basis for relating all the test results to the transmission rating model for loss and noise.

3.5 Generation of listener echo test conditions

The analog test tapes containing the various listener echo test conditions were generated by computer simulation. A conceptual diagram of the test configuration is shown in Fig. 5. A block diagram of the computer simulation facility used to generate the test conditions is shown in Fig. 6. As shown in Fig. 6, the one-way path of a digital office from 4-wire transmit to 4-wire receive was simulated. The analog filters were D3 channel bank transmit and receive filters. The analog speech was converted to digital with 8-kHz sampling and 15-bit uniform analog-to-digital conversion. The nature of the simulation can be understood by considering the closed-loop response of the 4-wire system:

$$S_0(f) = \frac{S_i(f)}{1 - B(f)e^{-j2\pi fD}}, \tag{2}$$

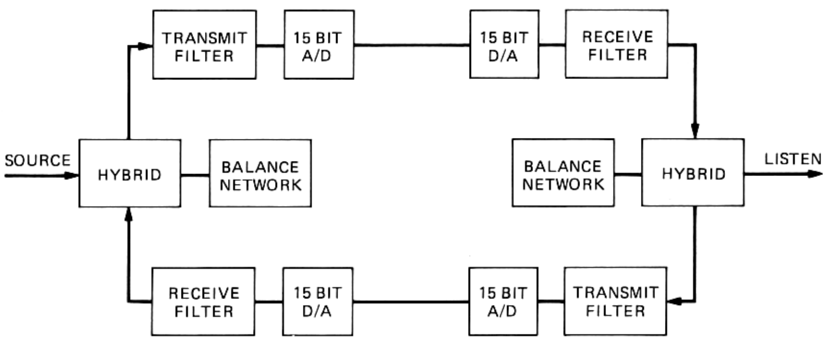


Fig. 5—Conceptual diagram of the computer simulation of the test conditions.

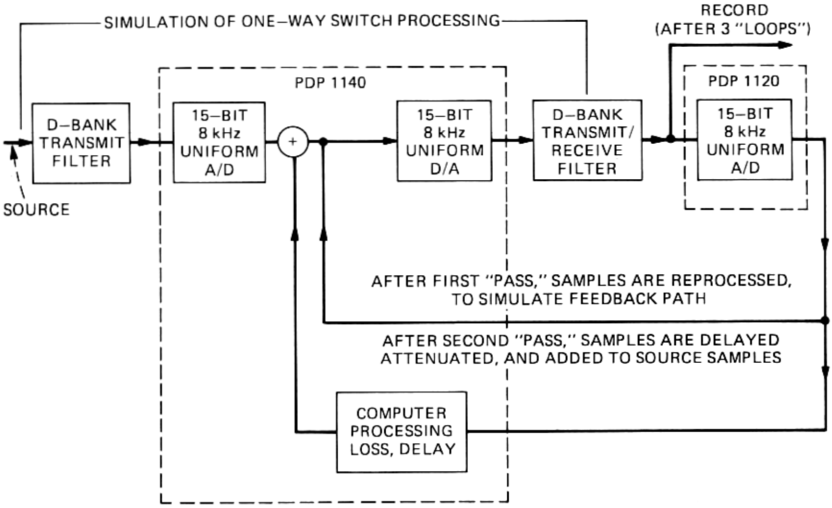


Fig. 6—Block diagram of the computer simulation facility used to generate the test conditions. The two feedback paths are used alternately to simulate round-trip feedback. Completion of both feedback paths constitutes one loop of the 4-wire system.

where

$S_i(f)$ = Speech source

$B(f)$ = Listener echo path response

D = Round-trip delay of simulated system

f = frequency.

This equation has the following Taylor series expansion:

$$S_0(f) = S_i(f) + S_i(f)B(f)e^{-j2\pi fD} + S_i(f)(B(f))^2e^{-j4\pi fD} + S_i(f)(B(f))^3e^{-j6\pi fD} + \cdots. \quad (3)$$

The first term represents the speech source. The second term represents the speech source attenuated by the listener echo-path loss and delayed by the round-trip delay of the system. The third term represents the speech source attenuated by twice the listener echo-path loss (in dB) and delayed by twice the round-trip delay. Each remaining term in the series represents a progressively increasing attenuation and delay of the source signal. Since the loss is increased for each succeeding term, the subjective effect of the higher order terms is insignificant with respect to the lower order terms. Thus, the near-singing conditions can be simulated by the first few terms from the series expansion.

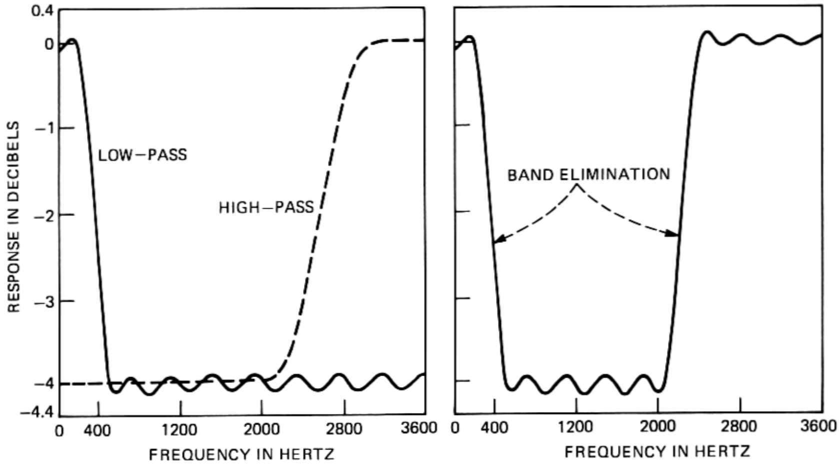


Fig. 7—Filter shapes used in various configurations to simulate listener echo-path loss.

To simulate the series expansion, the speech samples were first passed twice through the one-way path of Fig. 6. This simulates the forward and return paths of the 4-wire office. These "feedback" samples were then delayed, multiplied by the appropriate factor to obtain the desired loss, and added to the original speech samples. This process produced the first two terms of the series in eq. (3). If the resultant of the above process is again passed through the identical process; that is, coded, filtered, delayed, attenuated, and added to the original speech source, then the first three terms of the series expansion will result. Each succeeding pass through the system adds an additional term to the Taylor series and improves the approximation.

The shapes of the filters were based on an examination of the listener echo-path loss for typical connections of loops from the Bell System customer loop survey. It was determined that the variety of shaped listener echo-path-loss conditions which occur on typical telephone connections could be adequately represented by considering five basic shapes: low pass, high pass with roll-off beginning at both 2 and 2.5 kHz, and band elimination with high-frequency corners located at 2 and 2.5 kHz. Examples of the filter characteristic for each basic shape are shown in Fig. 7.

Each filter shape was normalized for 0-dB loss at the point where minimum echo-path loss occurs. The desired overall characteristic was then obtained by adding a flat loss at all frequencies if other than 0-dB minimum loss was desired. With this approach, a single filter characteristic could be used to generate multiple test conditions. For example, the filter characteristic designated low frequency in Fig. 7 was used to produce the condition with 2-dB echo-path loss at frequencies below 400 Hz and 6-dB loss at frequencies above 400 Hz by adding 2-dB flat loss. Similarly, the conditions with 6-dB loss below 400 Hz and 10-dB loss above 400 Hz were achieved by adding 6-dB flat loss. In all, 30 filter shapes were used to produce 105 different shaped echo-path conditions. The test conditions are described in the next section.

IV. THE TEST CONDITIONS

A summary of the test conditions for each of four tests described below is provided in Table I. Further details of the individual test conditions and opinion results for each of the four tests are given in Tables VIII to XI in the appendix. Each table contains the designation of each test condition, together with the total number of votes and the proportion of those votes for each of the five comment categories.

Included in the 44 test conditions from Test 1 are 24 test conditions of listener echo. Echo-path loss values of 2, 4, 6, 8, 10, and 15 dB were tested at echo-path delays of 0.75, 1.5, 3, and 5 ms. The other test conditions consisted of two reference conditions (i.e., speech source unimpaired), ten Q conditions consisting of two each at levels of Q of 5, 10, 15, 20, and 25 dB, and eight circuit noise conditions consisting of two each at levels of noise of 15, 25, 35, and 45 dBrnC as referred to a receive system with a receiving loudness rating of 26 dB. All conditions in tests 1, 2, and 3 were presented at a received volume of −24 VU referred to a receiving system with a receiving loudness rating of 26 dB. Note that the actual received volume used in the test was −29 VU, as measured at the input to the receiving test system which had a receiving loudness rating of 21 dB.

Table I—Test summary, listener echo test

	1	2	3	4
Number of subjects	52	55	59	39
Number of conditions	44	33	153	80
Received speech level (VU)	−24	−24	−24	−24, −34
Equivalent connection loudness loss (dB)	8.7	8.7	8.7	8.7, 18.7
Circuit noise (dBrnC)	5, 15, 25, 35, 45	5, 15, 25, 35, 45	5, 15, 25, 35, 45	5, 25, 45
Circuit Q	5, 10, 15, 20, 25	5, 10, 15, 20, 25	5, 10, 15, 20, 25	—
Echo-path loss (dB)	2, 4, 6, 8, 10, 15	2, 4, 8, 14, 16, 18	2, 4, 6, 8, 10, 12, 15, 16, 18	2, 4, 6, 8, 16
Echo-path delay (ms)	0.75, 1.5, 3, 5	1.5, 3, 5, 30, 60	0.75, 1.5, 2, 3, 4, 5, 30, 60	1.5, 3, 5, 30
Echo-path shape	Flat	Flat	Flat, LP, HP, BE*	Flat
Average room noise [dB(A)]	38	38	38	38

* Low-pass, high-pass, and band-elimination filter shapes.

Test 2 included 33 test conditions with 13 listener echo conditions, 2 reference conditions, 8 circuit noise conditions, and 10 Q conditions.

There were 153 test conditions in Test 3, which included 131 listener echo conditions, 4 reference conditions, 8 circuit noise conditions, and 10 Q conditions. The listener echo conditions included flat and shaped listener echo-path loss.

Test 4 was designed to validate and extend the model of subjective opinion developed from tests 1, 2, and 3. With this in mind, listener echo conditions were presented at two levels of received volume and three levels of circuit noise. There were 80 conditions in Test 4. Twelve combinations of echo-path loss and delay were tested at each of three circuit noise levels (5, 25, and 45 dBrnC) with a received volume of −24 VU, producing 36 test conditions. The same 12 combinations of echo loss and delay were also tested with 5 dBrnC and 25 dBrnC of circuit noise at a received volume of −34 VU, producing 24 more conditions. Twelve additional conditions were generated using four reference conditions at −24 VU received volume for the three values of circuit noise. The final eight conditions consisted of four reference conditions at −34 VU received volume with 5 and 25 dBrnC of circuit noise.

V. PRELIMINARY DATA ANALYSIS

The opinion results for each test condition consist of the proportion of votes, P_i, in each of the five comment categories "Excellent," "Good," "Fair," "Poor," and "Unsatisfactory." These categories are assigned the category numbers, $i = 5, 4, 3, 2$, and 1, respectively, from which a mean opinion score (MOS) and a standard deviation (SD) can be calculated as follows:

$$\text{MOS} = \sum_{i=1}^{5} iP_i$$

$$\text{SD} = \left[\sum_{i=1}^{5} i^2 P_i - (\text{MOS})^2 \right]^{1/2}$$

Following the method described in Ref. 2, the distribution of opinion for each condition is represented by a normal probability density function with mean, μ, and standard deviation, σ, and the predicted proportion of votes, $\hat{P}_i$, in the five categories are represented by areas under the normal density function as follows:

$$\hat{P}_i = \frac{1}{\sqrt{2\pi}} \int_{a_i}^{b_i} e^{-[(x-\mu)^2/2\sigma^2]}\, dx.$$

The method assumes that the actual opinion results can be represented satisfactorily when the intervals, $b_i - a_i$, for the three central categories are taken as equal with boundaries at 1.5, 2.5, 3.5, and 4.5.* Values of a_i and b_i are tabulated below:

Category	Category Number (i)	a_i	b_i
Unsatisfactory	1	$-\infty$	1.5
Poor	2	1.5	2.5
Fair	3	2.5	3.5
Good	4	3.5	4.5
Excellent	5	4.5	∞

A three-step procedure is used to determine the mean, μ, and the standard deviation, σ, for the normal density functions. The first step in this procedure is to find, for each condition in the test, the fit mean, μ, and fit standard deviation, σ, such that the MOS and SD predicted from the $\hat{P}_i$ are equal to the MOS and SD calculated from the P_i from the data. This step involves an iterative procedure. Next, a weighted average is taken of all the fit standard deviations from the first step. This establishes an average, or constant, standard deviation which is then used in the third step for all the conditions in the test. In the third step, the fit mean, μ, of the normal density curve for each condition is redetermined, using the constant standard deviation, such that the MOS predicted from the $\hat{P}_i$ is equal to the MOS calculated from the P_i from the data. This provides a fit mean, from step 3, μ, for each test condition, which is used in the subsequent development of an opinion model.† The step 3 fit means and the constant standard deviation are given in Tables VIII to XI. For simplicity in the remainder of the paper, the step 3 fit means will be referred to as the fit means.

VI. DEVELOPMENT OF MODEL

6.1 Combination of results from different tests

The results from tests 1, 2, and 3 were used to develop an initial model of subjective opinion for listener echo. To do this, the results from the three tests were combined into one common set of data using a method which assumes that the fit means for identical conditions in different tests may differ systematically as a consequence of factors such as the test group or the range of conditions tested. Table II shows the results from test conditions common to test 3 and either test 1 or test 2. A linear regression of 31 test 3 fit means versus the corresponding 31 test 1 fit means has a slope of 0.98, and an intercept of −0.33 with

* This assumption simplifies the analysis and, as illustrated in Figs 12–19 in Ref. 2, is a good approximation to the manner in which subjects utilize this scale in tests where they evaluate a number of stimuli.

† A more detailed description of the analysis method and an example of actual calculations are provided in Section 5.1 and Table XV of Ref. 2.

Table II—Results from test conditions common to test 3 and either of tests 1 or 2

		Constant Standard Deviation		
		($\sigma = 0.64$)	($\sigma = 0.71$)	($\sigma = 0.70$)
EPL	Delay	Test 1 μ_1	Test 2 μ_2	Test 3 μ_3
2	5	1.97	1.38	0.96
4	1.5	2.71	3.29	2.52
4	3	2.19	2.67	1.83
8	1.5	3.97	4.14	3.72
8	3	3.37	4.08	2.92
8	5	3.00	3.07	2.28
	Source	4.32	4.34	4.42, 4.11
	Source	4.30	4.45	4.17, 4.13
	$N = 15$	3.87	4.08	3.49
	$N = 15$	4.01	4.14	3.29
	$N = 25$	3.37	3.09	2.68
	$N = 25$	2.98	3.02	2.86
	$N = 35$	2.60	2.34	2.13
	$N = 35$	2.52	2.52	2.23
	$N = 45$	1.99	1.96	1.70
	$N = 45$	2.31	1.92	1.66
	$Q = 5$	0.37	1.37	0.76
	$Q = 5$	0.37	0.69	0.59
	$Q = 10$	1.47	1.55	1.15
	$Q = 10$	1.57	1.33	1.12
	$Q = 15$	2.92	2.64	1.93
	$Q = 15$	2.36	2.49	1.93
	$Q = 20$	3.21	3.59	2.71
	$Q = 20$	3.06	3.26	2.51
	$Q = 25$	4.13	4.55	3.72
	$Q = 25$	3.83	4.00	3.86
2	60		0.36	0.34
8	60		1.32	1.09
18	60		3.13	2.11
2	30		0.74	0.34
8	30		1.92	1.26
16	30	3.66	3.22	2.62
6	1.5	4.22		2.98
10	1.5	3.06		3.93
6	3	3.79		2.52
10	3	2.07		3.74
4	5			1.74

a correlation coefficient of 0.96. A similar treatment for the 32 conditions common to test 3 and test 2 yielded a linear regression with a slope of 0.88, an intercept of −0.22, and a correlation coefficient of 0.97.

The results were combined for further analysis by adjusting the fit means to a common test base. Tests 1 and 2 results were adjusted to the test 3 base (which had the largest number of test conditions) using the equations obtained for the appropriate linear regressions. For test 1:

$$\mu_3 = 0.98\,\mu_1 - 0.33. \tag{4}$$

For test 2:

$$\mu_3 = 0.88\,\mu_2 - 0.22, \quad (5)$$

where μ_1, μ_2, μ_3 represent the fit means for tests 1, 2, and 3, respectively.

6.2 Selection of a weighting function

The next step in the analysis of the test results was to obtain a model of subjective opinion for listener echo in which the fit means (with test 1 and 2 fit means adjusted as in eqs. (4) and (5), respectively) were expressed as a function of listener echo-path loss and listener echo-path delay.

Initially, the fit means were plotted separately for each value of echo-path delay as a function of the minimum listener echo-path loss, that is, as a function of the singing margin, for each test condition. These plots are shown in Figs. 8a through 15a for the delay values of 0.75, 1.5, 2, 3, 4, 5, 30, and 60 ms, respectively. In the plots for delays of 2, 4, 30, and 60 ms (Figs. 10a, 12a, 14a, and 15a, respectively), the plots appear as rather orderly functions of echo-path loss. These results came from conditions that had only flat echo-path loss. On the other hand, the plots for delays of 0.75, 1.5, 3, and 5 ms (Figures 8a, 9a, 11a, and 13a, respectively) include results from test conditions that had both flat and shaped echo-path loss. Those results are not orderly functions of singing margin. Examination of this phenomenon indicates that, when plotted as a function of singing margin, the opinions (as represented by the fit means) for shaped echo-path loss conditions are significantly higher than the opinions for flat echo-path loss conditions. This indicated the need for some form of weighting of the echo-path loss for the shaped loss conditions. The goal was that conditions with a given weighted echo-path loss (WEPL) regardless of the shape of the loss be subjectively equivalent if their delays were the same. The approach taken in this analysis was to fit equations for the fit means as a function of the weighted echo-path loss separately for each value of delay for six forms of weighting. For each of the six weighting methods, the contributions to listener echo in portions of the voiceband from 200 to 3400 Hz were combined using a specified law of addition and were weighted either linearly or logarithmically with frequency. The six methods of weighting were as follows:

Method	Frequency Weighting	Law of Addition
1	Logarithmic	Power (10 log)
2	Linear	Power (10 log)
3	Logarithmic	Voltage (20 log)
4	Linear	Voltage (20 log)
5	Linear	(30 log)
6	EARS (see Ref. 3)	

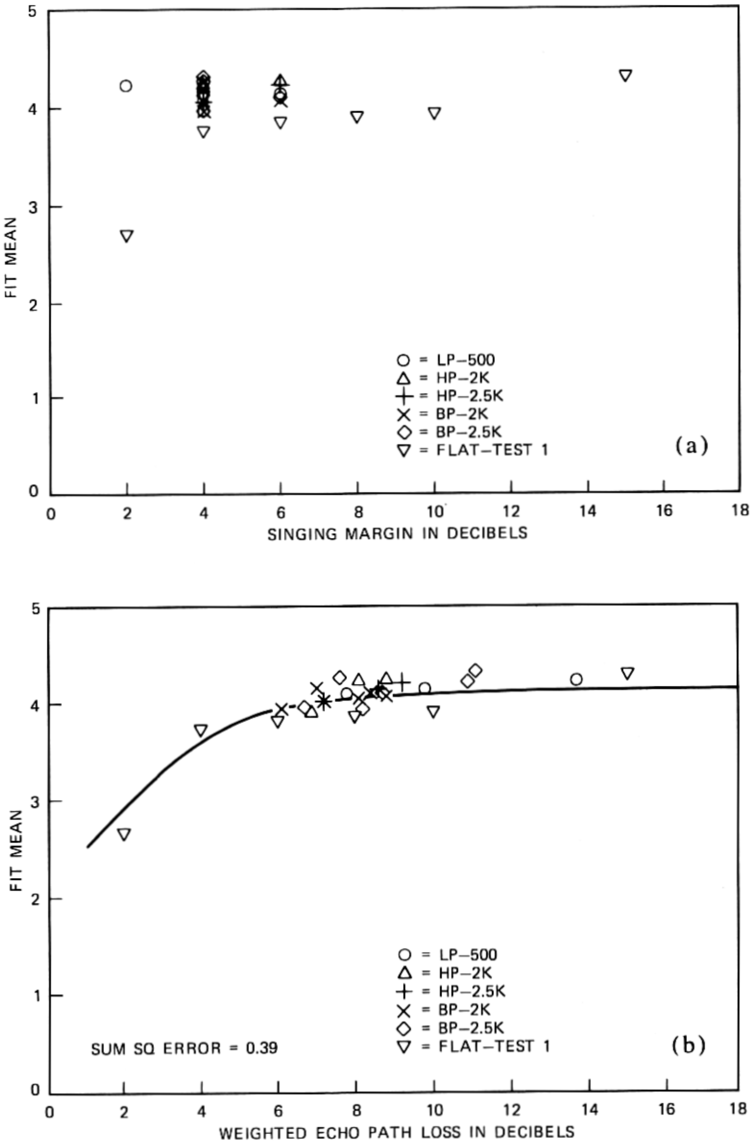


Fig. 8—Subjective test results for 0.75-ms echo-path delay in terms of (a) minimum echo-path loss (singing margin) and (b) weighted echo-path loss (WEPL).

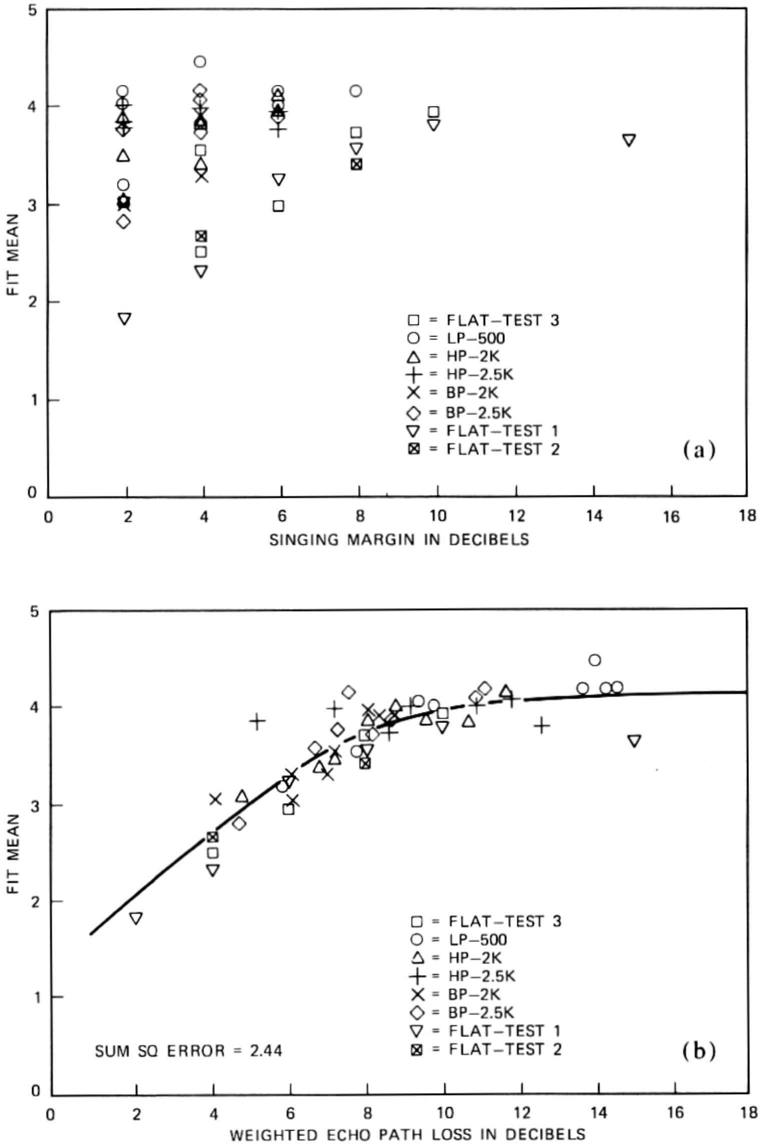


Fig. 9—Subjective test results for 1.5-ms echo-path delay in terms of (a) minimum echo-path loss (singing margin) and (b) weighted echo-path loss (WEPL).

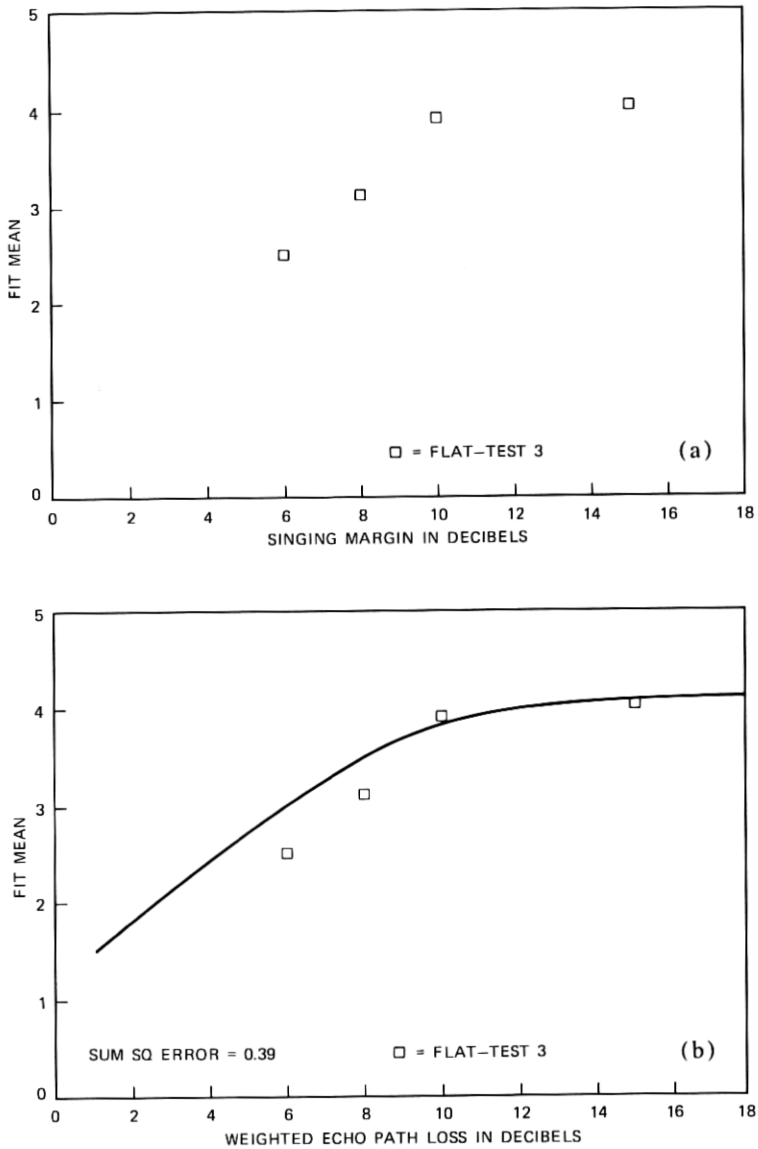


Fig. 10—Subjective test results for 2-ms echo-path delay in terms of (a) minimum echo-path loss (singing margin) and (b) weighted echo-path loss (WEPL).

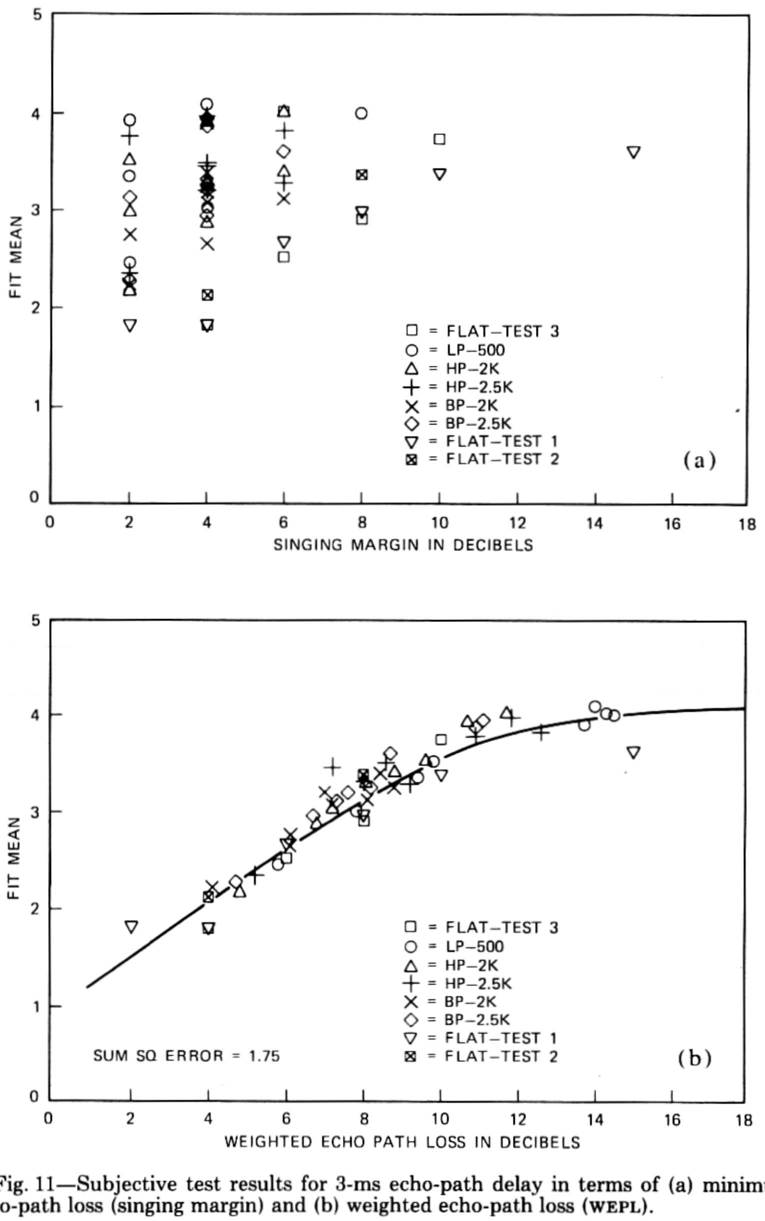


Fig. 11—Subjective test results for 3-ms echo-path delay in terms of (a) minimum echo-path loss (singing margin) and (b) weighted echo-path loss (WEPL).

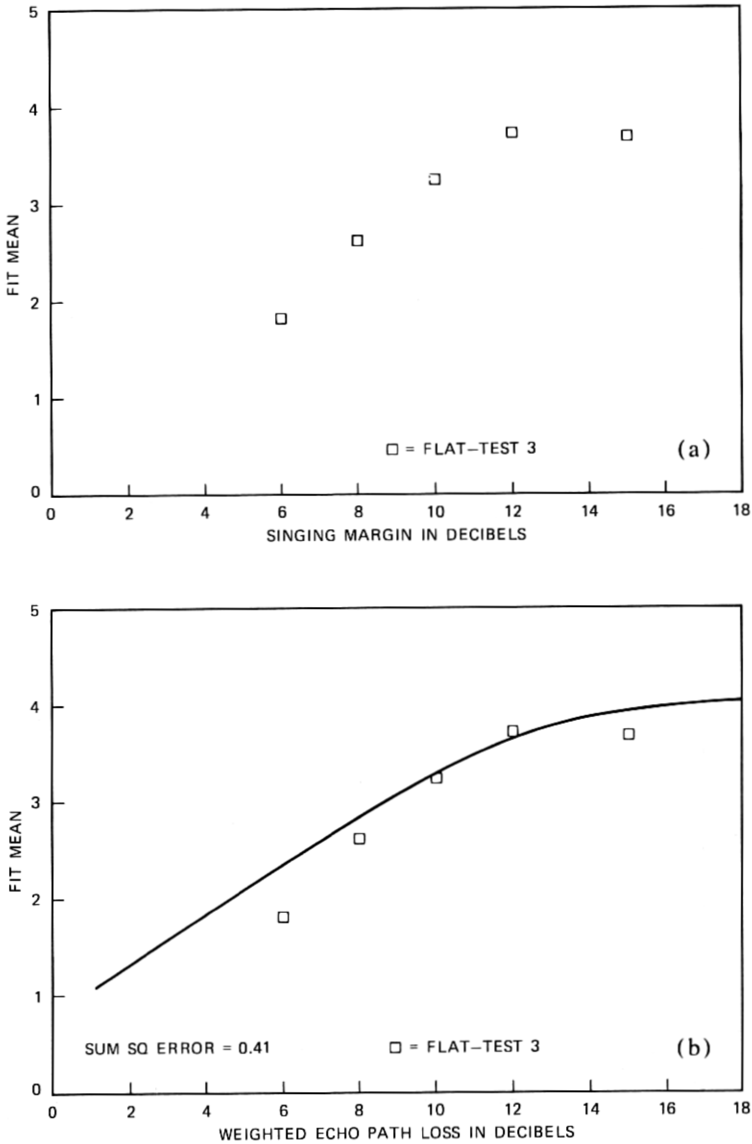


Fig. 12—Subjective test results for 4-ms echo-path delay in terms of (a) minimum echo-path loss (singing margin) and (b) weighted echo-path loss (WEPL).

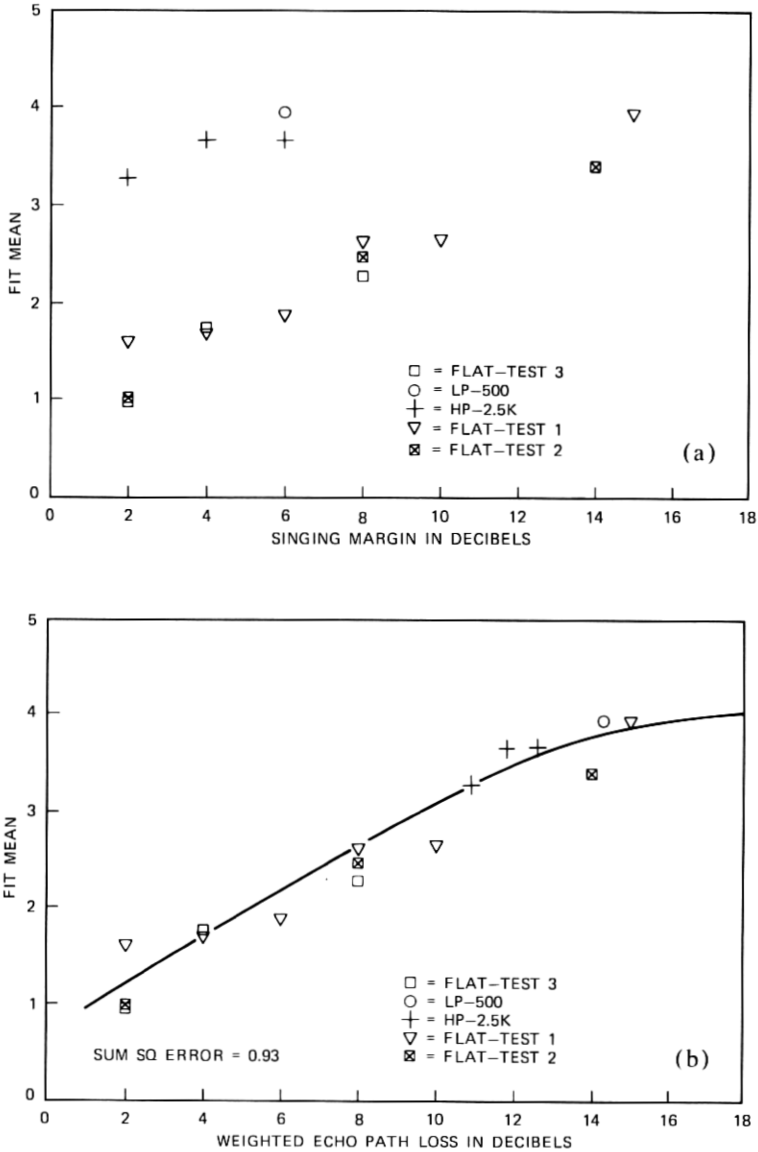


Fig. 13—Subjective test results for 5-ms echo-path delay in terms of (a) minimum echo-path loss (singing margin) and (b) weighted echo-path loss (WEPL).

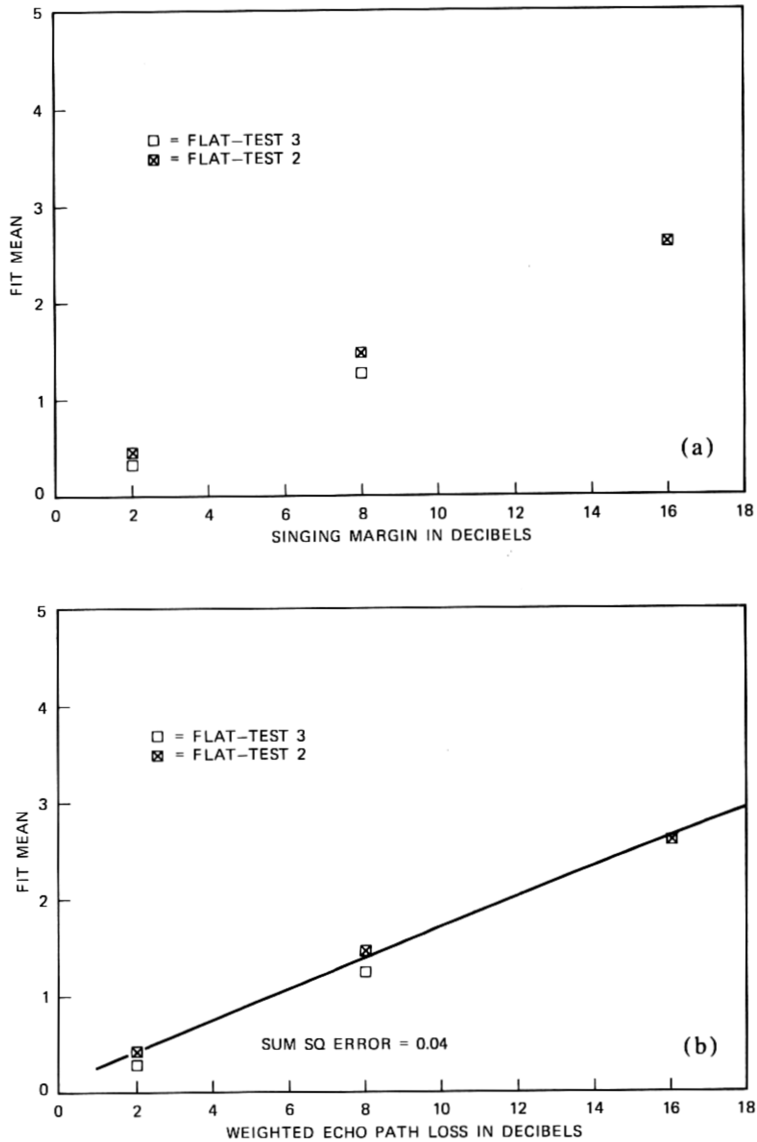


Fig. 14—Subjective test results for 30-ms echo-path delay in terms of (a) minimum echo-path loss (singing margin) and (b) weighted echo-path (WEPL).

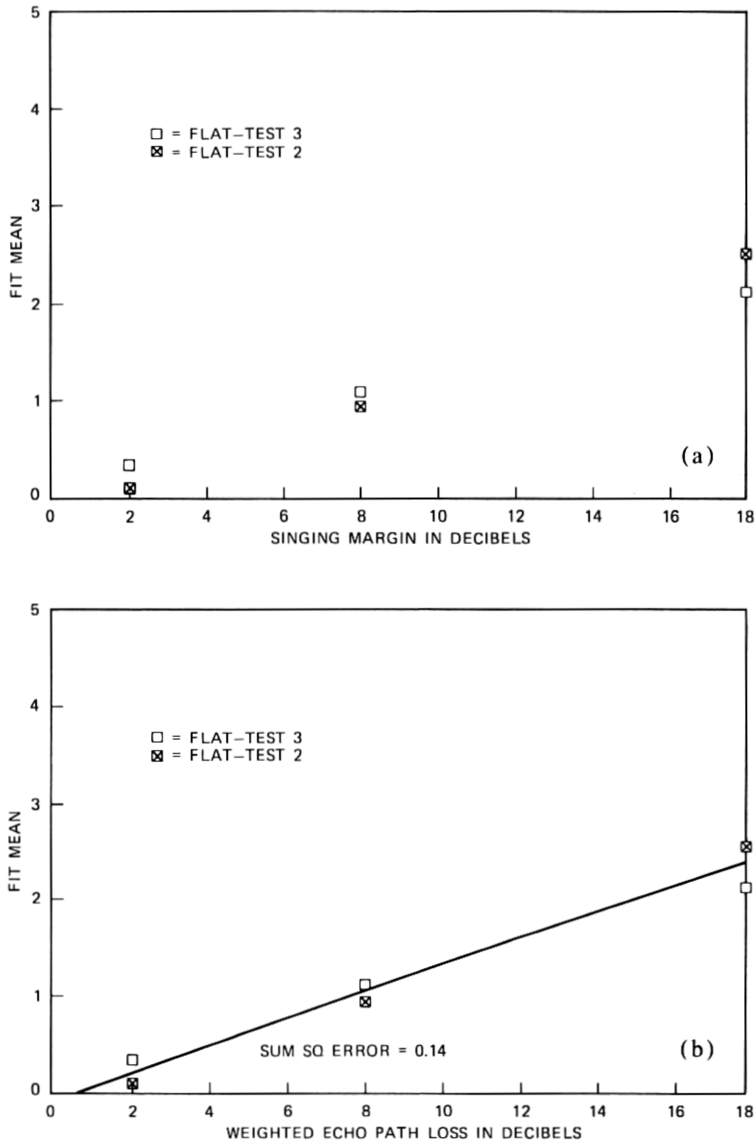


Fig. 15—Subjective test results for 60-ms echo-path delay in terms of (a) minimum echo-path loss (singing margin) and (b) weighted echo-path loss (WEPL).

The equation for fit mean versus loss was selected to be linear with weighted echo-path loss at the lower loss values and to approach an asymptote of 4.2 which represents the average fit mean for the reference test conditions (i.e., no listener echo) in test 3. The equations for

Table III—Sum square errors for six forms of weighting

Method	Weighting	Delay, ms			
		5	3	1.5	0.75
1	Log freq power	1.02	2.38	2.81	0.32
2	Lin freq power	1.28	2.39	2.84	0.34
3	Log freq voltage	0.89	1.94	2.56	0.31
4	Lin freq voltage	0.80	1.42	2.41	0.32
5	Lin freq 30 log	0.73	1.36	2.40	0.31
6	EARS	0.87	1.92	2.57	0.31

the fit means as a function of the WEPL were of the form given in eq. (6).

$$\mu_{VNLE} = \frac{\mu_{LE} + \mu_{VN}}{2} - \sqrt{\left(\frac{\mu_{LE} - \mu_{VN}}{2}\right)^2 + (0.5)^2}, \tag{6}$$

where

μ_{VNLE} = fit mean for volume, noise, and listener echo
μ_{VN} = fit mean for volume and noise = 4.2
μ_{LE} = fit mean for listener echo = $m \cdot \text{WEPL} + b$

with

m = slope
b = intercept

and

WEPL = weighted echo-path loss.

The six forms of weighting were evaluated for each of the four values of delay which were tested with the shaped echo-path loss conditions. At each delay and for each weighting, values of m and b were chosen to minimize the sum square error in the fits. The resulting sum square errors are given in Table III for the six forms of weighting.

The selected weighting was method 4 in Table III, in which the contributions to listener echo in portions of the voiceband from 200 to 3400 Hz were combined using voltage addition and were weighted linearly with the bandwidth in each portion.* Thus, the weighted echo-path loss was expressed by the following equation:

$$\text{WEPL} = -20 \log \frac{1}{3200} \int_{200}^{3400} 10^{-EPL(f)/20}\, df, \tag{7}$$

where EPL(f) = magnitude of the listener echo-path loss in decibels at frequency f.

* Method 5 which had slightly lower sum square errors was not selected because physical implementation of method 4 was straightforward.

Table IV—Weighted relative loss values for the 30 filters used for linear frequency weighting and voltage addition

Filter No.	Type	Weighted Relative Loss (dB)	Relative Loss (dB)	
			Midband	Band edge
1	LP-500	3.78	4	0
2	LP-500	7.41	8	0
3	LP-500	11.68	13	0
4	LP-500	10.01	11	0
5	LP-500	8.27	9	0
6	LP-500	6.51	7	0
7	HP-2k	2.82	4	0
8	HP-2k	5.20	8	0
9	HP-2k	4.07	6	0
10	HP-2k	7.55	13	0
11	HP-2k	6.69	11	0
12	HP-2k	5.72	9	0
13	HP-2.5k	3.17	4	0
14	HP-2.5k	5.98	8	0
15	HP-2.5k	4.64	6	0
16	HP-2.5k	8.92	13	0
17	HP-2.5k	7.82	11	0
18	BE-2.5k	6.62	9	0, 0
19	BE-2k	2.13	4	0, 0
20	BE-2k	4.09	8	0, 0
21	BE-2k	3.24	7	0, 0
22	BE-2k	2.99	6	2, 0
23	BE-2k	4.37	11	0, 0
24	BE-2k	4.83	11	4, 0
25	BE-2.5k	2.72	4	0, 0
26	BE-2.5k	5.31	8	0, 0
27	BE-2.5k	4.15	6	0, 0
28	BE-2.5k	3.61	6	2, 0
29	BE-2.5k	6.85	11	0, 0
30	BE-2.5k	7.10	11	4, 0

For flat echo-path loss, the weighted echo-path loss is equal to the flat value. For shaped echo paths, the weighted echo-path loss is a value between the maximum and minimum values of echo-path loss.

Table IV lists the 30 basic filters that were used in the tests and describes their characteristics in terms of filter types and relative loss. Application of eq. (7) to the 30 filter responses resulted in the weighted relative losses given in column 3. Thus, filter No. 1 (see Fig. 7) with 4-dB relative loss midband and 0-dB relative loss at the lower band edge has a weighted relative loss of 3.78 dB.

6.3 Extending the model as a function of delay

After the weighting function and the best fits were determined individually for each of the eight values of delay, the next step was to express μ_{LE} in eq. (6) as a function of both weighted echo-path loss and delay. This was done by a trial-and-error method in which various functions were tested until an acceptable fit was obtained. The resulting expression was:

$$\mu_{LE} = -1.0 + 0.3604(\text{WEPL} + 7)(D - 0.4)^{-0.229}, \quad (8)$$

where

$$D = \text{round trip delay in milliseconds}$$

and

$$\text{WEPL} = \text{weighted echo-path loss as defined in eq. (7).}$$

In Figs. 8b to 15b, the final opinion model given by eqs. (6) and (8) is plotted for each delay in the tests. For comparison, the fit means for each test condition are plotted as a function of the weighted echo-path loss as defined by eq. (7). These figures illustrate that the model defined by eqs. (6), (7), and (8) provides a good fit to the actual test results. Note the comparison between the two figures in each pair (8a, 8b), (9a, 9b), etc. through (15a, 15b) where the first part of each figure shows the fit means before applying weighting to the echo-path loss characteristics and the last part of each figure shows the fit means after applying the weighting. As shown, the WEPL is a much more accurate predictor of subjective quality than the singing margin.

6.4 Validation of the model

In Section 6.3, a model of listener echo opinion was presented in eqs. (6) and (8). This model was based on results from subjective tests involving echo conditions with a single combination of received volume and circuit noise for which the fit mean, μ_{VN}, was 4.2. The utility of this model would be improved if the model could be shown to be valid for other combinations of received volume and noise. With this in mind, test 4 described previously was conducted.

A comparison was made of the fit means predicted from eqs. (6) and (8) with the fit means for the 12 listener echo conditions repeated from the previous tests in test 4. This comparison indicated that the ratings for the repeated conditions in test 4 were generally higher than predicted by the model. A linear regression of the model fit means versus the test 4 fit means had a slope of 0.93 and an intercept of −0.37. The correlation coefficient was determined to be 0.99. The fit means for the conditions used in this regression plus other conditions common to tests 3 and 4 are shown in Table V.

The linear regression was used to adjust the fit means for all conditions in test 4 to the model data base. Thus,

$$\mu_m = 0.93\,\mu_4 - 0.37, \quad (9)$$

where

$$\mu_m = \text{fit mean for the model}$$

$$\mu_4 = \text{fit mean for test 4}$$

Table V—Results from test conditions common to tests 3 and 4 of the test

EPL	Delay	Fit Means: Test 3 μ_3	Test 4 μ_4	Predicted from Model μ_m
4	1.5	2.52	3.44	2.71
6	1.5	2.98	3.91	3.30
8	1.5	3.72	4.19	3.74
4	3	1.83	2.48	2.07
6	3	2.52	3.26	2.61
8	3	2.92	3.86	3.11
2	5	0.96	1.51	1.20
4	5	1.74	2.20	1.70
8	5	2.28	3.28	2.65
2	30	0.34	0.76	0.43
8	30	1.26	2.17	1.40
16	30	2.62	3.52	2.65
Source		4.42	4.62	4.20
Source		4.11	4.86	
Source		4.17	4.66	
Source		4.13	4.52	
$N = 25$ dBrnC		2.68	3.52, 3.57	
$N = 25$ dBrnC		2.86	3.88, 3.96	
$N = 45$ dBrnC		1.70	2.42, 2.38	
$N = 45$ dBrnC		1.66	2.38, 2.72	

The values of μ_{VN} for use in the model were determined by obtaining the averages of the adjusted fit means for each of the identical source conditions where no echo was present. The values obtained for μ_{VN} were 4.20, 3.10, and 1.94 for received volume of −24 VU and added noise levels of 5, 25, and 45 dBrnC, respectively. For a received volume of −34 VU and added noise of 5 and 25 dBrnC, the values for μ_{VN}, respectively, are 3.10 and 2.32. These values for μ_{VN} were then used together with eqs. (6) and (8) to extend the model to include the addition of combinations of volume and noise. This provides a model for the fit mean versus weighted echo-path loss (weighting = 0 for flat echo-path shape) for each combination of received volume and noise used in test 4 with echo delay as a parameter. Curves representing this model are shown in Figs. 16 to 19, respectively, for delays of 1.5, 3, 5, and 30 ms. The adjusted fit means for each test condition are also plotted on the appropriate curves.

A general comparison of the adjusted fit means from test 4 with those predicted from the extended model indicates that the extended model provides an acceptable prediction of opinion for received volume, noise, and listener echo. A linear regression between the fit means predicted by the model and the adjusted fit means from test 4 had a slope of 0.96, and an intercept of 0.03 with a correlation coefficient of 0.97.

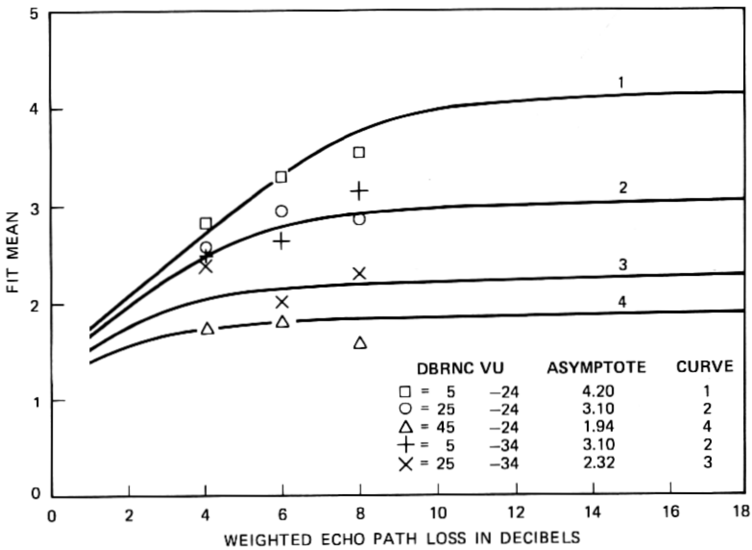


Fig. 16—Subjective test results for 1.5-ms echo-path delay in terms of weighted echo-path loss (WEPL) for Test 4.

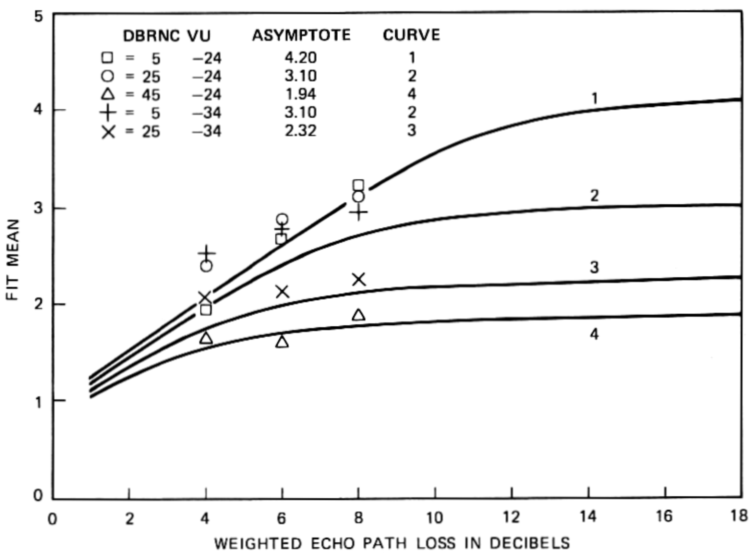


Fig. 17—Subjective test results for 3-ms echo-path delay in terms of weighted echo-path loss (WEPL) for Test 4.

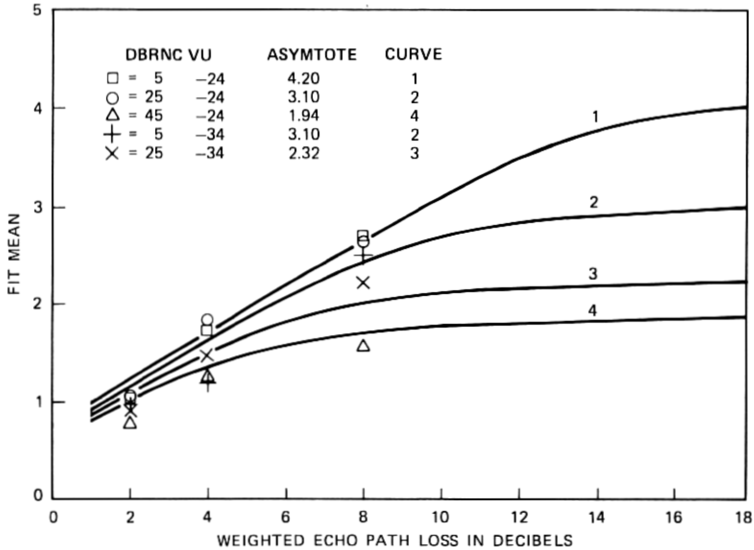


Fig. 18—Subjective test results for 5-ms echo-path delay in terms of weighted echo-path loss (WEPL) for Test 4.

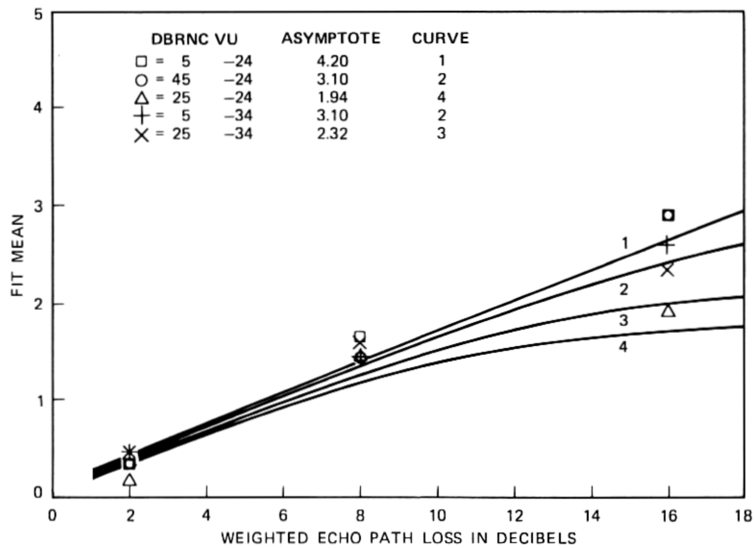


Fig. 19—Subjective test results for 30-ms echo-path delay in terms of weighted echo-path loss (WEPL) for Test 4.

VII. EXTENSION OF THE MODEL FOR USE WITH THE TRANSMISSION RATING MODEL

The opinion model presented in the previous section was derived primarily from listener echo test results. In most of the tests, a single combination of noise and speech level was used for each listener echo condition. The model was extended by a fourth test in which other combinations of received volume and circuit noise were examined. To generalize the results, it was desirable to incorporate the listener echo opinion model into the Transmission Rating Model,[2] which exists for loss, noise, and talker echo. The transformation from the opinion model described in the previous section to the transmission rating model is determined from conditions of circuit noise and speech-correlated noise, Q. Ratings for these conditions are available from the listener echo tests, and the transmission ratings are available from the indicated references.

Before extending the transmission rating model to include listener echo (Section 7.3), the speech level used in the tests had to be converted to an equivalent value of loudness loss (Section 7.1) and transmission ratings had to be determined for all of the test conditions (Section 7.2).

7.1 Derivation of equivalent overall loudness loss

The equivalent overall loudness loss was determined to be 8.7 dB, as shown below.

(*i*) The equivalent speech level at the input to a receiving system with a receiving loudness rating of 26 dB was −24 VU.

(*ii*) The average speech level at the transmitting class 5 office is −10.7 EPL, or −22.2 VU, based on a recent signal power survey.[6]

(*iii*) The listening levels in these tests referred to a receive system with a 26-dB receiving loudness rating are therefore 1.8 dB below those at the transmitting class 5 office, thus corresponding to a loss of 1.8 dB.

(*iv*) A representative transmitting EARS rating for 500-type set and loop is −19.1 dB.

(*v*) The speech levels in these tests are therefore typical of those which would be anticipated on a connection having an overall loudness loss of $-19.1 + 1.8 + 26 = 8.7$ dB.

7.2 Transfer to the transmission rating scale

The idle circuit noise and speech-correlated noise conditions for tests 1, 2, and 3 are listed in Table VI in terms of (*i*) equivalent loudness loss corresponding to the speech volume in the test, (*ii*) circuit noise referred to a receiving system with a receiving loudness rating of 26 dB and (*iii*) Q. For conditions with speech-correlated

Table VI—Comparison of noise and Q test results with transmission rating model

Equiv. Loss dB	Circuit Noise dBrnC	Q^* dB	Q^* Equiv. dBrnC	Adjusted† Test 1 Fit Mean	Adjusted‡ Test 2 Fit Mean	Test 3 Fit Mean	Avg. Mean	R¶ Rating
8.7	5	∞	—	3.90 3.88	3.60 3.70	4.42, 4.17 4.11, 4.13	3.99	128.
8.7	15	∞	—	3.46 3.60	3.37 3.42	3.49 3.29	3.45	115.3
8.7	25	∞	—	2.97 2.59	2.50 2.44	2.68 2.86	2.67	97.8
8.7	35	∞	—	2.22 2.14	1.84 1.98	2.12 2.23	2.09	79.6
8.7	45	∞	—	1.62 1.92	1.50 1.47	1.70 1.66	1.65	61.3
8.7	5	25	11.1	3.72 3.42	3.78 3.30	3.72 3.86	3.63	119.6
8.7	5	20	24.6	2.82 2.67	2.94 2.65	2.71 2.51	2.72	98.5
8.7	5	15	36.7	2.53 1.98	2.10 1.97	1.93 1.93	2.07	76.5
8.7	5	10	47.4	1.11 1.21	1.14 0.95	1.15 1.12	1.11	56.8
8.7	5	5	56.8	0.03 0.03	0.99 0.39	0.76 0.59	0.47	39.6

* Q = power ratio of speech to speech-correlated noise.
† Test 1 adjusted to test 3 by $\mu_3 = 0.98\,\mu_1 - 0.33$.
‡ Test 2 adjusted to test 3 by $\mu_3 = 0.88\,\mu_2 - 0.22$.
¶ Based on noise floor of 6 dBrnC in loss-noise R-model.

noise, the equivalent noise is also given based on an equivalence relationship between idle-circuit noise and Q which is currently under study. In addition, for each of the test conditions for circuit noise and speech-correlated noise, the values of adjusted fit means for each test are given. The average of these values are also listed.

The last column in Table VI gives the transmission rating as obtained from the transmission model.[2] The transmission ratings are based on the use of a noise floor of 6 dBrnC in the model, instead of the usual 27.37 dBrnC. This change reflects the subjects' ability to discriminate between low-noise conditions in the acoustically treated test rooms used in these tests and provides a better agreement between the test results and the transmission ratings. The transmission ratings are calculated from the loss-noise transmission rating model by using the values of equivalent connection loudness loss in column 1 of Table VI and the circuit noise level in column 2 for the noise conditions, and on the power sum of circuit noise and equivalent noise level in column 4 for the speech-correlated noise conditions. As indicated previously, the equivalent loss is based on the received volume for the test and, using the conversion described in Section 7.1, provides an equivalent connection loudness loss of 8.7 dB for the connection.

The transmission rating values for the Q and noise conditions as given in the last column of Table VI are plotted in Fig. 20 versus the fit means. A linear regression for this plot yielded a slope of 25.9, an intercept of 25.5, and a correlation coefficient of 0.99. The resulting relationship between transmission rating, R_{LN}, and the fit mean, μ_{LN}, is given in eq. (10) and is plotted in Fig. 20.

$$R_{LN} = 25.5 + 25.9\,\mu_{LN}, \tag{10}$$

where

R_{LN} = transmission rating for loss and noise

μ_{LN} = fit mean for loss and noise.

7.3 Loss-noise-listener echo model

In this section, the results from the previous sections are used to develop a transmission rating model for loss, noise, and listener echo. The transmission rating for loss, noise, and listener echo is defined in terms of the fit means for loss, noise, and listener echo using the relationship in eq. (10). Thus,

$$R_{LNLE} = 25.5 + 25.9\,\mu_{LNLE}, \tag{11}$$

where

R_{LNLE} = transmission rating for loss, noise, and listener echo

μ_{LNLE} = fit mean for loss, noise, and listener echo.

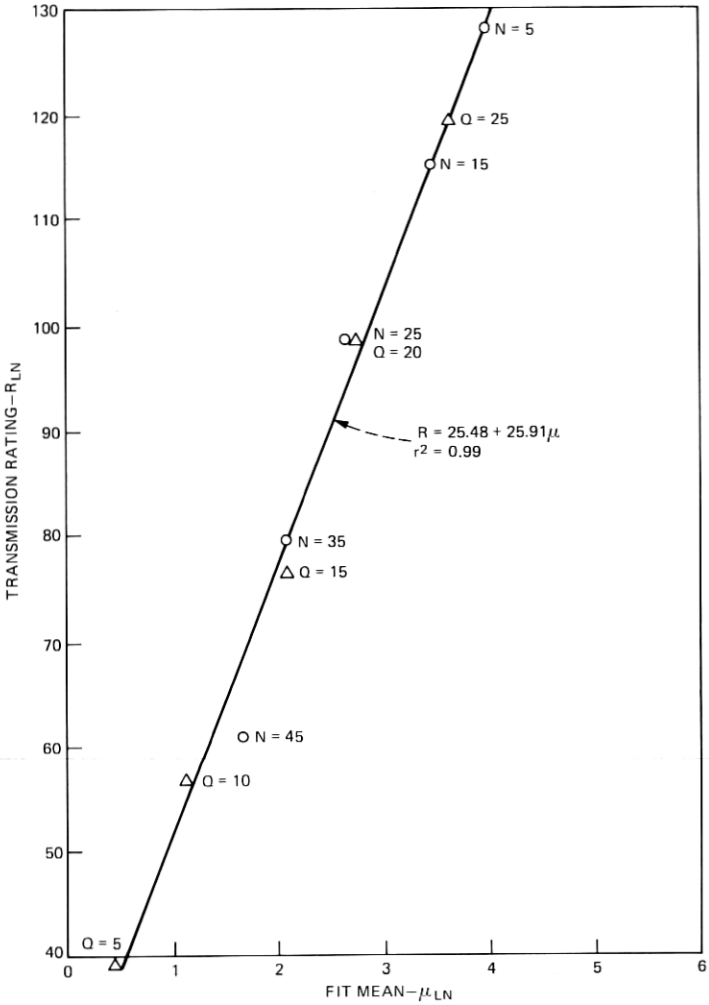


Fig. 20—Transmission rating, R_{LN}, and fit means for Q and noise conditions.

Rewriting eq. (6) in terms of μ_{LN} instead of μ_{VN} then gives

$$\mu_{LNLE} = \frac{\mu_{LE} + \mu_{LN}}{2} - \sqrt{\left(\frac{\mu_{LE} - \mu_{LN}}{2}\right)^2 + (0.5)^2}, \tag{12}$$

which can be combined with eq. (11) to obtain the result

$$R_{LNLE} = \frac{R_{LN} + R_{LE}}{2} - \sqrt{\left(\frac{R_{LN} - R_{LE}}{2}\right)^2 + (12.95)^2} \tag{13}$$

with

$$R_{LE} = \text{transmission rating for listener echo}$$
$$= 25.5 + 25.9\,\mu_{LE}$$
$$= -0.4 + 9.334\,(\text{WEPL} + 7)(D - 0.4)^{-0.229} \tag{14}$$

and

$$R_{LN} = \text{transmission rating for loss and noise.}$$

With very little effect on the final result, some simplification is possible as follows:

$$R_{LNLE} = \frac{R_{LN} + R_{LE}}{2} - \sqrt{\left(\frac{R_{LN} - R_{LE}}{2}\right)^2 + (13)^2} \tag{15}$$

$$R_{LE} = 9.3\,(\text{WEPL} + 7)(D - 0.4)^{-0.229}. \tag{16}$$

Equations (15) and (16) then provide the desired extension to include listener echo in the transmission rating model for loss and noise. The complete model for loss, noise, and listener echo is summarized in Table VII.

By using the equations in Table VIII, transmission ratings for combinations of loss, noise, and listener echo can be determined as illustrated in Fig. 21. These transmission ratings can then be used to estimate opinions in terms of percent good or better and percent poor or worse. Such opinion curves are shown, respectively, in Figs. 22 and 23, based on the transmission rating model for loss and noise described in Ref. 2 for the data base at Murray Hill, N.J. The curves are plotted as a function of weighted echo-path loss with delay as a parameter and assume an overall loudness loss of 15 dB and an idle circuit noise level of 30 dBrnC at the input of a receive system with a receiving loudness rating of 26 dB.

VIII. PROPOSED OBJECTIVES FOR LISTENER ECHO

For many years, listener echo performance has been controlled by objectives for singing margin and talker echo.[7] Although this approach has resulted in adequate listener echo control in trunks, the test results described in this paper indicate that, for shaped echo-path loss, typical of most telephone connections, singing margin by itself does not give an accurate indication of opinion. This indicates the desirability of controlling listener echo in 4-wire offices by objectives expressed in terms of weighted listener echo-path loss. Such objectives are proposed in this section.

Two considerations were used in arriving at the proposed recommendations for intraoffice connections:

Table VII—Model for estimating subjective reaction to loss, noise, and listener echo

The models in terms of the transmission rating scale for loss and noise (R_{LN}), listener echo (R_{LE}), and loss, noise listener echo (R_{LNLE}) are:

$$R_{LN} = 147.76 - 2.257\sqrt{(L_e - 7.2)^2 + 1} - 2.009N_F + 0.02037(L_e)N_F^*$$

$$R_{LE} = 9.3(\text{WEPL} + 7)(D - 0.4)^{-0.229} \quad (16)$$

$$R_{LNLE} = \frac{R_{LN} + R_{LE}}{2} - \sqrt{\left(\frac{R_{LN} - R_{LE}}{2}\right)^2 + (13)^2} \quad (15)$$

where R_{LN} is developed in Ref. 1.

L_e = acoustic-to-acoustic loudness loss (in dB) of an overall telephone connection determined using the EARS method,
N = circuit noise (in dBrnC) at the input to a receiving system with a receiving loudness rating of 26 dB, determined using the EARS method,
N_F = power sum of N with 27.37 dBrnC,
D = round trip delay (in ms) of the echo path,
WEPL = weighted echo path loss (in dB)

$$= -20 \log \frac{1}{3200} \int_{200}^{3400} 10^{-EPL(f)/20}\, df \quad (7)$$

$$\approx -20 \log \left\{ \frac{\sum_{i=1}^{N} [(10^{-EPL_i/20} + 10^{-EPL_{i-1}/20})/2](f_i - f_{i-1})}{f_N - f_0} \right\}$$

EPL_i = magnitude of listener echo path loss in decibels at frequency f_i
f_i = frequency at hertz
f_N = 3400 Hz
f_0 = 200 Hz.

The proportion of comments good or better (GoB) and poor or worse (PoW) are computed from R by

$$\text{GoB} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{A} e^{-t^2/2}\, dt \qquad \text{PoW} = \frac{1}{\sqrt{2\pi}} \int_{B}^{\infty} e^{-t^2/2}\, dt,$$

where A and B are

$$A = (R - 64.07)/17.57; \quad B = (R - 51.87)/17.57.$$

The model can also be expressed as

$$\mu_{MH} = (R - 21.37)/12.2 \quad \sigma = 1.44.$$

* Eq. (1) of Ref. 1.

(*i*) Listener echo-path loss in decibels is expected to be normally distributed, with a standard deviation of about 3 dB for a typical distribution of loop return loss.

(*ii*) The listener echo objectives should permit only a small added degradation to that which already exists for loss and noise.

Figure 24 shows the effect of listener echo on grade of service for several loss and noise conditions. These curves are based on the

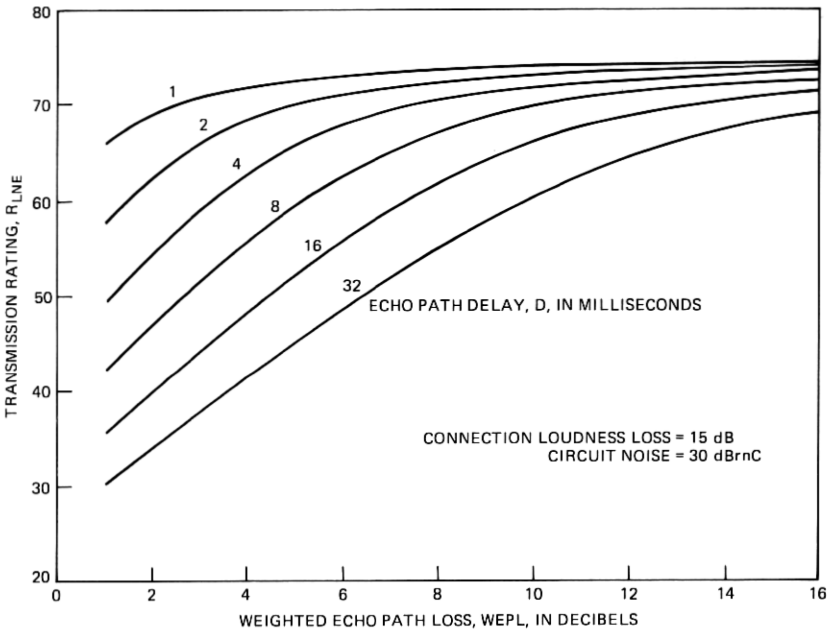


Fig. 21—Transmission rating for loss, noise, and listener echo.

transmission rating model for loss, noise, and listener echo presented in the previous section. The listener echo-path delay is taken as 4 ms, and the grade of service in terms of percent good or better is plotted as a function of weighted echo-path loss. The curve labeled Loss = 8.6 and N26 = 20 dBrnC corresponds to the average loss on an intraoffice call and noise at the telephone set terminals of approximately 16 dBrnC, a condition typical of the circuit noise expected with a digital central office. The curve labeled Loss = 10 dB and N26 = 24 dBrnC corresponds to loops having a slightly greater than average loss and meeting the loop noise objective of 20 dBrnC at the telephone set terminals. The curve labeled Loss = 14 dB and N26 = 24 dBrnC corresponds to the 90-percent point on the distribution of loudness loss for intraoffice connections (10 percent of the connections have loss higher than 14 dB) and the loop noise objective of 20 dBrnC. All these curves indicate a similar tendency. The grade of service falls off slowly as the weighted echo-path loss is reduced to about 10 to 15 dB and falls off sharply for lower values of weighted echo-path loss.

The proposed objective for weighted echo-path loss for an echo-path delay of 4 ms is also shown. This objective is just met by a normal

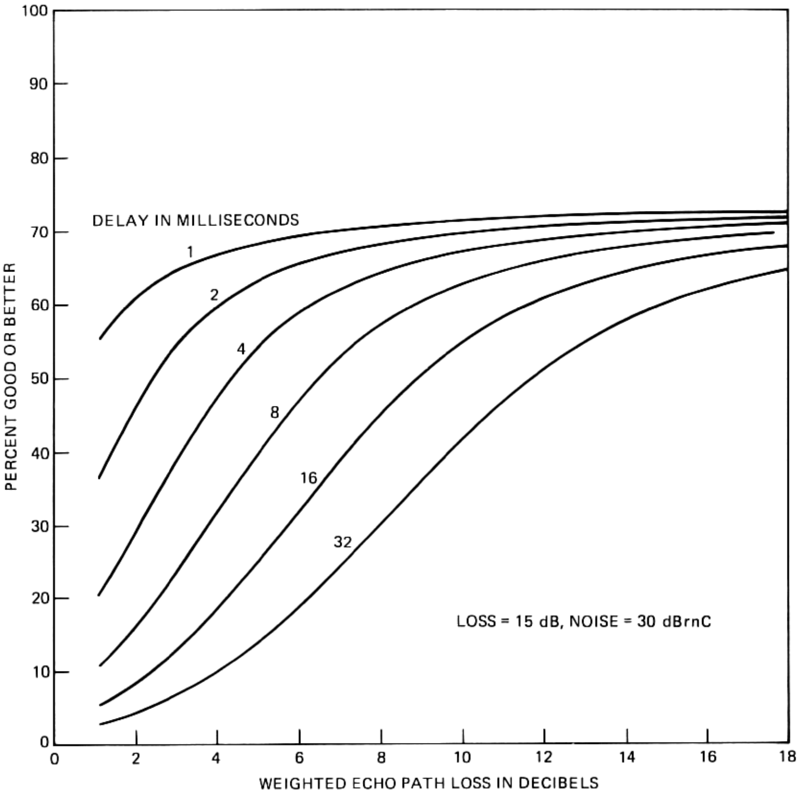


Fig. 22—Subjective opinion curves of percent good or better for the loss-noise-listener echo model at the Murray Hill base.

distribution with a mean of 18 dB and a standard deviation of 3 dB. The proposed objective and comparable objectives for other values of delay are shown in Fig. 25 and summarized (rounded to the nearest decibel) in the table below.

Echo-Path Delay (ms)	Minimum Weighted Echo-Path Loss Objectives in dB for Indicated Percent of Connections			
	50%	95%	99%	99.9%
4	18	13	11	9
5	19	14	12	10
6	20	15	13	11
7	21	16	14	12
8	22	17	14	12

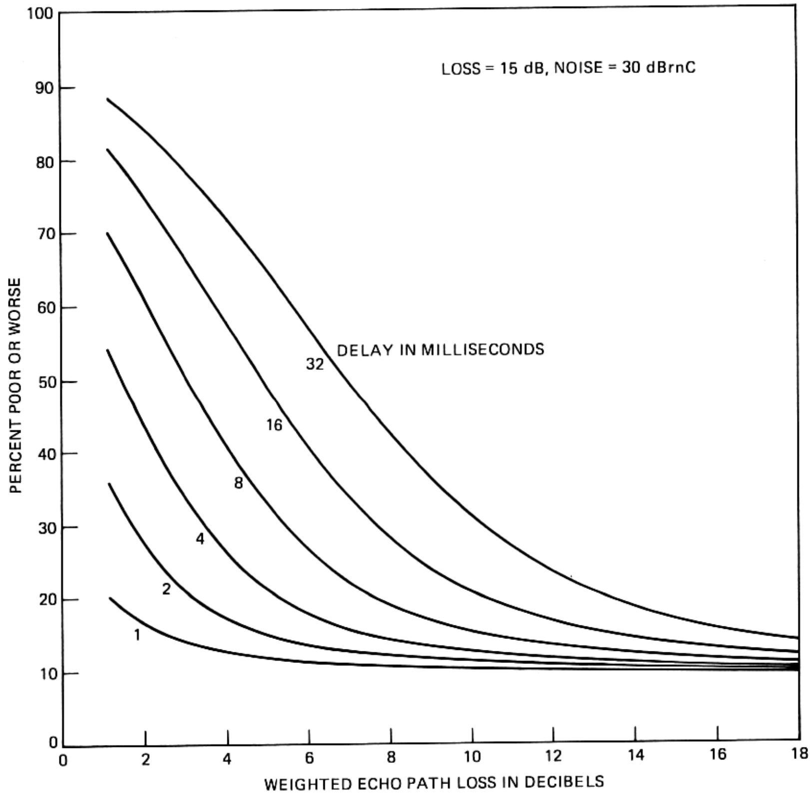


Fig. 23—Subjective opinion curves of percent poor or worse for the loss-noise-listener echo model at the Murray Hill base.

In each case, the proposed objectives are chosen to limit the degradation in the grade of service in terms of percent good or better at approximately the following levels.

% of Connections	Decrease in Percent Good or Better
50	1
5	2
1	3
0.1	5

IX. PROPOSED OBJECTIVES FOR SINGING MARGIN

In the previous section, control of listener echo or near-singing distortion has been proposed based on objectives for the weighted echo-path loss rather than on objectives for singing margin. This is

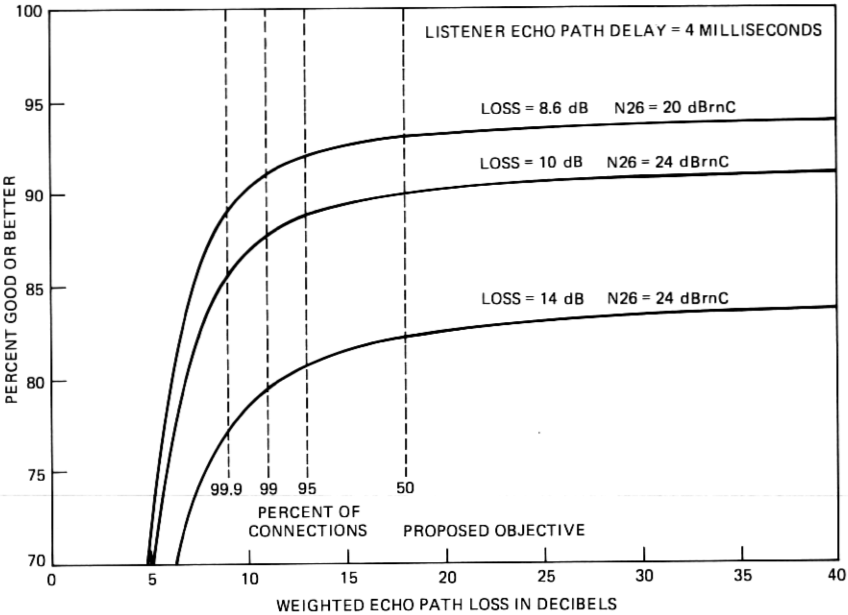


Fig. 24—Proposed objective and effect of listener echo with 4-ms echo-path delay on percent good or better grade of service based on the transmission rating model for loss, noise, and listener echo.

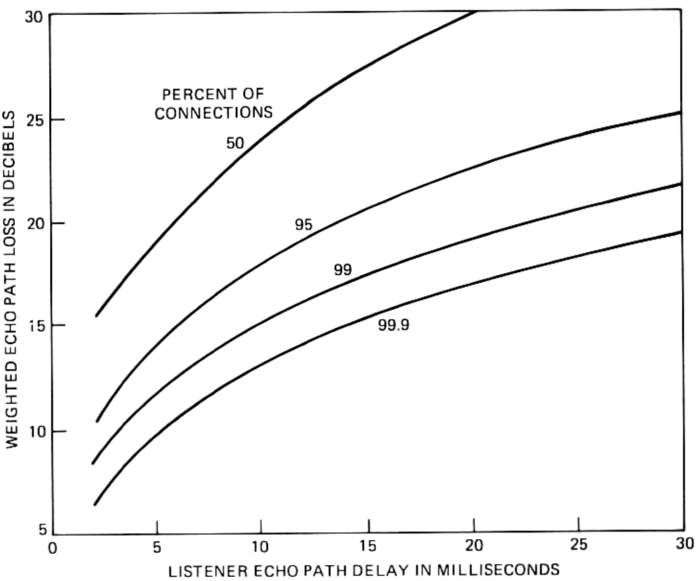


Fig. 25—Weighted listener echo-path loss objectives.

appropriate because the subjective opinion of listener echo is highly correlated with the weighted echo-path loss. However, this does not eliminate the need to provide sufficient margin against actual singing conditions. Thus, a need still exists for some minimum objective for singing margin itself. A minimum limit on singing margin of 4 dB is proposed for this purpose.

X. ACKNOWLEDGMENTS

The authors wish to acknowledge the contribution of a number of colleagues who contributed to the tests described in this paper. We wish to particularly thank W. R. Daumer who provided the software required for generating the near-singing conditions and the procedure for producing the analog test tapes.

APPENDIX

Tables of Data and Results for the Four Listener Echo Tests

Table VIII—Test 1: Test conditions and results

EPL = Echo-path loss in decibels, flat loss only.
V = Received volume = −24 VU for 26-dB set.
D = Delay in milliseconds.
N = Circuit noise, in dBrnC, referred to the input of a telephone set with a 26-dB receiving EARS rating (N = 5 dBrnC, except for noise conditions as noted).
Q = Radio of speech power to speech-correlated noise power in decibels.
Constant standard deviation for this data set = 0.64.

Listener Echo Conditions:

No.	EPL	D	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
1	2	0.75	51	3.92	19.61	56.89	19.61	0.00	3.08
2	2	1.5	52	0.00	7.69	23.08	51.92	17.31	2.21
3	2	3	52	0.00	0.00	34.62	50.00	15.38	2.19
4	2	5	52	0.00	0.00	11.54	75.00	13.46	1.97
5	4	0.75	52	28.85	55.77	15.38	0.00	0.00	4.15
6	4	1.5	52	0.00	11.54	48.08	40.38	0.00	2.71
7	4	3	52	1.92	1.92	19.23	67.31	9.62	2.19
8	4	5	52	0.00	0.00	21.15	65.38	13.46	2.07
9	6	0.75	52	28.85	63.46	7.69	0.00	0.00	4.24
10	6	1.5	52	13.46	46.15	34.62	3.85	1.92	3.66
11	6	3	52	1.92	23.08	55.77	17.31	1.92	3.06
12	6	5	52	0.00	1.92	30.77	57.69	9.62	2.25
13	8	0.75	52	32.65	61.54	5.77	0.00	0.00	4.30
14	8	1.5	51	23.53	50.98	23.53	1.96	0.00	3.97
15	8	3	51	9.80	33.33	43.14	11.76	1.96	3.37
16	8	5	52	0.00	21.15	59.62	17.31	1.92	3.00
17	10	0.75	52	36.54	57.69	5.77	0.00	0.00	4.34
18	10	1.5	50	34.00	52.00	14.00	0.00	0.00	4.22
19	10	3	52	15.38	51.92	28.85	3.85	0.00	3.79
20	10	5	52	1.92	19.23	59.62	19.23	0.00	3.04
21	15	0.75	52	30.77	65.38	3.85	0.00	0.00	4.30
22	15	1.5	51	29.41	47.00	21.57	1.96	0.00	4.05
23	15	3	52	26.92	48.08	25.00	0.00	0.00	4.03
24	15	5	52	42.31	48.08	7.69	1.92	0.00	4.34

Table VIII—*Continued*

Reference Conditions:

No.	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
25	52	36.54	55.77	7.69	0.00	0.00	4.32
26	52	38.46	50.00	11.54	0.00	0.00	4.30

Q Conditions:

No.	*Q*	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
27	5	52	0.00	0.00	0.00	3.85	96.15	0.37
28	5	52	0.00	0.00	0.00	3.85	96.15	0.37
29	10	52	0.00	0.00	1.92	50.00	48.08	1.47
30	10	52	0.00	1.92	3.85	48.08	46.15	1.57
31	15	52	1.92	19.23	50.00	26.92	1.92	2.92
32	15	52	0.00	5.77	34.62	50.00	9.62	2.36
33	20	52	1.92	23.08	69.23	5.77	0.00	3.21
34	20	52	3.85	25.00	44.23	26.92	0.00	3.06
35	25	52	23.08	65.38	11.54	0.00	0.00	4.13
36	25	51	13.73	56.86	27.45	1.96	0.00	3.83

Circuit Noise Conditions:

No.	*N*	No. votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
37	15	57	9.80	68.63	19.61	1.96	0.00	3.86
38	15	57	15.38	69.23	15.38	0.00	0.00	4.01
39	25	52	5.77	30.77	57.69	5.77	0.00	3.37
40	25	52	1.92	17.31	61.54	15.38	3.85	2.98
41	35	52	0.00	1.92	57.69	38.46	1.92	2.60
42	35	52	0.00	7.69	44.23	40.38	7.69	2.52
43	45	52	0.00	0.00	21.15	57.69	21.15	1.99
44	45	51	0.00	0.00	45.10	41.18	13.73	2.31

Table IX—Test 2: Test conditions and results

EPL = Echo-path loss in decibels, flat loss only.
V = Received volume = −24 VU at 26-dB set.
D = Delay in milliseconds.
N = Circuit noise, in dBrnC, referred to the input of a telephone set with a 26-dB receiving EARS rating (*N* = 5 dBrnC, except for noise conditions as noted).
Q = Ratio of speech power to speech-correlated noise power in decibels.

Constant standard deviation for the data set = 0.71.

Listener Echo Conditions:

No.	EPL	*D*	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
1	2	5	55	0.00	0.00	7.27	34.55	58.18	1.38
2	2	30	55	0.00	0.00	1.82	10.91	87.27	0.74
3	2	60	55	0.00	0.00	0.00	5.45	94.55	0.36
4	4	1.5	55	5.45	34.55	43.64	16.36	0.00	3.29
5	4	3	55	0.00	14.55	41.82	40.00	3.64	2.67
6	8	1.5	55	25.45	60.00	14.55	0.00	0.00	4.14
7	8	3	55	29.09	49.09	20.00	1.82	0.00	4.08
8	8	5	55	1.82	23.64	56.36	16.36	1.82	3.07
9	8	30	55	0.00	1.82	23.64	41.82	32.73	1.92
10	8	60	54	0.00	0.00	7.41	29.63	62.96	1.32
11	14	5	55	23.64	61.82	12.73	1.82	0.00	4.10
12	16	30	55	3.64	34.55	45.45	12.73	3.64	3.22
13	18	60	54	5.56	24.07	48.15	22.22	0.00	3.13

Table IX—*Continued*

Reference Conditions:

No.	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
14	55	36.36	56.36	7.27	0.00	0.00	4.34
15	55	40.00	58.18	1.82	0.00	0.00	4.45

Circuit Noise Conditions:

No.	N	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
16	15	55	25.45	56.36	16.36	1.82	0.00	4.08
17	15	54	33.33	44.44	22.22	0.00	0.00	4.14
18	25	54	1.85	27.78	48.15	22.22	0.00	3.09
19	25	55	5.45	23.64	41.82	25.45	3.64	3.02
20	35	55	0.00	5.45	38.18	41.82	14.55	2.34
21	35	54	0.00	11.11	40.74	37.04	11.11	2.52
22	45	53	0.00	0.00	28.30	41.51	30.19	1.96
23	45	55	0.00	1.82	18.18	52.73	27.27	1.92

Q Conditions:

No.	Q	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
24	5	54	0.00	0.00	0.00	48.15	51.85	1.37
25	5	54	0.00	0.00	1.85	9.26	88.89	0.69
26	10	55	0.00	0.00	9.09	43.64	47.27	1.55
27	10	55	0.00	0.00	5.45	34.55	60.00	1.33
28	15	55	0.00	9.09	50.91	34.55	5.45	2.64
29	15	55	0.00	9.09	38.18	45.45	7.27	2.49
30	20	53	11.32	41.51	41.51	5.66	0.00	3.59
31	20	55	7.27	27.27	49.09	16.36	0.00	3.26
32	25	55	50.91	43.64	5.45	0.00	0.00	4.55
33	25	55	25.45	47.27	27.27	0.00	0.00	4.00

Table X—Test 3: Test conditions and results

EPL1 = Midband echo-path loss in decibels.
EPL2 = Band edge echo-path loss in decibels.
V = Received volume = −24 VU at 26 dB set.
D = Delay in ms.
N = Circuit noise, in dBrnC, referred to the input of a telephone set with a 26-dB receive EARS rating (N = 5 dBrnC, except for noise conditions as noted).
Q = ratio of speech power to speech-correlated noise power in decibels.
Constant standard deviation for this data set = 0.70.

Flat Listener Echo-Path Conditions:

No.	EPL1	D	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
1	4	1.5	59	0.00	6.78	45.76	40.68	6.78	2.52
2	6	1.5	59	5.08	16.95	50.85	25.42	1.69	2.98
3	8	1.5	59	16.95	44.07	32.20	6.78	0.00	2.72
4	10	1.5	59	18.64	59.32	16.95	5.08	0.00	3.93
5	6	2	59	0.00	6.78	45.76	38.98	8.47	2.51
6	8	2	59	1.69	30.51	47.46	18.64	1.69	3.12
7	10	2	59	22.03	47.46	28.81	1.69	0.00	3.91
8	15	2	59	23.73	54.24	22.03	0.00	0.00	4.04
9	4	3	59	0.00	0.00	15.25	55.93	28.81	1.83
10	6	3	59	1.69	10.17	37.29	40.68	10.17	2.52
11	8	3	59	5.08	18.64	42.37	30.51	3.39	2.92
12	10	3	57	22.81	29.82	45.61	1.75	0.00	3.74
13	6	4	59	0.00	0.00	15.25	54.24	30.51	1.82
14	8	4	59	1.69	11.86	42.37	35.59	8.47	2.63
15	10	4	59	3.39	37.29	42.37	15.25	1.69	3.25
16	12	4	59	10.17	59.32	22.03	8.47	0.00	3.72
17	15	4	58	13.79	46.55	34.48	5.17	0.00	3.69
18	2	5	59	0.00	0.00	0.00	23.73	76.27	0.96
19	4	5	59	1.69	1.69	13.56	38.98	44.07	1.74
20	8	5	59	1.69	8.47	20.34	55.93	13.56	2.28
21	2	30	59	0.00	0.00	0.00	5.08	94.92	0.34
22	8	30	59	0.00	0.00	3.39	33.90	62.71	1.26
23	16	30	58	0.00	10.34	44.83	41.38	3.45	2.62
24	2	60	59	0.00	0.00	0.00	5.08	94.92	0.34
25	8	60	59	0.00	0.00	5.08	20.34	74.58	1.09
26	18	60	59	0.00	5.08	23.73	49.15	22.03	2.11

Table X—*Continued*

Low-Pass Filter in Listener Echo-Path Conditions:

No.	EPL1	EPL2	*D*	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
27	8	2	0.75	59	23.73	59.32	16.95	0.00	0.00	4.09
28	10	6	0.75	59	28.81	52.54	18.64	0.00	0.00	4.13
29	15	2	0.75	59	30.51	57.63	11.86	0.00	0.00	4.22
30	6	2	1.5	59	3.39	25.42	61.02	8.47	1.69	3.20
31	8	4	1.5	59	10.17	38.98	45.76	5.08	0.00	3.55
32	10	2	1.5	59	22.03	59.32	16.95	1.69	0.00	4.04
33	10	6	1.5	58	15.52	67.24	17.24	0.00	0.00	4.00
34	15	2	1.5	59	30.51	54.24	13.56	0.00	1.69	4.15
35	15	4	1.5	59	42.37	54.24	3.39	0.00	0.00	4.46
36	15	6	1.5	58	32.20	49.15	16.95	1.69	0.00	4.15
37	15	8	1.5	59	27.12	57.63	15.25	0.00	0.00	4.15
38	6	2	3	58	0.00	5.17	43.10	44.83	6.90	2.46
39	8	4	3	59	8.47	13.56	50.85	25.42	1.69	3.02
40	10	2	3	60	3.33	35.00	55.00	6.67	0.00	3.35
41	10	6	3	58	10.34	44.83	31.03	13.79	0.00	3.52
42	15	2	3	59	20.34	54.24	22.03	3.39	0.00	3.93
43	15	4	3	59	28.81	49.15	22.03	0.00	0.00	4.09
44	15	6	3	59	28.81	44.07	25.42	1.69	0.00	4.02
45	15	8	3	59	23.73	54.24	18.64	3.39	0.00	4.00
46	15	6	5	59	25.42	45.76	25.42	1.69	1.69	3.92

High-Pass Filter (2 kHz) in Listener Echo-Path Conditions:

No.	EPL1	EPL2	*D*	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
47	8	4	0.75	59	23.73	50.85	23.73	1.69	0.00	3.98
48	10	4	0.75	59	32.20	55.93	11.86	0.00	0.00	4.24
49	10	6	0.75	59	32.20	57.63	10.17	0.00	0.00	4.26
50	6	2	1.5	58	3.45	22.41	56.90	13.79	3.45	3.09
51	8	4	1.5	59	6.78	35.59	47.46	10.17	0.00	3.39
52	10	2	1.5	59	8.47	42.37	40.68	8.47	0.00	3.51
53	10	4	1.5	59	16.95	52.54	28.81	1.69	0.00	3.86
54	10	6	1.5	59	22.03	54.24	22.03	1.69	0.00	3.98
55	15	2	1.5	58	18.97	55.17	22.41	3.45	0.00	3.91

56	15	4	1.5	59	15.25	52.54	32.20	0.00	0.00	3.84
57	15	6	1.5	59	27.12	55.93	16.95	0.00	0.00	4.13
58	6	2	3	59	3.39	6.78	18.64	49.15	22.03	2.20
59	8	4	3	59	0.00	20.34	49.15	28.81	1.69	2.88
60	10	2	3	59	3.39	27.12	40.68	27.12	1.69	3.03
61	10	4	3	58	3.45	31.03	58.62	6.90	0.00	3.31
62	10	6	3	59	3.39	42.37	45.76	8.47	0.00	3.41
63	15	2	3	59	8.47	40.68	45.76	5.08	0.00	3.53
64	15	4	3	59	15.25	66.10	15.25	1.69	1.69	3.93
65	15	6	3	59	20.34	61.02	16.95	1.69	0.00	4.01

High-Pass Filter (2.5 kHz) in Listener Echo-Path Conditions:

No.	EPL1	EPL2	*D*	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
66	8	4	0.75	58	25.86	51.72	22.41	0.00	0.00	4.05
67	10	4	0.75	57	29.82	56.14	10.53	3.51	0.00	4.15
68	10	6	0.75	59	30.51	57.63	11.86	0.00	0.00	4.22
69	6	2	1.5	59	16.95	52.54	28.81	1.69	0.00	3.86
70	8	4	1.5	59	16.95	64.41	16.95	1.69	0.00	3.98
71	10	2	1.5	59	11.86	55.93	32.20	0.00	0.00	3.80
72	10	4	1.5	58	17.24	41.38	39.66	1.72	0.00	3.75
73	10	6	1.5	59	18.64	57.63	22.03	1.69	0.00	3.95
74	15	2	1.5	59	22.03	55.93	20.34	1.69	0.00	4.00
75	15	4	1.5	59	23.73	57.63	18.64	0.00	0.00	4.07
76	15	6	1.5	59	13.56	55.93	25.42	5.08	0.00	3.79
77	6	2	3	59	0.00	6.78	38.98	37.29	16.95	2.35
78	8	4	3	59	11.86	45.76	22.03	16.95	3.39	3.46
79	10	2	3	59	5.08	37.29	42.37	15.25	0.00	3.32
80	10	4	3	58	5.17	46.55	41.38	6.90	0.00	3.50
81	10	6	3	58	3.45	37.93	41.38	17.24	0.00	3.28
82	15	2	3	59	13.56	49.15	37.29	0.00	0.00	3.77
83	15	4	3	59	20.34	57.63	20.34	1.69	0.00	3.98
84	15	6	3	58	18.97	46.55	31.03	3.45	0.00	3.82
85	15	2	5	59	3.39	35.59	45.76	15.25	0.00	3.27
86	15	4	5	59	15.25	44.07	30.51	10.17	0.00	3.65
87	15	6	5	59	6.78	59.32	25.42	8.47	0.00	3.65

Table X—*Continued*

Band-Elimination Filters (2 kHz) in Listener Echo-Path Conditions (two values given in column labeled EPL2 designate loss at low and high frequencies, respectively):

No.	EPL1	EPL2	*D*	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
88	8	4, 4	0.75	59	20.34	55.93	22.03	1.69	0.00	3.96
89	10	4, 4	0.75	59	25.42	54.24	18.64	1.69	0.00	4.05
90	10	6, 4	0.75	59	30.51	55.93	10.17	3.39	0.00	4.17
91	10	6, 6	0.75	59	22.03	61.02	16.95	0.00	0.00	4.07
92	15	4, 4	0.75	59	28.81	50.85	20.34	0.00	0.00	4.11
93	15	8, 4	0.75	59	22.03	62.71	15.25	0.00	0.00	4.09
94	6	2, 2	1.5	59	5.08	25.42	45.76	18.64	5.08	3.07
95	8	4, 4	1.5	59	10.17	32.20	38.98	16.95	1.69	3.32
96	10	2, 2	1.5	58	1.72	27.59	48.28	18.97	3.45	3.05
97	10	4, 4	1.5	59	10.17	45.76	33.90	8.47	1.69	3.55
98	10	6, 4	1.5	59	3.39	42.37	37.29	16.95	0.00	3.32
99	10	6, 6	1.5	58	24.14	51.72	18.97	5.17	0.00	3.96
100	15	4, 4	1.5	59	23.73	45.76	27.12	3.39	0.00	3.91
101	15	8, 4	1.5	59	20.34	52.54	23.73	3.39	0.00	3.91
102	6	2, 2	3	59	0.0	3.39	32.20	49.15	15.25	2.23
103	8	4, 4	3	59	3.39	10.17	38.98	44.07	3.39	2.66
104	10	2, 2	3	59	1.69	13.56	44.07	40.68	0.00	2.76
105	10	4, 4	3	59	3.39	28.81	40.68	27.12	0.00	3.08
106	10	6, 4	3	59	5.08	28.81	49.15	15.25	1.69	3.20
107	10	6, 6	3	59	3.39	25.42	50.85	20.34	0.00	3.12
108	15	4, 4	3	59	6.78	30.51	57.63	5.08	0.00	3.39
109	15	8, 4	3	59	3.39	33.90	47.46	15.25	0.00	3.25

Band-Elimination Filters (2.5 kHz) in Listener Echo-Path (two values given in column EPL2 designated loss at low and high frequencies, respectively):

No.	EPL1	EPL2	*D*	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
110	8	4, 4	0.75	59	22.03	52.54	25.42	0.00	0.00	3.98
111	10	4, 4	0.75	59	15.25	66.10	16.95	1.69	0.00	3.96
112	10	6, 4	0.75	58	34.48	55.17	8.62	1.72	0.00	4.26
113	10	6, 6	0.75	59	22.03	64.41	13.56	0.00	0.00	4.11
114	15	4, 4	0.75	58	29.31	58.62	12.07	0.00	0.00	4.21
115	15	8, 4	0.75	59	35.59	55.93	6.78	1.69	0.00	4.30
116	6	2, 2	1.5	59	1.69	18.64	44.07	32.20	3.39	2.83
117	8	4, 4	1.5	59	6.78	47.46	40.68	5.08	0.00	3.56
118	10	2, 2	1.5	59	15.25	50.85	28.81	5.08	0.00	3.77
119	10	4, 4	1.5	59	13.56	50.85	32.20	3.39	0.00	3.75
120	10	6, 4	1.5	59	27.12	57.63	15.25	0.00	0.00	4.15
121	10	6, 6	1.5	59	18.64	55.93	18.64	6.78	0.00	3.87
122	15	4, 4	1.5	59	22.03	61.02	16.95	0.00	0.00	4.07
123	15	8, 4	1.5	59	25.42	61.02	13.56	0.00	0.00	4.15
124	6	2, 2	3	59	1.69	1.69	32.20	52.54	11.86	2.28
125	8	4, 4	3	59	0.00	25.42	45.76	27.12	1.69	2.95
126	10	2, 2	3	59	0.00	28.81	54.24	16.95	0.00	3.12
127	10	4, 4	3	59	3.39	32.20	50.85	13.56	0.00	3.25
128	10	6, 4	3	59	10.17	22.03	45.76	22.03	0.00	3.20
129	10	6, 6	3	59	10.17	42.37	44.07	3.39	0.00	3.60
130	15	4, 4	3	59	16.95	57.63	20.34	5.08	0.00	3.87
131	15	8, 4	3	59	20.34	54.24	23.73	1.69	0.00	3.95

Table X—*Continued*

Reference Conditions:

No.	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
132	59	45.76	45.76	6.78	1.69	0.00	4.42
133	59	23.73	61.02	15.25	0.00	0.00	4.11
134	59	30.51	52.54	16.95	0.00	0.00	4.17
135	59	30.51	52.54	13.56	3.39	0.00	4.13

Circuit Noise Conditions:

No.	*N*	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
136	15	59	6.78	40.68	47.46	5.08	0.00	3.49
137	15	59	5.08	30.51	52.54	11.86	0.00	3.29
138	25	59	3.39	10.17	45.76	32.20	8.47	2.68
139	25	59	1.69	13.56	54.24	30.51	0.00	2.86
140	35	59	0.00	1.69	28.81	50.85	18.64	2.13
141	35	59	1.69	3.39	25.42	55.93	13.56	2.23
142	45	59	0.00	0.00	11.86	50.85	37.29	1.70
143	45	59	0.00	0.00	10.17	50.85	38.98	1.66

Q Conditions:

No.	*Q*	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
144	5	59	0.00	0.00	0.00	15.25	84.75	0.76
145	5	59	0.00	0.00	0.00	10.17	89.83	0.59
146	10	59	0.00	0.00	1.69	30.51	67.80	1.15
147	10	59	0.00	0.00	0.00	32.20	67.80	1.12
148	15	59	0.00	1.69	13.56	62.71	22.03	1.93
149	15	59	1.69	1.69	11.86	59.32	25.42	1.93
150	20	59	0.00	13.56	45.76	38.98	1.69	2.71
151	20	59	0.00	6.78	44.07	42.37	6.78	2.51
152	25	59	13.56	45.76	38.98	1.69	0.00	3.73
153	25	59	10.17	71.19	11.86	6.78	0.00	3.86

Table XI—Test 4: Test conditions and results

EPL = echo-path loss in decibels.
N = Circuit noise in dBrnC referred to the input of a telephone set with a 26-dB receiving EARS rating.
D = Delay in milliseconds.
V = Received volume in VU referred to the input of a telephone set with a 26-dB receiving EARS rating.
Constant standard deviation for this data set = 0.71.

No.	EPL	D	N	V	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
1	4	1.5	5	−24	39	10.26	33.33	46.15	10.26	0.00	3.44
2	6	1.5	5	−24	39	23.08	48.72	23.08	5.13	0.00	3.91
3	8	1.5	5	−24	39	28.21	58.97	12.82	0.00	0.00	4.19
4	4	3	5	−24	39	5.13	10.26	28.21	41.03	15.38	2.48
5	6	3	5	−24	39	7.69	33.33	38.46	17.95	2.56	3.26
6	8	3	5	−24	39	23.08	46.15	23.08	7.69	0.00	3.86
7	2	5	5	−24	39	0.00	5.13	10.26	23.08	61.54	1.51
8	4	5	5	−24	38	2.63	5.26	26.32	42.11	23.68	2.20
9	8	5	5	−24	39	7.69	28.21	51.28	10.26	2.56	3.28
10	2	30	5	−24	39	0.00	0.00	0.00	15.38	84.62	0.76
11	8	30	5	−24	39	0.00	10.26	28.21	30.77	30.77	2.17
12	16	30	5	−24	39	20.51	28.21	35.90	12.82	2.56	3.51
13	Source		5	−24	39	56.41	38.46	5.13	0.00	0.00	4.62
14	Source		5	−24	39	69.23	28.21	2.56	0.00	0.00	4.86
15	Source		5	−24	39	56.41	41.03	2.56	0.00	0.00	4.66
16	Source		5	−24	39	53.85	35.90	10.26	0.00	0.00	4.52
17	4	1.5	5	−24	39	5.13	30.77	41.03	23.08	0.00	3.18
18	6	1.5	25	−24	39	5.13	48.72	43.59	2.56	0.00	3.57
19	8	1.5	25	−24	39	0.00	61.54	28.21	10.26	0.00	3.52
20	4	3	25	−24	39	5.13	20.51	41.03	33.33	0.00	2.97
21	6	3	25	−24	38	13.16	28.95	50.00	7.89	0.00	3.48
22	8	3	25	−24	38	13.16	52.63	28.95	5.26	0.00	3.74
23	2	5	25	−24	38	0.00	2.63	5.26	42.11	50.00	1.53
24	4	5	25	−24	39	0.00	2.56	35.90	53.85	7.69	2.33
25	8	5	25	−24	39	2.56	30.77	53.85	12.82	0.00	3.23
26	2	30	25	−24	38	0.00	0.00	0.00	13.16	86.84	0.69
27	8	30	25	−24	39	0.00	2.56	20.51	46.15	30.77	1.93
28	16	30	25	−24	39	5.13	46.15	43.59	5.13	0.00	3.52

Table XI—*Continued*

No.	EPL	D	N	V	No. Votes	% Excell.	% Good	% Fair	% Poor	% Unsat.	Fit Mean
29	Source		25	−24	39	5.13	43.59	48.72	2.56	0.00	3.52
30	Source		25	−24	39	5.13	46.15	48.72	0.00	0.00	3.57
31	Source		25	−24	39	15.38	56.41	28.21	0.00	0.00	3.88
32	Source		25	−24	39	23.08	48.72	28.21	0.00	0.00	3.96
33	4	1.5	45	−24	39	0.00	2.56	28.21	64.10	5.13	2.28
34	6	1.5	45	−24	38	0.00	5.26	31.58	60.53	2.63	2.39
35	8	1.5	45	−24	39	0.00	2.56	23.08	58.97	15.38	2.12
36	4	3	45	−24	39	0.00	2.56	28.21	53.85	15.38	2.17
37	6	3	45	−24	39	0.00	5.13	20.51	58.97	15.38	2.14
38	8	3	45	−24	39	0.00	5.13	35.90	56.41	2.56	2.43
39	2	5	45	−24	39	0.00	0.00	5.13	33.33	61.54	1.30
40	4	5	45	−24	39	0.00	0.00	12.82	56.41	30.77	1.79
41	8	5	45	−24	39	0.00	2.56	20.51	61.54	15.38	2.09
42	2	30	45	−24	39	0.00	0.00	0.00	10.26	89.74	0.59
43	8	30	45	−24	38	0.00	0.00	26.32	44.74	28.95	1.95
44	16	30	45	−24	39	2.56	10.26	30.77	48.72	7.69	2.51
45	Source		45	−24	38	0.00	5.26	39.47	47.37	7.89	2.42
46	Source		45	−24	39	0.00	5.13	33.33	56.41	5.13	2.38
47	Source		45	−24	39	0.00	7.69	33.33	48.72	10.26	2.38
48	Source		45	−24	39	0.00	23.08	35.90	30.77	10.26	2.72
49	4	1.5	5	−34	38	2.63	21.05	60.53	13.16	2.63	3.08
50	6	1.5	5	−34	39	5.13	33.33	48.72	7.69	5.13	3.26
51	8	1.5	5	−34	39	7.69	64.10	25.64	2.56	0.00	3.78
52	4	3	5	−34	38	2.63	36.84	31.58	26.32	2.63	3.11
53	6	3	5	−34	38	10.53	18.42	60.53	10.53	0.00	3.29
54	8	3	5	−34	39	7.69	51.28	30.77	10.26	0.00	3.57
55	2	5	5	−34	39	0.00	2.56	2.56	38.46	56.41	1.41
56	4	5	5	−34	39	0.00	0.00	15.38	43.59	41.03	1.70
57	8	5	5	−34	39	5.13	23.08	51.28	17.95	2.56	3.10
58	2	5	5	−34	39	0.00	0.00	2.56	15.38	82.05	0.89
59	8	5	5	−34	39	0.00	2.56	25.64	35.90	35.90	1.93
60	16	5	5	−34	39	5.13	25.64	53.85	15.38	0.00	3.21
61	Source		5	−34	39	12.82	46.15	35.90	5.13	0.00	3.67

62	Source		5	−34	39	15.38	64.10	17.95	0.00	2.56	3.91
63	Source		5	−34	39	5.13	74.36	17.95	0.00	2.56	3.80
64	Source		5	−34	39	7.69	46.15	35.90	10.26	0.00	3.52
65	4	25	25	−34	39	2.56	25.64	46.15	20.51	5.13	3.00
66	6	1.5	25	−34	39	0.00	0.00	58.97	38.46	2.56	2.56
67	8	1.5	25	−34	38	0.00	10.53	68.42	18.42	2.63	2.87
68	4	3	25	−34	39	0.00	10.26	46.15	41.03	2.56	2.64
69	6	3	25	−34	39	0.00	10.26	53.85	30.77	5.13	2.69
70	8	3	25	−34	39	0.00	7.69	69.23	20.51	2.56	2.82
71	2	5	25	−34	39	0.00	0.00	7.69	33.33	58.97	1.38
72	4	5	25	−34	39	0.00	2.56	17.95	56.41	23.08	1.98
73	8	5	25	−34	39	0.00	12.82	56.41	28.21	2.56	2.79
74	2	30	25	−34	39	0.00	0.00	0.00	20.51	79.49	0.89
75	8	30	25	−34	39	0.00	5.13	33.33	33.33	28.21	2.14
76	16	30	25	−34	39	2.56	20.51	53.85	17.95	5.13	2.97
77	Source		25	−34	39	0.00	15.38	56.41	25.64	2.56	2.85
78	Source		25	−34	39	0.00	12.82	71.79	15.38	0.00	2.97
79	Source		25	−34	39	0.00	17.95	58.97	20.51	2.56	2.92
80	Source		25	−34	39	0.00	10.26	64.10	23.08	2.56	2.82

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